*Managing Editors*
**Iqrar Ahmad Khan & Muhammad Farooq**

# Applied Irrigation Engineering


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University of Agriculture, Faisalabad, Pakistan

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# Foreword

The digital age has its preferences. The reading time has been encroached upon by a watching time. The access to information is easy and a plenty where Wikipedia has emerged as the most powerful encyclopedia ever. Yet, a book is a book! We wish to promote the habit of reading books. Finding books is not difficult or expensive (www.pdfdrive.com) but a local context and indigenous experiences could be missing.

The University of Agriculture, Faisalabad (UAF) has achieved global rankings of its flagship programs and acceptance as a leader in the field of agriculture and allied sciences. A competent faculty, the stimulating ecosystem and its learning environment have attracted increasing attention. Publication of books is an important KPI for any institution of higher learning. Hence, UAF has embarked upon an ambitious 'books project' to provide reference texts and to occupy our space as a knowledge powerhouse. It is intended that the UAF books shall be made available in both paper and electronic versions for a wider reach and affordability.

UAF offers more than 160 degree programs where agriculture remains our priority. There are about 20 institutions other than UAF who are also offering similar degree programs. Yet, there is no strong history of indigenously produced text/reference books that students and scholars could access. The last major effort dates back to the early 1990's when a USAID funded TIPAN project produced a few multiauthor text books. Those books are now obsoleted but still in demand because of lack of alternatives. The knowledge explosion simply demands that we undertake and expand the process anew.

Considering the significance of this project, I have personally overseen the entire process of short listing of the topics, assemblage of authors, review of contents and editorial work of 29 books being written in the first phase of this project. Each book has editor(s) who worked with a group of authors writing chapters of their choice and expertise. The draft texts were peer reviewed and language corrected as much as possible. There was a considerable consultation and revision undertaken before the final drafts were accepted for formatting and printing process.

This series of books cover a very broad range of subjects from theoretical physics and electronic image processing to hard core agricultural subjects and public policy. It is my considered opinion that the books produced here will find a wide acceptance across the country and overseas. That will serve a very important purpose of improving quality of teaching and learning. The reference texts will also be equally valued by the researchers and enthusiastic practitioners. Hopefully, this is a beginning of unleashing the knowledge potential of UAF which shall be continued. It is my dream to open a bookshop at UAF like the ones that we find in highly ranked universities across the globe.

Pakistani soils are derived from alluvial deposits of the river Indus and its tributaries. These soils are productive but endangered by salinity/sodicity, nutrient depletion, soil erosion and desertification and low organic matter contents. The rising population and urbanization are also pouching on fertile agricultural lands. This book highlights all aspects of Pakistani soils comprehensively and fills the gap of availability of a proper text in soils sciences.

Before concluding, I wish to record my appreciation for my coworker Dr. Muhammad Farooq who worked skillfully and tirelessly towards achieving a daunting task. Equally important was the contribution of the authors and editors of this book. I also acknowledge the financial support for this project provided by the USDA endowment fund available to UAF.

Prof. Iqrar A. Khan (*Sitara-e-Imtiaz*)
Vice Chancellor
Unviersity of Agriculture, Faisalabad

# Preface

This book has been written for providing information about Pakistan's water resources, its irrigation network and knowledge related to the principles governing sustained management of irrigation system; to Engineers, Professionals and students of various disciplines such as Agricultural Engineering, Civil Engineering and Agricultural sciences. The book is also a valuable resource for those who are engaged in the design, development and management of water resources of the country. Special emphasis has been laid to focus on application of engineering principles in the field. Efforts have also been made to equip the readers of this book with a basic understanding of the fundamental concepts and their practical aspects for better management of irrigation water. The unique feature of the book is that it contains information on local irrigation systems equipped with local terminologies used in the irrigation system, and role of various organizations such as WAPDA, IRSA, PID(s) and PIDA for managing water resources of the country, which is rarely available in the books written by the foreign and other national authors. After reading this book, the individuals will be in a better position to understand the history of the irrigation system in the Indus basin, Pakistan's irrigation network, and development of irrigation canals before and after the Indus Water Treaty (IWT) 1960 including the Water Apportionment Accord (WAA)1991 and water allowances of the main canal commands in the country.

This book is also a valuable reference for those, who want to appear in various examinations and interviews such as those conducted by Public Service Commissions, Selection Boards of the universitiesand other recruiting agencies because every chapter in the book contains MCQ (s), solved examples and exercise problems. The book will also serve as a valuable resource for finding crop water requirements under various agro-climatic zones of the country by using crop factors, specified under such conditions. The book includes guidelines in designing and selecting the most suitable irrigation practices for these cropping zones. The book can also be used as textbook for various professional degree programs and as a reference for technical writings relevant to water resources of Pakistan.

The book comprises 19 chapters, each covering one specialized area of the irrigation engineering starting from the source (watershed) to the point of use of water (agricultural fields). Although, it summarizes the main system of irrigation comprising rivers, dams, barrages, head works, link canals, main canals and distributaries, yet it puts special emphasis on the degree of water losses occurring during conveyance and the availability of water resources at the farms along with its management and use for agricultural purposes focused at crop productivity enhancement. The chapter on system management summarizes the institutions at the federal as well as at the provincial level that are involved in planning, design, development, operation and management of the Irrigation system in Pakistan. The knowledge of Water Laws and Treaties is necessary to understand for management staff of the Provincial Irrigation Departments serving as service providers as well as for the end users to coordinate on the water supply and demand issues. The book also explains the gauging and flow measurement systems installed on the canal network, which, along with water allowances provides the testable basis of water distribution among the shareholders, including neighbor farmers of various commands and also highlighting the potential and contribution of groundwater resources towards meeting crop water requirements.

As groundwater is the second largest contributors of the overall irrigation water supplies in the country, the chapter on Groundwater Management along with pumping technologies further strengthens the state of conjunctive water management in the country. Information supplied on water quality and rules governing the use of substandard water, facilitates the end users to utilize the waters of different qualities in efficient manners under difficult situations. Irrigation and drainage of agricultural lands are complimentary to each other for potential crop production. Therefore, the chapter on Drainage would provide the requisite knowledge to the farmers with a balanced soil-water -plant environment.

It is worth mentioning that this book is part of the UAF book writing initiative, which was launched under the supervision and support of the Vice Chancellor UAF, Prof. Dr. Iqrar Ahmad Khan, whose visionary leadership worked as a catalyst in writing such multi-authored books by various Departments of UAF, which has been ranked recently at 97$^{th}$ position among the top 100 Universities of the world. The authors are deeply indebted to the support and encouragement rendered by the UAF administration for accomplishing this noble task. The authors are grateful to the coordinator of the UAF book writing project, Dr. Muhammad Farooq for his technical guidance and also to the Anonymous reviewers for their valuable feedback and suggestions to improve the standard of this book. Any suggestions / comments are welcome to remove errors and further improve quality of the book.

Prof. Dr. Allah Bakhsh

Prof. Dr. Muhammad Rafiq Choudhry

Chapter1

# Water Resources and Irrigation Network of Pakistan

**Muhammad Arshad and Ramchand N. Oad***

## Abstract

The issues of growing water scarcity have spread due to several factors, including the increasing cost of water development, degradation of soil, mining of groundwater, water pollution, and wasteful use of already developed water supplies. Pakistan has been blessed with adequate water resources, including precipitation, groundwater and surface water. Groundwater of acceptable quality has potential to provide flexibility of water supplies in canal commanded areas and to extend irrigation to rain fed areas. Major source of surface water for irrigation in Pakistan is the Indus Basin Irrigation System. Many potential dam sites exist on river Indus and its tributaries, which can make a substantial contribution to irrigation supplies for agricultural lands, through the substitution of live storage loss of 7.27 BCM for on-line reservoirs; and ensuring the irrigation water supplies for existing projects in all the provinces as per additional allocations under 1991 Water Apportionment Accord. The major rivers of Pakistan originate in the northern highlands of Himalaya, Karakoram and Hindukush mountain ranges and act as tributaries of the Indus River system, which commands an agricultural area of more than 60 mha (0.6 million km$^2$). Following Indus Water Treaty, the country built several link canals and barrages to divert and transfer water from its western rivers to the eastern rivers to serve the areas left unirrigated after the treaty. To utilize these river resources, over the years, several reservoirs, dams, barrages and canals have been constructed to regulate irrigation

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water supplies. This chapter, therefore, presents a summary of rivers, dams, barrages link canals and a network of canals serving the Indus Basin Irrigation System which operates to support agriculture in Pakistan.

**Keywords:** Indus Basin, River, Dam, Barrage, Canal, Water Allowance, Warabandi

# Learning Objectives

- The primary purpose of this chapter is that the reader would learn about the historical developments and operational components of the existing irrigation system in Pakistan.
- To update the knowledge about various sources of water, such as canal water, groundwater and rainfall and their availability for agricultural production and other uses in the country.
- Learn about the rivers, water storage reservoirs and canal irrigation network of the Indus Basin Irrigation System supporting the agricultural production in Pakistan.
- Know about the available supplies of the irrigation system and water distribution at tertiary level.

# 1.1 Introduction

Amongst global resources, water is one of the most important natural resource. It is an essential input to domestic, municipal and industrial activities, and important requirement of agricultural production. Growing national, regional and seasonal water scarcities in the world pose severe challenges to agricultural development and food security (Shabbir et al., 2012; Shakoor et al., 2012; Shakoor, 2015). Agriculture worldwide is by far the largest water user, consuming about 80 to 90 percent of available fresh water. Water has been vital to food security and sustainability of the livelihood, especially in the developing countries. Considering the global importance of water for food security, major conflicts among the nations are just for the access to water. Increasing population in various countries, such as Pakistan, is putting pressure for the efficient use of available water supplies to enhance the crop and water productivity (Chatha et al., 2014; Javed et al., 2015; Mongat et al., 2015).

Water scarcity is a global issue that affects the population of each country. More than 1.2 billion people live in areas of physical scarcity, and about 500 million people are approaching this limit. Another 1.6 billion people, or one fourth of the world's population, face economic water shortage, where countries do not have the required infrastructure to take water from rivers and ground (FAO, 2007). Therefore, developing countries need to search methods to grow more food with the same or less consumption of water. Consequently, the world’s irrigated area would need to be increased by 29% to meet food and nutritional requirements. Thus, irrigation expansion would require construction of additional storage reservoirs and diversion facilities to increase the world’s primary water supplies by 17%. Further, the crop yields would also need to be increased by 38 percent, i.e., from a global average of 3.3 to 4.7 tons per hectare (IWMI, 2000).

As the population continues to grow in Pakistan, the country is approaching a worse water scarcity situation that evidently requires that the available supplies should be managed so that this precious resource is utilized more efficiently on a sustainable basis (Javaid et al., 2012; Arshad et al., 2013). Thus, understanding the irrigation water resources system of Pakistan in terms of its river and canal systems, operational management, availability and distribution of water to support the agricultural production is important for the professionals and planners for handling water and food security issues in the country.

## 1.2 Water Resources of Pakistan

Pakistan has been blessed with a variety of water resources in the form of glaciers, seasonal precipitation, groundwater and surface water through the Indus Basin Irrigation system. The potential and degree of availability of water through these resources is summarized below:

### 1.2.1 Glaciers

Significant part of the Indus River flow originates from Karakoram Himalaya, Western Himalaya, and Hindu Kush Mountains. The role of this runoff for the climatic characterization of the mountain catchments is well recognized, particularly, the glaciers carry great significance in the flow volume and timing of the Indus River and its tributaries, as well as on the potential impact of climate change on this water supply. The role of glaciers in the hydrologic regime of these mountains is due to the inaccessibility and altitude of Himalayan glaciers, which exist at an altitude of 4000 to 7000 meters. Estimates of the potential impact of the glaciers on flow regime are derived based on the available databases and topography obtained from satellite imagery. It is estimated that the surface area of the Upper Indus Basin is about 220,000 km$^2$, out of this, more than 60,000 km$^2$ exist above 5000 m, the estimated mean altitude of the summer season freezing level. The glaciers of the region flowing from this zone have been estimated to have 7000-8000 km$^2$ area below the summer-season freezing level, which is the source of the bulk of the annual glacier melt flowing into the Indus River tributaries. The glacier runoff contributes approximately 24.1 BCM to the total annual flow of the Upper Indus Basin: 17.3 BCM from the Karakoram Himalaya, 2.8 BCM from the western Himalaya, and 3.9 BCM from the Hindu Kush.

### 1.2.2 Rainfall

The regional distribution of average annual rainfall varies from less than 100 mm in Balochistan and Sindh provinces to more than 1500 mm in Northern mountainous areas. About 70 percent of annual rainfall is received during the monsoon period, i.e., the months of July and August. During Rabi season (October to March), it is less than 50 mm in parts of Sindh and more than 500 mm in Khyber PakhtoonKhaw (KPK) provinces. Similarly, the mean rainfall for the Kharif (April to September) season varies from 50 mm in Balochistan to more than 800 mm in the Northern Punjab and KPK. The extreme changing pattern of rainfall results in large variations in flows during the Rabi and the Kharif seasons. Due to this severe aridity, about 92% of areas of Pakistan is facing extreme shortage of water and hence classified as semi-arid to arid.

In terms of availability to crops, rainfall is neither regular nor sufficient. During monsoon, the rainfall intensity and volume is much more than that can be stored in the root zone. A large portion of the rainfall, therefore, either floods the riversides and low lying areas of riverside and results consequential miseries and losses, or flows into the sea without any beneficial use in the country. Most of the monsoon rains are also neither available for crop production nor contribute to groundwater due to runoff. About 16.5 BCM of rainwater contributes to crops in the Indus Basin Irrigation System (IBIS), which is only 13% of the average annual canal diversions (Ahmad, 2005).

### 1.2.3 Groundwater

Groundwater provides an alternate water resource for agriculture. It is estimated that around 33% of the world's population utilizes groundwater. Many countries, such as Pakistan, India, intensively exploit groundwater to supplement the canal water. The abstraction of groundwater has reached to its limits in much of the area of the world, especially in drought zones. The rice-wheat region (Central Punjab) of Pakistan is meeting 70% of their crop water requirements from groundwater (Arshad et al., 2008; Shakoor et al., 2015). Therefore, sustainability of groundwater resource is essential, which depends upon the relative contribution of rainfall to direct infiltration and river inflows for recharge of alluvial aquifers (Shiklomanov, 1997).

Groundwater of acceptable quality has the potential to provide flexibility of water supply in canal commanded areas and to extend irrigation to rain fed areas. If conjunctive surface and groundwater use can be implemented properly, there is a potential for further utilization of lower quality groundwater supported by careful management strategies. Consequently, one main policy issue now is to develop a legal framework for groundwater exploitation that should be environmentally sustainable and viable on long-term basis without causing undermining.

In Pakistan, most of the groundwater resources are stored in alluvial deposits formed by the Indus River and its joining tributaries starting from the Himalayan Mountains to Arabian Sea. The Indus Plain area is 1600 km long and extends over an area of 21 mha. This alluvial deposited plain has extensive unconfined aquifer, which is providing a supplemental source of water for irrigation. This groundwater reservoir has been enriched by the direct recharge from rainfall, river flow, and the continued seepage from the irrigation network of canals, distributaries and watercourses since the last 90 years (Kahlon et al., 2012). The groundwater use in different provinces of Pakistan is presented in Table 1.1. In the Punjab and Sindh, about 79 and 28% of the area is underlain by fresh groundwater, which is used as supplemental irrigation pumped through tubewells.

**Table 1.1** Groundwater Budget in Different Provinces of Pakistan in Normal Year

| Components | Billion Cubic Meter (BCM) |
|---|---|

| | Punjab | Sindh | KPK |
|---|---|---|---|
| Recharge components | | | |
| Recharge from rainfall | 7.99 | 2.42 | 1.08 |
| Recharge from irrigation system | 25.46 | 18.92 | 2.28 |
| Return flow from the GW abstraction | 5.70 | 0.97 | 0.16 |
| Recharge from the rivers | 4.00 | 0.37 | 0.16 |
| Total | 43.15 | 22.68 | 3.84 |
| Discharge components | | | |
| Groundwater abstraction (Public + Private) | 38.00 | 4.30 | 2.18 |
| Non-beneficial ET losses | 2.00 | 16.96 | 0.30 |
| Base flow to rivers | 3.15 | 1.42 | 1.81 |
| Total | 43.15 | 22.68 | 4.29 |
| Net change | 0.00 | 0.00 | -0.45 |

### 1.2.4 Surface Water

The agriculture sector is the one of the major users of water and its consumption will be continued to dominate over all other sectors. Out of a total of 193 BCM of water diverted from rivers, only about 130 BCM are made available annually at the farm level for irrigation. In addition, around 59 BCM are being supplemented from the groundwater resource. Direct rainfall contributes less than 15% of the water supplied to crops. Regarding, land resources, out of the cultivable land of 31 mha, only 16mha is canal commanded. Therefore, Pakistan still has an additional potential of bringing 9 mha of new land under irrigation.

According to Indus Water Treaty, signed in 1960 between India and Pakistan with the coordination of the World Bank, India was given the exclusive right to use the water of rivers Ravi, Sutlej and Bias, whereas the water of western rivers Chenab, Jhelum and Indus was given to Pakistan. This treaty included the replacement works comprising the construction of two major dams (Tarbela and Mangla), 5 barrages and 8 link canals to alleviate the problems. However, due to excessive sediments from the rivers, both dams are losing their capacity and it was estimated that their storage has been lost up to 34% (about 7 BCM, which is virtually equivalent to the storage capacity of one such major reservoir. Pakistan is heading towards a situation of acute water shortage due to increasing population pressure. Per capita surface water availability was 5650 cubic meters in 1951, which has been reduced to less than 950 cubic meters in 2015. Now, Pakistan has reached the stage of “acute water shortage” i.e., less than 1000 cubic meters per capita. Water escapes to the sea below Kotri vary from 10 to 113 BCM with an annual average of over 48 BCM. This surplus water in the rivers is only available during 70-100 days of summer. To save and beneficially utilize this available surplus water, the construction of newdams is essential for the sustainability of irrigated agriculture.

Pakistan has two cropping seasons, Kharif (Summer) and Rabi (Winter). Sowing season of Khari starts from April-June and the crops are harvested in September-October. The summer season crops include rice, sugarcane, cotton, maize, moong, mash, bajra and jowar. The sowing season of "Rabi" starts from October-November and the crops are harvested in April-May. The winter season crops include wheat, gram, lentil (masoor), tobacco, rapeseed, barley and mustard. The crop production depends on timely availability of water. During the year 2012-13, the water availability was 14% less than the normal supplies, but to compare with Kharif-2011, it was 4.4% less. The water availability during Rabi 2012-13 was estimated 39 BCM, which was 12.4% less than the normal availability, but 8.5% higher than the Rabi-2011 crop. The year wise actual availability of surface water during Kharif and Rabi seasons is given in Table 1.2.

**Table 1.2** Actual Surface Water Availability

| Period | Kharif (BCM) | Rabi (BCM) | Total (BCM) |
|---|---|---|---|
| Average system usage | 82.5 | 44.7 | 127.2 |
| 2004-05 | 72.7 | 28.4 | 101.1 |
| 2005-06 | 87.1 | 37.0 | 124.1 |
| 2006-07 | 77.6 | 38.4 | 116.0 |
| 2007-08 | 87.1 | 34.3 | 121.4 |
| 2008-09 | 82.3 | 30.6 | 112.9 |
| 2009-10 | 82.8 | 30.8 | 113.6 |
| 2010-11 | 65.7 | 42.6 | 108.3 |
| 2011-12 | 74.3 | 36.2 | 110.5 |
| 2012-13 | 71.0 | 39.2 | 110.2 |

*Source: Economic Survey of Pakistan, 2012-13*

### 1.2.5 Irrigation and Hydropower Storages

In addition to serving the agricultural sector for meeting crop demand, the water resources are also important for power generation. The national demand of electricity has been growing and would continue to grow rapidly due to increase in population and industrial growth in the country. Presently, the hydel and thermal mix generation capacity in the country is 28:72, against the potential requirement of 70:30 for the economic development. Table 1.3 gives the water storage reservoirs with power generation facilities on various rivers. Although the thermal generation initially helped in overcoming load shedding, yet it resulted in an increase in power tariff. Therefore, construction of hydropower generation units through multipurpose storages is a viable option to keep the electricity cost within affordable limits. In view of the situation, WAPDA prepared a Vision 2025 program for the development of water and power resources of Pakistan. The proposed water storage reservoirs and existing water storage reservoirs with their capacities are given in Table 1.4.

## 1.3 Irrigation Network of Pakistan

The major source of water for irrigation in Pakistan is the Indus River and its tributaries, including Jhelum, Chenab and Kabul rivers. The total canal supplies delivered by the system during 1960-61 were 105 BCM and the irrigated area was about 10.4 mha. The construction of dams enabled the country to enhance capability of river flow regulation. After attaining regulation in storage facilities, canal head diversions progressively increased, which also increased the recharge to groundwater. Presently, the irrigation system is utilizing annually a total of 129.7 BCM of river water diverted through the canal system. There is a potential to further

**Table 1.3** Existing Water Storage Reservoirs

| Dams and Lakes | River | Height of dam (m) | Live storage (BCM) | Power (MW) | Purpose* |
|---|---|---|---|---|---|
| Terbela | Indus | 147.8 | 11.38 | 3478 | I, P |
| Mangla | Jhelum | 115.8 | 5.90 | 1000 | I, P |
| Chashma | Indus | - | 0.75 | - | I, P |
| Warsak | Kabul | 76.2 | 0.05 | 240 | I, P |
| Baran Dam | Kurram | 32.6 | 0.04 | 4 | I, P |
| Hub | Hub | 46 | 0.93 | - | I, W |
| Khanpur | Haro | 50.9 | 0.11 | - | I, W |
| Tanda | KohatToi | 35 | 0.07 | - | I |
| Rawal | Kurang | 34.7 | 0.05 | - | W |
| Simply Dam | Soan | 65.5 | 0.02 | - | W |
| BKD Dam | Pishin | 10.7 | 0.05 | - | I |
| Hamal Lake | - | - | 0.09 | - | I |
| Manchar Lake | Indus | - | 0.92 | - | I |
| Kinjhar Lake | Indus | - | 0.39 | - | I, W |
| Chotiari Lake | Indus | - | 0.95 | - | I |

*I- Irrigation, P- Power, W- Water Supply*
*Source: WAPDA, 2002*

**Table 1.4** Proposed Water Storage Reservoirs and their Capacities

| Proposed Dams | River | Height of dam (m) | Live storage (BCM) | Power (MW) | Purpose* |
|---|---|---|---|---|---|
| Yugo | Syhok | 164.5 | 5.90 | 1000 | I, P |
| Skardu | Indus | 230.1 | 18.99 | 4000 | I, P |
| Bhasha | Indus | 201.1 | 6.98 | 4500 | I, P |
| Kalabagh | Indus | 79.3 | 7.46 | 3600 | I, P |
| Kalam | Swat | 137.1 | 0.32 | 110 | I, P |
| Mir Khani | Chitral | 124.9 | 0.71 | 150 | I, P |
| Khazana | Panjkora | 115.8 | 0.68 | 110 | I, P |
| Munda | Swat | 213.2 | 0.82 | 740 | I, P |
| | | Total | 21.90 | 13070 | |

*I- Irrigation, P- Power*
*Source: WAPDA, 2002*

increase the irrigated area by about 9.2 mha. The irrigation system of Pakistan includes 3 major storage reservoirs (Tarbela, Mangla and Chashma), 19 barrages, 82 small dams and 48 major command canals. Tarbela is the largest dam of Pakistan, which is also believed to be second largest in the world in terms of structural volume with a surface area of 240 square km, and is generating around 3500 megawatts of electricity.

During the post-Tarbela period of 24 years (1976-2000), an annual average of over 46.33 BCM of river flow escaped below the last barrage on the Indus River (Kotri) to the Arabian Sea, concentrated in about 70-90 days of summer only. No crop can be sown and taken to maturity in this short period (but the outflow could be stored for use later). Kharif crops need some water before the start of surplus flow and some water after the surplus ends. Such water availability can be possible from new storage reservoirs. Flow pattern of the Western rivers during the year is quite variable. Those carry high discharges in summer (Kharif) and disproportionately low discharges in winter (Rabi). About 88 percent of the flow occurs during the summer monsoon rains. With the help of Mangla and Tarbela dams, seasonal carry over capacity of Kharif and Rabi seasons was increased from 12to 21%.

The natural siltation is constantly reducing the capacity of the existing storages and according to an estimate this capability has now reduced from 21 to 19%. Their aggregate design gross storage was 22.01 BCM. Consequently, the available supply of canals in Rabi and Kharif for the sowing and maturing periods has been thus, progressively reducing. Development of more water storages is a dire need in the present situation.

Many potential dam sites exist on river Indus and its tributaries, which can make a substantial contribution to irrigation supplies for new irrigation projects. These projects would also contribute to the National Power Grid. Generation of relatively less expensive hydro power has assumed critical importance to keep the power tariff within affordability of consumers in view of large scale very costly induction of private thermal power in our system.

### 1.3.1 Major Rivers of Pakistan

River water is one of the most important sources for agriculture and generating large scale hydropower for industrial and domestic use. Nevertheless, these rivers provide ecological environments for the flora and fauna, where a great variety of plants and animal flourish. The river system of Pakistan includes more than 60 small and large rivers. The major rivers of Pakistan (Fig. 1.1) originate from Himalaya, Karakoram and Hindukush mountainous ranges and join as tributaries of the Indus River and cover an area of 0.6 million kilometers.

The Indus River and its tributaries pass through the Indian area before entering Pakistan. Since 1947, the use of river water and its distribution remained a burning issue between India and Pakistan. The Indus Water Treaty was signed in 1960 between Pakistan and India and accordingly all the water of the eastern rivers (Ravi, Sutlej and Bias)) was given to India, while the water of three western rivers (Indus, Jhelum and Chenab) was available to Pakistan. However, the continuously increasing demand for river water on one hand and inefficient use on the other hand, is putting these resources under extreme pressure. Consequently, its quality and ecosystem has been degraded badly (Khan, 2013). These rivers have been briefly discussed below.


**Fig. 1.1** Indus River System of Pakistan

#### 1.3.1.1 Indus River

The Indus River is the backbone of Pakistan's irrigation network. It originates from the Himalayas, firstly flows north westwards and then turning south to flow through Pakistan before entering the Arabian Sea through the Indus delta of Karachi. Indus River flows through the mountains of Gilgit and the KPK Province of Pakistan, and then across the fertile flood plains of the Punjab and arid deserted regions of Sindh. Indus River is the longest river of Pakistan with a total length of 3180 km (1,980 miles). The total drainage area is about 1,165,000 km$^2$. The annual flow is estimated at 207 km$^3$, and stands as twenty-first largest river in the world in terms of annual flow. In the Punjab plains, its left bank tributary is the Chenab River, which itself has four major tributaries, namely, the Jhelum, the Ravi, the Beas and the Sutlej. Its right bank tributaries include the Shyok, the Gilgit, the Kabul, the Gomal and the Kurram rivers.

In the Indus river, the flowing water level remains at its lowest from December to February and then starts rising at the end of March. The flow remains high during the summer months of April-August. The water level falls rapidly at the start of

October, when the water level subsides more gradually. Indus water plays an important role in the enhancement of agricultural productivity since long time. Following Indus Water Treaty, Pakistan Water and Power Development Authority (WAPDA) constructed several barrages and link canals to transfer water from western to eastern rivers to serve the command areas in the Punjab province. The major link canals linking the Indus, Jhelum, Chenab, Ravi and Sutlej rivers are Chashma-Jhelum, Taunsa-Punjnad, Rasul-Qadirabad, Trimun-Sidhnai, Qadirabad-Bulloki, Bulloki-Sulemanki Sidhnai-Mailsi and Mailsi-Bahawal. These canals also feed irrigation system of the lower Punjab province.

#### 1.3.1.2 Jhelum River

The Jhelum River, which is the westernmost of the five rivers in Punjab, is a tributary to the Indus River. It originates from Vernag of Indian-occupied portion of Jammu and Kashmir. The river passes through the Northern slope of the PirPanjal Range and enters in Wular Lake. Jhelum River crosses the PirPanjal through 2100 m deep gorge with an almost vertical slope. Jhelum River is about 725 km long with highest flood discharges exceeding 28300 $m^3/s$. The spring snowmelt and the monsoon heavy rains from June to September are the sources of water in the river.

#### 1.3.1.3 Chenab River

The River Chenab starts from Kulu and Kangra districts of the Himachal Pardesh state of India. After traversing about 644 km of mountainous regions, it moves toward the plains near Akhnur. River Chenab enters in Pakistan near Diawara village and flows through the alluvial plains of the Punjab for 5467 km. The Chenab River flows through Marala, Khanki, Qadirabad and Trimmu barrages. The average annual flow of this river is 30.37 BCM, out of which 23.83 BCM comes in Kharif and 6.53 BCM in Rabi (Ahmed et al., 2007).

#### 1.3.1.4 Ravi River

Ravi River arises from Himachal Pradesh state of India and flows in Chamba, takes a turn in the southwest along the boundary of Jammu and Kashmir. The river then flows along the Pakistani border for more than 80 km and enters in Pakistan. It joins the Chenab River near Ahmadpur Sial after a course of 725 km. The water of the Ravi depends on spring snowmelt and monsoon that causes heavy rains from June to September.

#### 1.3.1.5 Sutlej River

The longest of the five tributaries of the Indus River, Sutlej Rive originates from the north slope of the Himalayas in Langa Lake of Tibet. It passes through Himalayan gorges, crosses the Indian state of Himachal Pradesh and enters in the Punjab plain near Nangal. Continuing in a broad channel, it also receives the flow of Bias River and forms 105 km border of India and Pakistan and then enters in Pakistan. It flows for a distance of 350 km and then joins the Chenab River in the west of Bahawalpur. The flow in Sutlej is controlled by springs and summer snowmelt in the Himalayas and the rains of monsoon. The 1400 km long Sutlej is used extensively for irrigation.

### 1.3.2 Barrages

To utilize the river water resources for regulating and diverting irrigation water in Pakistan, barrages and canals were constructed. Some of the important barrages of Pakistan with their design discharge are given in Table 1.5. The structures built in the Indus river system and its tributaries for flow regulation are summarized in Table 1.6

**Table 1.5** Barrages of Indus Basin Irrigation System in Pakistan

| Barrages | Year of completion | Max. design discharge (cusecs) | Bays (No.) | Max. flood level from floor (ft) | Total design withdrawals for canal |
|---|---|---|---|---|---|
| Chashma | 1971 | 1,100,000 | 52 | 37 | 26,700 |
| Guddu | 1962 | 1,200,000 | 64 | 26 | - |
| Jinnah | 1946 | 950,000 | 42 | 28 | 7,500 |
| Kotri | 1955 | 875,000 | 44 | 43 | - |
| Sukkur | 1932 | 1,500,000 | 54 | 30 | 47,530 |
| Taunsa | 1959 | 750,000 | 53 | 26 | 36,501 |

**Table 1.6** Structures on Indus River and Tributaries

| S.No. | River | Structure | Year |
|---|---|---|---|
| | Indus River | | |
| 1 | Sukkar | Barrage | 1932 |
| 2 | Kalabagh | Barrage | 1946 |
| 3 | Kotri | Barrage | 1954 |
| 4 | Taunsa | Barrage | 1959 |
| 5 | Guddu | Barrage | 1962 |
| 6 | Chashma Jhelum River | Barrage | 1971 |
| 7 | Rasul | Barrage | 1967 |
| | Chenab River | | |
| 8 | Marala (old) | Barrage | 1912 |
| 9 | Panjnad | Barrage | 1932 |
| 10 | Trimmu | Barrage | 1939 |
| 11 | Qadirabad | Barrage | 1967 |
| 12 | Marala (new) | Barrage | 1968 |
| | Ravi River | | |
| 13 | Balloki | Weir | 1913 |
| 14 | Balloki | Weir (upgraded) | 1965 |
| 15 | Sidhnai | Barrage | 1965 |
| | Sutlej River | | |
| 16 | Sulemanki | Weir | 1926 |
| 17 | Islam | Weir | 1927 |
| 18 | Mailsi | Weir | 1965 |

### 1.3.3 Types of Irrigation System Canals

A canal is an artificial channel constructed to carry irrigation water from a river, dam, barrage or head work to the branch canals and distributaries and further conveyance to the irrigated fields. These canals can be classified as follows:

#### 1.3.3.1 Permanent canals

Permanent canals are those which are fed by a permanent source of water, such as ice fed river or a reservoir. The canal is a well graded channel provided with permanent head works, regulators and distribution works.

#### 1.3.3.2 Perennial canals

Perennial canals are permanent canals which get a continuous supply of water from a given river throughout the year. Such canals can irrigate the fields all the year around at a fairly equitable rate during the entire season of raising crops.

#### 1.3.3.3 Non-perennial canals

Canals, which can irrigate only for a part of the year, usually during the summer season and at the beginning and the end of the winter season, are known as non-perennial canals. They originate from a river, which has no assured supply throughout the year or the supply is not sufficient for the whole year.

#### 1.3.3.4 Inundation canals

Inundation canals are the earliest type of irrigation channels in the country. Inundation is the one in which there is no wear control system and the supply depends upon the periodical rise of water level in the river, from which it takes off. It is not provided with any headwork for diversion of the river flow, but the canal obtains a supply from open cut in the bank of the river or creeks, which are called heads. Due to the change in the river course, the heads should be changed often. A regulator is, however, provided on the canal 5 to 6 km downstream from the off-take point to control the discharge entering the canal. The surplus discharge, if any, is escaped back into the river. Inundation canals usually flow during the summer months but many remain in operation even during the winter season, depending upon the river flow to feed them. They draw large quantities of silt beneficial to crop.

These canals, like other canals, take water from the respective rivers, but the difference is that they get water when there is a flood and a rise in the water level. Therefore, the excess water is utilized in some beneficial way rather than letting it spoil. Inundation canal may be considered as seasonal, but the requirement is fulfilled by perennial canals.

#### 1.3.3.5 Main Canal

The principal channel or a channel system off-taking from a river or a reservoir or tail reach of a feeder is designated as Main canals which is also called Main line. An irrigation channel carrying discharge above 25 cubic meters / second (cumecs) and not used for direct irrigation are called main canals. They take-off in the river and derive water through the head regulator. They act as a carrier canal to feed the branch canals and major distributaries. The main function of such a canal is to carry the total amount of irrigation water from the head and distribute it to the downstream canal system.

#### 1.3.3.6 Branch Canals

Branch canals are irrigation channels taking off from the main canal on either side. Like the main canals, very little direct irrigation is done from them. Its discharge varies from 5 to 25 $m^3/s$. The discharge limit in some cases may be 10 $m^3/s$. Branch canals are usually feeder canals for major or minor distributaries. The main function of the branch canal is to make irrigation water available different parts of the tract for further distribution.

#### 1.3.3.7 Major Distributaries

Distributaries which supply water to other distributaries are major distributaries. Their flow capacity lies between a branch canal and a minor distributary. They are irrigation channels taking off from the branch canals. They can also take off from the main canal but the discharge collected then is less than the branch canal. They carry a discharge varying from 0.25 to 5 cumecs. The upper limit, in some cases, is 10 cumecs. Their main function is to distribute the water to water courses through outlets provided along them. They are called 'Rajbaha'.

#### 1.3.3.8 Minor Distributaries

They take off from the major distributaries or branch canals. They carry discharge less than 0.25 cumecs. Their main function is to reduce the length of water courses or field channels. They are provided when the length of the watercourse exceeds 3 km and are also known as 'minors'.

#### 1.3.3.9 Watercourses or Field channels

The main watercourses are small cannels carrying water from the outlet of a distributary or a minor to the farms, whereas the Field Channels are ones that carry water from the main watercourse to the fields. The main watercourses are owned by the Irrigation Department but constructed and maintained by the irrigators. The canals, branch canals, distributaries and minors are government properties, and are also maintained by the Irrigation Department. Thus, the authority of the government ends at the main watercourses, where water is diverted to the field channels or farmer branches. The Field Channels are constructed and maintained by the farm owners. However, their capacity is the same as the main watercourse to carry full flow rate as available in the main watercourse.

### 1.3.4 Canal Network of Pakistan

The Indus, Jhelum and Chenab Rivers are the main sources of canal water in Pakistan, which have been provided with diversion structures, including a network of main canals, branch canals, distributaries, minors and watercourses. Although the control over the waters of rivers Ravi and Sutlej were given to India through the Indus Water Treaty 1960, yet the major portions of their commanded areas fall in Pakistan. Therefore, the canals originating from each river of the Pakistan's Indus Basin are summarized below. The flow rates in the system are maximum during summer, but minimum during winter seasons.

#### 1.3.4.1 Canals of River Sutlej

Sutlej River has Ferozepur, Sulaimanki, Islam and Punjnad head works. However, Ferozpur headwork falls in the Indian territory. As control over water of River Sutlej was given to India by the Treaty, only the headworks and canals falling in Pakistan are considered here. The canals of Fordwah Eastern Sadiqia and Upper Pakpattan, take off from Sulemanki Barrage to irrigate the area of Nili Bar and Bahawalpur.LBC-Nil and UBC-Nil canals off-take from Islam Barrage. Similarly, Punjnad canal, Abbasia canal and abbasia Link Canal take off from Punjnad Barrage.

#### 1.3.4.2 Canals of River Ravi

River Ravi commands 3 main canals namely, Lower Bari Doab, Upper Bari Doab and Sidhnai canal. Lower Bari Doab takes off from the BallokiHeadworks. The Upper Bari Doab is an old canal, which was constructed in 1868 but has been closed because the control of Madhupur Headworks lies with India. Sidhnai Canal originates from the Sidhnai Headworks at left bank of the river Ravi.

#### 1.3.4.3 Canals of River Chenab

The Upper Chenab Canal (UCC) takes off from the Marala Barrage and Lower Chenab Canal (LCC) originates from the Khanki Barrage. Both the canals irrigate Rice-Wheat, Mixed and Cotton-Wheat zones of Rachna Doab. The Haveli Link Canal off-takes from Trimmu Headworks and irrigates the land in Rechna Doab.

The Lower Chenab Canal is one of the oldest and largest contiguous canal systems in the Rechna Doab area of Punjab, Pakistan. The LCC off-takes from the river Chenab at KhankiBarrage and covers the area between Qadirabad-Bulloki and Trimu-Sidhnai Link canals and small upper area of Qadirabad-Bulloki Link Canal along the river Chenab and lower area along Trimu-Sidhnai Link canal. The LCC was constructed in 1892 and initiated as weir controlled system for agriculture. Over the time, the canal was remodeled to enhance its capacity from non-perennial to perennial. Its commanded gross area is 1.42 mha with 376 cubic meter capacity to carry flow from Khanki Barrage and additional 116 cubic meters through the sub-link from the Qadirabad-Bulloki Link Canal. Administratively, LCC is divided into two command circles, i.e., Lower Chenab Canal East Circle and Lower Chenab Canal West Circle.

#### (i) Lower Chenab Canal East Circle

The Lower Chenab Canal East Circle (LCCE) area is bounded by Ravi River on the Eastern side and is located between the Qadirabad-Bulloki and Trimu-Sidhnai Link canals. The LCC East Circle includes the Mian Ali Branch, Upper Gugera Branch, Lower Gugera Branch and Burala Branch canals, and large network of distributaries, minors and watercourses. The Lower Chenab Canal East Circle has a gross area of 0.803 mha and culturable command area of 0.622 mha in the districts of Hafizabad, Sheikhupura, Faisalabad and Toba Tek Singh. Table 1.7 shows the salient features of various Canal Systems (LCC canal and Link canals).

**Table 1.7** TheAverage Monthly Flows (m$^3$/s) of Various Canal Systems

| Canal | LCC | QB Link | Sub-Link LCC | TS Link | Haveli |
|---|---|---|---|---|---|
| Apr | 175.6 | 529.6 | 108.6 | 118.0 | 122.7 |
| May | 192.6 | 597.6 | 105.7 | 244.5 | 135.9 |
| Jun | 228.5 | 587.2 | 102.9 | 291.7 | 145.4 |
| Jul | 216.2 | 550.4 | 97.2 | 212.4 | 130.3 |
| Aug | 235.1 | 546.6 | 99.1 | 91.6 | 84.0 |
| Sep | 238.8 | 558.8 | 105.7 | 67.0 | 94.4 |
| Oct | 224.7 | 491.8 | 115.2 | 203.9 | 133.1 |
| Nov | 200.1 | 487.1 | 111.4 | 68.8 | 127.4 |
| Dec | 191.6 | 433.3 | 91.6 | 99.1 | 127.4 |
| Jan | 89.7 | 157.7 | 0.9 | 51.9 | 36.8 |
| Feb | 78.4 | 477.7 | 86.9 | 204.9 | 103.8 |
| Mar | 175.6 | 433.3 | 115.2 | 138.8 | 117.1 |

The circle consists of Upper Gugera Division, Lower Gugera Division and Burala Division, each containing subdivisions for the management of the irrigation network. The salient features of the LCC East Circle are given in Table 1.8.

**Table 1.8** Division and Subdivision-wise Salient Features of Lower Chenab Canal East Circle

| Division/ Subdivision | GCA (ha) | CCA (ha) | Channels | Outlets | Q (cumec) |
|---|---|---|---|---|---|
| Upper Gugera Division | 288219 | 230631 | 60 | 1127 | 45.64 |
| Chuharkana Subdivision | 97417 | 70064 | 16 | 329 | 12.45 |
| Mohlan Subdivision | 112694 | 89538 | 25 | 437 | 17.59 |
| Paccadala Subdivision | 78108 | 71029 | 19 | 361 | 15.60 |
| Lower Gugera Division | 265786 | 206413 | 58 | 1046 | 46.93 |
| Bhagat Subdivision | 96394 | 75167 | 19 | 389 | 17.33 |
| Buchiana Subdivision | 81151 | 64178 | 21 | 302 | 13.10 |
| Tarkhani Subdivision | 88240 | 67068 | 18 | 355 | 16.50 |
| Burala Division | 248981 | 185390 | 64 | 960 | 47.07 |
| Kanya Subdivision | 77473 | 56114 | 15 | 302 | 13.05 |
| Sultanpur Subdivision | 60629 | 44524 | 14 | 219 | 11.27 |
| Tandlianwala Subdivision | 110879 | 84752 | 35 | 439 | 22.75 |
| LCC East Circle | 802986 | 622434 | 182 | 3133 | 139.64 |

*Source: Jehangir et al., 2002*

### (ii) Lower Chenab Canal West Circle

The Lower Chenab Canal West Circle (LCCW) is bounded by the river Chenab on its western side and covers a large area between Qadirabad-Bulloki and Trimu-Sidhnai Link canals and a small area below Trimu-Sidhnai /Haveli Link canals. The circle includes Rakh Branch, Jhang Branch and Bhowana Branch canals with a large network of distributaries, minors and watercourses. The circle has a gross area of 0.759 mha and culturable command area of 0.58 mha in the districts of Hafizabad, Faisalabad, and Jhang. The salient features of division and subdivision are given in Table 1.9.

**Table 1.9** Salient Features of Lower Chenab Canal West Circle

| Division/Subdivision | GCA (ha) | CCA (ha) | Channels | Outlets | Q (cumec) |
|---|---|---|---|---|---|
| Faisalabad Division | 173731 | 129393 | 54 | 870 | 27.2 |
| Kot Khudayar Subdivision | 81252 | 51289 | 27 | 405 | 13.8 |
| Aminpur Subdivision | 92479 | 78104 | 27 | 465 | 13.4 |
| Hafizabad Division | 170663 | 138547 | 40 | 766 | 29.3 |
| Sangla Subdivision | 51610 | 40225 | 20 | 246 | 7.1 |
| Uqbana Subdivision | 119053 | 98322 | 20 | 520 | 22.3 |
| Jhang Division | 299890 | 224620 | 75 | 1074 | 52.0 |
| Dhaular Subdivision | 98000 | 66012 | 25 | 379 | 10.7 |
| Veryam Subdivision | 108122 | 94924 | 26 | 382 | 24.4 |
| Wer Subdivision | 93768 | 63684 | 24 | 313 | 16.9 |
| Khanki Division | 115014 | 93565 | 31 | 485 | 27.1 |
| Sagar Subdivision | 115014 | 93565 | 31 | 485 | 27.1 |
| LCC West Circle | 759298 | 586125 | 200 | 3195 | 135.6 |

*Source: Jehangir et al., 2002*

**(iv) Qadirabad-Balloki Link Canal**

The Qadirabad-Bulloki Link Canal off-takes from the Qadirabad Barrage on the Chenab River and it was constructed 1960 to transfer 527 cumecs of water to the Ravi River at Balloki Headworks and to the LCC through a Sub-link Feeder canal. The canal constructed under the second phase of the Indus Basin Resettlement Plan and is 130 km long (Ahmed, 1988).

**(v) Trimu-Sidhnai and Haveli Link Canals**

The Trimu-Sidhnai and Haveli Link canal off-takes from the TrimuBarrage on the River Chenab, downstream of the confluence of the Jhelum River. The Trimu-Sidhnai Link Canal is 70 km long, has 312 cumecs and was constructed in1960 under the first phase of the Indus Basin Resettlement Plan (Ahmed, 1988). The Haveli Link Canal was constructed in 1930 to supply the Sidhnai Canal and has the capacity to carry 140 cumecs with command area of about 80,000 hectares.

### 1.3.4.4 Canals of River Jhelum

Upper Jhelum and Lower Jhelum canals lie in Chaj Doab. The Upper Jhelum canal off-takes from Mangla reservoir and it join the Chenab at Khanki and provide its surplus water to the lower Chenab Canal. The Lower Jhelum Canal off-takes from the Rasul Barrage, constructed on Jhelum River.

### 1.3.4.5 Canals of River Indus

The Thal canal originates from Jinnah Barrage near Kalabagh to irrigate the desert area of Thal Doab for agricultural purpose. The agricultural land of district D.G.

Khan and D.I. Khan are irrigated by link canals from Chashma, Taunsa and Guddu barrages.

## 1.3.5 Water allowance

Water Allowance is the quantity of irrigation water allowed for 1000 acres of culturable land. This also helps in designing an outlet for its command area. The Indus Basin Irrigation system was developed through clever engineering and human effort; it is not a natural gift. It needs good management if we want to maintain a high level of performance in the form of adequate water supplies. The details of major canals of Punjab Province with their water allowances and commanded areas are given in Table 1.10.

**Table 1.10** Water Allowance and Commanded Areas of Major Canals in Punjab Province

| Canal Name | Canal command area (ha) | Million ha | Acres | FSD | Water allowance |
|---|---|---|---|---|---|
| Thal Canal | 1089870 | 1.090 | 2691978.9 | 6000 | 2.23 |
| Upper Jehlum Canal | 268514 | 0.269 | 663229.0 | 1900 | 2.86 |
| Lower Jehlum Canal | 706405 | 0.706 | 1744821.4 | 5300 | 3.04 |
| Marala Ravi Canal | 65852 | 0.066 | 162655.1 | 2000 | 12.30 |
| Upper Chenab Canal | 434468 | 0.434 | 1073135.3 | 7800 | 7.27 |
| LCC (Jhang branch + Gugera) | 1530379 | 1.530 | 3780036.9 | 12000 | 3.17 |
| Raya Branch (BRBD Internal) | 179098 | 0.179 | 442372.6 | 3100 | 7.01 |
| Central Bari Doab Canal | 314574 | 0.315 | 776998.8 | 7000 | 9.01 |
| Lower Bari Doab Canal | 762006 | 0.762 | 1882153.9 | 8000 | 4.25 |
| Rangpur Canal | 158088 | 0.158 | 390477.3 | 2700 | 6.91 |
| Upper Dipalpur Canal | 171826 | 0.172 | 424409.5 | 2100 | 4.95 |
| Lower Dipalpur Canal | 248314 | 0.248 | 613335.1 | 4000 | 6.52 |
| Muzffgarh Canal | 323394 | 0.323 | 798782.5 | 6500 | 8.14 |
| Sidhnai Canal | 346552 | 0.347 | 855983.1 | 4500 | 5.26 |
| Pakpattan Canal | 454748 | 0.455 | 1123228.5 | 6600 | 5.88 |
| Fordwah | 214748 | 0.215 | 530428.0 | 3400 | 6.41 |
| Dera Ghazi Khan Canal | 399739 | 0.400 | 987356.0 | 8500 | 8.61 |
| Mailsi Canal | 434955 | 0.435 | 1074337.9 | 6100 | 5.68 |
| Sadiqia Canal | 465805 | 0.466 | 1150539.2 | 4900 | 4.26 |
| Bahawal Canal | 325066 | 0.325 | 802913.6 | 5500 | 6.85 |
| Abbasia Canal | 64550 | 0.065 | 159439.1 | 1100 | 6.90 |
| Panjnad Canal | 598151 | 0.598 | 1477431.9 | 9000 | 6.09 |

*Source: Punjab Irrigation Department*

### 1.3.6 Warabandi

The irrigation water allocation to the farmers is managed through Warabandi (turn) system. Warabandi is a rotational way for equitable distribution of water in the irrigation system by fixed turns according to a predetermined schedule. The water is distributed in the specified year, day, time and duration of supply to each irrigator in proportion to the size of farmers' landholding in the outlet command. The cycle of warabandi starts from the head and proceeds to the tail of the watercourse. During each turn, the farmer has the right to use all the water flowing in the watercourse at his specified turn. The main canals, distributaries and minor are managed by the provincial irrigation departments and deliver water at the head of watercourses through an outlet, which is designed to provide a quantity of water proportional to the culturable command area of the watercourse.

Presently, Kacha and Pakka warabandi systems are in practice in Pakistan, which has been decided by the farmers solely on their agreement, without formal involvement of any government agency. Warabandi system is expected to achieve two main objectives, such as water use efficiency is to be and equity in distributing water per unit area among all users.

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## Chapter 2

# Irrigation System Management

**Muhammad Rafiq Choudhry and Muhammad Irshad***

## Abstract

Efficient performance of any physical system, such as irrigation system, is dependent on many parameters such as design, infrastructure, operation and maintenance, coordination among the stakeholders and above all a devoted and well organized system management. Pakistan's irrigation system has been operative since 19th century. It is managed primarily at provincial level jointly by the Irrigation Department and PIDA and supported by many other organizations at Federal Level such as Ministry of Water and Power (MoW & P), P & D, IRSA, WAPDA, etc. Whereas, the Provincial Irrigation Department is a service provider and manager, the farmer is the end user and beneficiary of the system. The system operation cannot meet its objectives unless all the stakeholders understand the organizational set up, legal framework and operational rules of the system. Therefore, the chapter presents the concept and purposes of system management, management scenario at the world level as well as at national, provincial and command levels. The authorities, responsibilities as well as the contribution of Institutions at provincial and federal levels to strengthen and regulate the irrigation system of the country have been summarized that would enable the reader to understand which institution would respond to an activity. The chapter further explains the management system and functionaries of the Provincial Irrigation Departments such as Secretary, chief Engineers, Ex. Engineers and Sub Divisional Officers and Provincial Irrigation and Drainage Authorities such as PIDA, Area Water Boards and Farmer Organizations, particularly, regarding the Punjab Province. The chapter would facilitate the reader to update his knowledge about the organizational components of the system such as

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zones, circles and divisions along with the responsible authorities. The information provided by this chapter, along with other chapters of the book, including Water Resources, Water Law, Flow Measurements, Crop Water Requirements, Irrigation Methods, Irrigation System Issues and Drainage Requirements of Irrigated Lands; would enable the Engineers, Agricultural Professionals and the farmers to understand the management system and carry out their professional activities in line with the principles and rules of the system.

**Keywords:** System, Management, Operation and Maintenance, Water Laws, System Components-Zones and Circles, Management Functionaries, Responsibilities and Authorities

## Learning Objectives

The major objective of the chapter on Irrigation System Management is that the reader should be aware of the Pakistan's institutions and their organizational set up that are involved in planning, design, development, operation and maintenance of the irrigation system such that the services are delivered to the end users of the water in efficient and productive manner in accordance with the policies and rules of business. The readers may comprise Engineers, Managers, policy makers, farmers and the professional students. The other objectives may include updating professional knowledge about the following:

- Historical Developments and chronological improvements in the Irrigation System.
- Stakeholders of the Irrigation System and their role in execution, operation and maintenance.
- Activities of various Institutions involved in Project Planning, design, development, policy implementation, operation and maintenance of the irrigation system.
- Hierarchy of Irrigation System Management at Federal and provincial levels.
- Responsibilities and areas of Jurisdiction of Management Positions in the Irrigation Department and PIDA.
- Scope of Management Transfer of Irrigation System to Provincial Irrigation and Drainage Authorities.
- Irrigation System Management Issues and Options.

## 2.1 Introduction

Management can be defined as the organization and coordination of the activities of an enterprise in accordance with certain policies and objectives defined by the organization. Management in all systems, business and organizational activities is the act of coordinating the efforts of people to accomplish desired goals using available resources efficiently, and providing services to the end users in the most productive manner. It comprises planning, organizing, staffing, directing and controlling an organization or a group of one or more subsystems, and make efforts for accomplishing a set of goals and objectives. Since organizations such as Pakistan's Irrigation System can be viewed as a system, management can further be defined as human actions to facilitate the service providing activities leading to enhanced agricultural production activities from the irrigation and drainage systems.

In terms of Irrigation System Management, the system has been developed and is being operated with a set of goals to be achieved through planning, organizing and implementing policies to achieve the goals of facilitating the end users of irrigation water for enhancing crop production activities. Irrigation System Management is therefore, playing a key role in utilizing the water resources in a disciplined manner by overcoming the day to day problems and implementing the policies leading towards achieving maximum benefits from the available resources.

### 2.1.1 Managing Irrigation Water in the World

Water is the most important component of life on the earth. It covers 71% of the Earth's surface where 96.5% of the planet's water is found in seas and oceans, 1.7% as groundwater, 1.7% in glaciers and the ice caps of Antarctica and Greenland, a small fraction in other large water bodies, and 0.001% in the atmosphere in the form of vapors and precipitation. Only 2.5% of the water that reaches the Earth's surface, can be considered as freshwater. Out of this, less than 0.3% is available in rivers, lakes, and the atmosphere, which may be available as irrigation water for crop production and other uses for industrial, livestock and domestic purposes. Irrigation System Management is supposed to manage this component of the water as well as that present as groundwater.

It is estimated that approximately 70% of the available fresh river water is utilized for agricultural purposes, 7 percent for domestic and industrial purposes. Although access to safe drinking water has improved over the last decades in almost every part of the world, yet approximately one billion people in the developing regions of the world lack access to safe water. Some observers have estimated that by the year 2025, more than half of the world population may be facing serious water deficits. A recent report suggests that by the year 2030, water demand will increase by 50% (Sheikh, 2012).

To feed the growing population of the world, the food requirements continue to increase while the available water resources to produce food remain limited. The situation, therefore, emphasizes that the available water resources must be utilized with minimum loss opportunities, which require efficient management mechanism. Surface flows face several sources of water losses in the watersheds, rivers, canals, distribution system and fields. Even the controlled irrigation systems may lose large quantities of water through floods and breaches through the conveyance systems, bank erosion, undesirable storage on the banks and deep percolation opportunities. Poor management of the farms and fields would further cause unrecoverable losses to the available water resources. Under the increasing demand scenario, further shrinking of water resources cannot be permitted. To ensure sustained water supplies, efficient system management must be carried out at all levels, i.e., from the watersheds to the point of application and use in the field.

### 2.1.2 Managing Irrigation Water in Pakistan

Water resources in Pakistan are derived through the Indus Basin Irrigation System (IBIS) supplemented with groundwater exploitation and rainfall as summarized below. The system is being managed at different levels by various institutions such as Ministry of Water and Power (MoW&P), Indus River System Authority (IRSA), Federal Flood Commission, Planning Commission, Water and Power Development Authority (WAPDA), Dams and Barrages Safety Councils at federal level and Provincial Irrigation Departments at provincial level including Punjab Irrigation Department (PID), Sindh Irrigation Department (SID), KPK Irrigation Department (KID) and Baluchistan Irrigation Department (BID). Provincial Irrigation Departments exercise their control over all the components of canal irrigation system including main canals, branch canals, distributaries, minors and main watercourses. Before induction of Provincial Irrigation and Drainage Authorities (PIDAs), the farmers were involved only at the tertiary level for maintenance of the main watercourses and field channels. Under PIDA Act (1979), the farmers are being involved in the management and maintenance of the irrigation system from branch canal to the watercourses through various farmers' elected bodies.

### 2.1.3 Indus Basin Irrigation System

The Indus Basin Irrigation System extends over most the Irrigated areas of Pakistan and some areas of India, China and Afghanistan. With the creation of Pakistan in 1947, the Indus Basin Irrigation System was divided between India and Pakistan without considering the irrigation boundaries and commanded areas. Soon after partition, India stopped the canal water supply to one of the eastern river commands by closing the Ferozpur head works. This resulted in the creation of international water disputes in 1948 between Pakistan and India, which was finally resolved by the enforcement of the Indus Waters Treaty in 1960 with the mediation of the World Bank. Accordingly, the rights of three eastern rivers (Ravi, Beas and Sutlej) were given to India, with an estimated total mean annual flow of 33 million acre feet (maf) and the three western rivers (Indus, Jhelum and Chenab) were given to Pakistan with an estimated annual flow of 139 maf. This division of river water resources deprived Pakistan of the water required to irrigate vast areas, commanded by the eastern rivers in southern Punjab. Therefore, the treaty also provided for the transfer of irrigation supplies from the western rivers to areas through Link canals under the Indus Basin Development Plan to compensate for the perpetual loss of the eastern waters.

The Indus Basin Reconstruction Project included Tarbela Dam, Mangla Dam, 5 barrages, 1 siphon and 8 link canals, which were completed during 1960-76. The Kotri, Taunsa and Guddu Barrages on the Indus River were completed during the post partition time to provide controlled irrigation to areas previously served by inundation canals. Three additional inter-river link canals (Triple Canal Project, constructed during 1907 –1915) were built prior to the initiation of the Indus Basin Project. The link canals linked the Indus, Jhelum, Chenab, and Ravi rivers, allowing a transfer of some water from the Indus, Jhelum and Chenab to the rivers Ravi and Sutlej.

The Pakistan's Indus Basin Irrigation System is the largest contiguous gravity flow irrigation system that serves the Indus River and its tributaries, namely, Jhelum, Chenab, Ravi and Sutlej rivers. It consists of 3 major storage reservoirs, 19 barrages, 2 Headworks, 2 siphons across major rivers, 12 link canals, 44 independent canal commands (23 in Punjab, 14 in Sindh, 5 in KPK and 2 in Balochistan) and more than 107,000 main water courses commanding an irrigated area of 16 million hectares. The aggregate length of the canals is about 56,073 km. In addition, the watercourses, farm channels and field ditches are estimated cover a length of about 1.6 million km. A typical watercourse command ranges between 200 and 800 acres with an average of 400 acres (Anonymous, 2005).

The irrigation system of Pakistan further utilizes over 41.6 maf of groundwater, pumped through more than 700,000 public and private tubewells. Outside the Indus Basin, there are several smaller river basins, which drain directly to the sea. Out of these, one is located on the Mekran coast of Balochistan and the other one at the closed basin of Kharan. The total amount of inflow from both the systems is less than 4 maf annually. These streams are flashy in nature and do not have a perennial supply. About 25% of their inflow is used for flood irrigation. Thus, these systems' inflow cannot be merged into the overall annual river flow of the Indus Basin System. Currently, the total annual surface water diversions at the canal heads of the Indus Basin irrigation system are about 105 maf (Anonymous, 2005)

The total geographical area of Pakistan is 709.11 million hectares (mha). Out of this, only 34 mha area is suitable for agricultural production, while only 20.1 mha area is practically cultivated. The irrigated area in all the 4 provinces is estimated as 16 mha. The remaining cultivated area is rain fed. Although, some area is double cropped, about half of the cultivated area remains fallow during one cropping season (Rehman, 1993).

In addition to the river flows, incident precipitation and groundwater are the two major sources of surface water used to meet the requirements of agriculture and other sectors in Pakistan. Mean annual rainfall varies from less than 100 mm in Baluchistan and parts of Sindh provinces to over 1 500 mm in the foothills and northern mountains. The contribution of rainwater to crops in the Indus Basin Irrigation System (IBIS) is about 10 percent of the mean annual river flow (Choudhry, 1987). According to an estimate reported by Choudhry (1987), about 50 percent of the crop requirements is contributed by the groundwater and the canal irrigation system meets the remaining 40 percent requirements.

The Indus Basin river system makes a prime source of water for Pakistan's agriculture, which provides for an income source to about 75 percent of the country's population and contributes about 25 percent to the GDP of the country. It engages about 45 percent of the country's labor force and provides a sound base for the economy in terms of export and foreign exchange earnings. Success of agriculture, mainly depends on the consistent and equitable supply of irrigation water. In addition, the irrigation system supports to meet the water needs of industries, animals, domestic use and recreational facilities. Thus, water is directly or indirectly playing a pivotal role in the development of civilization in this part of the world.

Since the birth of civilization, the irrigation water in the Indus Basin has been playing a pivotal role in the establishment and development of the society by providing basic necessities of drinking water, food and fiber in the form. It converted nomadic life of man and animal into settled civilizations. Settlements of most of the prominent cities of the country on river banks such as, Lahore, Jhang, Harappa, Kamalia, Multan, Hyderabad, Sukker and Mohnjo Daro are good examples of water based settlements and developments of the country.

### 2.1.4 Management Perspective of Flooding and Inundation Systems

Although, the history of Indus Basin dates back to the unknown period of many centuries recorded with the first settlement of human kind in the region, yet its utility and importance has been remarkable during all periods and has been further growing with the development of the civilization. Initially, the water of the rivers was diverted through flooding of the areas along the banks of the rivers and growing food to meet the basic needs of the nomadic settlements (Randhawa, 2002). Crop productivity and water use efficiency at that time were never considered priority issues. Thus, man did not exercise any significant control on the movement or use of water. With the development of sustained settlements and their growing needs, the concept of inundation canals was introduced that helped to irrigate areas farther from the river banks during the flood periods. This provided a better control on the water at least during flood periods. However, no significant management of water supply system existed because water was not considered a scarce commodity and each user could use as much quantity of water to satisfy his needs. Until that time, irrigation was undertaken through a network of inundation canals, which were functional only during periods of high river flow. The inundation canals could only irrigate the flood plains where land was relatively flat and sloped downwards from the river banks. Thus, these canals provided water mainly for *kharif (*summer) crops and some soil moisture for *Rabi (*winter) crops. Consequently, inundation canals were mainly developed in Sindh and southern Punjab near Panjnad. Only limited number could take off from upper Indus, Jhelum, Chenab, Ravi and Sutlej rivers. The main inundation canals included Upper Sutlej, Lower Sutlej, Shahpur, and Chenab in Punjab; whereas, Rohri, Fuleli, Pinyari, and Kalri in Sindh.

Historically, the Emperor Feroz Shah Tughlaq initiated the construction of Inundation canals for the spread of civilization during middle of the $19^{th}$ century. Unlike the canals under weir controlled system, which are taken out from dams, barrages and headworks, the inundation canals were taken out directly from the rivers. The last inundation canals were connected to weir controlled supplies in 1962 with the completion of Guddu Barrage on Indus River (Anonymous, 2005). Today's Irrigation management system was not in force with the inundation canals. The primary consideration in supplying water was the satisfaction of water needs for the land of individual farmers. The system operated primarily to support civilization and human settlement rather than the water distribution focused on production potential.

### 2.1.5 Management Perspective of Weir Controlled System

The conversion of inundated irrigation system of old civilization/ settlements to weir controlled system was initiated by the British Engineers in the middle of the 19th century during British Regime. Weir controlled irrigation began in 1859 with the completion of the Upper Bari Doab Canal (UBDC) from Madhopur Headworks (now in India) on Ravi River. Until that time, irrigation was undertaken through a network of inundation canals, which were functional only during periods of high river flow. However, after the construction of barrages these canals were no more inundation canals, but got regulated water supply and some of them have become perennial while few are non-perennial. The inundation canals were, therefore, improved and reconstructed to regulate perennial canal by installing weirs, and barrages across the rivers. The canals were further regulated through head works, controlled diversions and outlets and by installing gauging stations to facilitate regulated and measured quantities of water to different commands. With the development opportunities induced by the British, the human settlement was also made more established by improving railways, roads, land ownership and village management through "Numberdar" system.

Under Weir Controlled system, the Upper Bari Doab Canal (UBDC) was followed by Sirhind Canal from Rupar Headworks on Sutlej in 1872 (presently in India) and Sidhnai Canal from Sidhnai Barrage on Ravi in 1886. The Lower Chenab canal was constructed on the Chenab River in 1892, and Lower Jhelum originating at Rasul on Jhelum in 1901. Lower and Upper Swat, Kabul River and Paharpur Canals in KPK were completed during the period 1885 to 1914. The water supplies of the individual rivers were not sufficient to serve the potential irrigable lands. For example, the Ravi River, serving a large area of Bari Doab, was deficient in supply while Jhelum had a surplus supply. The problem of imbalanced supply and demand was solved by developing the Triple Canal Project, constructed during 1907–1915. The project linked the Jhelum, Chenab, and Ravi rivers, allowing a transfer of surplus waters of the Jhelum and Chenab to the river Ravi. The Triple Canal Project acted as a milestone in the integrated inter-basin water resources management and provided the key concept for the resolution of the Indus Waters Dispute between India and Pakistan in 1960. The Sutlej Valley Project, comprising 4 barrages and 2 canals, was completed in 1933, resulting in the development of the unregulated flow resources of the Sutlej River. During the same period, the Sukkur Barrage and its system of 7 canals serving 2.95 million hectares of land in the Lower Indus were completed. Haveli and Rangpur canals from Trimmu Headworks on Chenab were constructed in 1939 and Thal Canal from Kalabagh Headworks on Indus, were completed in 1947.

## 2.2 Irrigation System Management in Pakistan

The Irrigation System of Pakistan with its water resources and components (Watershed, Rivers, Dams, Barrages, Head works, canals, distributaries, minors, watercourses and irrigated fields), is managed by different institutions of the country at different levels, including the Ministry of Water and Power, Planning Division, IRSA, WAPDA, Provincial Irrigation Departments and PIDA. For example, WAPDA exercises its control over design, construction and operation of Dams under the umbrella of the Ministry of Water and Power, while the barrages, head works, main canals, distributaries, minors and main watercourses along with canal outlets in the province, are mainly controlled by the provincial Irrigation Departments. Distribution of canal water among the provinces is the subject of IRSA based on the flow rates recorded at Rim Stations and the ongoing needs and rights of the provinces. Planning and development of mega water resource projects are carried out by the Planning Division Govt. of Pakistan. The management of canal water released by IRSA to the Provinces, is controlled by the Provincial Irrigation Departments and PIDAs for the operation and maintenance of the system as well as for supplying water to the end users. Thus, management of the system is practically spread over many federal and provincial institutions as summarized below.

### 2.2.1 Objectives of Water Sector Management

The following have been the major objectives of the water sector in Pakistan for its desirable performance:

- Development and implementation of policies and rules to help the water users for potential production.
- Development and integrated use of water resources, including canal water, rain water and groundwater.
- Conservation measures through development of water reservoirs, lining of irrigation channels, rehabilitation of irrigation system and watercourses improvement etc.
- Surface and sub-surface drainage of agricultural lands through, surface and subsurface drainage systems.
- Protection of infrastructure from flood damages and maintenance of irrigation and drainage systems.
- Institutional strengthening, capacity building and human resources development to operate and maintain the irrigation system successfully.
- Utilize the available resources efficiently by minimizing water losses and introducing efficient irrigation systems

To achieve the above given objectives for Pakistan's water resources development, the Government has established several institutions for managing irrigation water with funding opportunities from national and international institutions as given below:

### 2.2.2 Irrigation System Management Institutions

#### 2.2.2.1 Managing Institutions at Federal Level

- Ministry of Water & Power (MoW&P)
- Indus River System Authority (IRSA)
- Federal Flood Commission (FFC)
- Planning Commission (PC)
- Water and Power Development Authority (WAPDA)

#### 2.2.2.2 Managing Institutions at Provincial Level

(i) Provincial Irrigation Departments

- Punjab Irrigation Department (PID)
- Sindh Irrigation Department (SID)
- KPK Irrigation Department (KID)
- Balochistan Irrigation Department (BID)

(ii) Provincial Irrigation and Drainage Authorities

- Punjab Irrigation and Drainage Authority (PIDA)
- Sindh Irrigation and Drainage Authority (SIDA)
- KPK Irrigation and Drainage Authority (KIDA)
- Baluchistan Irrigation and Drainage Authority (BIDA)

### 2.2.3 Financial Assistance Institutions

- Federal Government of Pakistan
- Provincial Governments through their development programs
- World Bank
- Asian Development Bank
- JICA
- ACIAR
- IFAD
- CEIAR

### 2.2.4 Responsibilities of Irrigation Management Institutions

The administrative set up and responsibilities of both the federal and provincial irrigation management institutions are summarized below.

#### 2.2.4.1 Ministry of Water and Power (MoW&P)

Ministry of Water and Power has established a Management and Policy Implementation Unit (PMPIU) to implement the Asian Development Bank Financed Technical Assistance Program (TAP) and the World Bank (WB) assisted Water Sector Capacity Building and Advisory Services Project and a locally financed Feasibility Study of Small Dams and Rainwater Harvesting etc. It operates under the Federal Secretary, Ministry of Water and Power (MoW&P) through Project Director, Team Leader and Director Technical.

The Technical Assistance Program (TAP) has been engaged in building professional capacity and skills at IRSA, Water Wing of Ministry of Water and Power, Dams and Barrages Safety Organization, through the provision of latest technology, equipment, training, conducting special studies etc. for efficient and effective handling of the essential matters concerning the development of water resources through construction of large water reservoirs projects and the development activities being carried out under Vision 2025. It also contributes in the management of existing water resources through capacity building programs. Most of the field programs in water and power sectors are implemented through Water and Power Development Authority.

#### 2.2.4.2 Indus River System Authority (IRSA)

The Indus River System Authority (IRSA) is the federal authority for making water allocations to the provinces according to the predetermined share of water allocated under the treaties, accords and policy decisions taken by the Government of Pakistan from time to time. It was created in 1992 to implement the Water Apportionment Accord 1991 that was unanimously agreed among the Federal Government and 4 Provinces of Pakistan. Since its creation, IRSA has functioned effectively to judiciously allocate available water supplies and resolve inter-provincial disputes emerging from time to time.

The IRSA commands Indus Basin System water resources generated through the Tarbela reservoir on the Indus river, the Mangla reservoir on the Jhelum River, the network of link canals constructed under the Indus Replacement Works Program as a part of the Indus Water Treaty, and the system of barrages to divert water into the canals, some of which had existed since the 19th century. IRSA's policy decisions are also based upon the seasonal estimates of water availability in the river system. Water Apportionment Accord 1991 provides the bases under which the available water resources are apportioned to the provinces. It also takes decisions for sharing any surplus or shortage of river flows and incidental demands of the provinces. Thus, IRSA acts as an autonomous management body for the overall distribution of irrigation water among the provinces of the country, according to the predefined apportionment at the beginning of each crop season.

The rules governing the establishment and functioning of IRSA in accordance with the IRSA Act 1992 included:

- The Authority shall consist of five members, to be nominated one by each Province and one by the Federal Government from amongst high-ranking engineers in Irrigation or related engineering fields.
- The first Chairman shall be the member nominated by the Government of Balochistan and further followed by the nominees of the Governments of KPK, Punjab and Sindh Provinces and lastly by the Federal Government Representative and thereafter in the same order as given above.
- The term of office of the Chairman shall be one year and that of a member three years.
- Any member shall be eligible for re-appointment for one or more terms or of such shorter term as the Provincial Government or the Federal Government may decide.
- The Chairman and any member may, by writing addressed to the Secretary to the Government of Pakistan, Water and Power Division, resign from his membership position, if the resignation shall not take effect until it is accepted by the Federal Government.
- In the absence of the current Chairman, the member next due for appointment as Chairman (as mentioned in the chairman position cycle

given above) shall act as the Chairman to hold IRSA meetings till the actual chairman joins the position.

- In the absence of a member representing a Province, the Secretary Irrigation Department of the relevant Province shall represent that Province.
- In the absence of any member nominated by the Federal Government, the Chief Engineering Adviser, or his nominee shall represent the Federal Government in IRSA meetings.
- The Chairman of the Water and Power Development Authority and Chief Engineering Adviser, or their nominees shall be ex-officio members of the Authority, but they shall have no right to vote for decisions.

**(i) Powers and Duties of IRSA**

The duties of the IRSA include:

- Monitor the river flows at rim stations and gauging points and consequent releases of water to the provinces of the country. IRSA can take decisions on the methods and techniques of measuring river flows at predefined stations.
- Develop and elaborate the basis for the regulation and distribution of surface waters amongst the Provinces according to the allocations and policies mentioned in the Water Accord 1991.
- Review and specify river and reservoir operation patterns and periodically review the system of such operation.
- Coordinate and regulate the activities of the Water and Power Development Authority in exchange of data between the Provinces about the gauging and recording of surface water flows.
- Determine priorities regarding sub-clause (c) of clause 14 of the Water Accord for river and reservoir operations for Irrigation and hydropower requirements.
- Compile and review canal withdrawal indents as received from the Provinces on 5-daily or on 10-daily basis, as the case may be, and issue consolidated operational directives to Water and Power Development Authority for making such releases from reservoirs as the Authority may consider appropriate or is consistent with the Water Accord.
- Settle any question that may arise between two or more Provinces in respect of distribution of river and reservoir waters.
- Consider and make recommendations on the availability of water against the allocated shares of the Provinces within three months of receipt of fully substantiated water accounts for all new water projects for the assistance of the Executive Committee of the National Economic Council.
- Follow regulations pertaining to the distribution of the flow- cum-storage of waters, as per sub-section (1) (d), (e) of section 8 of the Act.
- Settle any question in respect of distribution of river and reservoir waters, if and when it arises between two or more Provinces, as per sub-section (f) of section 8 of ibid.

- Consider and make recommendations on the availability of water, against the allocated share of the Province concerned, whenever a new water project is received, as per sub-section 1 (g) of section 8 of the Act.
- Settle any question that may arise in respect of implementation of the Water Accord 1991, as per sub-section (2) of section 8.
- Consider such matters as are to be referred to the Advisory Committee (explained below), at the start of Kharif and Rabi cropping seasons, as per section 10 ibid.
- Decide administrative and financial matters, as per chapter IV and VI of the Act.
- Consider any matter under the Act that may arise at any time and take appropriate decision.

**(ii) Advisory Committee of IRSA**

The Advisory Committee of IRSA consists of the following members:

- Chairman, who shall also be the Chairman of the Advisory Committee;
- Provincial members of the Authority
- Chief Engineering Adviser to the Government of Pakistan
- Members, Water and Power Development Authority, in-charges of Water and Power Wings
- Secretaries, Agriculture Departments of the Provinces; and
- Secretaries, Irrigation Departments of the Provinces.

### 2.2.4.3 Federal Flood Commission (FFC)

The Federal Flood Commission was established in 1977. It prepares integrated national flood protection plans for the country, standardizes designs and specifications of flood works, monitors and improves flood forecasting and warning capabilities of concerned organizations. Up to the end of 1976, Provincial Governments were responsible for planning and execution of their respective flood protection works. However, inadequate planning for protective measures and flood protection facilities as well as the degree of disasters occurring during the floods of 1973 and 1976, indicated that provincial planning and resources were not enough to handle the disasters. Therefore, it was realized that the establishment of a federal level institution was needed to manage all issues of flood management on a country-wide basis. Consequently, the Federal Flood Commission (FFC) was established in 1977.

**(i) Responsibilities of FFC**

- Preparation of National Flood Protection Plans
- Approval of flood control schemes prepared by Provincial Governments and concerned Federal Agencies.
- Review of flood damages to flood protection infrastructure and of plans for restoration and reconstruction works.

- Take measures for improvement in Flood Forecasting and Flood Warning Systems.
- Standardization of designs and specifications for flood protection works.
- Evaluation and monitoring of the progress of implementation regarding the National Flood Protection Plans
- Preparation of a Research Program for flood control and protection
- Develop recommendations regarding principles of regulation of reservoirs for flood control.

**(ii) Contributions of FFC in Irrigation System Management**

- Installation and up gradation of 10-CM Quantitative Precipitation Measurement (QPM) Weather Radar for Flood Forecasting Division (FFD) Lahore.
- Procurement and installation of 1st phase of Meteor burst Telecommunication System including one Master Station and 24 remote site stations.
- Up gradation of 5.36-CM Sialkot Weather Radar into 10-CM Quantitative Precipitation Measurement Weather Radar.
- Procurement and installation of 24 No. HF-Radio Sets, also some coverage to Kabul River and Swat River.
- Procurement and installation of 20 additional remote stations under existing Meteor burst Telecommunication System (Phase-II)
- Procurement and installation of new 10-CM Quantitative Precipitation Measurement Weather Radar at Mangla.
- Development of an initial/1st version of Computer Based Early Warning System through NESPAK, PMD & Delft Hydraulics, Flood Early Warning System (FEWS).
- Expansion of Flood Plain Mapping activity covering remaining reaches of River Indus, along with rivers Jhelum, Chenab, Ravi, Sutlej etc.
- Install Flood Forecasting and Warning System for Lai Nullah Basin in Islamabadand Rawalpindi

### 2.2.4.4 Planning Commission of Pakistan (PC)

The Planning Commission (PC) is a financial and public policy development institution of the Government of Pakistan. It was instituted by the Federal Government in 1952. It undertakes research studies and state policy development initiatives for the growth of national economy and the expansion of the public and state infrastructure of the country, in tandem with the Ministry of Finance (MoF).

The commission develops the Five-year plans for the national economy. The major administrative positions on the commission include a Chairman who is the Prime Minister, Deputy Chairman (Federal Minister) and a science advisor. Other officials of the commissions include Secretary of Planning and Development Division, Chief economist, Director of PIDE, Executive Director of Policy Implementation and Monitoring (PIM), and members for Social Sectors, Science and Technology, Energy, Infrastructure, and Food and Agriculture. Loans were extended by the Asian Development Bank and World Bank to the Government of Pakistan through Infrastructure Management Unit (IMU) of the Planning Commission to develop the infrastructure sector in an integrated manner for the uplift of the national economy. The loans also aimed at strengthening analytical and planning capacity of Water Sector Organizations and related institutions such as IRSA and Dam and Barrage Safety Council in addition to some other development programs of the country dealing with water.

The Planning Commission is responsible to perform mainly the following functions:

i. Preparation of the National Plan, its review and evaluation as well as its implementation.
ii. Formulating an annual plan in accordance with the National Plan.
iii. Monitoring, evaluation and implementation of major development projects and programs.
iv. Preparation of projects including irrigation and drainage in the regions and sectors lacking adequate portfolio.
v. Coordinate economic policies.
vi. Organizing research and analytical studies in economic decision making process for the country.
vii. Assists in defining the national vision and undertake strategic planning
viii. Assists in formulating proposals for augmenting the country's resources
ix. Facilitates capacity building of agencies involved in the development
x. Any other functions assigned by the Prime Minister

#### 2.2.4.5 Water and Power Development Authority (WAPDA)

The Water and Power Development Authority (WAPDA) is a government organization whose prime responsibility is the planning and development of water resources as well as maintaining water and Power systems in Pakistan. Its headquarter is in Lahore with management sub offices all over Pakistan. Major water reservoirs that fall in the jurisdiction of WAPDA include Tarbela and Mangle dams and Chashma reservoir, which are also the main sources of regulating irrigation water supplies and power generation.

WAPDA was established in February 1959, initially as Groundwater Development Authority for exploiting groundwater resources, and later as Water and Power Development Authority extending its mandate to develop water and power resources of the country and maintenance of relevant infrastructure. Since October 2007, Pakistan Electric Power Company (PEPCO) was established for thermal power management.

WAPDA planned a comprehensive National Water Resource and Hydropower Development Program entitled Water Vision 2025 that was expected to generate 16,000 MW of hydroelectricity through various projects. Other goals of WAPDA were to prevent water shortages, minimize drought and increase water storage for a growing population. Five massive hydropower projects, as detailed below, were announced by the President of Pakistan, which were planned to be completed by 2016, with a generation capacity of 9,500 MW. Two of these projects are ready for the construction phase, while three are in the stages of feasibility studies and preparation of tender documents.

Under Water Vision 2025, WAPDA developed the following plans through 3 phases to improve water resources:

- Phase I included Gomal Zam Dam in KPK, Mirani Dam and Mithan Kot Barrage at Kachhi Canal in Balochistan, Raising of Mangla Dam in Azad Kashmir, Greater Thal Canal in Punjab and first part of Thar/Rainee Canals in Sindh province.
- Phase II, comprised Hingol Dam, Balochistan Dam and Satpara Dam in Northern Areas, Chashma Right Bank Canal and Khurram Tangi Dam in KPK, Akhori Dam and Sanjwal Dam in Punjab, the second part of Thar/Rainee Canal, Gajnai and Sehwan Barrages in Sindh and Bhasha Diamer Dam. These 11 projects will have a storage capacity of 12,790,000 acre feet (15.78 $km^3$), would generate over 3362 MW of power, and would irrigate 14000 square kilometres of land.
- Phase III included, Yugo Dam, Skardu Dam, Dhok Dam, Rohtas Dam, Naulang Dam and Khadji Dam.

#### 2.2.4.6 Provincial Irrigation Departments (PIDs)

From Management point of view, the irrigation system management at the provincial level by the Provincial Irrigation Department is the most important in terms of operation, maintenance and service providing to the end users/ farmers. This institution deals with all the issues and their solutions in totality, the system components from barrages /canal heads to the irrigated farms. The Provincial Irrigation Departments under their administrative heads i.e. Provincial Irrigation Secretaries with the Heads of Sections, Zones and Circles exercise their administrative control over the system operation, distribution of water, dispute resolution and implementation of policies and water laws. Previously, these institutions were named as Provincial Irrigation and Power Departments, which have now been renamed as Provincial Irrigation Departments with their mandate limited to the management of the irrigation water resources allocated to each province. The power sector has been put under different administrative set up.

#### 2.2.4.7 Provincial Irrigation and Drainage Authorities (PIDAs)

PIDA being a provincial organization is abbreviated with relevance to the province. For example, for the province of the Punjab, it is named as “Punjab Irrigation and Drainage Authority”. It was established under the Punjab Irrigation and Drainage Authority Act 1997, which permits PIDA to take over the functions of the Irrigation and Power Department of the Punjab relevant to the canal irrigation, drainage and flood control systems for the province of the Punjab. Thus, PIDA would finally take up to perform all the functions of the Provincial Irrigation Department to manage and operate the irrigation system through its functionaries Area Water Boards (AWBs) and Farmer Organizations (FOs) as provided in the PIDA Act 1997. This organization for the province of Sindh is called SIDA, for the province of Balochistan as BIDA and for the province of KPK as KIDA.

## 2.3 Organization of PIDs

### 2.3.1 Functions of the Provincial Irrigation Departments:

The main goal of Provincial irrigation departments is to manage the irrigation system with the objective to improve farmer's living through increased agricultural production that can in turn be achieved through proper management infrastructure of the existing irrigation system in terms of judicious and efficient use of available water supplies and improvement of social infrastructure and facilities of the water users. The main stakeholders of an effective irrigation management include farmers, the irrigation management agency (Provincial Irrigation Department) and Federal government leading to increased agricultural production. Thus, from management point of view, the Provincial Irrigation Departments have to deal with the issues of institutional organization, water supply, structures and maintenance of the system. The specific functions of the Provincial Irrigation Department are as under:

- Operation and maintenance of Irrigation System of the Province.
- Take appropriate measures of channel improvement and lining, etc., to minimize the water losses during conveyance.
- Monitoring and performance evaluation of the irrigation system.
- Develop projects and manage funds from financing institutions such as ADB, World Bank and JICA etc. for improving the system infrastructure and efficiency.
- Prioritization, Planning and implementation of maintenance works through approved O&M work plans under the supervision of third party/ consultants.
- Implementation of the development programs and foreign-aided Projects.
- Execution of plans for the management of river floods in the Province, and to construct and maintain flood protection works.
- Promoting the participation of beneficiaries in the management of the Irrigation and Drainage Systems of the province, in line with the requirements of the Provincial Irrigation and Drainage Authority (PIDA) Act, 1997.
- Planning, organization, motivation and control of all activities to achieve the purposes and goals of irrigation.
- Optimizing the use of water resources in the province by an equitable distribution of irrigation water supplies
- Assessment and implementation of water rates based on the defined policies, e.g., flat rate or Irrigated Area Based systems, whichever is applicable under the rules.

### 2.3.2 Management Organization of PIDs

The Stakeholders of the irrigation management system at provincial level include Provincial Government, irrigation managers at different levels and the farmers and other consumers of water. The key objective is to manage the irrigation and drainage systems in such a way that may fulfill the expectations of all the stakeholders of the system in accordance with the rules and policies. A coordinated approach among these stake holders would always be desired for meaningful output. The user, i.e., the farmers always tend to receive more water while the managers would permit only the permissible supplies and operate the system under given rules, policies and regulatory frame work. In fact, the canal water deliveries cannot be made as demanded by the farmers. These are rather controlled by the policies and water laws under a given supply and demand environment.

The key objective of the management is to manage the irrigation system in such a way that each shareholder may get an equitable share of water to satisfy the needs of crops, animals and other uses at the farm. The Provincial Irrigation Departments have well developed organizational structure that has been operating since centuries to maintain the systems and deliver the water resources in farmers' fields uninterrupted. Each province of the country independently operates the Irrigation System through respective Irrigation Departments namely, Punjab, KPK, Sindh and Balochistan Irrigation Departments. For further details, the organizational set up of the Punjab Irrigation Department is summarized below.

## 2.4 Punjab Irrigation Department

The Punjab Irrigation Department is serving 8 barrages and 8 head works as given in Table 2.1. The Punjab Irrigation System further comprises 24 main canal systems stretching over 6389 km (3993 miles) length, 30706 km (19191 miles) of distributaries and minors, 21million acres (8.5 million hectares) of cultivable command area through 58,000 outlets. The cropping intensities generally exceed 125%. In some areas, it may range from 150 to 170%. Economic opportunities in rural areas are primarily limited to agriculture related inputs and farming activities with water as the major input. Continued growth in agriculture is, therefore, a key to the alleviation of poverty, which is significantly higher in rural areas as compared to urban areas. Fig. 2.1 shows the network of the canal system and barrages managed by the Punjab Irrigation Department.

**Table 2.1** Barrages and Head Works Operating under Punjab Irrigation Department

| S. No. | Barrages | Head Works |
|---|---|---|
| 1 | Chashma | Balloki |
| 2 | Jinnah | Khanki |
| 3 | Rasul | Marala |
| 4 | Ghazi Brotha | Qaderabad |
| 5 | Trimu | Sidhnai |
| 6 | Taunsa | Sulemanki |
| 7 | Islam | Mohammadwala |
| 8 | Panjnad | |

### 2.4.1 Objectives of Punjab Irrigation Department

The Punjab Irrigation and Power Department (PIPD) was established with a vision to provide adequate, equitable and reliable irrigation water supplies to the cultivable lands of the Punjab Province aiming at enhanced agricultural productivity and institutional reforms to facilitate participatory management coordinated by the end users. Thus, the primary goal of the Department is to supply the available quantities of irrigation water as efficiently as possible to sustain crop productivity and improve farmers' living through increased agricultural production. Other objectives of establishing the Department include:

- Manage and improve water supply, drainage, flood protection, hill torrent systems in the command areas comprising irrigated, riverine and rain-fed areas.
- Take measures to provide environmental protection against degradation and groundwater mining.
- Optimize the use of water resources in the province by the equitable distribution of irrigation water supplies (about 54 maf) through 58,000 canal outlets.
- Promote the participation of beneficiaries in the management of the Irrigation and Drainage Systems of the province, in line with the requirements of the Provincial Irrigation and Drainage Authority (PIDA) Act, 1997.
- Introduce institutional reforms for improving operational efficiency
- Support irrigation functions by introducing planning and research activities.
- Augment renewable energy resource through the installation of low head hydro power stations on locations where head is available.
- Maintenance of irrigation structures and channels.
- Management of canal operations and infrastructure of the irrigation system in terms of safe conveyance of water and release to the farmers in accordance with the established schedule and rights.

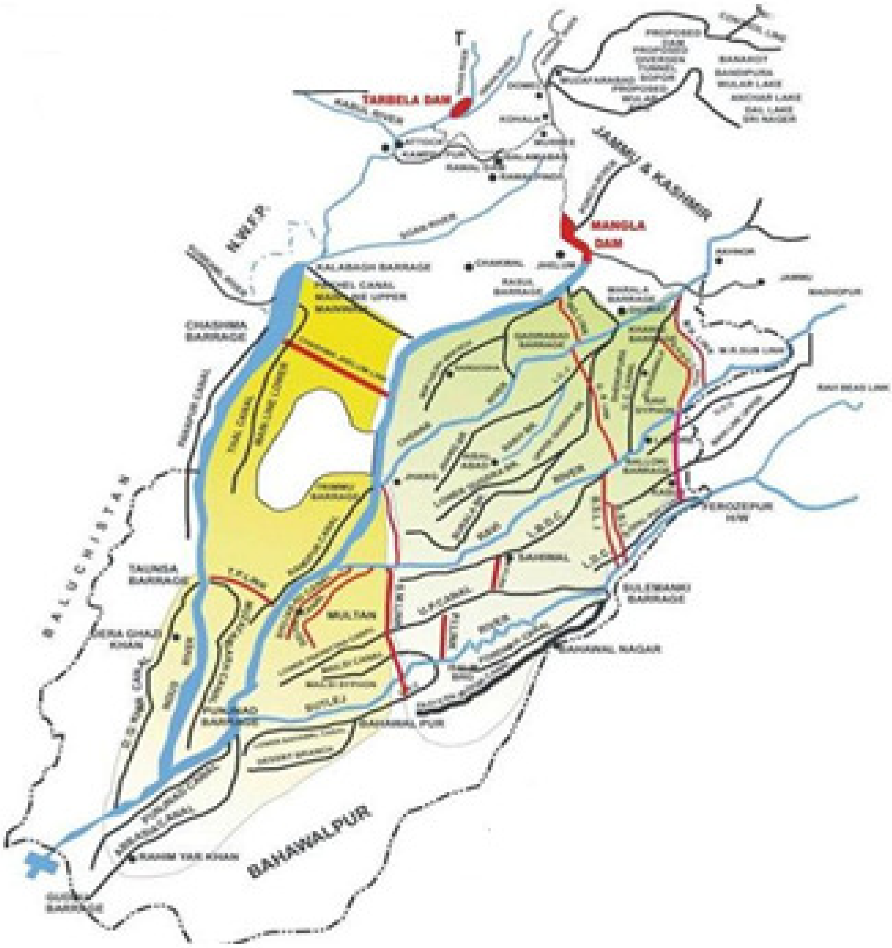



**Fig 2.1** Canal Network of Punjab Irrigation Department

## 2.4.2 Operational Components of Punjab Irrigation Department

The components of the Department to effectively operate the system can be categorized as:

- Management
- Planning
- Financial

### 2.4.3 Management Structure of Punjab Irrigation Department

Fig.2.2 shows the overall management structure of the Irrigation Department, which is headed by the Secretary, Irrigation, who further commands the following sections:

- Engineering Academy
- Project Management Units (PMUs)
- Punjab Irrigation and Drainage Authority (PIDA)
- Planning and Reform Unit (PRU)
- PMP Barrages and Head Works

From a management point of view, the primary duties of the Department is to provide management infrastructure for proper function of the system, take policy decisions and to implement them effectively in a way to deliver the goods to the end users in accordance with the defined rules and regulations focusing towards enhancing crop production. The key positions of the organizational structure of the department are defined below:

#### 2.4.3.1 Secretary

The management of the Department is headed by the Secretary who is the in charge of overall administration and management set up of the Irrigation System in the province. In addition, he is the principal accounting officer and therefore, possesses the authority and responsibilities of all financial and management matters. He holds the top executive position of the department who develops and implements the policies of the Government and gives necessary directions to the other management positions in this regard. He plays a leading role in setting and implementing the departmental policy objectives in the Province.

#### 2.4.3.2 Additional Secretaries and Deputy Secretaries

Secretary Irrigation & Power is assisted by three Additional Secretaries (Technical, Budget & Operations and Administration) and five Deputy Secretaries who are in-charge of 5 wings, i.e. Budget, Operations Technical, Administration and vigilance.

#### 2.4.3.3 Chief Engineers as Section Heads

In addition to the additional secretaries and Deputy Secretaries, the Secretary, Irrigation is assisted by 5 Chief Engineers, each heading the sections of P&R, Research, D &F, Power and Development. He is also supported by Managing Director Power and Director Land and Reclamation. Currently, the power section is separate from the department, leaving behind the other sections as stated above. For operational management of the system in the field, there are 6 operational zones, each headed by a Chief Engineer as detailed below.

## 2.4.4 Management Components of Punjab Irrigation Department

### 2.4.4.1 Irrigation Zones

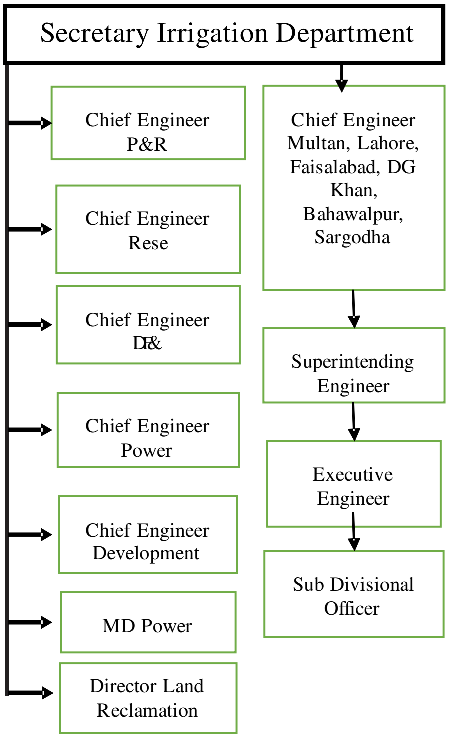
The irrigation system in the Province has been divided according to hydrological boundaries, and is managed through field Irrigation Zones. At present, there are six Irrigation Zones, namely Multan, Faisalabad, Lahore, DG Khan, Bahawalpur and Sargodha. Each zone is headed by a Chief Engineer and is responsible for management of irrigation system falling within its jurisdiction. In addition to the Irrigation Zones, there are also other special zones which perform special functions. These include Development Zone, Planning and Review Zone, Research Zone, Drainage and Flood Zone and Directorate of Land Reclamation. Each one of these Zone is headed by a Chief Engineer (CE).

In addition, several Project Management Units (PMUs) have been established for implementation of Mega/Foreign Aided Projects. A Strategic Planning and Reform Unit (SPRU) has also been setup in the department for streamlining the process of Strategic Planning and Institutional Reforms in the department.

### 2.4.4.2 Canal Circles

One Irrigation zone is further divided into several 'Circles' each under the charge of a Superintending Engineer (S.E). There are typically 2-4 canal circles and some subject specific circles such as drainage, tube-well operation, link canal, etc.

**Fig 2.2** Organizational Structure of the Punjab Irrigation Department



#### 2.4.4.3 Irrigation Divisions

For operation and maintenance of the canal system, a circle is in turn responsible for managing several ‘Divisions’. There are usually 4-5 Divisions under each circle. An Executive Engineer (XEN) is in-charge of a canal division under the administrative control of Superintending Engineer. The Division is the basic

Executive unit for operational activities, and the Executive Engineer enjoys the focal position in each division of the department. The engineers above him are controlling and directing officers, while engineers and staff under his supervision are to assist him in his field duties. For financial and accounting matters, an Executive Engineer, as head of a division, is responsible for reconciliation of budget spending and audit. For this purpose, a full time Divisional Accountant is also posted as a key representative of the provincial audit function to assist the Executive Engineer to maintain the accounts of the division properly, and exercise initial checks.

The Executive Engineers are further assisted by Sub Divisional Officers (SDOs) to manage the system further downstream in a division.

#### 2.4.4.4 Recent Developments by PID

- About 93% of the total water sector allocation was proposed for irrigation Projects in 2010-11.
- The lining of irrigation channels in saline zones has been undertaken in Punjab, Sindh and Khyber Pukhtoonkhwa to save the seepage and other losses.
- Works have been planned for 3 dams and 6 canal projects
- Rehabilitation of the irrigation systems of Sindh, Punjab and Khyber Pukhtoonkhwa have been funded and implemented.
- Maintenance of irrigation infrastructure is the responsibility of Provincial Irrigation Departments.
- Abiana collection on flat rates has been enforced for each crop and season, though its rate is very low as compared to actual operational costs.
- Pilot PIDA, AWBs and FOs have been established in LCC (East), LCC (West) Canal and LBDC commands.
- Rehabilitation of LBDC is being carried out with the financial assistance of Asian Development Bank (ADB).

## 2.5 Provincial Irrigation and Drainage Authorities (PIDAs)

The Provincial Irrigation and Drainage Authority (PIDA) is an autonomous body with mandate to establish, manage and monitor the Area Water Boards (AWBs), Farmers Organizations (FOs) and Khal Panchayats (KPs) to promote farmers’ participation in the operation and maintenance of the system, enhance recoveries of “Abiana”, minimize farmer conflicts, create better coordination between the service providers and users of water and, above all, to introduce the advanced irrigation practices in the Province, focusing on farm productivity enhancement. Developments pertaining to the creation of Provincial Irrigation and Drainage Authorities (PIDAs), their organizational structure and responsibilities are summarized below.

### 2.5.1 Need for Transfer of Irrigation Management to PIDA

The Irrigation system of Pakistan has been managed primarily by the Provincial Irrigation Departments since its birth for more than a Century with a variety of services provided to the farmers. During this period, the System had faced several social, technical, financial recovery, operational and management problems, which required improvement through institutional reforms for their rectification. The system entity of the public sector in planning, design, construction, operation, maintenance, policy framing, dispute resolution, financial recoveries and all management and decision matters neglectful of several management issues and constraints have been identified. To resolve the issues on a long term basis, the Punjab Government developed a vision to provide adequate, equitable and reliable irrigation supplies to the cultivable lands of Punjab aiming at enhanced agricultural productivity and sustainable development through broad based institutional reforms. The strategic vision includes institutional and policy reforms as well as critical investments in rehabilitation and system improvement. The relevant problems and issues, as mentioned by the PIDA (2005), included:

- Overall deterioration of system and its management
- General Lack of Agency responsiveness
- Inequitable distribution of water
- Inadequate maintenance of irrigation network
- Low Irrigation efficiencies
- Escalating gap between the revenues and expenditure
- Environmental degradation
- Lack of farmers' participation in decision making and management

### 2.5.2 Reform Program for Updating the Management System

The Government launched a Reforms Program for achieving the national water vision, which states that by 2025, Pakistan should have adequate water available through proper conservation and development programs; water supplies of good quality that should be equitably distributed as per the needs of all users through an efficient management; and the institutional and legal system that would ensure the sustainable utilization of water resources and would support economic and social development with due consideration to the environment, quality of life, economic value of resources, ability to pay and participation of all the stakeholders. These national reforms included:

(1) Institutional and Policy Reforms
(2) Water Resource Management
(3) Irrigation Service Delivery
(4) Reforms to encourage new technologies.

(5) Better coordination between the Government functionaries and the farmers

### 2.5.3 Purposes of Institutional Reforms

The institutional reforms were focused on improving the management and maintenance of the irrigation system for ensuring its long term physical and financial sustainability, while the purpose of Water Resources Management Reforms was to emphasize the critical importance of water entitlements, measurements and transparency. The objective of *Irrigation Services Delivery Reforms was* to improve the quality, efficiency and accountability of irrigation services, through greater participation of farmers, institutional reforms, and the use of contractual arrangements among water supply agencies and users. Encouragement of New Technology Reforms included improvement of water use efficiency and on farm productivity of the system through incentives.

The main purposes of irrigation reforms included:

- To implement the strategy of the Government of Punjab for streamlining the irrigation and drainage system.
- To replace the existing administrative set up and procedures with more responsive, efficient and transparent arrangements.
- To achieve economical and effective operation and maintenance of the irrigation, drainage and flood control system in the Province.
- To make the irrigation and drainage network sustainable on a long- term basis and introduce participation of beneficiaries in the operation and management thereof.
- To improve the service providing capabilities of the irrigation system administration.

### 2.5.4 Benefits of Institutional Reforms

Achievement of the above mentioned objectives will benefit the agricultural production in the province and help boost the economy of the country. It is expected that the said reforms would bring substantial benefits to the farmers, which may include the following:

- Solution of problems faced by the farmers at their doorstep without interference of the Government officers.
- Financial sustainability in terms of revenue collection and utilization of funds for system maintenance.
- Transparency in all matters dealing with the management and operation of the system and financial implications.
- Higher Efficiency of System performance.
- Equitable distribution of canal water to all the beneficiaries.
- Disputes settlement arising out of water theft, breaches, gross water losses and water distribution among the shareholders.
- Accurate assessment and recovery of “Abiana”.

- Proper distribution of canal water to the water users

In general, following are the major features of Irrigation Management Transfer (IMT):

- Management, operation and maintenance of irrigation infrastructure by the users.
- Obtaining irrigation water and supplying it equitably and efficiently to the farmers.
- Assessment and collection of water rates (Abiana).
- Remittance of an agreed share of the collected abiana to Government after retaining its share for the maintenance of the system.
- Settlement of water disputes relating to the farmers.
- Protecting environmental matters such as water quality and water losses within the command area.

## 2.5.5 Legal and Regulatory Frame work for Farmer Organizations

PIDA Act 1997 legislated by the Punjab Assembly, made the basis for the following reforms. Therefore, the elected bodies of AWB and FOs will function in accordance with the following provisions (PIDA, 2005):

- PIDA Act 1997
- Pilot Area Water Board Rules
- Pilot Farmer Organization Rules 2005
- Pilot FOs Conduct of Business Regulations, 2007
- Pilot FOs Financial Regulations 2000
- Pilot FOs Registration Regulations 1999
- Transfer Agreement between FOs and PIDA/ AWBs

## 2.5.6 Functions and Responsibilities of Reform Institutions

### 2.5.6.1 Functions of PIDA

The institutional reforms involved management transfer of the irrigation and drainage system to a three tier autonomous entities, namely,

- Punjab Irrigation and Drainage Authority (PIDA).
- Area Water Boards (AWBs) and
- Farmer Organizations (FOs) and
- Khal Panchayat

The elected bodies of PIDA by the farmers and among the farming community (AWA, FOs and KP) through Management transfer have taken up all responsibilities of management and operation of the irrigation system at the gross root level. This has permitted participation of farmer communities in the decision making, revenue collection and utilization of funds for the maintenance and efficient operation of the system.

The Participatory Irrigation Management (PIM) Model adopted by the Punjab was participatory in nature as the farmers were involved in management and control of irrigation system to develop their capacity, takeover the management responsibilities of the Irrigation Department and exercise their control over all the surface and groundwater resources of the province including rivers, canals, drains, hill torrents, etc. In terms of operation and maintenance, PIDA would perform the following specific functions after management transfer:

- Plan design, construct, operate and maintain the infrastructures pertaining to the irrigation, drainage and flood control.
- Take steps for efficient utilization of the water resources of the province.
- To adopt the concept of Participatory Irrigation Management through establishing the institutions of Area Water Board (AWB) and Farmer Organizations (FOs).
- To develop and implement policies regarding the establishment of farmer institutions and their monitoring and evaluation.
- To take measures for assessment and collection of water rate as well as drainage cess, utilization of the collected revenues and reduction of O&M expenditure.
- Enable the Authority financially sustainable for the operation and maintenance of the system.

#### 2.5.6.2 Functions of Area Water Board (AWB)

The Area Water Board is an elected body with the electoral area of the respective canal command and its shareholders acting as voters. The Area Water Boards will exercise their control over given Canal Command from Barrage to the distributary head and would take the responsibilities for managing the operation and maintenance of the commanded canal system as well as the drainage and flood control infrastructure. Beyond the distributary head, the management of the irrigation system is transferred to the FO. The AWB under AWB rules (PIDA, 2005) would perform any or all of the following functions.

- Review and monitor the work plan pertaining to the operation and maintenance of the canal.
- Develop and recommend the development schemes for inclusion in the annual development programs of the Government and review the progress of such programs.
- Prepare, implement and regulate the rotational program of water distribution among the distributaries in the canal commanded area.
- Monitor the irrigation system of a canal command for any breaches, gross water losses or theft of water or undue handling of irrigation water. Plan and implement the measures for preventing and checking of any instance of theft and other offenses committed by the farmers. The AWB would also take decisions on such offences and ensure their implementation.

- Review and supervise the collection of water rates and drainage cess.
- Prepare budget allocation and monitor any expenditure.
- Assist PIDA and the Provincial Government in the formation of Farmers Organizations and KhalPunchayats and recommend measures to improve their working to PIDA.
- Receive, utilize and control any funds, grant or donation from the Government, PIDA or any person with the approval of PIDA.
- Perform any other function assigned by the Authority from time to time.

#### 2.5.6.3 Functions and Responsibilities of Farmer Organization (FOs)

A Farmer Organization (FO) is an elected body with its voters comprising shareholders of the respective distributary. Consequently, it would be responsible to execute its control over a distributary inclusive of its minors, i.e., from the head of distributary to the canal outlets. The FO would take complete management responsibilities of operation, maintenance and financial implications over the distributary command as detailed below:

- Manage, operate and maintain all the infrastructures related to the irrigation, drainage and flood control over a given distributary command.
- Obtain the authorized irrigation water supplies from the main or branch canal at its head regulator and supply it to the farmers or shareholders equitably and efficiently by minimizing the conveyance water losses.
- Assess and collect the canal water charges, drainage cess and other fees and dues from the farmers of the command and deposit the collected revenues with the PIDA after retaining its share as permitted by the authority in accordance with the approved rules.
- Levy and collect any charges for additional services rendered by the farmer organization, including additional charges because of default in payments.
- Register and settle water disputes among the shareholders of the command.
- Preparation of operational plan of the distributary in accordance with the availability of water in the system and get approval of the General Body of FO as well as from AWB and PIDA.
- FO will maintain daily receipts and issues of water at the head of distributary and other control points of the system
- FO in collaboration with AWB and PIDA, will conduct a hydraulic survey of the distributary at least once in 3 years to facilitate remodeling and improvement activities
- FO will prepare an annual budget, O & M Budget, Capital Expenditure Budget and Financing Plan.
- FO should take necessary steps and make adequate arrangement for the security of the distributary structures for which inventory has been received by the AWB/ PIDA.
- The FO is an autonomous body in relation to their working, staffing and financial matters subject to the supervisory control of the AWB and PIDA as prescribed by the Rules and Regulations.

#### 2.5.6.4 Functions and Responsibilities of Khal Panchayat

The Khal Punchayat is the elected administrative body for a watercourse command. The primary function of Khal or Nehri Punchayat is to assist the relevant FO in the performance of its duties and functions under the directions of the FO. At this level the farmers of the watercourse command are governed by their elected representatives in a closed social set up. The Nehri Punchayat will perform the following functions:

- Receive and distribute the allocated share of irrigation water equitably among the farmers of the area.
- Operate and maintain the irrigation channels of the watercourse command, outlets and other structures in accordance with the approved design.
- The Khal Punchayat assists the FO in the collection of water charges, fees and other dues levied on the land owners/shareholders from time to time.
- Identify and report any offences such as water theft, damage to the diversion structures, carried out by the farmers and assist the authorities in the prosecution of offences under section 70 of the Canal and Drainage Act 1873.
- Supervise working of the staff and receive any complaints in this regard from the affected farmers for onward forwarding to the FO.

### 2.5.7 Organizational Management of Reformed Institutions

#### 2.5.7.1 PIDA

The organizational and management structure of the PIDA is given in Table 2.1. It comprises 7 representatives of farmers of various canal commands, Chairman P& D Department, Secretaries of Finance, I & P and Agriculture Departments and the Managing Director of PIDA in addition to the Chairman who is the Minister of Irrigation. The organizational and management structures of statuary bodies of PIDA, i.e., AWB and FO are given in Tables 2.2 and 2.3, respectively.

**Table 2.1** Organizational and Management Structure of PIDA

| Status in PIDA | Official Designation | Electoral PIDA Position |
|---|---|---|
| Chairman | Minister Irrigation | Ex-Officio |
| Members | 7 Farmer Representatives | Farmers of Commands |
| Member | Chairman P & D | Ex-Officio Member |
| Member | Secretary Finance | - do - |
| Member | Secretary I & P | - do - |
| Member | Secretary Agriculture | - do - |
| Member | Managing Director | - do - |

*Source: PIDA, 2005*

#### 2.5.7.2 Area Water Board

Management Structure of Area Water Board of a canal command is given in Table 2.2.

**Table 2.2** Organizational Management Structure of Area Water Board

| Status in PIDA/AWB | Official Designation | Electoral PIDA Position |
|---|---|---|
| Chairman | Elected Representative | FO Farmers |
| Vice Chairman | Elected Representative | FO Farmers |
| Members | 10 Elected Representatives | FO Farmers |
| Members | 9 Non Farmer Representatives | Non Farmers |
| Member | Chief Executive | Ex-Officio |

*Source: PIDA, 2005*

#### 2.5.7.3 Farmer Organization

As provided in the PIDA 1997 Act, each Farmer Organization comprises a General Body and a Management Committee. All the shareholders of the distributary command have the right to vote in electing these statuary bodies. Each elected member of General Body is represented by one watercourse of the distributary command administered by the FO. The Management Committee performs all the functions of FO and exercises all the powers of FO except such functions as to be performed by the General Body. The Management Committee comprises elected members as given in Table 2.3.

**Table 2.3** Organizational and Management Structure of Farmer Organization

| Position in PIDA | Number | Nature of Position |
|---|---|---|
| President | 1 | Elected by General Body of Farmer Organization |
| Vice President | 1 | Elected Representative of Farmers |
| Secretary | 1 | Elected Representative of Farmers |
| Treasurer | 1 | Elected Representative of Farmers |
| Executive Members | 5 | One from head of distributary<br>One from middle of distributary<br>Three from tail of distributary |

*Source: PIDA, 2005*

The Management Committee is elected for a period of 3 years by the General Body of the FO in accordance with the regulations. To carry out the operation and maintenance of the distributary and other assigned functions, FO may employ an FO Assistant, one Technical Manager and adequate technical staff as required to perform the assigned duties.

### 2.5.8 Performance of PIDA

The Provincial Irrigation and Drainage Authority (PIDA) was established under the 1997 Act. Under this act, the first Area Water Board (AWB) was established in the Lower Chenab Canal (East) on the Pilot Project basis followed by formation of Farmer Organizations (FOs). For this purpose, rules were framed by the Government under Section 16 of the PIDA Act and the process of establishing Farmer Organizations was therefore, initiated. The establishment of various institutions and activities carried out under PIDA are summarized below.

- The 1st Pilot Area Water Board was established at Lower Chenab Canal East Circle, i.e., LCC (E), Faisalabad in 2000, and 85 FOs were established in the pilot AWB till December, 2005, which were made operational in 2007.

Punjab PIDA provided training and capacity building to these FOs (within Pilot AWB) through its Social Mobilization Cell and imparted them the operational experience on joint management basis with PIDA functionaries. The Revised Regulatory Framework for FOs and Pilot AWBs was set up by the Punjab Water Sector Reforms Committee.

- Sixty seven FOs in AWB / LCC (W) Circle Faisalabad and 30 FOs in D.G. Khan were established during 2007. Each FO was an elected body among the shareholders of a distributary with the voters being among the farmers of the commanded area. These FOs were empowered under the Irrigation Management Transfer rules. Further process of establishing FOs in AWBs of Bahawal Nagar and D.G. Khan continued.
- Fifty three FOs were established at LBDC command covering districts of Qasoor, Okara, Sahiwal and Khanewal.

The Institutional Support and capacity building has been consistently provided by the PIDA to the FOs through the professionals in the fields of Technical, Social, Revenue and Finance. With the decentralization approach, organizational changes in Irrigation Management and participation of the farmers (Participatory Irrigation Management), the performance of the FOs in the Pilot AWB of LCC (E) as well as in LCC (W) Circles and the areas brought later under PIDA management, has been very encouraging in terms of revenue (Abiana) collection, improvement in water distribution from head to tails as well as in the maintenance and repair of the distributaries (PIDA, 2005). Accordingly, the major achievements under PIDA act 1997, included the following:

- Awareness regarding irrigation system operation, maintenance and management has been created amongst the farmers through social mobilization techniques. After establishment of 84 FOs of AWB/ LCC (E) Circle, PIDA has could resolve water disputes efficiently through cooperation at their doorstep and consequently, resolved 450 water disputes.
- Before implementation of PIDA, theft of irrigation water at various levels of the system has been one of the major issues of operational losses. Effective management of FOs has resulted in significant reduction such water theft cases, primarily due to the social pressure exerted by the FO office bearers and their capacity building in taking legal actions against the accused persons. According to the records, 84 FOs of AWB/ LCC (E) Circle registered 85 FIRs against the accused persons, which has established a good example of monitoring the system by the farming community. Thus, capacity building of FO representatives showed improvement in functioning of Farmer Organizations in organizational development and other issues.
- Inequity of water availability has been one of the problems of our irrigation system. After implementation of PIDA Act, the equity in the canal water distribution, from head to tail of the supplying channel, has significantly improved.

- Repair and maintenance work of channels of respective distributary command have been carried out successfully by the FOs on self-help basis, utilizing their share of 40% of Abiana collection.
- The FOs of AWB/ LCC (E) Circle actively considered and disposed off the pending cases of chakbandi.
- FOs of AWB / LCC (East) Circle checked the operational and management issues of 4233 outlets and rectified the identified problems of 693 outlets.
- The "Abiana" collection improved significantly in the PIDA administered areas as compared to the areas where Institutional Reforms has not been implemented yet.

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## Chapter 3

# Irrigation Water Laws in Pakistan

**Syed Hamid Hussain Shah and Bagh Ali Shahid***

## Abstract

Water has been a key ingredient in the human settlement, agricultural and socio-economic growth of the Indus Basin. Increase in population, put the pressure on the demand of water and created the water scarcity in the sectors of agricultural, industrial and domestic. As water scarcity increased, it not only became more crucial input into the economic well-being of Pakistani citizens, but also increased competition among various users and other stakeholders to achieve as much control on the water as possible. Consequently, issues emerging from management of such a system established greater need for framing rules and policies to run the system efficiently. Vested control of water is a valuable transferable right. The specifics of who controls and transfers water and who receives it along with the conditions for its use, are the essence of Pakistani water law. Water laws in Pakistan are usually overlooked and are left to be learnt through experience, which is a high cost option for the farmers and professionals. Recognition of water rights as well as their effective implementation is important for effective management of the irrigation system. Thus, this chapter has been designed to explain water laws and doctrines, including riparian and appropriate doctrines, water allocations through various accords and treaties and operational rules and policies so that each user and stakeholder understands the rights, provisions and to run the system smoothly. This

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chapter categorically explains water rights, including the rights of the way for water conveyance, method of appropriating water, and protection of water right, etc.

**Keywords:** Water Laws, Policies, Water Rights, Riparian, Legal Framework, Treaty, Accord and Right-of-Way

# Learning Objectives

- Understanding the reasons and background of signing Treaties and Accords and their consequences on the irrigation system at national and International levels.
- Updating one's information on water laws, according to the latest recommendations to promote the agricultural activities leading to enhanced the water productivity.
- Professionals and farmers involved in the use and management of irrigation water must be aware of the policies, rules and regulations of irrigation system operation.
- Planning and design of irrigation facilities must be based on true insight of the laws governing the basic infrastructure and its operational characteristics.
- Study of water laws gives insight to the readers about their rights as well as the rights of the others, in exercising operational rules of the system during water conveyance and application to their fields.
- Awareness of operational rules among the administrators and users minimizes the conflict opportunities. Therefore, all the stakeholders, including policy makers, irrigation managers and farmers, of the system, must study and adhere to the permissive rules of the system.
- Water laws in Pakistan are usually overlooked and are left to be learnt through experience, which is a high cost option for the farmers and professionals. This book will facilitate to learn laws and policies of the Government before implementation.

# 3.1 Introduction

Water has been a key ingredient in the human settlement and economic development of the Indus Basin. As water scarcity increases, there is a growing recognition that it will remain one of the crucial inputs into the economic well-being and quality of life of Pakistani citizens. Vested control of water is, thus, a valuable transferable right. The specifics of who controls and transfers water and who receives it along with the conditions for its use, are the essence of Pakistani water law. In addition, how and where this resource is used, will influence the economic development of the users, as surface waters are shared among many shareholders. In fact, distribution of water among various users has provided the basis for entering water treaties, accords and ordinances between countries, provinces and groups of farmers, such as Indus Water Treaty (1960), between Pakistan and India, Water Apportionment Accord (WAA) in

1991 between four provinces of Pakistan and PIDA Ordinance (1997) between farmers.

In the 19th century British engineers used the water of Indus Basin for irrigation purposes before development of the existing irrigation system. Inundation canals were used to divert water supplies from rivers during flood periods without any diversion head works. Management of these canals was done by the local farmers, societies, or states.

Since mid of the 19th century irrigation system was progressively improved by new irrigation methods and diversion works on rivers. Numerous agreements and treaties were taken on river-water sharing. Among these the most significant were IWT (1960) which was settled among Pakistan, India and WAA (1991) which was promised among the four provinces of Pakistan.

At the time of independence (1947) there as world's most developed irrigation system. The system commanded 37 million acres of land with Indus Rivers. The total available water was allocated to princely states and provinces on equity bases. The Indus Basin Irrigation System comprises of five main tributaries of the main Indus River in the east side, namely: Jhelum, Chenab, Ravi, Beas, and Sutlej. All these tributaries make junctions at different sites and finally at MithanKot, Pakistan site river Chenab the combination of all four tributaries fall in the Indus River and dumped into the Arabian Sea in Karachi. The Indus Basin covers nearly 365,000 square miles of land. Its major part lies in Pakistan and rest of it is part of other countries like India, China and Afghanistan.

In 1947 in Pakistan only the irrigated area was 31 million acres out of 37. The dividing lines at the time of separation of both countries (Pakistan and India) were drawn irrespective of the existing irrigation networks.

## 3.2 Water law Doctrines in Pakistan

Water laws in various parts of Pakistan are based upon one or both two general doctrines: Riparian rights and Prior appropriation.

### 3.2.1 Riparian Doctrine

Riparian refers to that belonging or relating to the bank of a river. An owner's land may be riparian to a river out to the boundary of the watershed of that river. However, land merely adjoining riparian land is not riparian to the river (Trelease, 1967; Sax, 1965; Davis, 1971).

A riparian retains his right to the water regardless of whether or not the use is made of the water; thus, the riparian owner can commence his use at any time and requires that his right be fulfilled. It is obvious that system will work only in those regions where there is adequate water to supply the needs of the users. Due to the scarcity of the water, this doctrine is read mostly in books, but not practiced in Pakistan. The riparian doctrine is also discussed in the Indus Water Treaty section 3.4.

### 3.2.2 Appropriation Doctrine

Prior appropriation water rights/appropriation doctrine is a system of allocating water rights from a water source that is markedly different from riparian water rights (Sax, 1965; Davis, 1971). Water law in Pakistan generally follows the appropriation doctrine instead of riparian rights which developed due to the scarcity of water in that area.

## 3.3 Acquisition of Water Rights

The acquisition of water rights means that all the natural streams having flowing water were declared to be the property of the public, and it was dedicated to the use of the people of Pakistan.

### 3.3.1 Right-of-Way for Water Conveyance

The right of way through the lands for conveyance is applicable to every person owning a water right or conditional water right, so that efficient utilization of water can be increased by increasing the irrigated command area of deprived water resources. The government can also take land for conveying water without paying compensation (Sax, 1965; Trelease, 1967; Davis, 1971). Application of this doctrine is seen frequently in many projects, like in the designing of irrigation projects in the un-gauged basins or in the development of new irrigation water courses in the areas where there is deprivation of this water course. This also applies to the main watercourses at the watercourse command where the watercourse is a property shared by the shareholders of the command.

### 3.3.2 Method of Appropriating Water

In Pakistan, there are two requirements to be met to acquire a water right. First, there must be a sharing of the water and, second, it must be applied to beneficial use. According to the latest developments in the field of irrigation science, water is allocated to the farmers according to the crop water requirements. This criterion has improved the method of appropriating water.

### 3.3.3 Restrictions on Right to Appropriate

The right to divert the inappropriate waters of any natural streams to beneficial uses shall never be denied. However, the right of appropriate water is limited to the situation (i) if there is no inappropriate water available from the proposed source, (ii) if the granting of the right would harm an existing water right, (iii) if the proposed appropriation is contrary to the public welfare, and/or (iv) if the right is limited based on the time during which the water may be used (Sax, 1965; Trelease, 1967). Regarding this restriction, we can say that this law would sustain on longer terms land and water resources. For efficient management of saline irrigation water among different farms along the river basin, a conceptual model has been developed by Ben Gal et al. (2013) which is application of this doctrine.

## 3.3.4 Doctrine of Relation Back

Relation back has been defined that relation by which appropriation of water relates back to the time when the first step to securing that appropriation was taken, if the work from that step on was prosecuted with reasonable diligence (Trelease, 1967). This doctrine keeps the appropriator on track. With the passage of time, changes in land cover depending on the market demand would affect the water rights of the appropriator.

## 3.3.5 Elements of Appropriation Right

Various elements of Appropriation rights are discussed below to regularize the priority of using water. Appropriation of right, in fact, minimizes the water losses by fixing the turn of water use and minimizing the chances of disputes.

### 3.3.5.1 Priority of Right

A prior appropriation doctrine ensures the exclusive right to divert water from a source when the supply of water is not adequate for the needs of all claiming the right to its use. This exclusive right depends on the date of appropriation regarding the dates of other appropriators. Thus, appropriator with earliest date of appropriation acquires a superior and exclusive right over all others appropriating water from the same body of water. This doctrine is a rough procedure to administrate the water body. The senior appropriator claims water without knowing the actual needs of the water. In this way, senior appropriator wastes the water, which could otherwise be used efficiently by more than one appropriators.

### 3.3.5.2 Preferential Uses of Water

The preferential use system gives the right to the most appropriate use between two same purposes of water. With low stream water, domestic water use takes up top priority, followed by agricultural, manufacturing, and so on (Sax, 1965; Trelease, 1967; Davis, 1971).

### 3.3.5.3 Exercise of the Appropriation Right

Appropriation of Right, in fact, minimizes the water losses by fixing the turn of water use and minimizing the chances of disputes. The user can use the water of its turn or the excess water can be delivered to the next user based on the consent of the user if the user does not need water.

## 3.3.6 Efficiency in Irrigation

In diverting, conveying, distributing and using the appropriation right, the appropriator is held to achieve reasonable efficiency not absolute efficiency. The reason is that due to the losses in irrigation water (conveyance, evaporation, seepage, etc.), the irrigation efficiency decreases. In order to increase the irrigation efficiency, different alternatives have been adopted such as watercourse lining to avoid from seepage, increasing depth of watercourse and plantation around the water course to avoid evaporation to some extent.

### 3.3.7 Rotational Use of Water

Rotation in the use of water avoids the loss and inefficiency that can result from the continuous delivery to farms of a multiplicity of small heads or streams. The purpose of the rotation is to enable irrigators to exercise their water rights more efficiently, and thus, to bring about more economical use of available water supplies. Regarding the rotation of water, warabandi system is an example and application of this doctrine. Warabandi means fixing of turns of irrigation water for each farmer at a water course according to some criteria. The objective of warabandi system is to provide only that amount of water which enables a farmer to irrigate one third of his cultivable command area during all season. There are two types of warabandi namely "Kacha and Pucca".

#### 3.3.7.1 KachaWarabandi

It means a temporary program of fixing water turns, which is arranged by the farmers themselves. Its rotation varies from 10 to 15 days depending on the number of farmers on the watercourse and available time (Qureshi and Zeb-un-Nisa, 1994). In each chak or village, a watch keeper is used to announce the irrigation turn time for the benefits of each farmer by drum beating.

#### 3.3.7.2 PaccaWarabandi

The Kachawarabandi system of water rotation has many problems such as the larger farmers do not care for the irrigation needs of smaller farmers. Consequently, the tail users are the main losers. To overcome this problem, the canal department regulates the supply of water and fixes the turns of each farmer in each crop year, which is called "PaccaWarabandi" system. If any farmer violates this arrangement, he is liable to prosecution under the canal act (Qureshi and Zeb-un-Nisa, 1994).

## 3. 4 Indus Water Treaty

International Bank for Reconstruction and Development and World Bank settled the water disputes between Pakistan and India on September 19, 1960. The transboundary agreement is known as the Indus Water Treaty. It was jointly signed by President of Pakistan Mohammad Ayub Khan and Indian Prime Minister Jawaharlal Nehru in Karachi.

### 3.4.1 Rationale for the Indus Water Treaty

Immediately after Pakistan came into existence, India stopped the water in every irrigation canal due to the control of the canal regulating structure. Due to this unethical attitude of India, 1.6 MA canal irrigated area of Pakistan was affected. These actions forced Pakistan towards atreaty among countries aimed at joint water allocation.

### 3.4.2 Pre-Treaty Dialogue

Pakistan claimed that excess water could be allocated among the riparian according to the population and area. This claim was also supported by many treaties, nations, and the provinces. On the other hand, India claimed absolute right of the upper riparian on water than lower (see section 3.2.1) treaty could only be possible if both riparian get same (see section 3.2.1). In May 1948 India restored some water with the concept that Pakistan will not survive without full supply restoration.

In May 1952, negotiations to resolve the dispute, started between both the parties with the assistance of the World Bank, but the discussion was not fruitful. The Indus Water Treaty was finalized 1960 as a result of eight years exhaustive dialogue between Pakistan and India (World Bank, 1960).

### 3.4.3 Main Constituents for Indus Water Treaty

September 19, 1960 in Karachi, the IWT was signed. There are 12 articles of the IWT and it consist of 8 appendices for detail information of the articles.

### 3.4.4 Salient Features of Indus Water Treaty

Eastern River's rights:

(i) India will use the Ravi, Sutlej and Bias water unrestrictedly.
(ii) Pakistan will not claim for the water of River Ravi, Sutlej and Beas.

Western River's rights:

(i) Pakistan shall receive the water from Indus, Jhelum and Chenab unrestrictedly.
(ii) India shall not take any water from the western rivers (Indus, Jhelum and Chenab).

Eastern and Western River's rights:

(i) Both parties would have free access to natural river channels for discharge of flood and excess water. Also, any damage to these channels would not be claimed by any party.
(ii) Each party declares that any sewage from the industry will be treated before allowing wastewater to flow in the river to avoid from water pollution.

### 3.4.5 Post-Treaty Views

According to Pakistan's perspective, the Indus Water Treaty resulted in some advantages as well as caused several problems.

The following benefits were achieved:

(i) The implementation of the Indus Basin Replacement Plan (IBRP) made both countries independent in operating their supplies after the completion of works.

(ii) It was the responsibilities of both countries to plan, construct and maintain the water project for their own interest (Ahmad, 1993; World Bank, 1960).

(iii) Each country can use the water effectively. Increase in efficiency for storage, transfer and reduction of losses benefits directly to that country.

(iv) The independence afforded by the program has decreased the mutual conflicts and resulting tension between two countries.

(v) Prior to IWT, 80% of the total flows were generated during the monsoon season. IWT increase the canal water diversion due to the construction of reservoir.

(vi) In addition to total withdrawals, water diversions from canals were increased from 67 MAF to 104.5 MAF (Ahmad, 1993; World Bank, 1960).

Defects of the settlement plan:

(i) The flooding reduced or disappeared causes the soil salinity and sodicity problem in the *sailab* areas.

(ii) The channels become silted up due to reduction in flows in the Eastern Rivers.

(iii) The development of new link canals and reservoirs resulted in additional burden on the maintenance cost of the system (World Bank, 1960; Ahmad, 1993).

## 3.4.6 Changes in River Flows

Average flows of major rivers of the Indus Basin have been presented in Table 3.1 for 1922-61, 1985-95 and 2001-02 to have insight into water situation before and after the Indus Water Treaty, and into the ensuing scenario.

**Table 3.1** Temporal Changes in River Flows

| River | Average Annual Flow (1922-61) MAF | Average Annual Flow (1985-95) MAF | Average Annual Flow (2001-02) MAF |
|---|---|---|---|
| Indus | 93.0 | 60.25 | 48.00 |
| Jhelum | 23.0 | 23.00 | 11.85 |
| Chenab | 26.0 | 25.70 | 12.38 |
| Ravi | 7.0 | 5.80 | 1.47 |
| Sutlej | 14.0 | 5.80 | 0.02 |
| Kabul | 26.0 | 22.30 | 18.90 |
| Total | 189.0 | 142.80 | 92.62 |

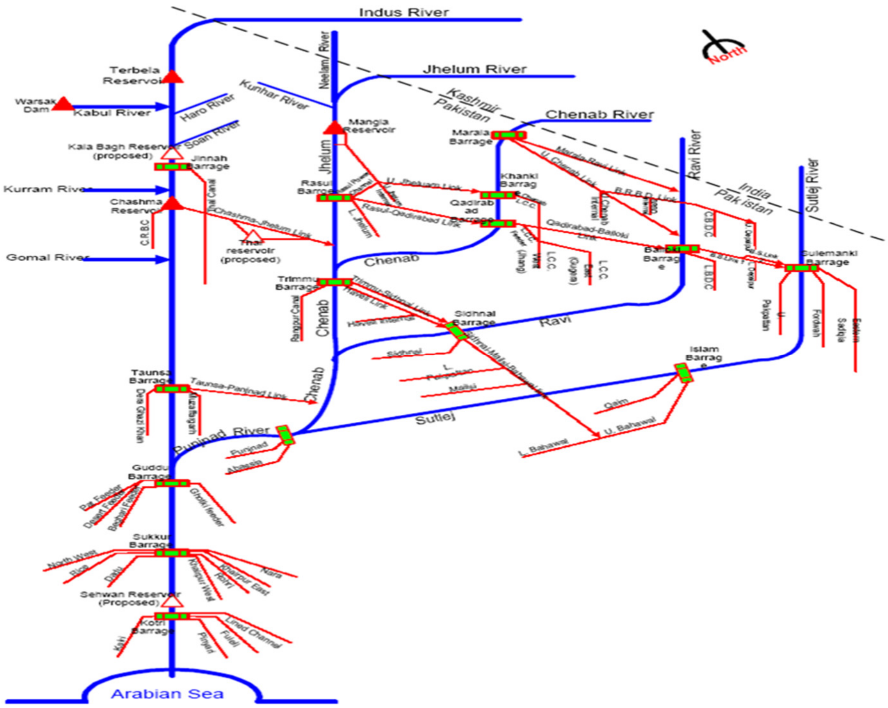
*Source: Federal Flood Commission, 2010*

### 3.4.7 Discussion and Post-treaty Works in Pakistan

After IWT 1960, both the countries appointed commissioners to the Indus Waters Commission as their respective representatives. In this way, there are two Commissioners who govern the Indus Commission. The main functions of the commission are: (i) to arrange cooperative atmosphere for the successful execution of the Treaty; (ii) to achieve sustainable development of the river waters by promoting collaboration between the two shareholders; (iii) to settle the issues raised by any stakeholder by utilizing all possible options; and (iv) to inspect river flows (for further explanation, please see annexure 1).

## 3.5 Indus Basin Irrigation System

The irrigation system of Pakistan is one of the largest irrigation systems, providing water to about 42 million acres land. Indus River is the main source of water in the system along with its tributaries (Fig. 3.1). The major reservoirs include: Tarbela, having live storage capacity 6.625 MAF against the original 9.70 MAF; Chasma, having live storage capacity 0.263 MAF against the original 0.70 MAF; and Mangla, having existing storage capacity of 4.54 MAF against the original 5.30 MAF. The total length of the canal system is 64000 km, whereas the watercourses have total length of about 1621000 km (Annual Flood Report 2010).




*Source: Annual Flood Report, 2010*

**Fig. 3.1** Schematic Diagram of Indus Basin Irrigation System

The Indus Basin comprises of about 365,000 miles$^2$ geographical area (Ahmad, 1993), major portion of which is in Pakistan and the minor areas in Jammu and Kashmir, India, China and Afghanistan. Water in the Indus River system is distributed first among different users like the domestic and industrial users, then for irrigation, and the rest is surplus water. Out of these users, Irrigation is the major user of water as tabulated in Table 3.2

**Table 3.2** Distribution of Water in Indus Rivers Basin

| Inflow into Indus Basin | 142MAF | |
|---|---|---|
| Outflow | | |
| Domestic use | | 5MAF |
| Industrial use | | 2MAF |
| Irrigation | | 97MAF |
| Requirement below last barrage (Kotri) for agriculture, preventing backflow from sea and protecting environment | | 10MAF |
| Possible allowable water use by India | | 5MAF |
| Total usage | | 119MAF |
| Remaining available water | | 23MAF |
| Total | 142MAF | 142MAF |

*Source: WAPDA, 2002*

# 3.6 Water Accord

## 3.6.1 Historic Developments

- In 1920, British kingdom gathered Punjab, a state of Bahawalpur and Bikaner states to have an agreement known as triple canal project keeping in view the mistrust among these provinces.
- Later, due to less quantity of supply compared to the assumed supply, in 1935 Anderson Committee was formed for the inspection of water distribution. Similarly, Government of Sindh dropped the complaint that Punjab is making project on the Sindh canals.
- To solve the issue a commission was established who presented its recommendations in 1942. Furthermore, in 1968, Governor of former West Pakistan constituted a Water Allocation and Rates Committee to review barrage water allocations, reservoir release patterns, drawdown levels and use of groundwater in relation to surface water deliveries. A report was submitted on July 01, 1970.
- Resultantly a committee (Justice Fazale Akbar) was formulated in October 1970 to give recommendations on the water distribution pattern of the Indus and its tributaries. Its report was submitted in 1971.Unfortunately, no judgment was drawn based on the recommendations of the committee and Govt. of Pakistan distributed the water on ad hoc basis (Ahmad, 1993).
- In 1977, the Government formed another commission with provincial high courts'Chief Justices being its members and Supreme Court's Chief Justice

as head to investigate the problem regarding the water distribution and provide consensus and sustainable solution. Report presented by the commission is awaited by the Government.

- Eventually the Chief Minister of the four provinces resolved the issue. The conclusion was drawn on March 16, 1991, after conducting a series of meetings in Lahore and Karachi (Ahmad, 1993).

### 3.6.2 Purposes of the Water Accord

WAA between Provinces was formulated by the Prime Minister of Pakistan with agreement of Provincial Chief Ministers. It had two important features:

(i) In each province, the protection of the existing canal water uses.
(ii) Insured balance river water supplies among the provinces, keeping in view the flood excess water and future storage requirements.

### 3.6.3 The Water Apportionment Accord, 1991

The Water Apportionment Accord was signed on March 16, 1991 in Karachi at a meeting of the Chief Ministers of the four provinces. The accord describes the shares of the provinces as given in Table 3.3.

The main provisions regarding water apportionment accord (Ahmad, 1993) as under:

(i) It was realized that there should be water storages on the River Indus and its tributaries for carrying healthy agricultural activities in future.
(ii) Provinces are free in making new projects within the allocated water limits.
(iii) No restrictions are imposed on development of irrigation in Kurrum, Gomal and Kohat basins till the time comes it will affect adversely on the existing uses on these rivers.

**Table 3.3** Apportionment of Water among Different Provinces during Rabi and Kharif season

| Province | Kharif (MAF) | Rabi (MAF) | Total (MAF) |
|---|---|---|---|
| Punjab | 37.07 | 18.87 | 55.94 |
| Sindh | 33.94 | 14.82 | 48.76 |
| KPK | 5.28 | 3.50 | 8.78 |
| Balochistan | 2.85 | 1.02 | 3.87 |
| Total | 79.14 | 38.21 | 117.35 |

*Source: Ahmad, 1993*

(i) Baluchistan will be restriction free for developing water resources on the right-bank tributaries of River Indus.
(ii) Need of another national authority named as Indus River System Authority (IRSA) which will overlook and implement this accord, was recognized and accepted.
(iii) Priority uses of water from existing reservoirs would be for irrigation in all provinces.

(iv) Within the allocated limit of water, the provinces would be free to modify the uses on the bases of system and period.
(v) Water wastages would be avoided with every possible effort. Surplus water might be utilized by another province rendering it with no permanent rights on that water

### 3.6.4 Discussion on the Accord

Twelve million acre feet of additional water were allocated through Water Apportionment Accord to the four provinces. During floods (June-September) the surplus quantity of water is available for the period of 70 to 100 days only. Around the year, during non-flood period, the additional allocations may be provided by necessary surplus storages. Provinces will forcibly share the water shortages in the absence of new storages. Thus, it is in the interest of all provinces to develop and efficiently utilize the water resources.

## 3.7 On-farm Water Management and Water User Association Ordinance

It is an ordinance which is provided for water management at the farm level through efficient utilization of irrigation water and introduction of participatory irrigation system by forming of water users' associations. This Ordinance may be called as On-Farm Water Management and Water Users' Associations Ordinance, 1981 (GOP, 1981). Following are the main important extracted points for the on farm water management team to consider for efficient use of irrigation water.

### 3.7.1 Field Officer to AdviseStakeholdersforWatercourse Re-construction

(i) If the watercourse requires rehabilitation or improvement, the officer can advise the irrigator to complete the task within a specified period.
(ii) Maintenance and reconstruction of watercourse are the responsibility of all the irrigators.
(iii) Field officer may take the necessary action regarding improvement of a watercourse, if the concerned person does not complete the task within a specified period.
(iv) Farmers are allowed for the maintenance and reconstruction of watercourse by making an association.
(v) Field officer may cancel the job of association if it does not complete the work timely.

### 3.7.2 Future Maintenance of a Watercourse

(i) The association will maintain the watercourse on behalf of all the stakeholders of the watercourse after handover by the field officer to the association.

(ii) The association shall have right to recover a prescribed share of the cost of watercourse rehabilitation.
(iii) If any of the irrigators refuses or fails to pay his share of the cost, it will be recovered by the Field officer as an arrear of land.

### 3.7.3 Checking of Watercourse Maintenance

The Field Officer (Assistant Executive Engineer) will make a spot-inspection and issue directions for the proper maintenance work.

### 3.7.4 Formation and Registration of Association

(i) On the basis of mutual co-operation in the reconstruction, maintenance or improvement of the watercourse, a group of irrigators form Panchayat (group of people from the watercourse) known as Water Users' Association.
(ii) For maintenance, improvement and reconstruction of a watercourse, an association shall apply to the Field Officer on a prescribed form containing such as a list of members with their particulars, list of all irrigators, and bye-laws of the association.
(iii) After receiving the application (mentioned in sub-Sec ii) the Officer will call a meeting of all beneficiaries.
(iv) The Officer will register the association and issue a certificate on prescribed form after being satisfied from all irrigators under the Ordinance.
(v) An association cannot be registered unless (a) members must be 51% of the total irrigators, (b) association formed by-lawsare dependable under the government laws, (c) duly elected member and office workers, and (d) account must be in listed bank.
(vi) The decision of the Field officer to grant or refuse registration will be final.
(vii) Field Officer shall decide that a person is an irrigator or not. His decision shall be considered as final.
(viii) A register shall be maintained by Field Officer for the certificates issued by him.

### 3.7.5 Association as a Corporate Body

Under the Ordinance an association rendered as a corporate body corporate by the name under which it was registered will enter contracts, institute and defend suits and other legal proceedings.

### 3.7.6 Certificate of Registration to be Conclusive Evidence

A certificate of registration issued to an Association will be conclusive; otherwise it will be assumed that registration of the Association has been cancelled.

### 3.7.7 Disputes

Field officer will be consulted in case of any dispute among the members (past and existing) of an association, touching business of an association, shall be referred to the Field Officer. The Field Officer may hear the dispute and give his decision, which will be considered as final.

### 3.7.8 Cancellation of Registration

The registration will be cancelled if the association violates the rules discussed in section 3.6.4. The association will appoint a person to close all the pending matter of the user association under legal action. Additionally, it is under the power of field officer to order the association to hand over all properties provided by any Government agency.

### 3.7.9 Water Laws

**Table 3.4 (a)** Main National Legislation Related to the Water Sector

| Enactment | Year | Responsible Agency |
|---|---|---|
| Pakistan Penal Code (Act XLV of 1860) | 1860 | Federal Government |
| West Pakistan Water and Power Development Authority Act | 1958 | Federal Government |
| The Indus Water Treaty | 1960 | Federal Government |
| The Constitution of Islamic Republic of Pakistan | 1973 | Federal Government |
| On Farm Water Management Water Users Association Ordinance | 1981 | Federal Government |
| Water Apportionment Accord | 1991 | Federal Government |
| Indus River System Authority Act | 1992 | Federal Government |

## 3.8 Canal and Drainage Act, 1873

### 3.8.1 Historical Overview

The Canal & Drainage Act was enacted in 1873. It was substantially amended soon after its enactment in 1873 and later in 1874. It worked well throughout the colonial rule and only minor changes were made during this period. After Independence, some amendments in the Act were made in 1952 regarding compensation. Thereafter, some other amendments were made at different times, but most of them were minor in nature except the transfer of powers from the Divisional Canal Officers (XEN) under S.68 to Sub Divisional Canal Officers (SDO).

**Table 3.4 (b)** Main Provincial Legislation Related to the Water Sector

| Enactment | Year | Responsible Agency |
|---|---|---|
| The Canal and Drainage Act | 1873 | Punjab Irrigation Department |
| Sindh Irrigation Act | 1879 | Sindh Irrigation Department |
| Punjab Minor Canal Act | 1905 | Punjab Irrigation Department |
| KPK Amendment Act | 1948 | Khyber Pakhtunkhwa Irrigation Department |
| Baluchistan Canal and Drainage Act | 1980 | Baluchistan Irrigation Department |
| Soil Reclamation Act | 1952 | All Irrigation Departments and WAPDA |
| Baluchistan Ground Water Rights | 1978 | Department of Irrigation Baluchistan |
| Punjab Water Users' Associations Ordinance | 1981 | Punjab Agriculture Department |
| KPK Water Users' Associations Ordinance | 1981 | Khyber Pakhtunkhwa Agriculture Department |
| Baluchistan Water Users' Associations Ordinance | 1981 | Baluchistan Agriculture Department |
| Sindh Water Users' Associations Ordinance | 1982 | Sindh Agriculture Department |
| Rural Area Drinking Water Supply Act | 1985 | Khyber Pakhtunkhwa Irrigation Department |
| Salinity Control and Reclamation of Land Ordinance | 1987 | Khyber Pakhtunkhwa Irrigation Department |

Several amendments were made in 1975. But these two did not bring much substantial changes in the law. Since then, no amendments have been made in the Canal & Drainage Act, 1873. The Canal & Drainage Act, 1873 was further amended in 2004 to incorporate the changes, keeping in view the following principles:

- Decentralization
- Transparency
- Efficiency
- Participation of the Farmers
- Needs of the Time
- Protection of Environment
- Proper management of canal water resources
- New canal projects
- Simplified Procedures
- Rationalization of Penalties
- Repeal of Redundant provision
- Proper Enforcement
- Removing in consistencies with the constitution

The important sections of Canal & Drainage Act, 1873 as amended to date concerning sanction of irrigation water, distribution of irrigation water, management of irrigation water, and the canal offences under the Act for damage to the canal and its structures are described below:

### 3.8.2 Terminology Used

(a) **The Khal** is a watercourse, not maintained at the cost of the exchequer, which leads water from the outlet to the land of the person interested. It would normally be not more than 2 miles in length commencing from the outer and of the outlet to the last Nakka or cut in the watercourse where the Nikal or the process of emptying watercourse completes and the upper shareholder (irrigator) starts feeding through a fresh turn in the branch watercourse in rotation. (ii) The words "Main Watercourse" used in paragraph 8 (a) of Appendix E in the Revenue Manual means the tail Nakka of which is the farthest from the outlet. The mere fact that channel of watercourse runs in a straight line in continuation of the main watercourse cannot necessarily make that continuation also a part of main watercourse.

(b) **The Outlet** is maintained by the Canal Officers at the cost of exchequer and is a measuring device for water from the distributary, minor or sub-minor discharging into the watercourse.

(c) **The Nakka** is a cut in the watercourse from which water is carried directly into the fields. Normally it is fixed by the Canal Officers at Killa No.1 on the left and killa No.5 on the right while facing down the flow of water in the square, but it can be changed on request and re-fixed depending on the denudation of fields bed which either rises by silt deposit in due course of time or is depressed after leveling, etc.

(d) **The Nikal** is the water which empties into the last Nakka in the field from the main watercourse and the rotation changes in favor of the upper irrigator at the head or the next branch of the watercourse. In fact, this is the extra water supply for the last irrigator who has the advantage of water present in the watercourse to discharge into his field over and above his own turn. The period of turn of water fixed by the Canal authorities is the part Warabandi. This, however, cannot be claimed as of right and, is left at the discretion of the Canal Officer who, while sanctioning Nikal, should consider the area, time, nature of soil and the configuration of lands, etc.

(e) **The Turn** is the period of turn of water fixed by the SDO for every shareholder of watercourse proportionate to the area of the land.

(f) **Warabandi:** The arrangement of turns of taking water, when sanctioned by the SDO under Section 68 is known as Warabandi. It is binding on all the shareholders of the Chak being irrigated from the watercourse. Any contravention amounts to offence known as Warashikni and is liable to penal action under Section 33 read with Rule 32 and 33 of this Act.

   **(a) Part Warabandi** is the schematic Schedule of turn of water which contains the following information:

      i) Name of Shareholders
      ii) Number of the Squares (with the Shareholders)
      iii) Area of land in "Kanals" or Acres.
      iv) Period of turn of water in hours and is minutes

v) Clock time allotted, with extra time and deductions
vi) The last outlet or "nakka" from where the water is to be brought and the one where water is to be delivered to the next shareholders by the irrigator.
vii) Remarks and the person entitled to the "nikal" of water-
    1) Turn or "Wari" is rounded up to minutes only.
    2) Because leading water and compensation for nikal, etc.

The record of Warabandi is maintained in the office of the Divisional Canal Officer from where a copy can be obtained to prove a claim for change in turn. The copy is obtained on payment in accordance with the Schedule of Court-fees fixed in the relevant Act.

(g) **"Chak"** is the gross area of land holdings fixed for irrigation by an outlet. It includes un-commanded area also.
(h) **Culturable Commanded Area (CCA)** is the area under the command of an outlet excluding area which is not commanded.
(i) **GhairMumkin** is the area from within the extremities of Chak Boundary not likely to come under irrigation command (not commandable) because of the area covered by population, graveyard, high and dry land, green meadow reserved for future development near temporarily used for grazing animals, roads, pathways, school buildings, play-grounds, rural health centers, dispensary, etc.
(j) **Gross Commanded Area (GCA)** is the area command-able by the outlet from within a Gross Area. It includes an area which is likely to come under the command and for which water is available in the project, but is left un-irrigated because of its remaining unbroken.
(k) **Gross Area** is the entire area spread over the extremities of Chak of an outlet.
(l) **Area cultivated** is the area under crop or fruit trees or both and has been under crop in the previous three harvests.
(m) **Area Assessed** is the area irrigated on which water is levied. It is generally the same as the area matured.
(n) **"Rajbaha"** includes distributary, minor and sub-minor, which are maintained by and at the cost of Government under the direct charge and supervision of Canal Officer and which are used to supply water to a watercourse through the outlet.
(o) **"Bhal"** means the Silt, discharged through the outlet as of suspended material from the government channels, which gets deposited in the bed and on the banks of watercourse in due course of time.
(p) **"Bhal Safai"**is the process of removing Silt on self-help or cooperative basis by the shareholders from the bed of the watercourse. Although the Government under normal circumstance does not interfere, the Canal Officer is empowered under Section 34, Rule 33, to force the shareholders to clear the silt of the watercourse. Similarly, under Section 18 of this Act, Canal Officer can repair the watercourse not being properly maintained by the shareholders at their cost.

### 3.8.3 Section 33 – Liability when water is illegally taken from Canal or Watercourse

1. The Divisional Canal Officer will conduct inquiry about the unauthorized water allocation or use by the framer, after the offense being committed is pointed out to him with evidence by the farmer Organization, and the levy charges will be charged to the person who gets benefit or the land where water flows to it under this act:
2. Subject to sub-section (1), where the water used in an unauthorized manner has been taken from a watercourse, the Deputy Collector after holding an inquiry, may levy the charges:
   (a) From the person by whose act or neglect such use has taken place; or
   (b) If such a person cannot be identified, from the person on whose land the water has flowed and such land has derived benefit therefrom; and
   (c) If such a person cannot be identified or the land, on which water has flowed, has derived no benefit therefrom, from all persons chargeable in respect of the water supplied through such water course.

### 3.8.4 Section 68 – Settlement of difference as to mutual rights and liabilities of persons interested in watercourse

1. Settlement of difference has to be in terms of mutual rights and liabilities of the persons interested in the use of water from a canal outlet, such that whenever a difference arises between two or more persons with regards to the distribution of water from a canal outlet, construction, use, or maintenance or the watercourse supplied with water from the outlet, or deposit of soil from watercourse clearance, or mutual rights and liabilities in that respect, any such person may apply in writing to the Sub-Divisional Canal Officers, stating the matter under dispute. The Sub-Divisional Canal Officer, shall thereupon proceed in the matter as laid down hereafter. Provided that the Sub-Divisional Canal Officer, shall proceed without any application on the basis of the orders passed under Section 20-B, Section 20-C or an order canceling the extra water supplies.
2. The Provincial Government may entrust the functions of SDCO under this Section to an Organization of Farmers established under Section 4-A in such area wherever it deems necessary.
3. The Sub-Divisional Canal Officer or the Organization of Farmers shall give notice to all persons interested and liable to be affected, regarding the enquiry in the said matter and after such inquiry, shall pass orders thereon.
4. Any person aggrieved by an order made under sub-section (3) may, within fifteen days of the passing of such order, prefer an appeal to the Divisional Canal Officer.
5. Where an appeal has been preferred under sub-section (3), the Divisional Canal Officer:
   (a) Shall decide the appeal as expeditiously as possible; and
   (b) may, pending the disposal of the appeal, stay the operation of the order appealed against; provided the stay order does not adversely affect any standing crops

6. The applicant shall not be entitled to use the watercourse that may be sanctioned under sub-sections (2) or (3) above for conveyance of water to his land or the land required for the deposit of soil from watercourse clearance, until:
   (a) He has paid to the landowner the compensation for the land occupied for any of the aforesaid purposes in whatever shape it is determined through agreement; or
   (b) Possession of the land has been acquired under the provision of this Act.
7. Any order passed under sub-section (2), if there be no appeal preferred against it and an order passed in appeal under sub-section (3) shall be final as to the use or distribution of water for any crop sown or growing at the time when such order is made, and shall thereafter remain in force until it is set aside by a decree of the Civil Court.

### 3.8.5 Section 68-A – Power to Restore interrupted supply

If the canal water supply of any land is interrupted by dismantling a watercourse or internal khal, the Sub-Divisional Canal Officer, upon application made in this respect and after such enquiry as is deemed necessary, may order interim restoration of the dismantled watercourse or the internal khal and the interrupted supply of water at the cost of person who interrupted the supply; and if necessary by use of such agency or force as may be called for. And such an order shall remain in force until the dispute is finally settled under Section 68 and if necessary a watercourse link is constructed under this Act.

Provided that where the Provincial Government has entrusted the functions of SDCO under Section 68-A to the Organizations of Farmers established under Section 4-A, the functions of SDCO under this Section shall be mutatis mutandis performed by the said Organization.

Any charge determined for restoration of the watercourse or internal kahl shall be recoverable from the person at faults as arrears of land revenue.

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## Chapter 4

# Gauging and Flow Measurement

**Abdul Shabbir and Muhammad Yasin***


## Abstarct

Irrigation water provides primary support to the irrigated agriculture, particularly under arid and semiarid conditions as prevailing in most of the cultivated areas of Pakistan. Under constrained and limited water supplies, application of measured quantities of water is quite desirable for efficient irrigation. Further, it helps in overcoming both the under or over irrigation opportunities as both tend to reduce crop yields. Seasonal variations of flow during Kharif and Rabi seasons and equitable distribution of water among the shareholders also demand a consistently measured records of irrigation deliveries at various levels. Flow measurement permits the farmers to plan their cropping schedules in a better way. Correct measurements give a feeling of satisfaction to all concerned parties (both the farmers of a command and irrigation managers), and promote more efficient utilization of limited resources. Therefore, flow measurement and gauging at all levels of the canal irrigation, groundwater pumping and other water supply systems are a basic requirement of successful agriculture. At each control point, it becomes very important to keep the record of releases to various channels and finally to the fields. Therefore, it is important that all the stakeholders of Irrigation and drainage systems (including managers, policy makers, farmers and other water users) may understand not only the availability of water resources but also their efficient use to achieve the goals of potential crop production. They should further learn about the benefits of measured quantities of water delivered for protection of their water rights and its efficient use.


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Correct measurement of water deliveries minimizes the chances of disputes among the shareholders. This chapter of the book has been designed to explain the importance of water measurement, various techniques for flow measurement, in the laboratory as well as in the field, such as volumetric, weighing, velocity area and trajectory methods. The flow measuring devices such as weirs, flumes, venture meter, orifice meter, flow meters, etc. have also been discussed in detail.

**Keywords:** Water Measurement, Measuring Devices, Watercourse, Pipe Flow, Telemetry System and Gauging

# Learning Objectives

Flow measurement and gauging are important elements of an irrigation system to keep the record of releases to various channels and finally to the fields. Therefore, following are the objectives of the chapter on Gauging and Flow Measurements:

- The major objective of the chapter on gauging and flow measurement is to facilitate all the stakeholders of Irrigation System (system managers, policy makers, farmers and other water users) to understand the methodology of measurement and keep a record of the delivered and received amounts of water to safeguard their water rights and its efficient use.
- To understand the seasonal variations of flow during kharif and Rabi seasons, which may help the farmers to plan their cropping schedules.
- The reader may update his knowledge about assuring the correct deliveries to his farm.

# 4.1 Introduction

Increasing competition exists between multiple users, including irrigation, municipal, industrial, environmental, recreation, aesthetic, fish farming and wildlife uses. Therefore, optimal use of this scarce commodity would be required to satisfy the needs of competing users in terms of quantities and time of use. Good management measures and practices leading to conservation of water will always require accurate measurement of this commodity at all levels.

## 4.1.1 Types of Flow

Fluid flow may be classified as: (i) Open channel flow (ii) Pipe flow or Closed Conduit flow. Open channel flow conditions exist when the surface of flowing stream is free and open to the atmosphere. The driving force here is gravity creating a gravitational head of water. Flow in canals, watercourses or in vented pipelines, which are not flowing full are typical examples of open channel flow. The presence of the free water surface prevents transmission of pressure from one end of the conveyance channel to another. In case of fully flowing pipelines, the applied pressure dominates the gravitational forces, and therefore, the flow occurs under pressure.

In hydraulics, a pipe is any closed conduit that carries fluid under pressure. Regardless of the cross-sectional shape of the conduit, the pressure in the pipe is equally distributed along the cross section. If flow is occurring in a conduit that does not completely fill it, the flow is not considered as conduit flow, but is classified as open channel flow. The head loss due to friction takes place in the conduit as well as in the open channel. However, different factors are responsible to cause the head loss. Therefore, head loss measurement and consequently, the discharge measurement is carried out using different devices. In most of the cases, the flow considerations in canal irrigation are the open channel flow that will be the focus of this chapter.

### 4.1.2 Flow Measurement

Determination of the quantity of fluid flowing per unit time across any section of the channel (spillway, under sluice, “mogha”, “nakka” or flume etc.) is called Flow Measurement and is usually expressed as flow rate i.e. volume or weight or mass of fluid moving per unit time. The units of measurement may include cubic meter per second ($m^3/s$), cubic feet per second ($ft^3/s$), etc. or in terms of weight flow rate such as kilo newton per second (kN/s), or mass flow rate such as kilograms per second (kg/s). In dealing with incompressible fluids (liquids) such as water, oil, etc., volume flow rate is used, whereas the weight flow rate or mass flow rate is more convenient for compressible fluids such as gases. As the irrigation system utilizes water as a fluid, the flow rate is measured in terms of volume of water per unit time.

### 4.1.3 Importance and Need

For efficient use of irrigation water supplies and potential crop production, water should be applied in measured quantities, which otherwise may cause under irrigation or over irrigation to crops. The under irrigation will cause loss in yield due to water stress and salt accumulation, while over irrigation will cause dual damage i.e. losses of water and reduction in crop yield. The over irrigation further leads to water logging that would ultimately reduce the crop yield. The over irrigation also causes loss of soil nutrients, which ultimately affect soil health and ground water quality. Thus, to get maximum benefit out of limited water resources. Required amount of water should be applied, which is only possible by measuring it. Various uses and benefits of water measurement in irrigation include:

- Application of measured water to crops requires accurate water measurement
- Provision of equitable shares of water between competing uses.
- Water measurement facilitates accurate and equitable distribution of water within farms.
- Employing accurate and convenient water measurement methods improves the evaluation of seepage losses in lined and unlined channels
- Delivery of measured amounts of water to the farms allows the farmers to plan and execute farming activities with better confidence and management options. It also develops a better working relationship with Government functionaries

- Correct measurement of water deliveries minimizes the disputes among the shareholders.
- Correct measurements give a feeling of satisfaction to all concerned parties (farmers of a command, provincial Governments or and promote more efficient utilization

### 4.1.4 Units of Measurement

Water is found in two states on the earth's surface, at rest or in motion. Water at rest means water in reservoirs, lakes, ponds, tanks and containers, etc., and it is measured in volumetric units like hectare-meter, acre-feet, acre-inches, cubic meters, cubic feet, liters, gallons, etc. When water is in the state of motion, such as in water channels, rivers, canals and in watercourses, etc., it is measured in volume per unit time, units that include cubic meter per second, cubic foot per second, liter per second, cubic meter per hour, cubic foot per hour, etc. Definitions for some of the commonly used units for water measurement have been given in Table 4.1.

**Table 4.1** Some Examples of the Units of Water Measurement in the Field

| Volume Units | | | |
|---|---|---|---|
| S. | Unit | Definition | Symbol |
| 1 | Hectare-meter | Volume of water required to cover an area of one hectare up to a depth of one meter, which may be mathematically presented as : 1 hectare-meter = 10,000 $m^2$ X 1m = 10,000 $m^3$ | ha-m |
| 2 | Acre-foot | Volume of water required to cover an area of one acre up to a depth of one foot.1 Acre-foot: 43,560 $ft^2$ X 1 ft = 43,560 $ft^3$ | Ac-ft |
| 3 | Acre-inch | It is a volume of water required to cover an area of one acre up to a depth of one inch. It is most widely used unit for irrigation application to crops locally. 1 Acre-inch: 43,560 $ft^2$ X 1/12 ft = 3630 $ft^3$ | Ac-in |
| Flow Rate Units | | | |
| 1 | Cubic meter per second | If a volume of one cubic meter of water passes across a control section ("mogha", "nakka", weir, etc.) per second, the discharge is measured as one cubic meter per second ($m^3/s$). | $m^3/s$ |
| 2 | Cubic foot per second | If a volume of one cubic foot of water passes across a control section (mogha, nakka, Weir etc.) per second, the discharge is measured as one cubic foot per second | $ft^3/s$ |
| 3 | Liter per second | If a volume of one liter of water passes across a control section (mogha, nakka, weir, etc.) per second, the discharge is measured as one liter per second | l/s |

## 4.2 Methods of Flow Measurement

There are several methods available for flow measurement suitable for various situations as discussed below:

### 4.2.1 Volumetric Method

The simplest method to estimate small discharges is by direct measurement of the time to fill a container of known capacity. The flow is diverted into a channel or a pipe, which discharges into a suitable container, and the time to fill is determined by stopwatch. The time to fill must be noted accurately, especially when it is only a few seconds. The variation between several measurements taken in succession will give an indication of the accuracy of results. For a given volume and time, the flow rate can be determined as:

Discharge $Q$ = Tank Volume (V)/Filling Time (T)

i.e. $Q = V/T$

Where;

$Q$ = Discharge ($m^3/s$)

$V$ = Volume of tank ($m^3$)

$T$ = Filling Time (s)

### 4.2.2 Weighing Method

Another method of determining the flow rate accurately, is to find the time to collect a known weight of the fluid. The weight of water is divided by time to calculate the weight flow rate, which is then divided by a unit weight of water to get the volumetric flow rate as summarized below.

Weight flow rate = Weight /Time i.e. $G = W/T$ and

If $G = \gamma Q$

Thus, $Q = (W / \gamma) / T$

Where;

$G$ = Weight flow rate (Kilo Newton per second or kN/s)

$W$ = Weight collected (kN)

$T$ = Collection time (s)

$Q$ = Volumetric flow rate ($m^3/s$)

$\gamma$ = Unit weight or Specific weight of water (9.81 $kN/m^3$)

### 4.2.3 Velocity-Area Method

In flow measurement, the rate of flow is assessed by determining the velocity of fluid passing through a given cross-sectional area using the continuity equation:

i.e. $Q = AV$

Where

$Q$ = Flow Rate - Cubic meter per second

A= Cross Sectional Area – Square meters

V= Velocity of fluid – Meter per second

T= Time- Seconds

The units of flow measurement (volume per unit time) include: gallon per minute (gpm), cubic feet per second (cfs), liter per second (L/s), or cubic meters per second ($m^3$/s) etc. (Michael 2009).

#### 4.2.3.1 Measurement of Area

Generally, channels are of two types lined (regular section) and unlined (irregular section). The

areas of the regular channel section area are determined using the equations given below:

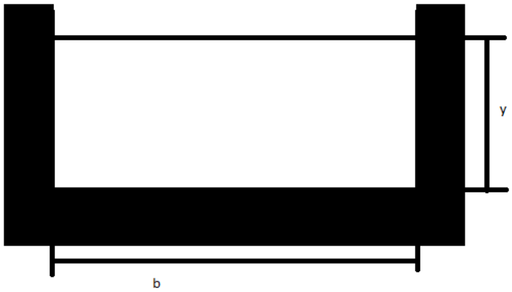
**i) Regular Cross Section:**

The regular cross sections of a channel include rectangular, trapezoidal and triangular (Fig. 4.1), which can be defined as:

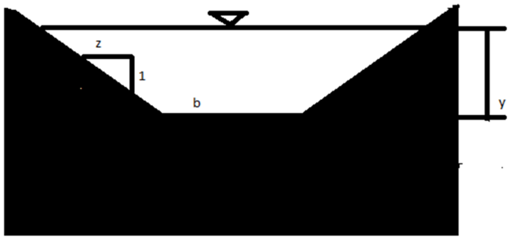
**ii) Irregular Cross Section**

The area of irregular section is determined by dividing the total width of the channel into several smaller widths and then multiplying each width with respective average depth and finally summing all the smaller areas thus determined as shown in the blue shaded cross section of the channel in Fig. 4.2. The number and widths of the subdivisions depend upon the accuracy needed. The smaller the width, the more accurate is the area.

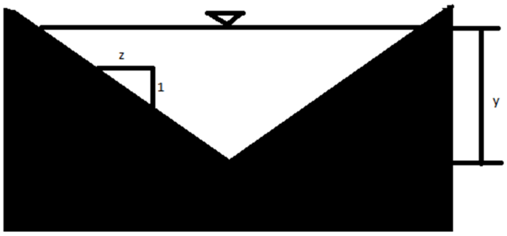
Rectangular section:
A = b .y




Trapezoidal section:
A = (b + z. y) y




Triangular section:
A = z x $y^2$




Where: A= Cross sectional area
b = Width of channel
y = Depth of water in the channel
z = Side slope i.e. Horizontal/vertical

**Fig. 4.1** Cross sectional areas of various channel shapes

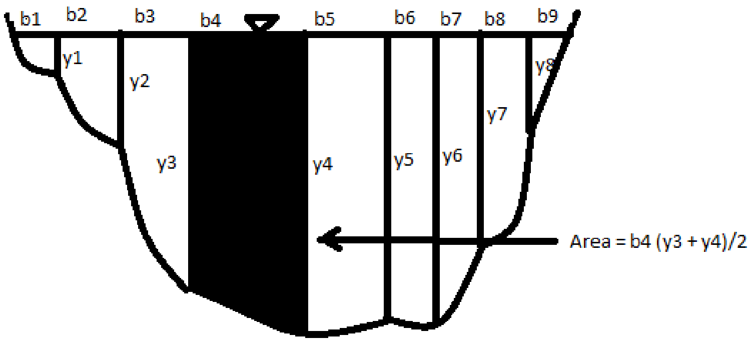



**Fig. 4.2** Cross Sectional Area of a Large Unlined Channel with Irregular Cross Section

#### 4.2.3.2 Velocity Measurement

Various methods are in use for velocity measurement out of which only two are given below:

**i) Float Method**

The float method of flow measurement comprises the use of a float, which may be a piece of wood, a ball or any other object that is dipped in water by 2/3 of its length so that it moves along the water currents (Martin, 2011). The velocity can be determined by noting the time of travel for a predetermined distance and then dividing the distance traversed by the object by the time. Thus, velocity can be measured in units of ft/s, m/s etc. as given below:

Velocity = distance travelled / elapsed time of travel

In an open channel, Volume flow rate is determined by the product of the average flow velocity and the average cross-sectional area of the stream as given below:

$$Q = AV$$

In an open channel, the velocity of flow varies from zero at the bottom surface of the channel to the maximum just below the surface of water in the channel. A well dipped float allows average measurement of velocity. However, more than one measurement would allow to find the average velocity, which is needed the accuracy of flow measurement. For flows in canals and reasonably smooth streams, the measured surface float velocities should be multiplied by the correction factor of 0.85. The corrected velocities should then be multiplied by the cross-sectional area of the corresponding stream sub section to obtain the sub section discharges. The summation of the segment discharges will be the gross discharge.

**ii) Current Meter**

The Current Meter measures the velocity of fluid currents and thereby the velocity of fluid flow. The velocity of water flowing in an open channel is not the same throughout the cross-section. It approaches zero at the bottom as well as along the sides of the channel and maximum in the mid cross sectional area. To find the mean flow rate, mean current velocity and accurate cross-sectional area of the stream are needed. For determining mean velocity, the top width of the cross-sectional area of the channel is divided into several sections. The average velocity is estimated by the average of the current meter observations taken at 0.2D (20 % of depth) and 0.8D (80 % of the Depth) of channel in the rectangular sub sections. In the triangular subsections near the sides of the channel, the average velocity of flow is determined by taking only one observation at 0.6D (i.e. 60% of the depth) as shown below in Fig. 4.3.

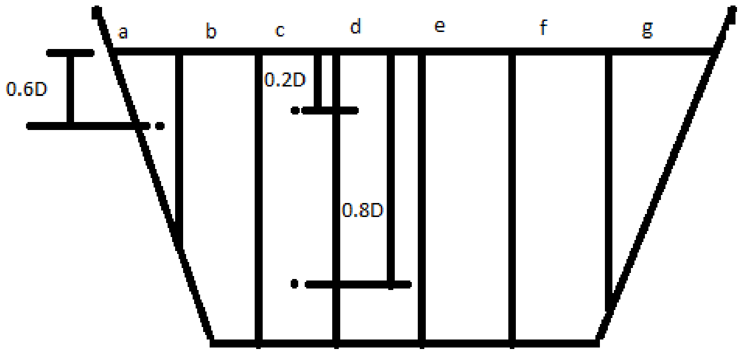



**Fig. 4.3** Measuring Points in Channel Cross Section

The flow for each subsection is calculated by the product cross-sectional area of the subsection and the average flow velocity within the subsection. The flow rate through this channel, for example, would be:

Flow = (AaVa) +(AbVb) +(AcVc) +(AdVd) +(AeVe) +(AfVf) +(AgVg) +(AhVh)

Where: Aa, Ab, ... Ah = cross-sectional areas of subdivisions a, b, ...h
Va, Vb, ...Vh = average flow velocities of subdivisions a, b, ...h

Aa, Ab, … are the areas of subsections (average depth multiplied by the subsection width or width multiplied by the depth as the shape may be)

Va = V0.6D (as it is a shallow section)

Vb = (V0.2D + V0.8D) / 2 (as it is as deep section) and so on

### 4.2.4 Trajectory Method of Tube well Flow Measurement

Trajectory method consists of measuring the horizontal and vertical coordinates of a point in the jet issuing from the end of a pipe (Stock, 1955) as shown in Fig 4.4. The pipe may be positioned either vertically or horizontally. The main difficulty with this technique is the accuracy in measuring the coordinates of the flowing stream.

$$Q = A.\ X/\ (2Y/g)^{0.5}$$

Where;

Q = Flow rate ($m^3/s$)

X = Horizontal component of water jet (m)

Y = Vertical component of water jet (m)

g = Acceleration due to gravity ($m/s^2$)

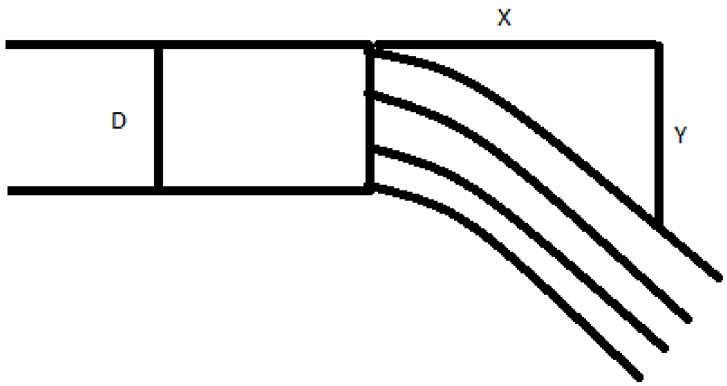



**Fig. 4.4** Trajectory Method of Flow Measurement

## 4.2.5 Telemetry System

Telemetry System has been devised through Supervisory Control and Data Acquisition (SCADA) to observe the flow rate with the help of gate openings and water levels using Sensors equipped with the system. The telemetry system is attached to the gauging points of the entire network and may be connected to other locations through electronic systems. Data loggers can be used to collect data regarding the depth and velocity of flow. Thus, it assists the system managers to properly regulate and distribute irrigation water to various users. This system has been widely used in the developed as well as in many developing countries. Telemetry System has been recently used by WAPDA and IRSA to monitor the canal irrigation system of Pakistan. The telemetry system is working very well and has opened new scenario; however, it requires willingness and participation on the part of the engineers and farmers.

### 4.2.5.1 Components of Telemetry System

The major components of a telemetry system include:

- Field instrumentation and control equipment
- Remote station
- Communication network, and
- Central monitoring station

Field instrumentation and control equipment collect data from the field. The instruments include sensors, meters and actuators that are directly attached to the canal gates at flow regulators. The telemetry system may utilize telephone, radio and cable or satellite to effectively transfer the collected data to other locations equipped with a computer system. The computer output consists of real time water levels and canal discharge. At the central communication station, the data are processed automatically by computers and gives the flow distribution to various canal systems feeding the provincial irrigation systems.

#### 4.2.5.2 Benefits of Telemetry Systems

The benefits of Telemetry System include:

1. Improve operational and service capability of the system.
2. Standardize operating procedures to run the system more efficiently and to better utilize staff.
3. Reduced operational costs and risks.
4. Better ability to negotiate with water managers and stakeholders.
5. Opportunity to manage the system with equitable distribution among the stakeholders, such as provincial Irrigation Departments.
6. Improved ability to collect data regarding flow rates and sharing status of the stakeholders.

## 4.3 Gauging

In case of flow over a weir, the flow can be measured by relating flow rate with the flowing depth. Such a control section on a channel is considered as a gauging station. Recording of flow depth through a vertical scale at that section is called stream gauging. The scale is installed in a stilling well provided in the bank of the channel at the measuring point, so that the surface of water becomes still to facilitate accurate recording the depth data.

## 4.4 Devices for Flow Measurement

Commonly used devices for flow measurement are discussed below:

### 4.4.1 Weirs

Weirs are devices which can be used to measure the discharge rate in the open channels. As water flows over the weir crest, the depth or head of the water is measured over the weir crest, which acts as a flow control section. The flow equation utilizes the depth information to find the discharge. However, different cross sectional shapes of weirs use different flow equations as shown in Fig 4.5.

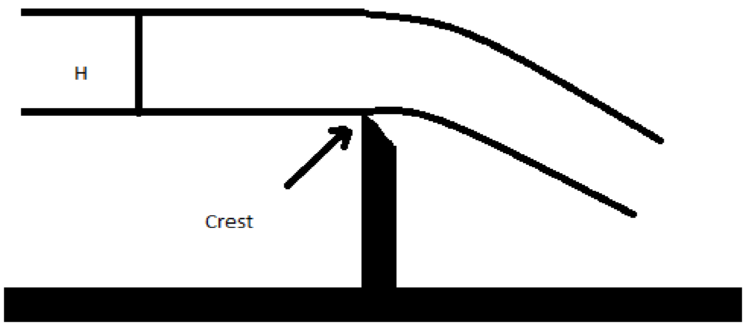



**Fig. 4.5** Water Flowing Over a Sharp Crested Weir

Some general terms pertaining to weirs are:

Notch: It is the opening which water flows through

Crest: It is the edge which water flows over

Nappe: It is the free-flowing jet over a weir. There is aeration zone below the nappe

Head: Depth of water above the edge, denoted by (H) and should be measured at 4H from edge.

Length: Distance of V Notch across the width section of the weir notch formulae for different weirs cross sections are given below:

### 4.4.2 Flumes

Flumes include various specially shaped and stabilized channel sections that are used to measure flow. Use of flumes is similar to the use of weirs in that flow is related to flow depths at specific points along the flume. Various types of flumes are in practice but the most usually used flume is cutthroat as discussed below:

The Cut-Throat Flume was developed by Ralph Parshall. It is suited to flat gradient applications in open-channels. The Cut-Throat Flume has a rectangular constriction with a flat surface floor and throat length reduced to zero that named it as Cut-Throat Flume.

These flumes are available in standard length of 3 feet and standard throat widths of 4, 8, 12 and 16 inches for which discharge rating tables are available. It allows these flumes to be applicable to a wide range of discharge measurement. The advantages of using Cut-Throat Flumes include the following:

- It is less costly to construct than other types of flumes due to its simplicity.
- Easy to install due to flat floor.
- Usable at lower gradient channels due to less head loss.
- Angles of convergence / divergence are the same for all sizes of Cut-Throat Flumes, which allows these flumes to be developed by simply moving the sidewalls in and out as necessary.

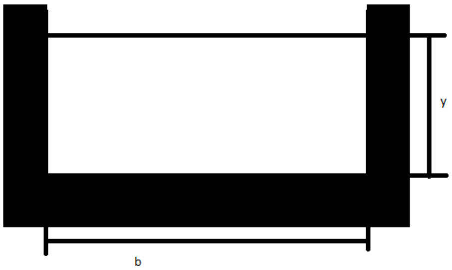
A dimensioned sketch of Cut-Throat Flume is shown in Fig 4.7.

#### 4.4.2.1 Submergence

Cut-Throat Flumes need a minimum head loss to make sure that free-flow conditions exist. Under free flow condition, only one value of upstream head measurement (ha) is needed to determine the discharge rate. When the water surface in the downstream part of the flume rises above a critical point, the resistance to flow of the channel becomes sufficient to reduce the upstream velocity, which causes to increase the flow depth at the upstream component of the flume because of the backwater effect in the flume.

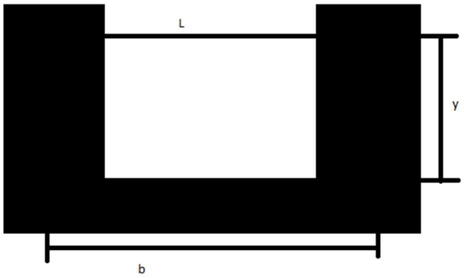
Rectangular weir

$Q = \frac{2}{3} Cd\sqrt{2g}\, L\, H^{3/2}$



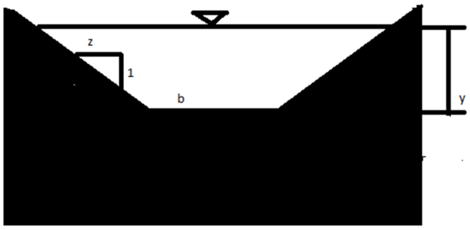

Rectangular contracted weir

$Q = \frac{2}{3} Cd\sqrt{2g}(L - 0.1nH)H^{3/2}$



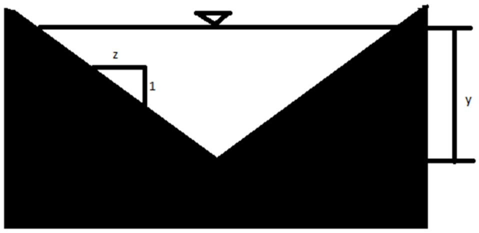

Cipolletti weir

$Q = 1.86\, L\, H^{3/2}$




V-notch weir

$Q = \frac{8}{15} Cd\sqrt{2g}\tan\frac{\theta}{2}\, H^{5/2}$




Q = flow rate ($m^3/s$)
H = head on the weir (m)
L = width of the weir (m)
g = 9.81 ($m/s^2$) - gravity
θ = v-notch angle
n = number of end contractions (n = 2 in Fig 4.7 (b))
Cd= discharge constant for the weir - must be determined

**Fig. 4.6** Types of Weirs

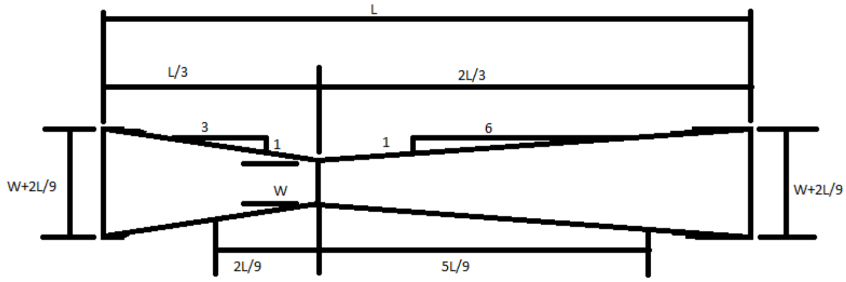



**Fig. 4.7** Sketch of Cutthroat Flume (Top View)

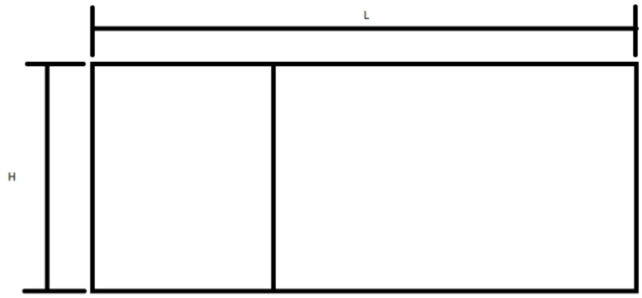



**Fig. 4.8** Sketch of Cut-Throat Flume (Side View)

Submerged flow conditions in the flume occur when the resistance to flow at downstream controls the flow upstream. Under submerged flow condition, the flow velocities reduce and the flow depth increases as compared to that achieved under free-flow conditions.

The submergence ratio can be defined as the ratio of the downstream depth of the flume (Hb) to the upstream depth (Ha). Thus, the Submergence Ratio (Hb/Ha) can be is expressed mathematically either as a ratio or as a percentage.

#### 4.4.2.2 Flume Installation

It is advised to follow the following steps to ensure a successful Cut-Throat Flume installation:

- Install the flume at a straight section of the channel, which should be free of bends, dips, elbows, or flow junctions.
- The approaching flow should be sub-critical and uniformly distributed across the channel. Avoid any turbulent, surging, unbalanced flow situation at the channel section where flume is installed. In addition, a poorly distributed velocity pattern should also be avoided.
- The flume should be centered in the channel / flow stream
- The floor of the flume should be set high enough to ensure a free flow condition.

- The floor of the flume must be installed at Zero level, both in the parallel and transverse directions with the flow of water.
- The dimensions of the flume must be checked before installation.
- Check for leakage on the outer sides as well as below the flume during flow measurements by the proper filling of soil.
- Open channel flow conditions must exist at all times

## 4.4.3 Venturimeter

Venturimeter is used in pipes to find out the flow rate. The Venturi effect is the reduction in fluid pressure that results when a fluid flows through a constricted section of pipe (Doughtery et al, 1985). The Venturi effect is a jet effect; as with a funnel the velocity of the fluid increases as the cross-sectional area decreases, with the static pressure correspondingly decreasing as shown in Fig 4.9. According to the laws governing fluid dynamics, a fluid's velocity must increase as it passes through a constriction to satisfy the principle of continuity, while its pressure must decrease to satisfy the principle of conservation of mechanical energy. Thus, any gain in kinetic energy a fluid may accrue due to its increased velocity through a constriction is negated by a drop in pressure.

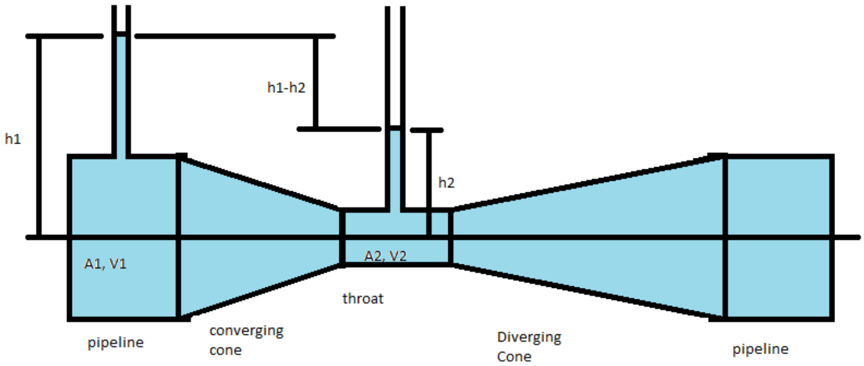



**Fig. 4.9** Venturimeter

A venturi can be used to measure the volumetric flow rate, Q.

$$Q = A_2V_2 = \frac{CA_2}{\{1 - (D_2/D_1)^{-4}\}^{0.5}} \{2g\{(\frac{p_1}{\gamma} + Z_1) - (\frac{p_2}{\gamma} + Z_2)\}\}^{0.5}$$

Where

Q = Flow rate, $m^3/s$

C = Coefficient of discharge, -

$D_1$ = Diameter of pipe, m

$D_2$ = Diameter of throat, m

$Z_1$ and $Z_2$ = respective elevations, m

$P_1/\gamma$ and $P_2/\gamma$ are respective pressure heads ($h_1$ and $h_2$), m

### 4.4.4 Orifice Meter (Orifice Plate)

An orifice plate is a device used for measuring the flow rate in pipelines. It also uses the Bernoulli's principle which states that there is a relationship between the pressure of the fluid and the velocity of the fluid. When the velocity increases, the pressure decreases and vice versa (Doughtery et al., 1985).

An orifice plate is a thin plate with a hole in the middle. It is placed in a pipe where a fluid is flowing. When the fluid reaches the orifice plate, the fluid is forced to converge through the hole where maximum convergence takes place at the vena contracta point (Fig. 4.10).

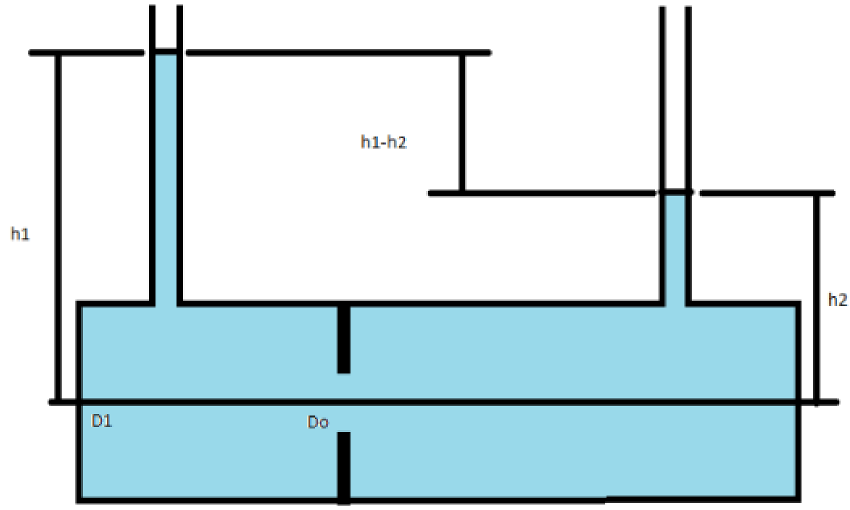



**Fig 4.10** Orifice Plate

Orifice plates are used for continuous measurement of fluid flow in pipes. They are also used in some small river systems to measure flow rates at locations where the river passes through a culvert or drain. Only a small number of rivers are appropriate for the use of the technology since the plate must remain completely immersed i.e. the approach pipe must be full, and the river must be substantially free of debris.

$$Q = A_o V_2 = \frac{CA_o}{\{1 - (D_o/D_1)\text{-}^4\}^{0.5}} \{2g\left\{\left(\frac{p_1}{\gamma} + Z_1\right) - \left(\frac{p_2}{\gamma} + Z_2\right)\right\}\}^{0.5}$$

Q = Flow rate, $m^3/s$

C = Coefficient of discharge, -

$D_1$ = Diameter of pipe, m

$D_o$ = Diameter of orifice, m

$Z_1$ and $Z_2$ = respective elevations, m

$P_1/\gamma$ and $P_2/\gamma$ are respective pressure heads ($h_1$ and $h_2$), m

### 4.4.5 Water Meter

Water meters are used to measure the volume of water flowing through a pipe system. Some water meters show the flow in addition to total volume delivered. Several types of water meters are installed on sprinkler as well as on drip irrigation systems to manage the correct application of water to the crop.

### 4.4.6 Siphon Tube

If siphon tubes (Fig. 4.11) allow application of irrigation to the crop from an open ditch without cutting through the bank of the channel, the difference in head between the channel and the field is utilized to determine the flow rate as well as the total amount of water applied to the field. The siphon may operate under free flow as well as submerged flow conditions. The larger the tube size or the greater the head, the higher will be the flow rate (Gertrudys, 2006).

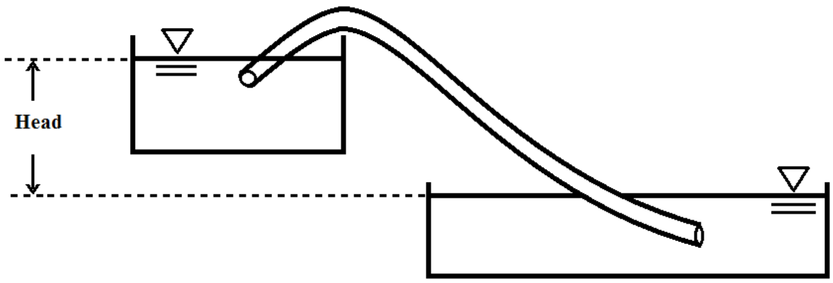



**Fig. 4.11** Measurement of Head for Siphon Tube

## 4.5 Selection of Water Measuring Devices

The following factors should be considered while selecting a suitable measuring device:

- Accuracy
- Cost
- Legal constraints
- Range of flow rates
- Head loss
- Adaptability to site conditions
- Adaptability to operating conditions

- Type of measurements and records needed
- Operating requirements
- Ability to pass sediment and debris
- Suitability to environment
- Maintenance requirements
- Construction and installation requirements
- Minimum troubleshooting opportunities
- Vandalism potential

## 4.6 Solved Examples

**Example 4.1:** Calculate the flow rate in a regularly maintained irrigation channel by float method. A 60 m length of channel (Fig. 4.12) is marked at 3 points as A, B and C with the section of channel starting at point A and ending at C. The interval between two points is 30 m each. The mean width of the channel at the bottom and surface of water at three points (A, B and C) are 100, 101 and 102 cm, respectively, with depth of water at those points are 30, 30 and 31 cm, respectively. The time taken by float to cross points B and C are 90 and 186 s respectively after it runs from the point A.

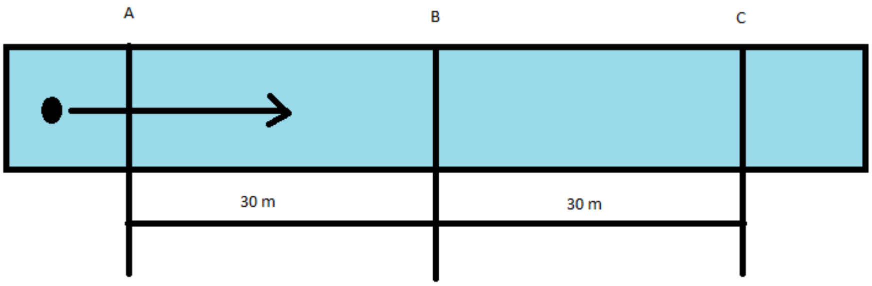



**Fig. 4.12** Top View of an Irrigation Channel

**Solution**

Average depth = (30+30+31)/3 = 30.33 cm

Average width = (100+101+102)/3 = 101 cm

Average area = 0.3033 X 1.01 = 0.3063 $m^2$

Average velocity = (30/90 + 30/96) x 1/2 x 0.85 = 0.2745 m/s

Discharge = average area x average velocity

= 0.3063 x 0.2745

= 0.0841 $m^3/s$

**Example 4.2:** Water flows into a cylindrical tank at a rate of 0.4 $m^3/s$ and is to be discharged from the tank at the same rate over a sharpe-crested, suppressed rectangular weir. Due to the geometry of the tank and the potential for overflow, the maximum head on the weir is 45 cm. Determine the minimum required length of the weir. Take Cd = 0.62.

**Solution**

$Q = \frac{2}{3} Cd\sqrt{2g}\, L\, H^{3/2}$

$0.4 = \frac{2}{3} 0.62\sqrt{2 * 9.81}\, L\, 0.45^{3/2}$

L= 0.73 m

**Example 4.3:** Solve problem of example 4.2 using a sharp-crested, contacted weir

**Solution**

$Q = \frac{2}{3} Cd\sqrt{2g}(L - 0.1nH)H^{3/2}$

$0.4 = \frac{2}{3} * 0.62\sqrt{2 * 9.81}(L - 0.1 * 2 * 0.45) * 0.45^{3/2}$

L = 0.82 m

**Example 4.4:** Discharge (Q) through a channel is controlled using a 90° v-notch. For a measured head of 0.3 m, evaluate the flow rate. How does the value of Q if the opening angle is instead 45°? Assume Cd = 0.60

**Solution**

For $\theta = 90^o$ $\quad Q = \frac{8}{15} Cd\sqrt{2g} \tan\frac{\theta}{2}\, H^{5/2}$

$Q = \frac{8}{15} * 0.60\sqrt{2 * 9.81} \tan\frac{90}{2} * 0.3^{5/2}$

Q = 0.07 $m^3/s$

For $\theta = 45^o$ $\quad$ Q = 0.029 $m^3/s$

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# 4.8 Appendix

Flow Measuring Table for Different Sizes of Cut-Throat Flumes

## 4.10.1 Appendix– Flow Measuring Table for Cut Throat Flumes

**1.5 Foot Flume**

| Hu ft | 2in cfs | 4in cfs | 6in cfs | 8in cfs |
|---|---|---|---|---|
| 0.30 | 0.089 | 0.184 | 0.283 | 0.387 |
| 0.32 | 0.101 | 0.209 | 0.321 | 0.439 |
| 0.34 | 0.114 | 0.235 | 0.362 | 0.494 |
| 0.36 | 0.128 | 0.263 | 0.405 | 0.552 |
| 0.38 | 0.142 | 0.293 | 0.450 | 0.613 |
| 0.40 | 0.157 | 0.324 | 0.497 | 0.677 |
| 0.42 | 0.173 | 0.356 | 0.547 | 0.744 |
| 0.44 | 0.190 | 0.391 | 0.599 | 0.814 |
| 0.46 | 0.207 | 0.426 | 0.653 | 0.887 |
| 0.48 | 0.226 | 0.463 | 0.710 | 0.964 |
| 0.50 | 0.245 | 0.502 | 0.769 | 1.043 |

**3.0 Foot Flume**

| Hu ft | 4in cfs | 8in cfs | 12in cfs | 16in cfs |
|---|---|---|---|---|
| 0.30 | 0.153 | 0.317 | 0.489 | 0.668 |
| 0.32 | 0.173 | 0.357 | 0.550 | 0.750 |
| 0.34 | 0.193 | 0.399 | 0.614 | 0.837 |
| 0.36 | 0.214 | 0.442 | 0.681 | 0.927 |
| 0.38 | 0.237 | 0.488 | 0.751 | 1.022 |
| 0.40 | 0.260 | 0.536 | 0.824 | 1.121 |
| 0.42 | 0.285 | 0.586 | 0.900 | 1.223 |
| 0.44 | 0.310 | 0.638 | 0.979 | 1.330 |
| 0.46 | 0.336 | 0.692 | 1.061 | 1.441 |
| 0.48 | 0.364 | 0.748 | 1.146 | 1.555 |
| 0.50 | 0.392 | 0.806 | 1.234 | 1.673 |
| 0.52 | 0.422 | 0.866 | 1.325 | 1.796 |
| 0.54 | 0.452 | 0.928 | 1.419 | 1.922 |
| 0.56 | 0.483 | 0.991 | 1.515 | 2.051 |
| 0.58 | 0.515 | 1.057 | 1.615 | 2.185 |
| 0.60 | 0.548 | 1.125 | 1.717 | 2.322 |
| 0.62 | 0.583 | 1.194 | 1.822 | 2.463 |
| 0.64 | 0.618 | 1.265 | 1.930 | 2.608 |
| 0.66 | 0.654 | 1.338 | 2.040 | 2.756 |
| 0.68 | 0.691 | 1.413 | 2.154 | 2.908 |
| 0.70 | 0.728 | 1.490 | 2.270 | 3.063 |
| 0.72 | 0.767 | 1.569 | 2.388 | 3.222 |
| 0.74 | 0.807 | 1.649 | 2.510 | 3.385 |
| 0.76 | 0.847 | 1.732 | 2.634 | 3.551 |
| 0.78 | 0.889 | 1.816 | 2.761 | 3.721 |
| 0.80 | 0.931 | 1.902 | 2.891 | 3.894 |
| 0.82 | 0.975 | 1.989 | 3.023 | 4.071 |
| 0.84 | 1.019 | 2.079 | 3.158 | 4.251 |
| 0.86 | 1.064 | 2.170 | 3.295 | 4.434 |
| 0.88 | 1.110 | 2.263 | 3.435 | 4.622 |
| 0.90 | 1.157 | 2.358 | 3.578 | 4.812 |
| 0.92 | 1.204 | 2.454 | 3.723 | 5.006 |
| 0.94 | 1.253 | 2.553 | 3.871 | 5.203 |
| 0.96 | 1.302 | 2.653 | 4.021 | 5.404 |
| 0.98 | 1.353 | 2.754 | 4.174 | 5.608 |
| 1.00 | 1.404 | 2.858 | 4.330 | 5.815 |

**4.5 Foot Flume**

| Hu ft | 6in cfs | 12in cfs | 18in cfs | 24in cfs |
|---|---|---|---|---|
| 0.30 | 0.237 | 0.491 | 0.757 | 1.034 |
| 0.32 | 0.265 | 0.548 | 0.844 | 1.152 |
| 0.34 | 0.294 | 0.607 | 0.935 | 1.275 |
| 0.36 | 0.324 | 0.670 | 1.030 | 1.404 |
| 0.38 | 0.356 | 0.734 | 1.129 | 1.537 |
| 0.40 | 0.389 | 0.802 | 1.231 | 1.675 |
| 0.42 | 0.423 | 0.871 | 1.337 | 1.818 |
| 0.44 | 0.458 | 0.943 | 1.447 | 1.966 |
| 0.46 | 0.495 | 1.017 | 1.560 | 2.118 |
| 0.48 | 0.532 | 1.094 | 1.676 | 2.274 |
| 0.50 | 0.571 | 1.173 | 1.796 | 2.436 |
| 0.52 | 0.611 | 1.254 | 1.920 | 2.601 |
| 0.54 | 0.652 | 1.338 | 2.046 | 2.772 |
| 0.56 | 0.694 | 1.423 | 2.176 | 2.946 |
| 0.58 | 0.737 | 1.511 | 2.309 | 3.125 |
| 0.60 | 0.781 | 1.601 | 2.445 | 3.307 |
| 0.62 | 0.827 | 1.694 | 2.585 | 3.495 |
| 0.64 | 0.873 | 1.788 | 2.728 | 3.686 |
| 0.66 | 0.921 | 1.884 | 2.873 | 3.881 |
| 0.68 | 0.969 | 1.983 | 3.022 | 4.080 |
| 0.70 | 1.019 | 2.083 | 3.174 | 4.284 |
| 0.72 | 1.069 | 2.186 | 3.329 | 4.491 |
| 0.74 | 1.121 | 2.291 | 3.487 | 4.703 |
| 0.76 | 1.174 | 2.397 | 3.648 | 4.918 |
| 0.78 | 1.227 | 2.506 | 3.812 | 5.137 |
| 0.80 | 1.282 | 2.617 | 3.979 | 5.360 |
| 0.82 | 1.337 | 2.729 | 4.149 | 5.587 |
| 0.84 | 1.394 | 2.844 | 4.321 | 5.817 |
| 0.86 | 1.452 | 2.961 | 4.497 | 6.051 |
| 0.88 | 1.510 | 3.079 | 4.675 | 6.289 |
| 0.90 | 1.570 | 3.200 | 4.856 | 6.531 |
| 0.92 | 1.630 | 3.322 | 5.040 | 6.776 |
| 0.94 | 1.692 | 3.446 | 5.227 | 7.025 |
| 0.96 | 1.754 | 3.572 | 5.417 | 7.278 |
| 0.98 | 1.818 | 3.700 | 5.609 | 7.534 |
| 1.00 | 1.882 | 3.830 | 5.804 | 7.794 |
| 1.05 | 2.047 | 4.163 | 6.303 | 8.459 |
| 1.10 | 2.217 | 4.507 | 6.820 | 9.146 |
| 1.15 | 2.394 | 4.862 | 7.352 | 9.854 |
| 1.20 | 2.576 | 5.228 | 7.901 | 10.583 |
| 1.25 | 2.763 | 5.606 | 8.466 | 11.334 |
| 1.30 | 2.956 | 5.994 | 9.047 | 12.105 |
| 1.35 | 3.154 | 6.393 | 9.644 | 12.896 |
| 1.40 | 3.358 | 6.802 | 10.256 | 13.708 |
| 1.45 | 3.567 | 7.222 | 10.883 | 14.539 |
| 1.50 | 3.782 | 7.652 | 11.526 | 15.390 |

*Source: Federal Water Management Cell, 1996*

## 4.10.2 Appendix (continued) – Flow Measuring Table for Cut-Throat Flumes

**1.5 Foot Flume**

| S | 2in Qs/Qf | 4in Qs/Qf | 6in Qs/Qf | 8in Qs/Qf |
|---|---|---|---|---|
| 0.610 | 0.993 | | | |
| 0.620 | 0.990 | | | |
| 0.630 | 0.987 | | | |
| 0.640 | 0.983 | | | |
| 0.650 | 0.979 | | | |
| 0.660 | 0.974 | | | |
| 0.670 | 0.968 | 0.999 | | |
| 0.680 | 0.962 | 0.998 | | |
| 0.690 | 0.956 | 0.996 | | |
| 0.700 | 0.949 | 0.994 | | |
| 0.710 | 0.941 | 0.991 | | |
| 0.720 | 0.932 | 0.988 | | |
| 0.730 | 0.923 | 0.984 | | |
| 0.740 | 0.914 | 0.980 | | |
| 0.750 | 0.903 | 0.974 | 0.999 | |
| 0.760 | 0.892 | 0.969 | 0.998 | |
| 0.770 | 0.880 | 0.962 | 0.996 | |
| 0.780 | 0.867 | 0.955 | 0.994 | |
| 0.790 | 0.854 | 0.946 | 0.991 | |
| 0.800 | 0.839 | 0.937 | 0.987 | |
| 0.810 | 0.824 | 0.927 | 0.982 | |
| 0.820 | 0.808 | 0.916 | 0.977 | 0.998 |
| 0.830 | 0.790 | 0.905 | 0.971 | 0.997 |
| 0.840 | 0.772 | 0.891 | 0.963 | 0.994 |
| 0.850 | 0.752 | 0.877 | 0.955 | 0.990 |
| 0.855 | 0.742 | 0.869 | 0.950 | 0.988 |
| 0.860 | 0.731 | 0.861 | 0.945 | 0.985 |
| 0.865 | 0.720 | 0.853 | 0.940 | 0.983 |
| 0.870 | 0.709 | 0.844 | 0.934 | 0.980 |
| 0.875 | 0.697 | 0.835 | 0.928 | 0.976 |
| 0.880 | 0.685 | 0.825 | 0.921 | 0.973 |
| 0.885 | 0.673 | 0.815 | 0.914 | 0.969 |
| 0.890 | 0.660 | 0.805 | 0.907 | 0.964 |
| 0.895 | 0.646 | 0.793 | 0.899 | 0.959 |
| 0.900 | 0.632 | 0.782 | 0.891 | 0.954 |
| 0.905 | 0.618 | 0.770 | 0.882 | 0.948 |
| 0.910 | 0.603 | 0.757 | 0.872 | 0.942 |
| 0.915 | 0.587 | 0.743 | 0.862 | 0.935 |
| 0.920 | 0.571 | 0.729 | 0.851 | 0.927 |
| 0.925 | 0.554 | 0.713 | 0.839 | 0.919 |

**3.0 Foot Flume**

| S | 4in Qs/Qf | 8in Qs/Qf | 12in Qs/Qf | 16in Qs/Qf |
|---|---|---|---|---|
| 0.610 | 0.998 | | | |
| 0.620 | 0.996 | | | |
| 0.630 | 0.994 | | | |
| 0.640 | 0.992 | | | |
| 0.650 | 0.989 | | | |
| 0.660 | 0.986 | | | |
| 0.670 | 0.982 | | | |
| 0.680 | 0.978 | | | |
| 0.690 | 0.973 | 0.999 | | |
| 0.700 | 0.967 | 0.998 | | |
| 0.710 | 0.961 | 0.997 | | |
| 0.720 | 0.955 | 0.995 | | |
| 0.730 | 0.948 | 0.992 | | |
| 0.740 | 0.940 | 0.989 | | |
| 0.750 | 0.931 | 0.986 | | |
| 0.760 | 0.922 | 0.981 | | |
| 0.770 | 0.912 | 0.976 | 0.999 | |
| 0.780 | 0.902 | 0.971 | 0.998 | |
| 0.790 | 0.890 | 0.964 | 0.996 | |
| 0.800 | 0.878 | 0.957 | 0.994 | |
| 0.810 | 0.865 | 0.949 | 0.991 | |
| 0.820 | 0.851 | 0.940 | 0.987 | |
| 0.830 | 0.835 | 0.931 | 0.982 | 0.999 |
| 0.840 | 0.819 | 0.920 | 0.977 | 0.998 |
| 0.850 | 0.802 | 0.908 | 0.970 | 0.996 |
| 0.855 | 0.793 | 0.901 | 0.966 | 0.994 |
| 0.860 | 0.783 | 0.894 | 0.963 | 0.993 |
| 0.865 | 0.773 | 0.887 | 0.958 | 0.991 |
| 0.870 | 0.763 | 0.880 | 0.954 | 0.989 |
| 0.875 | 0.752 | 0.872 | 0.949 | 0.986 |
| 0.880 | 0.741 | 0.863 | 0.943 | 0.984 |
| 0.885 | 0.730 | 0.855 | 0.938 | 0.981 |
| 0.890 | 0.718 | 0.845 | 0.932 | 0.977 |
| 0.895 | 0.706 | 0.836 | 0.925 | 0.973 |
| 0.900 | 0.693 | 0.825 | 0.918 | 0.969 |
| 0.905 | 0.679 | 0.814 | 0.911 | 0.965 |
| 0.910 | 0.665 | 0.803 | 0.902 | 0.960 |
| 0.915 | 0.651 | 0.791 | 0.894 | 0.954 |
| 0.920 | 0.635 | 0.778 | 0.884 | 0.948 |
| 0.925 | 0.619 | 0.764 | 0.874 | 0.941 |

**4.5 Foot Flume**

| S | 6in Qs/Qf | 12in Qs/Qf | 18in Qs/Qf | 24in Qs/Qf |
|---|---|---|---|---|
| 0.610 | | | | |
| 0.620 | | | | |
| 0.630 | | | | |
| 0.640 | 0.999 | | | |
| 0.650 | 0.997 | | | |
| 0.660 | 0.996 | | | |
| 0.670 | 0.994 | | | |
| 0.680 | 0.991 | | | |
| 0.690 | 0.988 | | | |
| 0.700 | 0.984 | | | |
| 0.710 | 0.980 | | | |
| 0.720 | 0.976 | | | |
| 0.730 | 0.970 | 0.999 | | |
| 0.740 | 0.965 | 0.998 | | |
| 0.750 | 0.958 | 0.996 | | |
| 0.760 | 0.951 | 0.993 | | |
| 0.770 | 0.944 | 0.991 | | |
| 0.780 | 0.935 | 0.987 | | |
| 0.790 | 0.926 | 0.983 | | |
| 0.800 | 0.916 | 0.978 | | |
| 0.810 | 0.905 | 0.973 | 0.999 | |
| 0.820 | 0.894 | 0.966 | 0.997 | |
| 0.830 | 0.881 | 0.959 | 0.995 | |
| 0.840 | 0.868 | 0.951 | 0.992 | |
| 0.850 | 0.853 | 0.942 | 0.988 | |
| 0.855 | 0.845 | 0.937 | 0.986 | |
| 0.860 | 0.837 | 0.931 | 0.983 | |
| 0.865 | 0.828 | 0.926 | 0.980 | 0.999 |
| 0.870 | 0.819 | 0.920 | 0.977 | 0.998 |
| 0.875 | 0.810 | 0.913 | 0.974 | 0.997 |
| 0.880 | 0.800 | 0.907 | 0.970 | 0.996 |
| 0.885 | 0.790 | 0.900 | 0.966 | 0.995 |
| 0.890 | 0.780 | 0.892 | 0.962 | 0.993 |
| 0.895 | 0.768 | 0.884 | 0.957 | 0.991 |
| 0.900 | 0.757 | 0.876 | 0.952 | 0.989 |
| 0.905 | 0.745 | 0.867 | 0.947 | 0.986 |
| 0.910 | 0.732 | 0.857 | 0.941 | 0.983 |
| 0.915 | 0.719 | 0.847 | 0.934 | 0.980 |
| 0.920 | 0.705 | 0.836 | 0.927 | 0.976 |
| 0.925 | 0.690 | 0.824 | 0.919 | 0.972 |

*Source: Federal Water Management Cell, 1996*

## Chapter 5

# Channel Design and Control Structures

**Muhammad Jehanzeb Masud, Muhammad Jamal Khan and Abid Sarwar***

## Abstract

Apart from many other factors, the design of Irrigation channels and control structures plays very important role in the successful performance of an irrigation system. Irrigation projects are launched for equitable distribution of water among the shareholders and its efficient use at the farms, for which design of diversions and control structures provide basic framework. Both the service providers and users of water desire that the system should be free of problems and minimum loss of efficiencies. Therefore, all the stake holders need to update their knowledge about the design parameters, principles of design, construction and the properly measured deliveries by the system to the users. This chapter has thus, been designed to include basic concepts, design terminology and principles of design based on various regime theories including Kennedy's Theory, Lindley's Theory and Lacy's Theory proposed for the lined and unlined canals. The chapter further presents the design specifications of control structures, farm outlets and types of intake structures for small canals. It also provides opportunity to the readers for learning from relevant practical examples and multiple choice questions relevant to the subject.

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# Learning Objectives

- The purpose of this chapter is to:
- Update the knowledge of a reader about various terminologies and design procedures used in the channel design.
- Enhance the knowledge of the reader about various types of irrigation channels being operated in the irrigation system, which may include main canal, branch canal, distributary and watercourse etc.
- Familiarize the readers about the design parameters and models developed for designing irrigation channels.

# 5.1 Introduction

The performance of an irrigation system is dependent on the design of the network of canals and control structures. The canals might be excavated in different kinds of soils such as alluvial soil, non-alluvial soil etc., the plan consideration in nature differ according to the kind of soil. In addition, the velocity of flow in the canal must be less than critical. That means, the velocity must be non-silting and non-scouring. If the velocity gets less than critical silting may take place and the capability of the canal to carry the design flow will be reduced. If the velocity of flow exceeds the critical velocity, scouring may take place and the waterway will be distorted. Consequently, determination of critical velocity is extremely vital in canal design. Dependent on the water necessities of the plants on the area to be irrigated, the whole structure of major canal, secondary canal, tertiary canal and field distributaries must be planned appropriately for a definite practical value of climax discharge that should pass through them, thus supply sufficient irrigation to the commands. Once more, the design of unlined plus lined canals requires special realistic and economical reflection.

# 5.2 Terminology Related to the Channel Design

## 5.2.1 Alluvial Soil

The fine grained fertile soil deposited, developed and shaped by the flowing water is recognized as alluvial soil. The river carries weighty charge of silt, clay and fine sand during raining season. When the river overflows its banks, through the flood these fine soil particles get deposited on the adjacent places. This deposition process continues year past year. This kind of soil is initiated in deltaic area of a river. This soil is permeable and soft plus extremely productive.

### 5.2.2 Non-alluvial Soil

The soils that form and develop through the breakdown of rock formation because of weather, are recognized as non-alluvial soil. It comes into being in the mountains regions of a river. The soil is rigid and impervious in nature and low in fertility.

### 5.2.3 Silt Factor (f)

In design and operation of a canal in alluvial soils, the suspended sediment plus the deposited silt inside the canal bed must be taken into consideration. Through the inspection work within various canals in alluvial soil, Lacey recognized the consequence of silt on the determination of discharge plus the canal section. Consequently, he presented a factor which is accepted as 'silt factor'. It is dependent on the key particle size of silt. It is denoted by 'f', which may be determined by the expression

$$f = 1.76\sqrt{m_f} \qquad (5.1)$$

Where $m_f$ = Mean particle size of silt in mm. Table 5.1 summarizes the Particle Size and Silt Factor for Various Soil Textures.

**Table 5.1** Particle Size and Silt Factor for Various Soil Textures

| S. No | Soil Texture | Particle Size (mm) | Silt Factor (f) |
|---|---|---|---|
| 1 | very fine silt | 0.05 | 0.40 |
| 2 | fine silt | 0.12 | 0.60 |
| 3 | medium silt | 0.23 | 0.85 |
| 4 | coarse silt | 0.32 | 1.00 |

*Source: Van Reeuwijk, 2002*

### 5.2.4 Coefficient of Roughness (N)

The irregularity of the channel bed influences the velocity of flow. The roughness coefficient (N) represents the integrated consequence of the waterway cross sectional resistance. Table 5.2 gives the values of 'N' for various Bed Materials.

**Table 5.2** Values of 'N' for Various Bed Materials (Hazan, 1911)

| Materials | Value of N |
|---|---|
| earth | 0.0225 |
| masonry | 0.02 |
| concrete | 0.013 to 0.018 |

### 5.2.5 Mean Velocity

Velocity distribution in a channel section mostly varies from bottom (Least value) to free water surface (Maximum value), this is owing to shear stress at the base and at the sides. Field inspection indicates that mean velocity for open channel flow to be the average velocity calculated at 0.2 plus 0.8 of depth (y) from the free water surface. If the depth of the channel exceeds 0.5 m and if the depth of water in the channel is less than 0.5 m then there is one point method that is, the velocity should be determined at 0.6 d, where d

$$V_{av} = \frac{V_{0.2y} + V_{0.8y}}{2} \qquad (5.2)$$

If the depth of the channel exceeds 0.5 m and if the depth of water in the channel is less than 0.5 m then one point method is that, the velocity should be determined at 0.6 d, where d is the flow depth.

### 5.2.6. Critical Velocity ($V_o$)

If the flow velocity of the stream is not silting or scouring, then that velocity is recognized as critical velocity. Usually the critical velocity depends on the kind of the soil formation in which the water flows. Table shows the critical velocities for different soil formations.

**Table 5.3** Critical Velocities for different Soil Formations

| S. No | Nature of soil | Critical Velocity m/s |
|---|---|---|
| 1 | Sandy soil | 0.3 to 0.6 |
| 2 | Black cotton soil | 0.6 to 0.9 |
| 3 | Firm clay and loom | 0.9 to 1.15 |
| 4 | Gravel | 1.20 |
| 5 | Hard rock | More than 3.00 |
| 6 | Concrete | 6.00 |
| 7 | Steel lining | 10.00 |

*Source: Boadu, 2000*

### 5.2.7 Critical Velocity Ratio (CVR)

Ratio of the mean velocity ‘V’ to the critical velocity ‘Vo’ is known as critical velocity ratio. It is denoted by m.

$$CVR = \frac{V}{V_o} = m \qquad (5.3)$$

When m=1 there is neither silting nor scouring, when m > 1, scouring will occur and when m < 1 Silting will occur. So, by finding the value of m, the condition of the canal can be predicted whether it will have silting or scouring.

### 5.2.8 Hydraulic Radius (R)

The Hydraulic Radius (R) is defined as the ratio of the cross-sectional area (A) to the wetted perimeter (P) of the channel

$$R = A/P \qquad (5.4)$$

### 5.2.9 Hydraulic Depth (D)

The Hydraulic Depth (D) is the ratio of the flow area (A) to the top width (T) of channel or

$$D = A/T$$

### 5.2.10 Full Supply Level (FSL)

The water level in the canal at the design discharge of the canal is known as full supply level.

### 5.2.11 Best Hydraulic Section

In general, it has been found that the conveyance capacity of channel increases as the hydraulic radius increases or the wetted perimeter decreases. Among all the possible cross-sections, the best hydraulic section is a semicircle one, which has minimum wetted perimeter for a given area. However, it should be noted that the best hydraulic section is not always the most economical section. Most of the lined sections of the irrigation channels should be constructed considering the best hydraulic section; however, sometime the full supply level in the canal or irrigation channel and the relevant command areas may not allow the construction of best hydraulic section. In practice the following factors must be considered:

- The best hydraulic section minimizes the area required to convey a specified flow; however, the area which must be excavated to achieve the flow area required by the best hydraulic section may be significantly larger if the overburden is considered.
- It may not be possible to construct a stable best hydraulic section in the available natural material. If the channel is lined up, the cost of the lining must be comparable with the cost of excavation.
- The cost of the excavation depends not only on the amount of material which is removed but also on the ease of access to the site and the cost of disposing of the material removed.
- The slope of the channel in many cases must also be considered a variable since it is not necessarily completely defined by topographic consideration.

**Table 5.4** Geometric Elements of Best Hydraulic Sections

| Cross sections | Area (A) | Wetted perimeters (P) | Hydraulic Radius (R) | Top Width (T) |
|---|---|---|---|---|
| Trapezoidal: half of hexagon | 1.73 $Y^2$ | 3.46 Y | 0.500 Y | 2.31 Y |
| Rectangular: half of a square | 2.00 $Y^2$ | 4.00 Y | 0.500 Y | 2.00 Y |
| Triangular | 2.00 $Y^2$ | 2.83 Y | 0.354 Y | 2.00 Y |
| Semicircle | 0.50 $\vartheta Y^2$ | $\vartheta$ Y | 0.500 Y | 2.00 Y |
| Parabola T = 2 + 2 Y | 1.89 $Y^2$ | 3.77 Y | | 2.83 Y |

*Source: Stern, 1979*

## 5.2.10 Efficient Section

In open channel, water flows under the force of gravity, on the way to irrigate the command areas on its left and or right sides. The FSL of the channel is usually kept above the natural surface level (NSL). In nature, to hold the water within the canal, it is partially excavated underneath the NSL plus partially on top of the NSL. To be economical, the deepness of excavation is set that the amount of the soil excavated from the canal segment is simply enough to build the banks. The deepness of dig is called balancing depth. In addition to that the transportation of the channel will be proficient when the channel segment has least perimeter for a specified area, slope and roughness coefficient are permanent

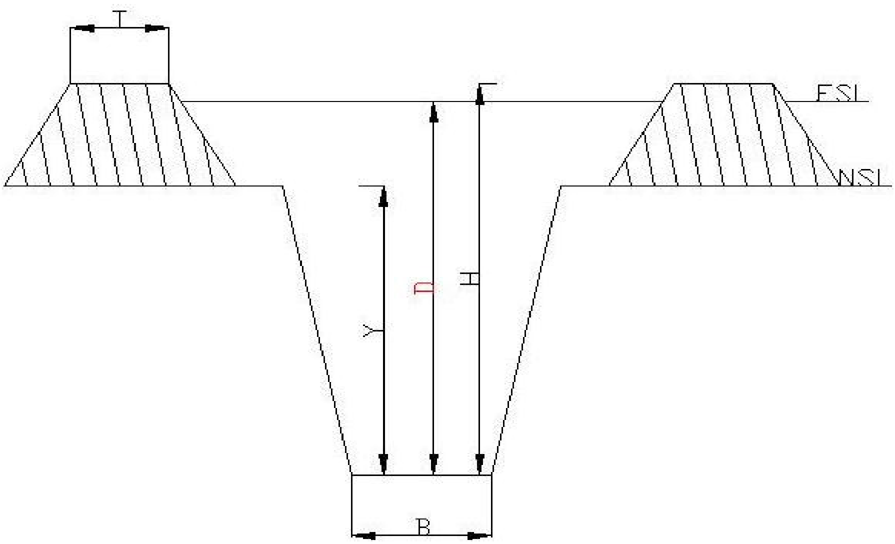


**Fig. 5.1** Channel Water Levels

Where:

Y is balancing depth

D is full supply depth

H is height of the top of bank above the bed of bank

T is top width of the bank

B is bed width of the cannel

m: 1 is side slope in cutting

n:1 is side slope in filling

For economical section Cutting = filling in banks

$Y(B+my)=2(H-y)(T+n(H-y))$ (5.5)

Generally side slope in cutting is kept 1:1 and filling kept as 1.5:1.

### 5.2.13 Design Approach

In general, two design approaches are commonly used, i.e. for Silt free water (Manning's equation) and for Silt laden water (Empirical Approach and tractive force approach).

### 5.2.14 Regime Channel

As the features of the bed substance of the channel are like that of the transported matter plus at the time the silt charges and silt grades are steady, then the channel is supposed to be in its regime and is called a regime channel. A channel in which, neither silting nor scouring takes place and this is known as regime channel or stable channel.

## 5.3 Design of Non-Alluvial Channels

### 5.3.1 Design Equations:

The non-alluvial soils are stable and almost impermeable. For the design of channel, in this type of soil, the coefficient of resistance plays a significant role, however, the other factor similar to silt factor has no role. Here, the velocity of the flow is measured very close to critical velocity. Consequently, the mean velocity known by Chezy's expression or Manning's expression is measured for the design of channel in this soil. After along inspection in a variety of canals, Chezy and Manning have recognized the following expressions intended for finding the mean velocity flow.

#### 5.3.1.1 Chezy formula

$$V = C\sqrt{RS_o} \qquad (5.6)$$

Where C is a coefficient which depends on the nature of the surface and the flow and known as chezy coefficient, $S_o$ is bed slope of the channel. C can be calculated from the following formula:

#### 5.3.1.2 Pavlovski formula

$$C = \frac{1}{n} R^{x} \qquad (5.7)$$

In which x= 2.5 $\sqrt{n}$- 0.13 - 0.75 $\sqrt{R}$ ($\sqrt{n}$- 0.1) and n is Manning's coefficient

As a standard, for each equation or formula, we will use the word "Equation" and for explanation of its variables, we will use "Where:"

#### 5.3.1.3 Ganguiller and Kutter formula

$$C = \frac{23+\frac{1}{n}+\frac{0.00155}{S_O}}{1+\left[23+\frac{0.00155}{S_O}\right]\frac{n}{\sqrt{R}}} \qquad (5.8)$$

#### 5.3.1.4 Bazin's formula

$$C = \frac{87.0}{1+\frac{M}{\sqrt{R}}} \qquad (5.9)$$

Channel M for unlined channel M = 1.30 to 1.75, for lined channel M = 0.45 to 0.85

#### 5.3.1.5 Manning's formula

$$V = \frac{1}{n} R^{2/3} S_o^{1/2} \qquad (5.10)$$

Where:

Manning's n is roughness coefficient known as.

$$Q = AV \qquad (5.11)$$

Where Q is design discharge, $m^3/s$

A is cross sectional area of the channel $m^2$

V is the mean velocity of flow

### 5.3.2 Design Procedures of Non-Alluvial Channels

1. Start through means of a design discharge and select an appropriate permissible velocity (V)
2. Find out the area of the canal from the continuity equation (Q = AV) and A = Q/V
3. Calculate for the hydraulics radius through using Chezy or Mannings equation
4. Write down the hydraulics radius in expressions of B and Y plus, equate it with result of step three
5. Write down the area in expressions of B and Y plus replace with B of step 4 in this equation, and after that you will contain quadratic equation to work out for the value of Y.
6. Add desired free board

**Table 5.5** Non-erosive Velocities (Permissible Velocity) in m/s

| Channel bed material | Water with sediment (m/s) | Clean water (m/s) |
|---|---|---|
| 1. Very fine sand | 0.75 | 0.45 |
| 2. Sandy loam | 0.75 | 0.55 |
| 3. Silty loam | 0.90 | 0.60 |
| 4. Alluvial silt | 1.00 | 0.60 |
| 5. Dense clay | 1.00 | 0.75 |

*Source: Kinort, 1970*

**Table 5.6** Minimum Freeboard requirements for Irrigation Channels

| | |
|---|---|
| 1. Earthen Channels | 1/3 of the design flow depth or 15 cm whichever is greater |
| 2. Rectangular lined channels | 10 cm |
| 3. Trapezoidal lined channels | 7.5 cm |

*Source: Federal Water Management Cell, 1986*

**Table 5.7** Permissible side Slope (Z) in Earthen Channels

| Bed Material | Excavated Side Slope (Z) | | Fill Section, Side Slope (Z) | |
|---|---|---|---|---|
| | Permissible | Recommended | Permissible | Recommended |
| 1. silt loams, silty clays and clays | 1:1 | 1:1 | 1:1 | 1.5:1 |
| 2. Sandy loams | 1.1 | 1:1 | 1.5:1 | 2:1 |
| 3. Loamy sands and sand | 1.5:1 | 2:1 | 2:1 | 3:1 |

*Source: Federal Water Management Cell, 1986*

In may unlined earthen canals side slopes of 1.5:1 have been used, however, side slopes as steep as 1:1 can be used when the channels run through cohesive materials. In lined canals the side slopes are generally steeper than an unlined canal.

**Table 5.8** Permissible side Slope (Z) in Earthen Canals (Chow, 1959)

| Material | Permissible Z |
|---|---|
| 1. Rock | Near vertical |
| 2. Muck and peat soils | ¼:1 |
| 3. Stiff clay or earth with concrete lining | ½:1 to 1:1 |
| 4. Earth with stone lining or earth for large channels | 1:1 |
| 5. Firm clay or earth for small ditches | 1 ½:1 |
| 6. Loose sandy, earth | 2:1 |

## 5.4 Design of Alluvial Channels

If the process adopted for the plan of channels at non-alluvial soil is applied over alluvial channels, after that the silt weight carried by the irrigation water is not measured. The rule of design of a channel on alluvial soil is completely unique from that of channel on non-alluvial soils. Channels on alluvial soil take appreciable silt plus sand load. While the channel water has surplus silt load silting takes place in the channel. On the other hand, when the water is silt free, it picks up the silt from the channel bed plus sides, it comes out in erosion of waterway section. Manning's and Chezy's equation do not consider this feature. When silting takes place, the channel section is minimized plus thus capability of the channel is abridged. When scouring happens initially, the water level is lowered which in turn reduces the command. Secondly, the eroded material is deposited at some other place to upset the equilibrium situation there. Taking the trouble of silt moving in to account, it was essential to evolve certain basis for the design of a steady segment by critical velocity. There are two vital and most usually used theories. They are Kennedy's silt theory plus Lacey's theory.

After extended investigation in different canals plus different environment R.G Kennedy, Punjab and Gerald Lacey have recognized several theories for the design of canals which are identified as 'Kennedy's theory' and 'Lacey theory'. Those two theories are dependent on the features of deposit load (i.e. silt) in canal water. The behavior of the silt load is explained by the theory which is known as ‘silt theory’.

## 5.4.1 Kennedy’s Regime Theory

Kennedy recognized a relation among non-scouring, non-silting velocity, termed as "critical velocity" of flow plus the stage of flow on the base of experimental work composed from 22 channels on the upper Bari-Doab canal system in Punjab. For any known canal having a specific soil circumstance, the critical velocity ratio which is a role of silt charge in addition to grade as well as rugosity coefficient is uniquely permanent. Kennedy had recommended a common form of equation for critical velocity $V_o = CD^n$. The value of m is dependent upon the silt charge in addition to silt grade. The coefficient "C" plus the power index n are not steady and alteration from site to site. The mainly prevalent values of C as well as n as labored out by Kennedy are 0.546 plus 0.64 correspondingly. Kennedy plotted a variety of graphs among $V_o$ and depth of flow and finally gave a formula to calculate $V_o$. the formula is

$$V_o = 0.546D^{0.64} \tag{5.12}$$

Kennedy as well documented that sediment magnitude plays a significant role in shaping the association between velocity and depth. Hence, he projected that for the sediment dimensions other than the one originate in the upper Bari Doab canal system the above equation should be customized to:

$$V_o = 0.546\, m\, D^{0.64} \tag{5.13}$$

Where $V_o$ critical velocity / no silting velocity [m/s] as well as Y full supply depth [m] plus C is a constant. It is dependent on nature of silt. Coarser the material, greater is the value of the constant plus n is some index. It too depends on the kind of silt. Where m is included to show the function of sediment size $m=V/V_o$=CVR, for course sand value of m might be taken as 1.1 to 1.2. While for finer substance, it might be reserved 0.8 plus 0.9. In adding to approximation, the actual velocity he planned the employ of Chezy's equation in addition to Kutter's coefficient N equal to 0.0225 for Punjab canals. V is the real velocity by Chezy

**Table 5.9** Typical "n" Values for Kennedy Regime (Government of India, 1982)

| Type of silt load | Value of n |
|---|---|
| Fine silt | 0.53 |
| Sandy silt | 0.64 |

#### 5.4.1.1 Limitations of Kennedy's theory

1. In the lack of B/Y ratio the Kennedy's assumption do not give a straight answer to deal with the channel dimension however by trial and error.
2. Ideal description of silt grade plus silt charge is not given.
3. Complicated phenomena of silt transport is not fully accounted and merely critical velocity ratio idea is measured adequately.
4. There is no provision on the way to decide longitudinal slope beneath the scope of the theory.

#### 5.4.1.2 Sketch of Irrigation Canal by Kennedy Theory

When an irrigation canal is to be planned by Kennedy theory, it is necessary to recognize FSD Q, coefficient of regosity N, CVR m plus longitudinal slope of the channel. Then by means of equations 5.13, 5.11 and 5.6 the canal section can be planned.

The process of scheming might be outlined in the subsequent steps:

a. Suppose practical trial full supply depth Y
b. By equation (5.13) find out the value of $V_o$
c. By this value of V, using equation (5.11) plus design discharge find out A
d. Suppose side slope in addition from the information of A and Y find out the bed width B
e. Work out the hydraulic radius (R)
f. Using equation 5.6 locate the value of the real velocity V
g. While the assumed value of Y is accurate, the value of V in step f will be similar as Vocalculated in step b, if not, suppose another appropriate value of Y plus replicate the process till both values of velocity are the identical.

### 5.4.2 Lindley's Regime Theory

Information from steady channels of Punjab were analyzed in addition to provide the subsequent similar equations like Kennedy for non-silting as well as non-scouring velocity taking Manning's n=0.025 along with side slope 0.5:1.

$$V_o = 0.57Y^{0.57} \qquad (5.14)$$

$$V_o = 0.27B^{0.35} \qquad (5.15)$$

Equating the above two will give as:

$$B = 7.80Y^{1.61} \qquad (5.16)$$

Among the few alterations by Lindley one is that he articulated an equation for merely B/y ratio. He also formulated equation of $V_o$ taking depth y along with B as a function.

### 5.4.3 Lacey's Regime Theory

Improved and customized technique was developed by Lacey. His regime theory postulates that dimension of bed width; depth as well as slope of canal attains a condition of equilibrium with time which is called regime state. Lacey distinct a regime canal as a steady channel transporting a smallest amount bed load coherent with fully active bed. In accordance to him, a waterway will be in regime if it carries a steady discharge as well as it flows uniformly in unlined incoherent alluvium of similar character. Lacey also stated regime between the initial along with the final regime conditions of channel. The initial regime condition is attained soon after it is put into process after building and the channel begins to regulate its bed slope either by silting or scouring even though bed width is not changed. The cannel subsequently appears to have attained stability, except it is not actually the last condition of stability and hence it still represents the initial regime state. Ultimately continuous action of water overcomes the opposition the resistance of the banks and sets up a state such that the channel adjusts its whole section, after that final or true regime condition is attained.

In accordance to Lacey, there is only single longitudinal slope at which the canal will carry a specific discharge with a specific silt grade. Usual silt transporting channels have an affinity to assume semi-elliptical section. The coarser is the silt, larger the water way of such channel with narrower depth. The finer the deposit, larger is the deepness with small waterway as revealed below:

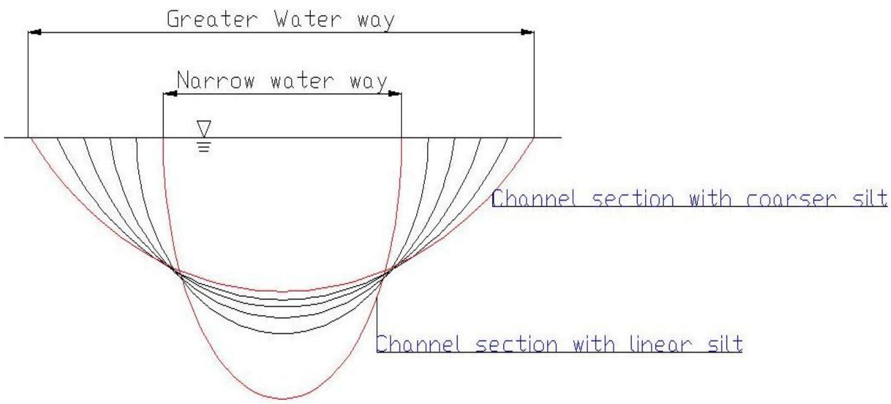


**Fig. 5.2** Channel Section According to Lacey's Theory

#### 5.4.3.1 Lacey's Regime Equations

Lacey collected a large number of data of stable channels in Indo-Gangetic plains. Analyzing the data, he gave the following equation of regime channel relating regime velocity $V_o$, silting factor f, hydraulic radius R, area A, sediment size in mm and bed slope So. Lacey plotted a graph between regime mean velocity and hydraulic mean radius and gave the relationship:

$$V_o = KR^{1/2} \tag{5.17}$$

Where K is a constant

Lacey recognized the importance of silt grade in the problem and introduced a concept of function 'f' known as silt factor. Above equation is modified as:

$$V_o = K\sqrt{Rf} \tag{5.18}$$

After studying and plotting of large data to justify his theory, Lacey gave four fundamental equations for design of irrigation channels.

$$V_o = 0.639\sqrt{Rf} \tag{5.19}$$

$$Af^2 = 141.2V_o^5 \tag{5.20}$$

$$V_o = 10.8R^{2/3}S^{1/3} \tag{5.21}$$

$$f = 1.76\sqrt{d} \tag{5.22}$$

#### 5.4.3.2 Relationship between Wetted Perimeter (P) and river Discharge (Q)

The relationship between wetted perimeter and discharge can be given be the equation as follows:

$$P = 2.667\,Q^{1/2} \tag{5.23}$$

From the relationship the approximate width of stable waterways (Ww) can be determined as:

$$Ww = 2.667\,Q^{1/2} \tag{5.24}$$

#### 5.4.3.3 Scour Depth (R)

The river channel is continuously in state of change for attainment of regime condition and adjusts its slope by meandering, scouring or silting. The scour depth for river work, weir or barrage can be determined from Lacey's formula given below:

$$R = 0.9\,(q^2/f)^{1/3} \tag{5.25}$$

q = flow discharge per unit width, cfs

f = silt factor

## 5.5 Control structures

For regulated discharges and water levels in the main canal, distributaries, minor and outlets of various types of control structures are required at different locations along and across the canal. These consist of canal regulation structures, cross drainage structures and outlets. Engineering planning, design and construction of dams, barrages, diversion weirs, main intake works, pumping stations and main canals are usually carried out at a high degree of efficiency. Generally, the operation of such headworks is also efficient and well organized and thus the amount of water lost from the total supply is usually small. The Canal regulation structures generally consist of head, regulator, cross regulator, fall regulator, escapes, silt ejectors and farm outlets.

### 5.5.1 Head Regulator

A structure constructed across a canal to regulate supply level, allow full supply discharge and control entry of silt into canal is called Head Regulator. In general, the capacity of the canal is kept 10% more than the required discharge for silt build up, weeds or to tackle other emergency situation.

Head Regulator for an off-taking channel (branch canal, distributory or minor) allow designed supplies to the off-taking canal, manage supplies in the canal network and distribute silt load as well as allow desired supplies to the off-taking canal as per rotation schedule in case of low supply in the canal system.

### 5.5.2 Cross Regulator

Structures constructed across the main canal are at regular intervals, at locations of off-takes of branch canals, distributaries or minor canals to maintain the desired level and supplies into off-taking canals (branch canal, distributary or minor canal).

### 5.5.3 Fall Regulator

Fall regulator structures are provided on the canal to break the long steep slope and to maintain the water surface level close to the natural ground surface to reduce the flow velocity to permissible limit and to minimize the cost of cutting and filling. The depth of falls may be different and depends on the topography of the land, however, very deep fall should be avoided and should be replaced with several small falls.

### 5.5.4 Tail Regulator

A regulator is provided at the tail of the canal to control water level and for proportional distribution of water among different watercourses is called tail regulator.

**Escapes:** Escapes on the canal are provided for quick removal of water from the canal under emergency situation. The emergency situations may arise from sudden breach in the canal, unexpected rise in the water level or due to rainfall events, runoff water into the canal. Under these scenarios, the canal has to be emptied quickly, therefore, escapes on the canal are provided and the water is generally drained into natural waterways through escapes to avoid damage to life, property and agriculture land.

Sometimes secondary and tertiary canals and control structures are less carefully made, while smaller canals and those at the farm level and their structures are more often badly made or omitted entirely from engineering plans. It must not be overlooked that besides headwork's and larger canals, irrigation works involve in the building of many small structures and small earthworks of unsophisticated design spread over extensive areas of land. Engineers have often neglected these "minor" works, particularly those required at the farm level; to contractors these do not mean much profit and these are dispersed and difficult to supervise; and last but not least, authorities have sometimes appeared less willing to invest in tens of thousands of such small scattered works than in large works having greater prestige value. This results in many omissions of essential small structures, and failures or unnecessary deficiencies in some irrigation systems.

The great impact of small structures on satisfactory operation and overall performance of gravity irrigation systems is, however, apparent from their large number. In gravity flow systems, 90 out of 100 structures usually have capacities of less than 1,000 liters per second. The total number per unit area depends largely on the size of holdings and fields, on the delivery pattern and on the topography, but ranges from a few hundred to several thousand per thousand ha. The total irrigated area of the world at present exceeds 200 million ha and potentials exist for doubling this area. The number of small hydraulic structures already in existence exceeds 100 million, and the number that will need to be modified, replaced or newly built every year is s likely to run into millions.

In view of their great impact on the saving, equitable delivery and reliable supply of water, small hydraulic structures must be designed, built and operated with much the same completeness, efficiency and accuracy as large ones.

The factors governing the design and subsequent construction and operation of irrigation works are the water resources available, the methods of water delivery to farmers, and the methods of water application practiced by them. Successful operation requires adequate facilities for the control and measurement of flow at all strategic points along the whole network, including the farm and field levels. Each small hydraulic structure must be efficient, simple in design, construction and operation, and must be durable. The largest structures discussed in this publication are the intakes from tertiary canals or intakes from small rivers into complete irrigation systems, the head discharges of which do not exceed one cubic meter per second. Intakes are required to control flow into a subsequent canal or canal system; often they are combined with silt- excluding devices, Intakes should be designed to control and regulate water with minimum entrance losses and as little disturbance as possible.

1. *Intake Structures*
2. *Intakes of Small Canals*
3. *Silt Selective Head intake.*
4. *Venturi head intake.*
5. *Square head intake.*

### 5.5.5 Canal Outlets

The Canal Outlet is a turnout structure at the head of a watercourse through which irrigation water is diverted from the main canal, distributary or a minor into the watercourse. The supply (or distribution) canal is usually under the control of an irrigation authority. The authority may be a Government department, a public, or semi-public organization such as a district or an irrigation association. Thus, the farm outlet is the connecting link between the canal operator representing the authority and the farmer or user. Types of Intakes can be classified into the following categories depending on their sensitivity to water level in the parent canal and watercourse.

1. Modular farm outlets
2. Semi-modular
3. Non-modular farm outlets

The intakes for minor as well as sub-minor canals urbanized in Punjab are planned for proportional sharing of supplies. In general, the "Open Flumes (OF)" and the "Adjustable Proportional Flumes (APF) are used as Intakes. Whichever of the two types are adopted, the following conditions should be satisfied.

(a) For open flumes the setting of the crest must be at 0.9 of the full supply depth of the mother canal (Y1); the crest should be on top of the level of the downstream canal bed; the width of the crest across the flow should be at least 6 cm.
(b) If the above situation does not exist, an adjustable proportional flume must be used wherever the crest will be at 0.75 of the full supply deepness of the off-take canal (Y2), along with so that the-depth of the base of the roof block underneath the full supply level in the parent canal (Hsof) ranges between 0.35 y1 to 0.48 y1. The setting of the crest should also be on top of the level of the downstream canal bed.

Here are some commonly used outlets in Pakistan

(i) Open Flume Farm Outlet
(ii) Adjustable Orifice Semi- Module
(iii) Jamrao Type Orifice Semi-Module
(iv) Pipe Semi-Module
(v) Scratchley Outlet
(vi) Pipe Outlet

Intake structures or head regulators are hydraulic devices constructed at the start of an irrigation canal. The reason of these devices is to acknowledge and control water from a parent canal or else original source of supply, such as a dam or a stream. These set ups may also serve up measuring the amount of water flowing through them

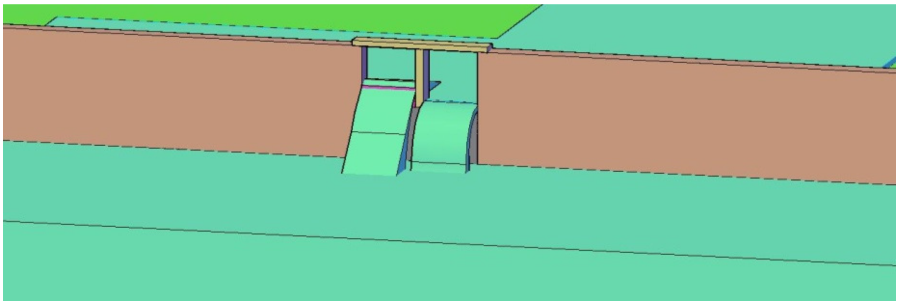

**Fig. 5.3** Intake Structure on Secondary Canals, Spillway and Wooden Gate

### 5.5.5.1 Open Flume

$$Q = CB_tH_{crt}^{\frac{3}{2}} \quad (5.26)$$

Where:

Q is the discharge rate

$H_{crt}$ is the head over the crest

B (t) is the width of throat.

C is the Coefficient

Values of 'C' for various flow rates are given in Table …

**Table 5.10** Value of C for Various Flow Rates

| Q | value of C | |
|---|---|---|
| | Intake angle 60° | Intake angle 45° |
| up to 0.56 m3/s | 1.60 | 1.61 |
| 0.57 to 1.4 m3/s | 1.61 | 1.63 |

### 5.5.5.2 Adjustable Proportional Flume (APF)

$$Q = 0.0403B_tH_{orf}\sqrt{H_{sof}} \quad (5.27)$$

Where,

$H_{orf}$ = the height of the opening or orifice above the crest,

$H_{sof}$ = the depth of the underside of the roof block below the full supply level in the parent canal,

$B_t$= width of throat.

The value of $H_{sof}$ should fall within the range of 0.375 y to 0.48 $y_1$

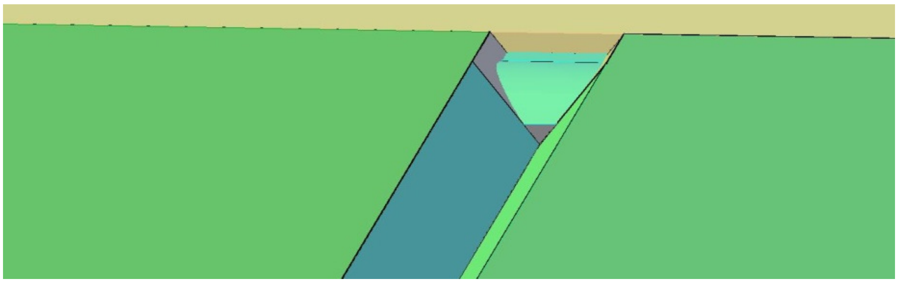

**Fig. 5.4** Intake Structure on Secondary Canals

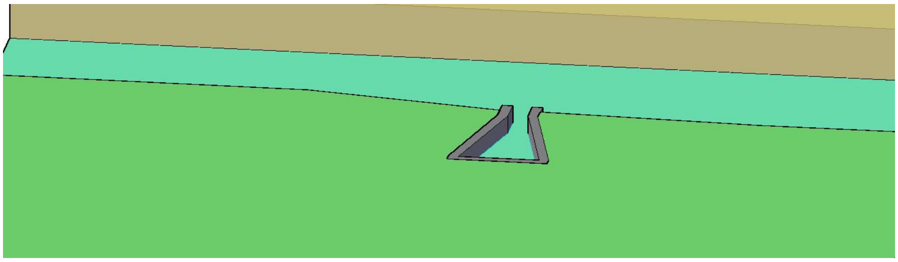

**Fig. 5.5** Open Flume Farm Outlet

### 5.5.5.3 Modular Farm Outlets

In a modular outlet, the discharge is within reasonable working limits, independent of the water level in the supply canal and the watercourse or field lateral. This class of outlets may be regarded as the best type of farm outlets from the farmer's viewpoint. However, modules cannot absorb fluctuations of water supplies in the parent canal and, therefore, the parent canal could either flood or become dry in the tail reach. Thus, modules should be limited to:

- Branch canals or distributaries and minors in which the supply varies only within predetermined limits;
- Outlets located above control points where water levels can be maintained;
- Canals in which additional water is delivered to certain selected outlets for leaching or for other purposes.

### 5.5.5.4 Semi-modular

The discharge of a semi-module outlet is independent of the water levels in the watercourse or field lateral, but dependent on the water levels in the supply canal, so long as a minimum working head is available for the device. These types of modules are not useful for supplying water to farmers on a volumetric basis unless they are accompanied by an auxiliary device, such as a notch or a weir, a venturi flume, a Parshall flume or an open flow-meter attachment on the downstream side. The usual use of semi-modules is to distribute, equitably, upstream variations in the supply canal within their range of operation. When the water supply to the farm outlets is charged with silt, it is essential to use semi-modules which can draw a proportional share of the silt. In this case, proportional distribution of the water is neither necessary nor feasible and the following types of outlets may be used.

When the-water supply to the outlets is free of silt and a shut-off gate is not necessary, the following types of outlets are open to choose.

(i) **Open flume outlets** – Preferred at tail clusters, and in tail reaches with setting of the crest at 0.9 y for proportional discharge.

(ii) **Adjustable orifice semi-module** – Installed in head reaches with setting of the crest at 0.6 y for proportional discharge.

(iii) **Jamrao type orifice semi-module** – Preferred in head reaches with setting of the crest at 0.96 y for proportional discharge.

(iv)**Scratchley outlet** – It can be a choice if it is not desirable to install any other type of semi-module, which may be probably due to cost.

(v) **Pipe semi-module**– when the banks of the supply canal are very wide; the setting of the module will be as indicated in Open flume outlets and Adjustable orifice semi-module.

(vi) **Fayoum standard weir outlet**– Its setting has been standardized, and it may be used successfully on all distributing canals.

(vii) **Pipe outlet**– in view of its low cost, a pipe outlet may be used on all distributing channels with center of the pipe set at 0. *3* y.

#### 5.5.5.5 Non-Modular Farm Outlets

The discharge of non-modular outlets depends on the difference of water levels in the supply canal and the watercourse. The water level in the watercourse below the outlet varies considerably, depending on: whether high or low areas are being irrigated at any given time; and where silting occurs, the extent of silt clearance in the farm lateral. Where silting is a dominant feature, the canals fitted with non-modular outlets are always liable to flooding at the tail of the canal when farmers in the head reach do not clear silt so that they draw their full share of water during periods of slack demand. On the other hand, water is always in short supply at the tail end during periods of keen demand, when farmers in the upper reaches tend to do the opposite, to clear their watercourses too much. Non-modular outlets should, therefore, be avoided as far as possible. Their use is justified only when the working head available is so small that a semi- modular outlet cannot be used.

#### 5.5.5.6 Design Requirements for a Farm Outlet

As far back as, Kennedy (1906) set forth criteria for the efficient design of a farm outlet in Punjab Irrigation as summarized below.

a. To keep the discharge automatically constant as adjusted and indicated, however much (within working limits) the water levels may vary in the distributary channel, or in the watercourse, or in both at once
b. To allow the slight variations in the discharges as adjusted, so as to avoid the need of constantly removing and replacing the outlet, whenever the discharge must be somewhat altered.
c. Work with high 'heads' as well as low - down to three inches or so to:
d. Be free from derangement by silt or weeds.
e. Be light, portable, easily removed and replaced elsewhere.
f. Be cheap and durable, with no complicated mechanism.
g. Be all closed in and immune from outside interference or derangement in working.
h. Be capable of being opened or closed off entirely by the cultivators from outside.
i. Indicate from outside when the working head is insufficient to give the full discharge, and therefore also the necessity for clearance of the watercourse.
j. Work as a module, only within certain limits of level in the feeder, above and below these limits to give proportionately increased or decreased

discharges if that is desired and adjusted. This is with special reference to farmer's canals, where each man is entitled to a proportion of the whole available supply.

k. Allow floods- in the distributary to be passed off by increased discharges through the outlets, to avoid damage.
l. When the distributary supply is very low and inadequate, it will be proportionally distributed to all outlets, those with very high command not being allowed to draw off all the water there is.
m. Discharges may be provided for anything between half and four cusecs with possible duplication above the latter Fig.

## 5.5.6 Intake Structures

### 5.5.6.1 Silt Selective Head Intake.

The sketch of a silt selective intake was developed by the late K.R. Sharma of the Punjab Irrigation Department in 1936 on the supposition so as to the concentration of silt in a stream in the lower layers is larger than that in the upper ones, in addition to if the lower layers had been permitted to run away with no interfering with the silt sharing, the left over water would have fewer silt per unit quantity than the water upstream of the intake.

### 5.5.6.2 Venturi Head Intake

The design of this venturi head intake was developed in the 1920's through the development of the Sarda Canal in Uttar Pradesh, India, to stimulate economy by providing a flumed throat with appropriate wing wall connections to re-establish the full bed width of the off take canal.

The characteristics of this structure are as following.

a. The head loss is Hcrt /9 or less as well as the discharge is a small over the theoretical value due to the streamlined approach.
b. The venturi head may be planned for any angle of off take from and for any bed width of the off take canal up to 7.5 m.
c. The design is like that the surplus energy of the water is dissolute by the creation of a hydraulic jump.
d. The structure does not gauge discharge properly as well as is not successful in scheming the entry of silt into the off take canal.

### 5.5.6.3 Square head intake.

The square-head regulator is a straight forward intake arrangement supplied at the heads of secondary and tertiary canals to extract water supplies from a main or branch or secondary canal, the last one is called the parent canal plus the former the off taking canal. The structure is typically positioned at right angles to the parent canal. The arrangement is not a meter plus it is not silt- selective. It is primarily intended to control water supplies into the off taking canal. Regulation is influenced by process of the insertion of stop-logs or a sliding gate within the grooves supplied on the upstream side in the abutments.

## 5.5.7 Silt Control Devices

1. King's silt vanes,
2. Gibbls Groyne.
3. Curved wing with silt vanes
4. Silt platforms:

a. simple platform;
b. silt platform with a guide wall

5. Reverse vanes.
6. Vortex tube sand trap.
7. Sloping- sill sand screen.

### 5.5.7.1 King's Silt Vanes

Amongst the silt-excluding devices, King's silt vanes are not appropriate wherever a minor off taking canal is located among two large canal branches plus when its bed is at an elevated level, and/or wherever the water level is possible to rush forward over a substantial range. When the off taking, canal has its bed at a high level, the mechanism Silt platforms is preferable.

### 5.5.7.2 GibblsGroyne

GibblsGroyne is used while together the off taking plus the supply canals contain the similar sediment transportation capacity. When the consequence of this mechanism is not enough to manage the entrance of silt into the off taking canal, the mechanism King's silt vanes might be used in addition to improve the presentation of GibblsGroyne.

### 5.5.7.3 Silt Platforms

The silt platforms are appropriate merely wherever the parent canal is deep enough. The mechanism Silt platforms (b) have the benefit that (no relation of the slight heading triggered by the curved wing) a minute head of 3 to. 4.5 cm is shaped at the off take which raises the velocity of the water plus prevents silt being deposited in the head reach of the off taking canal. While a canal divides into two canals, one of which silts up very poorly, as well as there is no sufficient space to accommodate vanes, the device (incomplete)

### 5.5.7.4 Reverse Vanes

Reverse vanes may be constructed to pass by additional silt into the canal that does not silt.

### 5.5.7.5 Sand Trap

The mechanism Vortex tube sand trap is appropriate for minor canals whose bed widths are less than 3 meters. It demands that some additional discharge be allowed into the off taking canal for the process of the tube.

#### 5.5.3.6 Sloping- Sill Sand Screen

The device Sloping- sill sand screen has been used in Egypt to accurate local irregularity in the flow outline at the intake of distributary canals.

### 5.5.8 Flow Dividing Structures

Flow Dividing Structures are used in irrigation networks to separate the flow of a channel into two or more segments. Every division is a defined amount of the whole flow. Therefore, flow separating set ups vary from intakes as well as off takes in that the last are planned to draw off a specific portion of the flow in the parent channel, but the precise quantity of this fraction to the whole flow or to the remainder in the parent channel is usually irrelevant. A flow separating structure demands a control section in both the off take channel plus in the parent channel. Yet, not all flow dividing structures are built to provide precisely proportional separation.

#### 5.5.8.1 Fixed Proportional Divisors

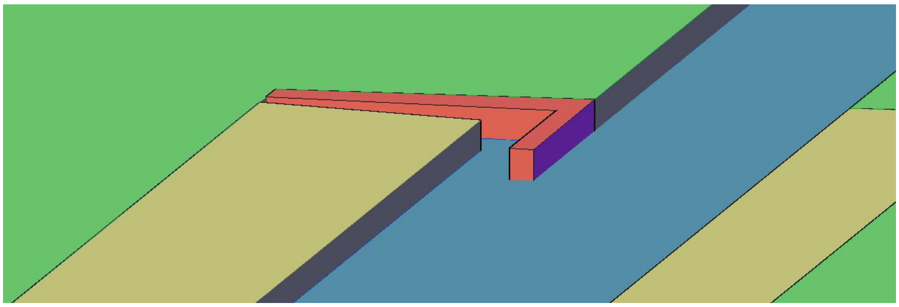

**Fig. 5.6** Simple Fixed Proportional Flow Divisor of Low Accuracy

The major characteristic of fixed proportional divisors is that the everlasting splitting of the' flow into two or more than two components required in a control segment wherever a condition of supercritical flow, i. e. Free fall or shooting flow is produced. This calling for certain head loss in the arrangement by allowing the flow pass a ridge or flumed section or by producing a drop, but is not necessary for the splitting of a flow into two precisely equal proportions supplied that: the dimensions are symmetrical; that the flow segment in the arrangement is of consistent roughness; that there is a level canal alignment of 5 to 10 m upstream of the divisor; as well as, finally, that no backwater influence is produced in any of the off take channels. Through setting up a succeeding 1:1 divisor, the flow will be divided into the proportions of 2: (i.e. 1:1). Through rejoining two of the streams, a proportion of 3:1 might be provided.

#### 5.5.8.2 Structures with Adjustable Splitter

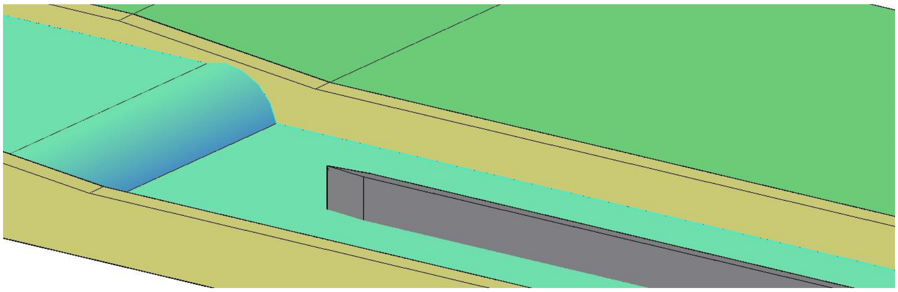

**Fig. 5.7** Flow Divisor with Adjustable Splitter, Argentina

Set ups with an adjustable splitter typically consist of a hinged gate made of sheet metal, which can move across the flow segment of the parent channel as well as inflexible in any preferred location through the help of an arch bar or screw bar. The flow must be finished supercritical for precise proportioning through the induction of a control crest or drop in bed level.

#### 5.5.8.3 Proportional Distributors

A typical feature of proportional distributors is that the flow is not divided into fractions by thin plated divisors but is diverted from the parent channel into the off takes by means of individual openings, which however, are grouped to form a single structure. Each opening or off take is constructed as a flume or free over fall weir and is dimensioned to pass a given fraction of the total flow. In other words, the controlling section (flume section, elevated floor, or weir crest) is not in the supply channel, but is in the individual off takes. This arrangement requires accurate calibration by model tests or field rating and great accuracy in construction.

#### 5.5.8.4 Distribution Boxes

Division Boxes normalize the flow as of one channel to another one, or to several others. They mostly consist of a box in addition to vertical walls in which convenient openings are supplied. Metallic, wooden slide gates or stop-logs are usually set up to control the separation of flow at a given point of channel in addition to shut off flow in any branch when preferred. The walls of the box can be of concrete (pre-cast or in situ), masonry or of wood.

## 5.6 Solved Examples

**Example 1:** Design an irrigation canal with the following data

(a) Discharge of the canal = 24 cubic meters / second
(b) Permissible mean velocity = 0.8. m/sec
(c) Bed slope = 1:5000
(d) Side slope = 1:1
(e) Chezy's Constant, C = 44

Given data, Q = 24 cumec, V = 0.8. m/sec, S = 1/5000 = 0.0002, Side slope = 1:1

**Solution:**

Let, B = bed width, D = depth of water.

Cross-sectional area, A = (B + D) D

Using the relationship of Q and V with A, we get A = Q/V = -24/0.8 = 30 $m^2$

Thus, 30 = (B + D)D

Wetted Perimeter $P_w = B + 2\sqrt{2}\ D = B + 2.828\ D$

Hydraulic Mean Depth, $R = A/P_w = \frac{-30}{B+2.828D}$

From Chezy's formula

$$V = C * \sqrt{RS}$$

$$0.80 = 44\sqrt{R * 0.0002}$$

$$0.64 = 1936 * R * 0.0002$$

or $R = 1.65$

From (2) and (3), $1.65 = \frac{30}{B+2.82\ D}$

or $1.65\ B + 4.67\ D = 30$

$$B = 18.18 – 2.83\ D$$

Putting the value of B in Eq. A= (B + D) D

$$30 = (18.18 – 2.83\ D + D)D$$

$$= (18.18 – 1.83\ D)D$$

$$=18.18\ D – 1.83\ D^2$$

or $1.83D^2 – 18.18\ D + 30 = 0$

or $D = \frac{18.18 \pm\sqrt{(18.18)^2-4*1.83*30}}{2*1.83}$ When, D = 2.09 m

$= \frac{18.18 \pm 10.53}{3.66} = 7.84$ or 2.09 m B = 18.18 – 2.83 * 2.09

When D = 7.84 m = 12.27 m (it is acceptable)

$B = 18.18 – 2.83 * 7.84$

= - 4.00 (It is absurb)

Check: A = (B + D)D

A = (12.27 + 2.09) * 2.09

= 30.01 (Checked and found correct)

So, finally, bed width = 12.27 m, depth of water = 2.09

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## Chapter 6

# Groundwater Management

**Muhammad Waqar Akram and Abdul Khaliq***

## Abstract

Water exists both above and below the earth's surface. About 97.5% of water is contained in the Oceans and is highly saline. The fresh water is present in the form of rivers, lakes, glaciers, soil water and groundwater. Groundwater constitutes about 22% of the world freshwater. In most of the irrigated areas of Pakistan under cotton -wheat rotation, farmers are meeting more than 50 percent of crop water demand from pumped groundwater, where as in areas with rice-wheat rotation, the use of groundwater exceeds 70 percent (IWMI 2003). Therefore, groundwater is playing major role not only in meeting the crop water demand but also in domestic and industrial uses in the country. Thus, sustainable irrigated agriculture requires conjunctive management of surface and groundwater. However, the groundwater faces several problems such as depletion due to over exploitation, water logging and salinization because of inadequate drainage and constrained utilization due to pollution, salinity, waterlogging agricultural, industrial and other human activities. To overcome problems related to the groundwater, there is need to create comprehensive and strong information base regarding data on groundwater users, use of groundwater, groundwater withdrawal, aquifer conditions, groundwater table depth and groundwater quality. The chapter on groundwater management has been designed to give sufficient information to the users, managers, policy makers and learning students about complete information related to the terminology, basic concepts of existence, extraction and use as well as planning and policy making about the groundwater resources.

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**Keywords:** Groundwater, Aquifer, Permeability, Aquifer Characteristics, Groundwater Management, Storage Coefficient, Specific yield

# Learning Objectives

- To understand basic principles and themes of groundwater hydrology and management.
- Assessment of groundwater potential.
- To understand the quality and use of groundwater resources in agriculture.
- To assess the contribution of groundwater to irrigation activities in meeting the water requirements of crops.
- Learn the challenges faced during management of groundwater in conjunction with surface water and the need for new approaches to solve the resource management problems.
- To highlight key advantages of groundwater exploitation over surface water resources in irrigation water resource planning and management.

# 6.1 Introduction

Rapid increase in the world population demands increased crop productivity per unit of water supplies available from surface, groundwater and other resources of water consumed for irrigated agriculture. Environmental sustainability of irrigated agriculture requires protection of land and water resources while enhancing crop productivity. Irrigation activities need to be sustainable economically as well as environmentally, which require efficient management of both surface and groundwater.

Pakistan's population increased from 87 to 184 million during 1982–2012. However, the live storage capacity of major storage dams in Pakistan is decreasing due to sedimentation, e.g., the original live capacity of Mangla Dam 5.30 MAF (6.5×109 $m^3$) decreased by about 20% from 1967 to 2000 and the live capacity of Tarbela 9.30 MAF (11.5×109 $m^3$) decreased by over 40% from 1975 to 2000. The population trends show further increase in food and fibre demands, and therefore, escalating crop water demand. A major proportion of the increasing crop water requirement is being fulfilled through increased ground water pumping. This has its limitations in terms of declining water quality and increasing soil salinity and sodicity. Scenario analysis shows that if dry conditions persist, there will be an overall decline in groundwater levels of around 10 m for the whole of RD during the next 25 years (Khan et al., 2008).

Groundwater flow is the "part of stream flow that has infiltrated the ground, has entered the phreatic zone, and has been stored in the porous zone of the aquifer or dischargedintoa stream channel, via springs or seepage water". It exists in the mega pores of soil, which originates from the infiltration of water through the soil profile and accumulates below the earth's surface in a porous medium. It constitutes 22% of the world freshwater and groundwater comprises one sixth of the total freshwater resources available in the world.

It is the most flexible and reliable water supply system. Most of the potable supplies of the urban and rural areas are obtained from groundwater. About 40 to 60% of the irrigation requirements in various cropping zones are being met from groundwater in Pakistan (Qureshi et al., 2010). It is a limited resource and needs proper management to avoid its quantitative depletion and qualitative deterioration.

Throughout the world regions that have sustainable groundwater balance, are shrinking with time. Three problems dominate the groundwater use: depletion due to overdraft; water logging and salinization due to inadequate drainage and insufficient conjunctive use; and pollution due to agricultural, industrial and other human activities. In many regions of the world, especially with high population density and insufficient surface water, many consequences of groundwater development are becoming increasingly evident.

Conjunctive management of surface and groundwater offers a potential solution to ensure environmental sustainability in irrigated agriculture. Sources of water within a basin, which can be managed conjunctively, include supplies from dams and reservoirs, groundwater, agricultural drainage, sewage, industrial effluent and rainwater. There are many difficulties in carrying out effective and sustainable conjunctive water management. These include lack of institutional arrangements and rules to control the use of surface water and groundwater, and availability of resource data and management tools for water professionals to manage multiple sources of water.

The chapter on Groundwater Management has thus, been designed to include concept and terminology related to groundwater.

### 6.1.1 Terminology in Groundwater

The terminology used in groundwater management refers to the aquifer characteristics and movement of water into and out of the soil as porous media. As groundwater refers to the storage and movement of water under pressure as well as under gravity flow conditions, it is important to learn about various hydrological terms involved in the systems, which are explained below.

a. **Hydrological cycle:** The hydrological cycle describes the circulation of water in nature, starting with evaporation from the oceans and other open water surfaces, conversion of vapors into water, continuing with precipitation and returning to the earth as surface water in the form of lakes and river flow, and further entrance into subsoil as subsurface flow and as runoff and eventually returning to the oceans. Fig. 6.1 shows a schematic description of hydrological cycle.

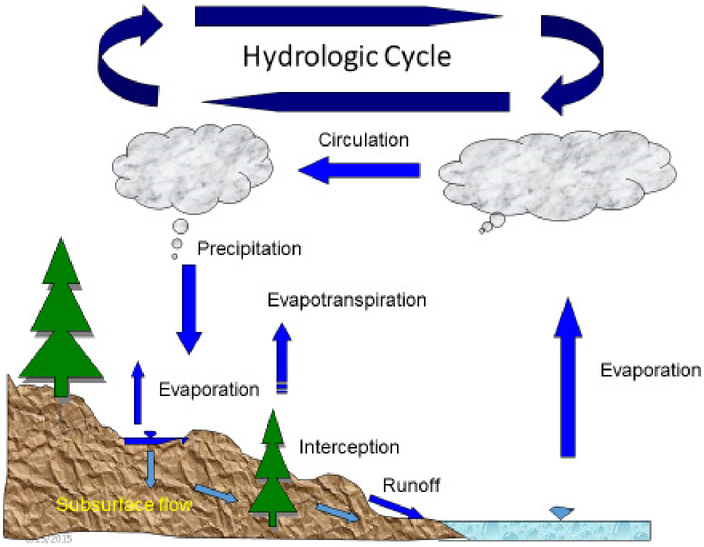


**Fig. 6.1** Hydrological Cycle

b. **Aquifer:**It is saturated, permeable geologic medium that can store enough water and can yield economically useful quantities of water to wells and other points of use.
c. **Aquiclude:** It is low permeable geologic medium that, although porous and able to absorb water but incapable of transmitting significant quantities of water.
d. **Aquitard:** It is low permeable geologic medium that retards groundwater flow through it. It may not yield its stored water in significant quantities to wells.
**e.** **Aquifuge:** It is low permeable geologic medium that neither stores nor transmits water.
f. **Aquifer system:** A series of multiple connected aquifers in which flow can occur between aquifers.
g. **Isotropic Aquifer:** It is aquifer in which physical properties, such as hydraulic conductivity, remains same with direction.
h. **Anisotropic Aquifer:** It is aquifer in which physical properties, such as hydraulic conductivity, vary with direction.
i. **Aquifer:** It is aquifer in which physical properties, such as hydraulic conductivity and porosity, vary with location.
j. **Leakage and Vertical Flow:** Leakage is the flow of water from one hydrogeological unit to another. The term ‘vertical flow’ is also used interchangeably with leakage, to emphasise the vertical component of flow. The term leakage has been used to describe vertical flow between deposits under natural flow conditions, as well as when an aquifer is influenced by abstraction. Flow between deposits caused by the alteration of groundwater pressure is referred to as pumping-induced leakage (Bear and Cheng, 2000).

k. **Darcy's Law:** Discharge through a porous medium is directly proportional to the hydraulic gradient, hydraulic conductivity, and cross-sectional area through which the flow is occurring.

l. **Hydraulic conductivity (K):** It is the coefficient of proportionality describing the rate of fluid flow for an isotropic porous medium and homogeneous fluid and may be defined as "the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow".

m. **Permeability:** It is a term commonly used as a qualitative synonym for hydraulic conductivity of a porous medium. It is the ability of formation to transmit water through its pores when subjected to a difference in head.

n. **Intrinsic permeability:** It is a measure of the ease with which a fluid move through a porous medium that is dependent upon the physical properties of the medium itself, and not upon the fluid being transmitted.

o. **Saturated zone:** Subsurface zone in which all the voids in a porous material are filled with water. The water table is the top of the saturated zone in an unconfined aquifer.

p. **Specific discharge:** It is discharge per unit drawdown in a pumping well.

q. **Specific storage (Ss):** Volume of water that a unit volume of aquifer releases from or takes into storage under a unit change in hydraulic head.

r. **Specific yield (Sy):** The volume of water, expressed as percentage of the total volume of saturated aquifer, that can be drained by gravity is called specific yield.

s. **Specific Retention (Sr):** The volume of water retained by molecular and surface tension forces, against the force of gravity, expressed as percentage of the total volume of saturated aquifer, is called specific retention.

t. **Storivity (S):** Volume of water released from or taken into storage in an aquifer per unit surface area per unit change in the component of hydraulic head normal to that surface. In an unconfined aquifer, this is approximately equal to the specific yield.

u. **Transmissivity (T):** The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer and is a function of properties of the liquid and the porous media.

v. **Recharge:** The infiltration of water into the soil zone, unsaturated zone and ultimately to the saturated zone i.e. watertable. This term is commonly combined with other terms to indicate some specific mode of recharge such as recharge well, recharge area, or artificial recharge.

w. **Infiltration:** The flow or movement of precipitation or surface water through the ground surface into the subsurface. Infiltration is the main factor in recharge of groundwater reserves.

x. **Piezometer:** Non-pumping well, generally of a small diameter, that is used to measure elevation of the watertable or piezometric surface at the point opening to the water at the bottom.

y. **Piezometric surface:** An imaginary surface representing the head of the groundwater within a hydrogeologic unit. It may be contoured to indicate direction of groundwater flow.

**z. Piezometric head:** Hydraulic head or piezometric head is a specific measurement of liquid pressure above a geodetic datum. Consider a point in a fluid continuum. The elevation of the point is z above some selected datum level. Let p denote the pressure in the fluid at the considered point. The piezometric head at the considered point is defined as

$$h = z + \frac{p}{\rho g} \qquad \text{(i)}$$

Where ρ is the fluid's mass density (i.e., mass per unit volume), and g is the gravity acceleration.

The piezometric head expresses the energy per unit weight of the fluid, due to:

- The elevation, z, of the point above the datum level, and
- The fluid's pressure head, $p/\rho g$.

Each of these two terms expresses an amount of energy per unit weight of fluid. The piezometric head is not the total head. The later includes also the kinetic energy. Fig. 6.2 shows Piezometric head.

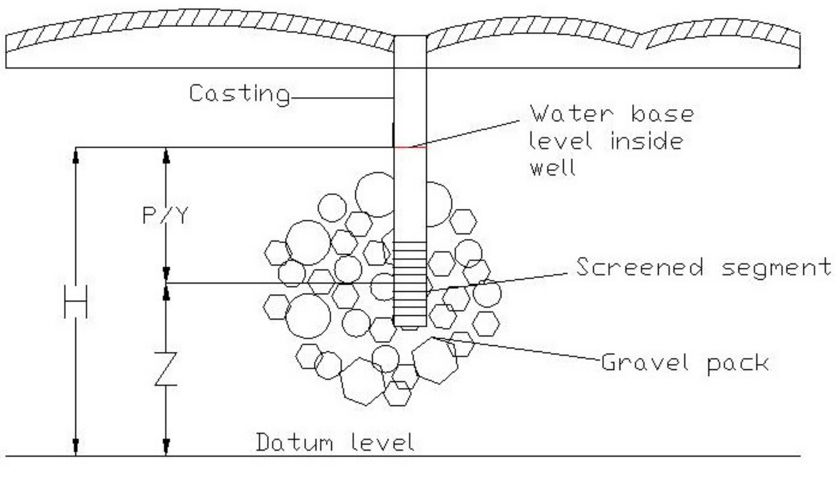


**Fig. 6.2** Piezometric Head

## 6.1.2 Classification of Aquifers

The water bearing geologic formations or strata which yield significant quantity of water for economic extraction from the wells are classified mainly into confined and unconfined aquifers. These confined and unconfined aquifers are further characterized by special cases.

### 6.1.2.1 Confined Aquifer

A confined aquifer is confined above and below by an impervious (may contain water but can't transmit it) layer under pressure greater than the atmospheric. Therefore, in a well penetrating such an aquifer, the water level rises above the bottom of the top confining bed. The water in a confined aquifer is called confined or artesian water. Fig. 6.3 shows a sketch of a confined aquifer. Note that the piezometric surface may be anywhere above the ceiling of the aquifer.

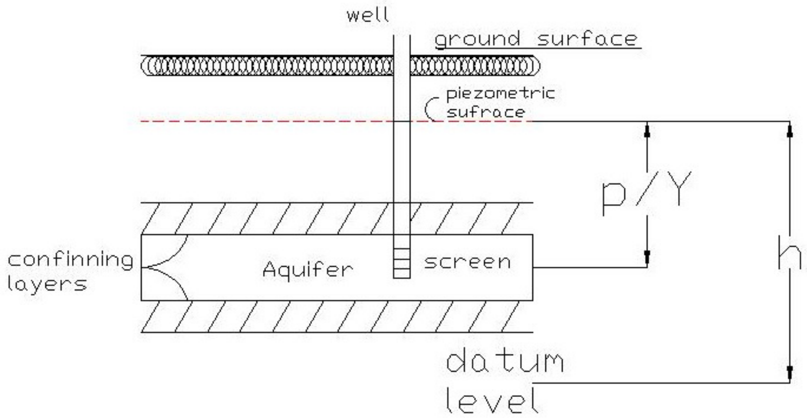


**Fig. 6.3** Confined Aquifer

### 6.1.2.2 Artesian Aquifer

It is the part of confined aquifer in which the piezometric surface is above both the ceiling of the aquifer and ground level. Water from artesian wells flows freely without pumping. Fig. 6.4 shows artesian aquifer.

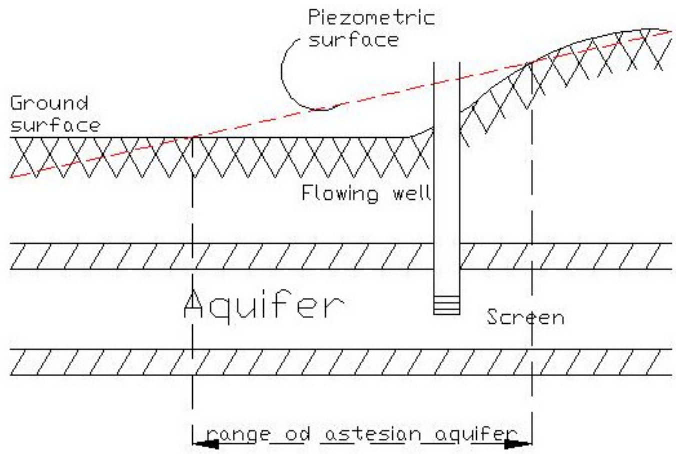


**Fig. 6.4** Artesian Aquifer

### 6.1.2.3 Unconfined Aquifer

An unconfined aquifer or phreatic aquifer is one in which a water table (phreatic surface) serves as it supper boundary. A phreaticaquiferdirectly recharged from the ground surface above it. The water level in well taping an unconfined aquifer and the watertable in the aquifer are the same. Fig. 6.5 shows phreatic aquifer.

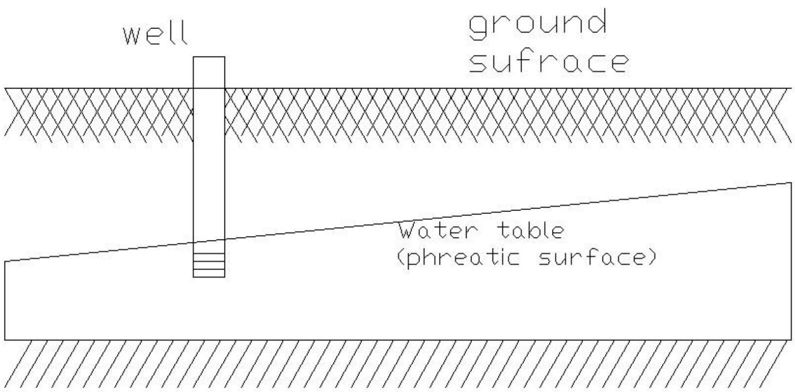


**Fig. 6.5** Phreatic Aquifer

#### 6.1.2.4 Perched Aquifer

Perched aquifers are special kinds of phreatic aquifers occurring whenever an impervious (or semi-pervious) layer of limited extent is located between the water table of a phreatic aquifer and the ground surface, thereby making a groundwater body, separated from the main groundwater body, to be formed. Sometimes, these aquifers exist only during a relatively short part of each year as theydrain to the underlying phreatic aquifer. Therefore, wells taping such aquifers yield only temporaryor small quantities of water. Fig. 6.6 shows perched aquifer.

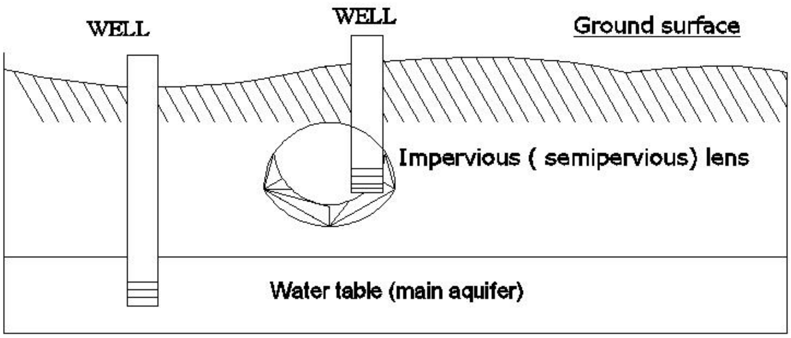


**Fig. 6.6** Perched Aquifer

#### 6.1.2.5 Leaky Aquifer

A leaky aquifer is under lain or over lain by semi-pervious strata. Pumping from a well in a leaky aquifer removes watering two ways: by horizontal flow with in the aquifer and by vertical leakage or seepage through the semi-confining layer into the aquifer. Aquifers that are completely confined or unconfined occur less frequently than leaky aquifers. Fig. 6.7 shows leaky aquifers.

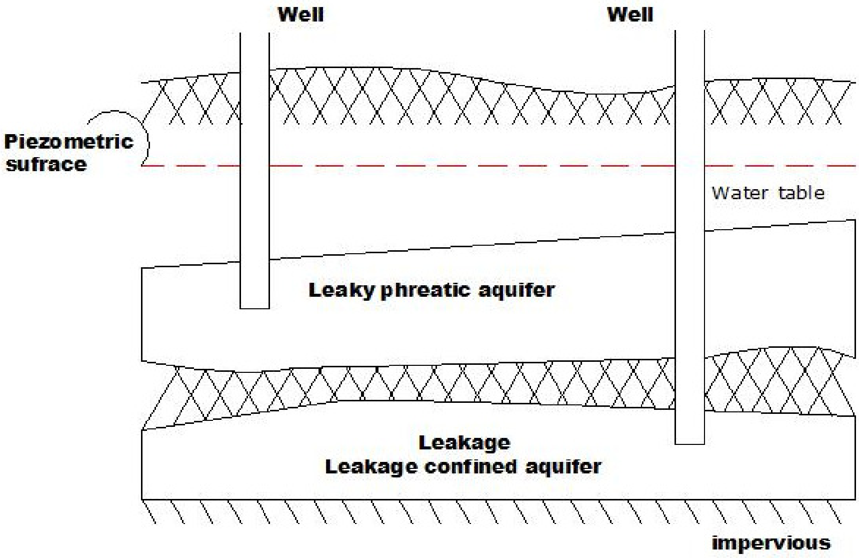


**Fig. 6.7** Leaky Aquifer

# 6.2 Groundwater Resources

## 6.2.1 Historical Developments

About a century ago, the Indus Basin Irrigation System (IBIS) was designed for an annual cropping intensity (i.e. yearly cropped area) of about 75%. The major objective of irrigation development at that time was to prevent crop failure and avoid famine (Jurriens and Mollinga, 1996). Over time, many canals no longer have their design capacity due to siltation and erosion of banks. Thus, canal water availability per unit of irrigated land has become even more limited (Sarwar et al., 2000). Thus, farming communities came forward to rescue themselves by installing agricultural wells to extract groundwater.

Realizing the benefits of groundwater irrigation, the government subsidized the power supply to facilitate expansion of irrigated areas and maintain higher production levels. Subsidized power supply and the introduction of locally made small diesel engines provided the impetus for a dramatic increase in the number of private tubewells from 10000 in 1960 to about 0.6 million in 2002 (Qureshi et al., 2003) and about 0.8 million in 2006 (World Bank, 2002). Large-scale extraction and use of groundwater for irrigated agriculture in Pakistan started in the early 1960s with the launching of Salinity Control and Reclamation Projects (SCARP). Under this programme, thousands of large capacity tubewells were installed to control the groundwater table and supplement irrigation supplies. SCARP tubewells managed to lower the groundwater level below 1.5 m over an area of 2 million ha and below 3 m over 4 million ha, thereby alleviating the problem of water logging significantly. The additional water made available by the SCARP tubewells increased cropping intensities from 80 to 120% in most of the SCARP areas (IWASRI, 1998). The uncontrolled and relatively cheap access to groundwater proved significant not only for the livelihoods and food security of the poor, but also as a driving force for rural and regional economies.

The groundwater is currently providing more than 50% of the total crop water requirements (though of course much of the groundwater recharge is from surface irrigation), with the flexibility of its availability as and when needed (Haq, 2000). The role groundwater irrigation has attained in maintaining the agricultural boom is unique and vital and will further expand in future due to mounting pressure to grow more food and increasing incidences of drought in the region. Qureshi et al. (2003) showed that more than 70% of the farmers in the Punjab province depend directly or indirectly on groundwater to meet their crop demands. This clearly indicates that without groundwater availability not only Punjab but the whole country would face serious food shortages, as Punjab province produces more than 90% of the total grain.

## 6.2.2 Groundwater Uses

Groundwater as a resource plays an important role in water supply for different uses. However, irrigation is the main user of groundwater. In U.S. about 40% of the irrigation requirements are met from groundwater. In Pakistan groundwater pump age for agriculture use has been estimated as 40 MAF and that its supplies make up as 33% of the irrigation water supplied at the farm gate (Qureshi et al., 2010). It is also used for domestic and industrial water supplies. The merits and demerits of using groundwater are as under.

### 6.2.2.1 Advantages of Groundwater

- It can be extracted near the farm gate for irrigation purposes. This results in less conveyance and distribution losses with consequent higher overall irrigation efficiencies.
- It is generally free of pathogenic organisms and needs no or minimum treatment or purification for domestic or industrial uses
- It does not require large surface reservoirs for storage.
- Heavy and off-season rains can be used effectively by creating potential groundwater storage space before the onset of rains. This is done by heavy pumping and consequent lowering of water table.
- It is usually available at constant temperature.
- Turbidity and color are generally absent and chemical composition is commonly constant.
- Radio-chemical and biological contamination of most groundwater is slow and difficult.

### 6.2.2.2 Limitations of Groundwater

- It is generally more saline (500 to 3000 ppm) than river water (200 to 500 ppm).

- It is generally more costly due to pump/engine equipment cost and energy/O&M costs except when conveyance channels/conduits are required for delivering the surface water under gravity.
- Excessive pumping may cause land settlements and sink holes.
- Some areas may not have adequate groundwater reservoirs.
- Clean up of contaminated groundwater is very difficult, slow and expensive.
- It may not be available at every place.
- It may be very deep, and special machinery is required for its exploitation.
- Groundwater of unacceptable quality is not useful.
- It may be available in limited quantities with or without a recharge source for replenishment.
- It can be easily overexploited, thus may not be sustainable.

### 6.2.3 Groundwater Quality

The groundwater quality is determined by the quantity of salts, pollutants; bacteria and other sources present in it which make water unfit for different purposes such as irrigation, domestic and other purposes. Scientists have established water quality standard for irrigation, domestic/drinking and industrials uses.

In Indus basin groundwater quality varies spatially from completely fresh water to extremely saline water. The quality of groundwater depends upon its origin, the recovery sources and groundwater movement in the aquifer. Along the rivers and lakes, groundwater is found fresh due to recharging of fresh water from rivers and lakes. The groundwater quality is deteriorated as we move from sides to center and southwest of each Doab (Doab is the area between two rivers).

In Pakistan, groundwater quality varies from fresh 49% (salinity less than 1000 mg/L TDS) along the major rivers to extremely saline 36% (salinity more than 3000 mg/L TDS) towards center and 15% of water is marginally saline (salinity between 1000-3000 mg/L TDS). The general distribution of fresh and saline groundwater in the country is shown in Fig. 6.8.

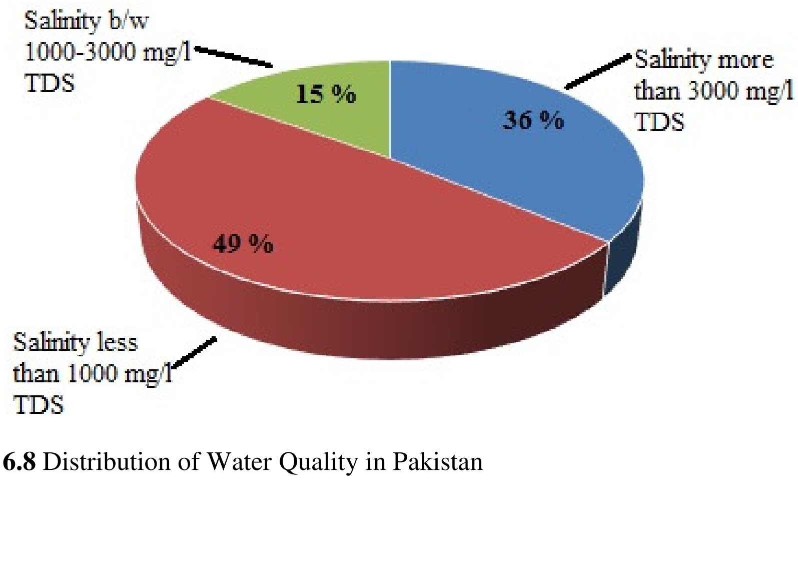


**Fig. 6.8** Distribution of Water Quality in Pakistan

The groundwater survey conducted by IWMI in 2002 reveal that electrical conductivity varies from 0.3 dS/m to 4.6 dS/m in the central Punjab. Groundwater quality is almost unfit for irrigation purposes in lower Punjab. In Sindh, groundwater quality is usually good along the river. As we move away from the river, it is found deteriorated. In Sindh, groundwater quality varies from 0.5 dS/m to 7.1 dS/m. In lower Indus plain, local groundwater is extremely saline due to marine origin. A portion of saline groundwater of region is found in delta, where salinity is nearly double than sea water.

### 6.2.4 Groundwater and Climate Variability

Climate varies due to global warming in the atmosphere. This is the result of high concentration of greenhouse gases in the environment. Climate variability is the problem in which cause and effect are separated over very long period and there are large uncertainties about effects. Climate change is a threat for future water supply.

The lasting groundwater yield from groundwater resources is estimated based on prevailing climate conditions. A long time deviation to more dry or wet years has an effect on pattern of rainfall distribution. It will seriously affect the flow of rivers, recovery to aquifers and water availability. A shift to more dry years has negative impact on sustainable yield of groundwater. This will result in reduction of water allocation and use. On the other side; a long time deviation to more wet years could have the opposite impact on groundwater yield.

Our society should be aware of impact of climate variability on availability of groundwater in future. There is need to develop strategies by involving both water managers and water users as climate variability will not only affect the water availability but also the way to allocate and use. A shift to more dry years may increase length of drought conditions.

## 6.3 Province wise Groundwater Potential

The aquifers are replenished by recovery from rainfall water and irrigation system. The groundwater potential of a region is based on replenishment of aquifers from different recovery sources and groundwater movement to region due to hydraulic gradient. The province wise groundwater potential in Pakistan is described below.

### 6.3.1 Groundwater Potential in Punjab

About 79% of Punjab province has access to fresh groundwater. In Punjab, nearly 9.78millions acres are underlain with groundwater of less than 1000 mg/l TDS, 3 million acres are underlain with groundwater having salinity varying between 1000-3000 mg/l TDS. There are four hydro geological zones in Punjab which are major sources of groundwater. These are Potohar plateau and salt range, piedmont areas, alluvial plains and Cholistan desert. In Punjab, surface water flows in Indus River and its tributaries. In past, a lot of strategies are developed and implemented for seepage from irrigation system and resulting recovery to the groundwater (PPSGWP, 1998). The groundwater potential is based on augmentation of aquifers through recovery from rainfall and irrigation system. The rainfall recharge of 9.90 MAF (15% from 380 mm/year) in different SCARP areas was worked out during the period 1987-97 (PPSGWP, 1998). The recharge from return flow, irrigation system and sub-surface inflows was assessed 7.08 MAF (22.5% of 31.5 MAF). A delivery of 24 large canals for irrigation year 1990-91 was with an average of 54 MAF. The recharge from these canals estimated 21.70 MAF (40% of 54 MAF). The recharge from rivers was 3.5 MAF and return flows from industrial and domestic use were assessed as 0.57 MAF (22.5% of 2.52 MAF). The total available groundwater resource of the Punjab province was estimated 42.75 MAF.

### 6.3.2 Groundwater Potential in Sindh

Around 28% of the Sindh province has access to fresh groundwater (having less than 1000 mg/l TDS). This water is suitable for irrigation. In Sindh, fresh groundwater can be found at 20-25 m depth along the edges of the irrigated lands. Most of the regions in Sindh are underlain with poor quality groundwater.

There are three hydro geological zones in Sindh where groundwater lies. These are Eastern (Thar) desert, Western mountain and Indus valleys. Useable groundwater is mainly found in the Indus Plain. This plain is replenished from the meandering river and from the irrigation system. The other source of recharge is rainfall. Recharge through rainfall is quite small and its contribution to the resource is limited. Rainfall recharge was 1.96 MAF (2% of 265 mm per year) as worked out by ACE and Halcrow (2001). The recharge from return flows (22.5% of 38.2 MAF), irrigation returns (22.5% of 3.5 MAF) was assessed 8.58 MAF and 0.79 MAF respectively. In the Sindh, canal water losses have been taken as 15 % of the total average canal supply of 45 MAF for the period 1988-2000. The recharges from these canals was estimated 6.76 MAF. The recharge from the rivers was assessed 0.3 MAF. The total available resource of the Sindh Province was assessed to be 18 MAF.

### 6.3.3 Groundwater Potential in Khyber Pakhtunkhwa (KPK)

In Khyber Pakhtunkhwa (KPK), there are certain areas such as Karak, Kohat, Bannu and D.I. Khan where abstraction rate is significantly higher than recharge rate. This results in downward movement of water table and water gets mixed from underlying saline water.

In the province, groundwater lies in alluvial plains and many valleys, which are intermountain basins of tectonic origin. The rainfall recharge was estimated 0.7 MAF (7% of rainfall over a sub-catchment). The average flows for the period 1988-2000 was 6.68 MAF (ACE and Halcrow, 2001). In this Province, recharges from the canal system were worked out 1.0 MAF (15% of 6.7 MAF). The groundwater is replenished by recharge from irrigation network, other return flows, sub-surface inflows and recharge from rivers. The recharge from the return irrigation flows was assessed 1 MAF (15% of 6.5 MAF) and other return flows (15% of 0.88 MAF) were worked out to be 0.13 MAF. The total groundwater resource of the KPK was assessed as 3.11 MAF.

### 6.3.4 Groundwater Potential in Baluchistan

There are five hydrological zones in the province. These are Mountain ranges, Piedmont plains, Valley floor, plains and rolling sand plains. The groundwater occurs in unconsolidated aquifers in almost all basins and sub-basins, in substantial quantities. The groundwater resources in six basins of the province namely Hamune, Lora, Kachhi Plain, Nari, Pishin and Zhob have been assessed. The effective rainfall coefficient of 20% to the annual rainfall for the mountain areas is used to estimate rainfall of 1.21 MAF. In Balochistan canal supplies are small in total and restricted to the east of the Province, adjacent to Sindh Province. The Makran coastal zone and several other basins contain highly brackish groundwater. Local communities use groundwater with TDS as high as 3000 mg/L, for drinking purposes, as there are no alternatives.

For the period 1988-2000 the average canal flow was 1.94 MAF and recharge from these canals was assessed as 0.29 MAF (15% of 1.94 MAF). Most of irrigated area of this Province lies in a saline groundwater zone. Other components of groundwater recharge include return flows from irrigation application, other return flows, sub-surface inflows and recharge from rivers. The recharge from return flows of irrigation application was estimated 0.37 (22.5% of 1.62 MAF) and other return flow was 0.08 MAF (20% of 0.45 MAF). The total groundwater resource of Baluchistan Province was assessed as 2.13 MAF.

## 6.4 Problems of Groundwater Development in Pakistan

Groundwater is a limited resource and need proper management to avoid its quantitative depletion and qualitative deterioration but groundwater over development is becoming increasingly trend. Many problems are associated with groundwater development in Pakistan: depletion due to groundwater overdraft, deterioration of Groundwater Quality, water logging and Soil Salinization due to inadequate drainage and use of poor quality groundwater and Socio-economic and Environmental Impacts due to declining groundwater tables and land degradation. These problems are briefly discussed below.

### 6.4.1 Groundwater Overdraft

Shortage of surface water supplies is major cause of trend of groundwater use for irrigation purpose. Unreliability of surface water availability shifted more and more farming communities to use groundwater. On the other hand, cheap drilling techniques allows even small farmer to use groundwater for irrigation purpose. The trend of continuous lowering of water table has been observed in many areas of Pakistan. This condition reveals serious imbalance between abstraction rate and recovery rate. As groundwater table kept on declining (>15m), farmers were shifted to more deep wells. This deviation finally results in increased installation and operational cost. As we move deeper (beyond 20 m depth), turbine and submersible pumps are needed to pump groundwater. Under these circumstances, access to groundwater was restricted only to large and rich farming communities and poor farmer had to content on surface water.

### 6.4.2 Deterioration of Groundwater Quality

The declining groundwater table caused deterioration of groundwater quality. In Indus plain, groundwater quality varies widely both from place to place and with depth. It is associated with groundwater movement in the aquifer. Areas receiving heavy rain falls in Punjab have greater recovery. In upper parts of the Punjab, water of low mineralization lies underground. Similarly, recovery from main rivers and unlined canals has resulted in relatively fresh water zones along them. As we move away from rivers and canals, salinity generally increases. There are several number of saline groundwater pockets in the canals command areas of Punjab and Sindh. In Punjab, 23% of area has hazardous groundwater quality, while it is 78% in Sindh (Haider, 2000).

### 6.4.3 Soil Salinization

In Indus basin, the soils are affected by salts due to use of poor quality groundwater for irrigation purposes. According to the latest estimates, extend of soil affected soil has decreased to about 4.5 million hectares from about 6 million hectares in 1980s (WAPDA, 2007). The problem of salinity is very much intense in the lower part of Indus basin (Sindh province) due to difference in annual rainfall and geo-morphological conditions. Here 56% of total irrigated land is affected with salinity due to marine salts, poor natural drainage conditions and the use of poor quality groundwater for irrigation purposes. Surface water available in Sindh is much less than actual crop water requirements of the area. The leaching of salts is also very less due to presence of highly saline Soils at shallow depth and highly saline groundwater at deeper depths (Bhutta and Smedema, 2007). These problems are threatening the sustainability of the system and capacity of the country to provide food to its increasing population.

### 6.4.4 Socio-economic and Environmental Impacts

The use of poor quality groundwater for irrigation purposes in Pakistan results in lowering of groundwater table depth and degradation of soils. This problem has severely affected the societies. In Baluchistan, large scale migration of partners for money earning is observed. This has increased the livelihoods burden on women as Karez systems get dry in the province and on average, a woman carries more than 200 liters of water each day. This huge burden affects her time and physical abilities.

In cholistan areas of Punjab province, a woman must walk miles to bring fresh drinking water. She collects water from natural streams flowing for away from her residence as groundwater is very deep and hazardous to health. On the other hand, soil degradation due to use of poor quality groundwater has reduced the production potential of major crops by 25%. Sea water intrusion also takes place in coastal areas of Indus basin due to groundwater overdraft. This is a threat for ecology of wet lands.

## 6.5 Problems of Groundwater Management

Until recently, groundwater management in Pakistan has been neglected due to an apparent abundance of resource and full concentration being given to groundwater development. Cheap drilling techniques shifted trend of surface water use to groundwater use. Farming communities exploit groundwater extensively for irrigation purposes which resulted in high production of crops and helped lift millions of people out of poverty. But the situation turns serious when this unregulated pumping causes imbalance between abstraction and recharge of aquifer and threatens sustainable groundwater yield. The only reason for this imbalance of system is that groundwater management is neglected and full attention should be given to its development. Over the last three decades, Pakistan has tried many management strategies to regulate the pumping of groundwater and control the over exploitation of groundwater but pragmatic and viable solutions have proven elusive.

### 6.5.1 Direct Management:

Over the last three decades, government of Pakistan has introduced many laws for regulated pumping of groundwater in the country. In 1980s, to restrict the installation of private tubewells in critical areas where the groundwater was declining at high rate and/or where quality of groundwater was deteriorating, licensing system was introduced. Groundwater regulatory frame work was prepared for Punjab province in the mid-1990s with the assistance of World Bank. The national groundwater management rules were also introduced under provincial irrigation and drainage authority (PIDA, 1997). These rules were then included in the canal act of 2006.Similar rule was also introduced by the Baluchistan government named Baluchistan Groundwater Rights Administration Ordinance 2001. These laws suggest separation of critical areas, introduction of licensing system for installation of private tubewells especially in critical areas and registration of all tubewells. This regulatory framework was submitted to the provincial Governments for implementation.

Despite huge number of laws and policies introduced by the government, no serious efforts were made for their implementation. Another reason of unexecution was lack of respect for law and rule in society. In addition to this corruption in public sector was also a reason. Furthermore, licensing policy seems impractical and ineffective for large number of groundwater users in the country as government is usually under stress to feed its growing population and reduce poverty especially in rural areas where more than 70% of the population lives. The allocation of funds for major investments in surface water resources and irrigation network had declined sharply, thus resulted in over exploitation of groundwater for expansion of irrigated agriculture. With large number of farming communities now highly dependent on groundwater irrigated agriculture for their earnings, the government was feeling hesitation to implement the regulatory laws.

### 6.5.2 Indirect Management

Pakistan has also tried many indirect management strategies to control the over exploitation of groundwater. Manipulation of energy prices was one of those strategies. In 1970s, rural electricity grid was expanded in the country and government provided subsidies to farmers for the installation of tubewells to expand the agriculture. During this period, farmers just pay according to what he consumed. While all capital installation costs were paid by government and bills were based on metering system. With passage of time, electricity cost increased and the government withdrew incentives for farmers in the Punjab and Sindh province. This resulted in the transformation of trend from electricity use to diesel use for tubewells and the ratio of electricity to diesel pumps increased to 1:4 which was 1:1 in 1970s (GOP, 2010).

This reveals that changing electricity prices forces only farming communities to transform from one mode of energy to another but could not help resolve the real issue of groundwater over exploitation. As farmers were highly dependent on groundwater for their livelihoods, they continued the abstraction of groundwater. It should be noted that the electric pumps were now less than 10% of total private tubewells in Pakistan. Their share in total groundwater extraction is about 20%. Therefore, manipulation of electricity prices would have minor effect on controlling the groundwater over-exploitation. This clearly shows the need of hour to introduce more innovative ways to resolve issue of groundwater over development while keeping in view the increasing need of food for growing population.

## 6.6 Groundwater Management Indicators

The sustainable groundwater management is an integrated approach. This includes amount of groundwater recharge, the rate of groundwater extraction, rate of population increase and rate of number of increasing pumping wells. There should be stability between rate of extraction, recharge and aquifer capacity and yield. UNESCO has created some indicators for sustainable development and management of groundwater resources:

- Renewable groundwater resources per capita
- Total groundwater abstraction/ Groundwater recharge
- Total groundwater abstraction/Exploitable groundwater resources
- Groundwater as a percentage of total use of drinking water at national level
- Groundwater depletion
- Total exploitable non-renewable groundwater resources/ Annual abstraction of non-renewable groundwater resources
- Groundwater vulnerability
- Groundwater quality
- Groundwater treatment requirements
- Dependence of agricultural population on groundwater

## 6.7 Prospects of Groundwater Management in Pakistan

The problems of management of groundwater in Pakistan are complex and pragmatic and viable solutions have proven elusive. Pakistan has tried many direct and indirect strategies for management of groundwater but they have not given the required results and groundwater over draft keeps on increasing. A major hurdle against shift from mode of resource development to resource management is the absence of strong information base. Despite hectic efforts by different national and international organizations, the available data on availability of groundwater, groundwater distribution, groundwater quality, groundwater extraction and other variables is very limited and not properly synthesized. This clearly demonstrates the need to create comprehensive and strong information base regarding data on groundwater users, use of groundwater, groundwater withdrawal, aquifer conditions, groundwater table depth and groundwater quality. This data is important in understanding the regions where aquifers are under stress, those where groundwater resources are under drafted and those where it is over drafted. The socio-economic and environmental conditions of these areas should be studied for future planning. In addition to this, the potential interventions should also be studied that helps in groundwater management. The demand and supply management strategies should be tried for reducing groundwater over-exploitation. The potential interventions: conjunctive use, introducing water saving technologies, revised cropping pattern, harvesting rain water, artificial recharging, developing laws, etc. that might be helpful for reducing demand are briefly discussed below.

### 6.7.1 Demand Based Management Interventions

One of the pragmatic solutions for resolving issue of groundwater overdevelopment is to reduce the demand of water for agriculture purpose while keeping in view the increasing need of food for growing population. Some potential demand management interventions are based on the idea to use each drop of surface and groundwater in a best and managed way. Other demand management interventions include revised cropping pattern according to availability of water and harvesting rain for reducing the stress on groundwater.

#### 6.7.1.1 Conjunctive Use of Surface and Groundwater

Agricultural sector is the biggest user of water and irrigated agriculture is expected to continue as major consumer of both surface and groundwater in future. In Pakistan, groundwater is usually used in combination with the surface water. Farmers reduce the salinity of irrigation water to prevent soil degradation due to salts by using surface water in conjunction with groundwater. In most of canal command areas of country, conjunctive use is equally practiced in head and tail ends. One of the negative impacts of this unmanaged use is that areas at head ends are subjected to inclining water tables and soil gets water logged whereas downstream regions are subjected to salinity problem due to deterioration of groundwater quality. Thus, managed use of groundwater in conjunctive with surface water should be introduced and encouraged. The farmers of head ends should make better use of surface water of the canals which are more reliable for them. For encouragement of managed conjunctive use, department of irrigation and power needs to regulate the surface supplies to match with the requirements. Farming families also need to be educated about managed conjunctive use (proper mixing ratios) of surface and groundwater in order to boost agricultural production and prevent land degradation.

#### 6.7.1.2 Improving Water Productivity

Despite the limited availability of water, current irrigation methods, adopted by our farmers, result in over irrigation and huge loss of water at farm level. This situation is directly related to poor management of irrigation network and low efficiency of our irrigation methods. In practical terms, about 40% of applied irrigation water is lost by seepage from the irrigation canals and deep percolation in the fields (Butta and Smedema, 2007). In Pakistan, overall system irrigation efficiency is 40% (Bakhsh and Awan, 2002).

Even though much of the water percolated is now captured by heavy groundwater extraction, this does not apply to poor quality groundwater zone and the groundwater extraction involves extra costs. The crop water productivity (crop production per unit drop) in Pakistan is among the lowest in the world. This clearly shows a heavy potential for increasing the crop water productivity. Water metering and pricing systems are unlikely to be introduced in the near future. It makes water conservation financially charming. Thus, more efforts are needed to get farmers involved in water saving techniques and then crop water productivity can be increased in Pakistan.

#### 6.7.1.3 Introducing Resource Conservation Technologies

Water conservation techniques can result in less water loss and decrease the threat of water logging in regions of the Indus basin. Small and poor farmers should be provided with incentives to transform from flood irrigation to high efficiency irrigation methods (Drip irrigation, sprinkler irrigation, etc.), improve leveling of their fields with use of laser land leveling technique, introduce soil mulching. These resource conservation technologies have proved successful in improving crop water productivity at farm level. In addition to these, other technologies such as zero tillage and bed planting have also proved successful in water saving. Introduction of these technologies in (semi-) arid areas of Pakistan require careful planning as reduced irrigation applications may increase the chances of soil salinization and reduce the recovery to groundwater which is vital for downstream users. Thus, evaluation of impact of these technologies at different levels for different metrological conditions within a basin is inevitable

#### 6.7.1.4 Rationalizing Cropping Patterns

The conventional crops such as rice and sugarcane have benefited from increased irrigation supplies. Since rice is a water-intensive crop (uses huge amount of water for its production), it is necessary to make study whether Pakistan should continue to grow water-intensive crop such as rice or instead use this water to grow another high market value crops where the country has more earning. Stress on groundwater can be reduced by limiting the rice production to its local needs and using the water for the less water intensive and high market values crops. Introductions of other irrigations methods such as alternate wet and dry irrigation (AWADI) for rice crop can also help in reduction of groundwater use. Similarly, if sugarcane crop is replaced with less water intensive and high market value crops, the pressure on groundwater can be reduced. Introduction and encouragements of use of high market value and low water demanding crops like pulses, vegetables, sunflower and orchards can also boost the agricultural incomes. Rationalizations of cropping pattern should be encouraged by the Government as Pakistan is importing more than one billion U.S. dollars of edible oil.

#### 6.7.1.5 Promoting Rainwater Harvesting

Rains fed areas of Pakistan contribute 10% of total agricultural production. The production potential of these areas is very high but their production level is very low i.e. 1 - 1.5 t/ha due to unavailability of water at critical growth stages of crops. Oweis and Hachum (2001) argue that the production level of these areas can be made double by providing one or two supplemental irrigation at critical growth stages of crops.

In areas where farmers are provided with supplemental irrigations, they extract groundwater for this purpose. However, rainwater harvesting should be introduced and encouraged to use rainwater for supplemental irrigations instead of groundwater. Thus, it will help in reduction of groundwater use. Collection of rainwater and watershed management strategies can increase the productions level of these rain fed regions and help in reduction of demand on groundwater. There is need to formulate a comprehensive policy by government to promote rainwater harvesting and adoption of watershed management strategies.

### 6.7.2 Supply Based Management Interventions

In addition to demand management interventions, another viable solution for resolving issue of groundwater declining and deterioration of groundwater quality is to increase the availability of groundwater. Supply management interventions are mainly based on the idea of replenishment of aquifers and use of waste water. Other supply management interventions include exploration of fresh groundwater regions, control on sea water intrusion and use of partially penetrating wells. These are described below.

#### 6.7.2.1 Artificial Recharging of Aquifers

For management of groundwater resource, resource development mode should be shifted to resource management mode. Resource management mode is actually the creation of balance between discharge and recharge of aquifers. To improve the ability of groundwater at farm level, small scale recharging structure should be introduced.

Groundwater discharge is hydrologic process where water infiltrates from surface to subsurface and then moves deep percolated to groundwater. Groundwater recharge occurs both through the water cycle (natural recharge) and through anthropogenic process (artificial recharge).

Artificial recharge involves injection of surface water in the ground in the time of surplus. This water is pumped out when needed. The purposes of recharging aquifers by artificial means are to control salt water intrusion or land subsidence, to make a water bank and to prevent deterioration of quality of groundwater. Artificial recharging is done by ponding water on the land with borders, furrows, etc. In addition to this infiltration trenches, shafts or wells in the vadose zone are filled by water for recharging of aquifers.

The conventional method for water storage has been with reservoirs but good dam sites are becoming scarce and require a large area of land. In addition, there are several disadvantages, such as evaporation losses (about 2m/year in warm dry climates), sedimentation, failure of structure, and increased human diseases in the area and severe effects on ecology, environment and culture. On the other hand, underground water dams require no land and there are zero evaporation losses.

Artificial recharge systems are engineered systems where surface water is injected into the ground. There are three main artificial recharge systems: surface infiltration system, vadose-zone infiltration system and combine system. These are described below.

- **Surface Infiltration**

It consists of dams placed across ephemeral or perennial streams to back the water up and spread it out, thus increasing the wetted area of the streambed or Floodplain so that more water infiltrates into the ground and percolates to the groundwater. Surface infiltration systems normally require permeable surface soils to get high infiltration rates and to minimize land requirements.

- **Vadose-Zone Infiltration**

Where sufficiently permeable soils and/or sufficient land areas for surface infiltration systems are not available, groundwater recharge can also be achieved with vertical infiltration systems, such as trenches or wells in the vadose zone. The main advantage of recharge trenches or wells in the vadose zone is that they are relatively inexpensive.

- **Combine System**

Surface infiltration systems are preferred, because there are fewer options for clogging and they offer best soil-aquifer treatment for improvement of quality of water. If permeable soil occurs at ground surface and fine textured soil layers at some depth, then downward water movement is subjected to restriction and perched groundwater table starts to incline. In these conditions surface infiltration is used in combination with vertical infiltration system. Vertical infiltration systems are installed through fine-textured restricting zone. The upper parts of the system work as drainage system of perched groundwater, while lower parts work as systems for infiltration and replenishment of aquifers.

#### 6.7.2.2 Use of Alternate Resources of Water

The total annual quantity of wastewater produced in Pakistan is estimated at $4.5\times10^9$ $m^3$. Most of this water is either disposed off in rivers or discharged into open areas on the outskirts of big cities. A small amount of this water is being used to grow vegetables in the cities. As our groundwater resource is limited, we can make reduction in its use by making profitable use of wastewater. We should grow valuable crops by using waste water instead of throwing it in rivers. Salt resistant crops like grasses, bushes and trees such as eucalyptus can provide a handsome economic return to farmers of saline lands. A large amount of work is needed to be done on improvement of use of saline soils and saline waters.

#### 6.7.2.3 Policy Reforms

Due to the peculiarities of Pakistan's groundwater socio-ecology, a multi-dimensional approach is needed. In Baluchistan province, for example, the policy of providing incentives on energy needs to be revised. Currently, the annual subsidy on agricultural tubewells is Rs. 8.5 billion (US$ 140 million). This subsidy facilitates only 2.5% of the farmers who own deep electric tubewells. Most small farmers are deprived of this facility, which is creating serious equity concerns in the rural communities. Moreover, farming communities should be taught to replace conventional wheat and fodder crops with high market value crops for the best use of expensive groundwater.

In the Punjab province, more work is needed to be done to revise the cropping patterns for areas where groundwater resources are insufficient to support intensive agriculture. In such areas, less water intensive crops should be grown. Separate strategies should be developed for large scale farmers and for small poor farmers. Cropped areas for different crops should be fixed based on the country's food requirements and the availability of water resources. In areas like Cholistan where groundwater resources are not yet tapped due to lack of resources of the local population, groundwater still presents the opportunity to secure the livelihoods of the large population living in this region.

There are laws and policies regarding effective management of groundwater, but these are not implemented effectively. The government needs to implement all the strategies and policies. Pakistani farmers need to be educated about groundwater management options and taken into confidence to implement possible strategies to protect groundwater resources. Policies should also be developed for the economic shift of the population that currently depends on intensive irrigated agriculture to earn their living.

#### 6.7.2.4 Identification of Fresh Groundwater Areas

Fresh groundwater areas should be explored and mapped about depth of water table, potential and quality of groundwater. From this database, we can decide where to install new tubewells and where to implement the strategy regarding lining of conveyance systems.

#### 6.7.2.5 Controlling Salt Water Intrusion

Sea water/salt water intrusion is the process of movement of saline water (having high salinity) towards fresh groundwater areas. This intrusion causes contamination of groundwater resources. Salt water intrusion takes place mostly in coastal areas. Saline water is denser and has higher water pressure because it has higher mineral contents. Thus, salt water intrudes into freshwater.

Salt water movement towards fresh groundwater areas can be controlled by artificial recharge. The water injected by artificial recharge creates a hydraulic barrier by raising the piezometric head of fresh water aquifer and thus prevents or reduce saline water intrusion. Hydraulic barriers against saline water are created with either artificial recharge basins or artificial recharge wells.

### 6.7.2.6 Skimming Well Options

Skimming wells are low discharge, partially penetrating wells screened in the upper zone of fresh-saline aquifer to extract relatively fresh water from shallow depth. Rates of pimping is a crucial decision variable for sustainable yield of groundwater on long term basis. Unregulated pumping results in upcoming and disturbs the skimming process of relatively least saline water (Saeed et al., 2002).

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Chapter 7

# Irrigation Water Quality

**Muhammad Arshad and Aamir Shakoor***

## Abstract

The quality of the available water must be tested to check its fitness prior to use. Irrigation water, whether diverted from streams or pumped from tube wells, contain appreciable quantities of harmful substances in solution those may reduce crop yield and deteriorate soil fertility. The main characteristics to assess the quality of irrigation water are Total Dissolved Solids (TDS), Sodium Absorptions Ratio (SAR), Electrical Conductivity (EC) and Residual Sodium Carbonate (RSC). Unfortunately, in Pakistan, the quality of surface and groundwater is not routinely monitored as water supplies for domestic use and irrigation. The quality of water is being deteriorated due to disposal of untreated industrial wastewater and agricultural saline effluents directly to groundwater and canal water. The salt water intrusion in fresh groundwater areas from saline water zone due to the over drafting of water with tubewellsalso caused the deterioration of groundwater quality. Due to continuous recharge of comparative fresh water from rivers to aquifer, the groundwater has good quality water near water bodies while varies to saline and hazardous away in the middle of Doabs. The application of poor quality water for irrigation can cause soil problems such as salinity, sodicity, alkalinity, toxicity and water infiltration rate. Proper intention should be given to manage poor quality water and to reclaim the salt effected soil. The chapter on irrigation water quality has, therefore, been designed to include basic concepts of water quality parameters, criteria, and standards to define drinking and irrigation water quality. The given information would update the

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knowledge of each reader including farmers, engineers and agricultural professionals, to manage their soil and water resources for potential production.

**Keywords:** Water Quality Standards, Water Quality Indices, TDS, Alkalinity, Sodicity.

# Learning Objectives

- The primary purpose of this chapter is that readers may have opportunity to:
- Learn about the historical variations in water quality and update their knowledge about water quality criteria and standards in Pakistan.
- Learn about the importance of salinity and sodicity in irrigation and crop production.
- To update the knowledge of the scientists, researchers, policy makers and farmers about the soil and water quality and adopt advanced technologies such as conjunctive use, cyclic irrigation and soil additives to overcome salinity problems.

## 7.1 Introduction

Water quality influences its suitability for a particular use, i.e. how well the quality fulfills the requirement of the user. Water quality deals with the physical, chemical and biological characteristics of water in relation to all other hydrological properties. For example, river water having good quality with sediment load can be applied for irrigation successfully but may be objectionable for municipal use without treatment. Similarly, snowmelt water is acceptable for municipal purpose and may not be applicable for industrial due to its corrosion potential. The characteristics of water quality have become important in water resources planning and development for drinking, industrial and irrigation purposes (Shakoor, 2015). Water quality is the basic to judge the fitness of water for its proposed application for existing conditions. The current information is required, provided by water quality monitor for optimum development and management of water for its proficient uses (Haydar et al., 2009).

The evaluation of quality of water resulted to find out the causes, relationship and effects among water constituents and level of acceptability. Certain constituents emerge as indicators of quality-related problems with sufficient reported experiences and measured responses (FAO, 2013). The major concerns in terms of water quality and quantity are due to its inadequate distribution on the surface of earth and the rapid declining of fresh useable water (Irfan et al., 2014). The possible contamination in water included organic matter, nutrients, suspended solids, heavy metals, pesticides and industrial chemicals. Anthropogenic activities within river basins, erosion, and atmospheric depositions were also the main negative impacts on the water quality of most the reservoirs (Haydar et al., 2009).

The salinity of soil is also important factor for the determination of water quality. Soil salinity is developed when soil becomes more salty as a result of water movement in the soil especially due to irrigation. Water quality is critical for the survival of humans, animals, industry and agriculture. Furthermore, the proper management is requisite to meet water quality standards and for ecosystem health. The agriculture success is highly dependable on the quality of water applied in an agriculture area. Due to the application of poor or hazardous quality water the agriculture land/soil is affected and damages the crop yield in several ways. The accumulation of salts in root zone, limited the availability of water and plant can take up lesser water which resulted in high plant stress and decreased crop yields (Shakoor, 2015). The presence of metals in irrigation water also has adverse effects on crop production. Also, high concentration of salts can change the plant nutrients balance in the soil meanwhile some salts are toxic to certain plants (Shakoor et al., 2015; Irfan et al., 2014).

It is also notable that most of the normal plants tolerate wide range of salt but pasture plants are not highly salt-tolerant and would finally die out under saline conditions. The physical and chemical properties of soil are also affected by salinity that leads in soil loss in term of surface soil compaction and erosion. Salinity also dehydrates the soil bacteria and fungi and reduces soil health. These microorganisms are useful for the formation of organic matter and nutrient recycling. Irrigation water quality is described by different parameters such as Electrical Conductivity (EC), Total Dissolved Solids (TDS) and Residual Sodium Carbonate (RSC) (Shakoor et al., 2015).

# 7.2 Water Quality Indices

The water quality indices /parameters that describe the quality of water which are given below:

## 7.2.1 pH of Water

The pH is the concentration of hydrogen ions ($H^+$) and hydroxyl ions ($OH^-$) in the water. It is used to determine the acidic, basic or neutral behaviors of water. The pH values ranges from 1 to 14, which means, if pH of water is less than 7 then it is called acidic water whereas, pH equal to 7 as neutral and more than 7 is called the basic nature water. The pH of water and soil could not harm the plant growth directly (Tahir et al., 2003). pH highly affects the efficiency of coagulation and flocculation process (Kahlown et al., 2006).

## 7.2.2 Electrical Conductivity (EC)

The electrical conductivity (EC) of water is defined as the capacity of water to transmit the electric current. It depends on the dissolved ions in the water and their charge and movement. Because it is a good solvent, water dissolved mineral salts in the form of ions, which hold the electric current due to ionic conduction. When the EC of water is high, it shows that there is high concentration of ions in the water. The EC indicates the number of tota l solids in water and is dependent on the temperature of water. The electrical conductivity of water also affects the plant growth. The measurement of EC at 25°C temperature is considered as reference.

### 7.2.3 Total Dissolved Solids (TDS)

The salinity behavior of water is indicated by total dissolved solids (TDS). TDS contain the anions (negatively change ions) and cations (+ve changes ions). Total dissolved solids change the color and properties of water. The relationship between total dissolved solids and EC is:

$$\text{TDS (mg/L)} = \text{EC (dS/m)} \times \text{K} \qquad (1)$$

Where, K = 640 in most cases (for EC: 0.5 -5 dS/m) or

K = 735 for mixed waters or

K = 800 for EC > 5 dS/m

The above relationship in most cases is applied for EC ranging from 0.5 to 5 dS/m and not applicable for wastewater (Kahlown and Khan, 2002). TDS is the measure of the amount of material dissolved in water including carbonate, chloride, bicarbonate, phosphate, sulfate, nitrate, sodium, calcium, magnesium, organic ions etc. The density of the water, can be harmful due to increase in TDS concentrations, determined the flow of water into and out of an organism's cells. Moreover, the high concentrations of TDS may also reduce water clarity, contribute to a decrease in photosynthesis, combine with toxic compounds and heavy metals, and lead to an increase in water temperature. Flat insipid taste because of extremely low TDS level was also unacceptable (Kahlown et al., 2006).

### 7.2.4 Total Suspended Solids (TSS)

Total suspended solids (TSS) are the fine particles consisted of microorganisms, algae, mineral particles and organic matter, suspended in water. Total suspended solid is an indicator of erosion and sediment transport and it absorbs heat energy from sun resulted in water temperature increase and consequently, decrease the level of dissolved oxygen as we know warmer water holds less oxygen than cooler water.

### 7.2.5 Total Solids (TS)

Total solids (TS) are the combination of total suspended solids and total dissolved solids in the water and measured in milligrams per liter (mg/L). The dissolved solids pass through a filter of around 2 microns in size. Suspended solids are bigger in size than dissolved solids which includes clay, silt, algae, plankton, organic debris etc. those would not pass through a 2-micron filter (APHA, 1992). In water, the suspended and dissolved solids came from different sources such as soil erosion, sewage, fertilizer, industrial discharges, and road runoff.

### 7.2.6 Turbidity

The amount of cloudiness in the water is known as turbidity which is caused by dissolved or total suspended solids and most of the time those are invisible to the naked eye as smoke in air. It is important parameter to measure for water quality. Turbidity can be caused by i.e. Silt, sand and mud; Bacteria and germs; Chemical precipitates.

The turbidity is measured in Nephelometric Turbidity Units (NTU) defined by US Environmental Monitoring Standard unit. Turbidity is the values of light absorbing or light scattering property of water. High level of turbidity in drinking water possessed a higher risk to people for developing gastrointestinal diseases. Similarly, high level of material affects light penetration and productivity, recreational values, and habitat quality. In streams, the life of fish and other aquatics can be in danger due to increased sedimentation and siltation (Kahlown et al., 2006).

### 7.2.7 Color

The water color is an important indicator to define water and pollutants source. Water color represents the type of solid material present in it. Transparent water with low level of dissolved solids has blue color while yellow or brown color is due to the dissolved organic matter. The apparent blue color of water bodies is due to selective absorption and scattering of light spectrum. Some algae produce reddish or deep yellow waters. Similarly, the water rich in phytoplankton and other algae appears as green. True color could be measured by filtering the water after removing all suspended material (CWT, 2004).

### 7.2.8 Taste and Oder

Taste and order property of water is commonly used for drinking water. Taste (gustation) is one of the traditional five senses and is a form of direct chemoreception. It is the ability to observe the flavour of contents such as food, certain minerals, and poisons. The following are the basic taste types: sour, salty, sweet and bitter. Taste in the drinking water is mainly due to cations such as sodium, potassium, calcium and magnesium after their dilution of approximately 100, 300 100 and 30 mg/L, respectively (Kahlown et al., 2006). A human nose can detect the very low concentration of a substance and this is termed as odor (smells), which can be categorized as pleasant and unpleasant. Pure water is odorless.

The primary sources of taste and odor were algae and bacteria while anthropogenic sources include sewage wastewater and chemical spills, which could affect the groundwater and surface water (Hoehn, 2002). Some chemical contaminants can be detected by consumers at very low concentrations, have very low taste and odor thresholds (Young et al., 1996).

### 7.2.9 Calcium and Magnesium (Ca, Mg)

The calcium and magnesium in water resulted from the decomposition of calcium and magnesium aluminosilicates and from dissolution of limestone, magnesium limestone, magnesite, gypsum and other minerals. Calcium is an essential element for living organisms basically in cell physiology and mineralization of bones and shells. In water, magnesium is usually in less quantity than calcium. Moreover, in groundwater and surface water, the concentration by weight of calcium is very high. Whereas, the total concentrations of calcium and magnesium is referred as water hardness. When soap is added to hard water it forms precipitates on boiling. The calcium carbonate is the most dominant factor because of calcium and carbonate and referred as total hardness, measured in mg/L.

### 7.2.10 Carbonates and Bicarbonates ($CO_3^{2-}$, $HCO_3^-$)

Carbonate and bicarbonate ions referred by the dissolving of carbon dioxide ($CO_2$) by naturally circulating waters. A bond between the carbon and the hydrologic cycle is known to be carbonate. The atmospheric carbon dioxide is partly intercepted by photosynthesizing vegetation, which is converted to cellulose starch and related carbohydrates. The concentration of carbonates in natural waters is a function of dissolved carbon dioxide, temperature, pH, cations and other dissolved salts. Carbonate is a salt of carbonic acid, which originates from dissolving of carbonate minerals. A carbonate salt is formed when a positively charged ion, attaches to the negatively charged oxygen atoms of the carbonate ion.

The bicarbonate ion (hydrogenated-carbonate ion) is an anion with a negative charge and is the conjugate acid of carbonate. The weathering of rocks contributes to bicarbonate content in water as mostly these are soluble in water and their concentration in water depends on pH of water. It is a principal alkaline constituent in almost all water sources, therefore, influences hardness and alkalinity of water. Many types of bicarbonate are soluble in water at standard temperature and pressure, particularly sodium bicarbonate and magnesium bicarbonate; both of these substances contribute to total dissolved salts which are a common parameter for assessing water quality. The concentration of carbonates and bicarbonates should be under the limit in water and if the level of carbonates and bicarbonates is increased, it may be harmful for humans, animals and plants.

### 7.2.11 Sodium Adsorption Ratio (SAR)

Sodium adsorption ratio (SAR) is an easily measured property that gives information on the comparative concentrations of sodium, calcium and magnesium. The SAR can be calculated as:

$$SAR = [Na^+] / [\ (Ca^{2\,+} Mg^{2+})/2]^{1/2} \qquad (2)$$

Where [Na+], [$Ca^{2+}$], and [$Mg^{2+}$] are the concentrations in meq/L of sodium, calcium, and magnesium ions.

A high sodium ion in irrigation water affects the hydraulic conductivity (permeability) of soil and creates water infiltration problems. This is because when sodium present in the soil in exchangeable form replaces calcium and magnesium, adsorbed on the soil clays and causes dispersion of soil particles (i.e. if calcium and magnesium are the predominant cations adsorbed on the soil exchange complex, the soil tends to be easily cultivated and has a permeable and granular structure). Due high value of SAR, the soil becomes hard and compact when dry and resultantly, reduces the infiltration rates of water and air into the soil affecting its structure. This problem is also related with several factors such as the salinity rate and type of soil. For example, sandy soils may not get damage as easily as other heavier soils when it is irrigated with a high SAR water.

### 7.2.12 Residual Sodium Carbonates (RSC)

It is used to predict the additional sodium hazard associated with $CaCO_3$ precipitation involve calculation of the residual sodium carbonate. RSC is another alternative measure of the sodium content in relation with calcium and magnesium. This can be calculated as:

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{+2}) \quad (3)$$

Where, all concentration is in meq/L.

## 7.3 Water Quality Standards for Drinking Water

Framing of water quality standards means to provide safe drinking water to the citizens. Safe drinking water does not represent any significant risk to health over the life time of consumption, including different sensitivities that may occur between life stages. The World Health Organization (WHO) has provided general guidelines for drinking water, based on scientific research. To overcome this generality, many countries have prepared their own water quality standards according to their economic, technical, social, cultural, and political requirements. The Pakistan Council of Research in Water Resources (PCRWR) has also prepared drinking water quality standards, which are discussed below:

### 7.3.1 WHO Standards

The World Health Organization (WHO) has prepared standards for drinking water. The chemical qualities, other parameters and Disinfectants and Disinfectant By-products are given in Tables 7.1, 7.2 and 7.3, respectively. The values of seventeen parameters are given in Table 7.1, related to define water quality chemically. The excess in the level of theses parameters as described can cause different diseases and is dangerous to human health. Therefore, water quality should be tested against all these parameters prior to use for drinking. The miscellaneous parameters also have their own importance regarding human health.

**Table 7.1** Chemical Qualities (WHO)

| Inorganic | Value (mg/L) | Inorganic | Value (mg/L) | Inorganic | Value (mg/L) |
|---|---|---|---|---|---|
| Antimony | 0.005 | Copper | 2.000 | Chromium | 0.003 |
| Selenium | 0.010 | Nitrate ($NO_3$) | 50.00 | Nitrite ($NO_2$) | 03.00 |
| Cyanide | 0.070 | Arsenic | 0.010 | Nickel | 0.020 |
| Manganese | 0.500 | Fluoride | 1.500 | Mercury | 0.001 |
| Molybdenum | 0.070 | Lead | 0.010 | Barium | 0.700 |
| Cadmium | 0.300 | Chromium | 0.050 | | |

*Source: PCRWR, 2007*

**Table 7.2** Miscellaneous Parameters

| Inorganic | Value | Unit | Inorganic | Value | Unit |
|---|---|---|---|---|---|
| Manganese | 0.1 | mg/L | Synthetic detergents | - | - |
| Sodium | 200 | mg/L | Hardness, pH, DO | - | - |
| Chloride | 250 | mg/L | Taste, Odour. | - | - |
| TDS | 1000 | mg/L | Colour | 15 | TCU |
| Zinc | 3 | mg/L | Turbidity | 5 | NTU |
| Aluminum | 0.2 | mg/L | Dichlorobenzene | 5-50 | mg/L |
| Toluene | 24-170 | mg/L | Sulfate | 250 | mg/L |
| Copper | 1 | mg/L | Ethyl-benzene | 2.4-200 | mg/L |
| Eylenes | 20-1800 | mg/L | Hydrogen Sulfide | 0.05 | mg/L |
| 1,2 dichlorobenzene | 1-10 | mg/L | 1,4 dichlorobenzene | 0.3-30 | mg/L |
| Ammonia | 1.5 | mg/L | Iron | 0.3 | mg/L |

*Source: PCRWR, 2007*

**Table 7.3** Disinfectants and Disinfectant By-products

| Name | Value | Name | Value |
|---|---|---|---|
| 2,4,6, Trichlorophenol | 2-300 | 2,4-dichlorophenol | 0.3-40 |
| 2-chlororphenol | 0.1-10 | Chlorine chlorophenol | 600-1000 |

*Source: PCRWR, 2007*

### 7.3.2 PCRWR Drinking Water Quality Standards

The Pakistan Council of Research in Water Resources (PCRWR) has prepared quality standards for drinking water. The drinking water having chemical qualities and other drinking water qualities are given in Tables 7.4 and7.5, respectively.

**Table 7.4** Drinking Water Chemical Qualities (PCRWR)

| Constituent | Highest desirable level | Maximum permissible level | Unit | Toxic Effects |
|---|---|---|---|---|
| Lead | 0.050 | 0.050 | mg/L | Central nervous system (the brain and the spinal cord) |
| Fluoride | 1.000 | 1.500 | mg/L | mottling of tooth enamel (dental Fluorosis) in children, excessive absorption may cause skeletal fluorosis or crippling bone |
| Mercury | 0.001 | 0.001 | mg/L | Neurological disorder |
| Netrate | 45.00 | 45.00 | mg/L | Childish, Immature, infantile, the presence of methaemoglobin in the blood |

*Source: PCRWR, 2007*

**Table 7.5** Other Drinking Water Qualities (PCRWR)

| Constituent | Unit | Highest desirable level | Maximum permissible level | Undesirable effect |
|---|---|---|---|---|
| pH | mg/L | 7.0-8.5 | 6.5-9.2 | Taste, Corrosion |
| Hardness | mg/L | 200 | 500 | Scale formation or Corrosion |
| Phenolic | mg/L | 0.001 | 0.002 | Taste |
| Chloride | mg/L | 200 | 600 | Taste, Corrosion |
| Magnesium | mg/L | 30 | 150 | Stomach problems |
| Zinc | mg/L | 5 | 15.0 | Taste |
| TDS | mg/L | 500 | 1500 | Taste of salts (Fault), corrosion of instruction |
| Turbidity | NTU | 2.5 | 5 | unattractive, reduction in disinfections process |
| Sulfate ($SO_4$) | mg/L | 200 | 400 | Corrosion, Laxative effect |
| Copper (CU) | mg/L | 0.05 | 1.5 | Taste, Corrosion of pipes and utensils taste |
| Manganese | mg/L | 0.05 | 0.5 | Taste, Discoloration |
| Iron | mg/L | 0.1 | 1.0 | Taste, Discoloration |
| Colour | PCU | 5 | 15 | Un-Aesthetic |

*Source: PCRWR, 2007*

### 7.3.3 Water Quality Standards by Pakistan Standard's Institution (PSI)

The Pakistan Standard's Institution (PSI) has prepared water quality standards for drinking water. The drinking water physical requirements, chemical requirements are given in Tables 7.6 and 7.7, respectively.

**Table 7.6** Physical Requirements

| S. No. | Characteristics | Unit | MAC (mg/L) | MAC (mg/L) |
|---|---|---|---|---|
| 1 | pH | - | 7.0-8.5 | $\geq$ 6.5-$\leq$9.2 |
| 2 | Colour | TCU | 5 | 50 |
| 3 | Turbidity | NTU | 5 | 25 |
| 4 | Taste &odour | - | Unobjectionable | |

*Source: PCRWR, 2007*

**Table 7.7** Chemical Requirements

| S. No. | Characteristics | Abbreviation | MAC (mg/L) | MAC (mg/L) |
|---|---|---|---|---|
| 1 | Total dissolved | TD | 1000 | 1500 |
| 2 | Magnesium | Mg | 50 | 150 |
| 3 | Chloride | Cl | 200 | 600 |
| 4 | Calcium | Ca | 75 | 200 |
| 5 | Sulfate | $SO_4$ | 2000 | 400 |
| 6 | Copper | Cu | 1.0 | 1.5 |
| 7 | Nitrate | $NO_3$ | - | 45 |
| 8 | Manganese | Mn | 0.1 | 0.5 |
| 9 | Total Hardness | $CaCo_3$ | 20 | 500 |
| 10 | Zinc | Zn | 5.0 | 15.0 |
| 11 | Nitrite | $NO_2$ | Nil | Nil |
| 12 | Iron | Fe | 0.3 | 1.0 |
| 13 | Magnesium | Mg | 500 | 1000 |
| 14 | Fluoride | F | - | 1.5 |
| 15 | Total Ammonia | TA | 0.1 | 0.5 |
| 16 | Phenolic substances | PS | 0.001 | 0.002 |
| 17 | Hydrogen Sulfide | HS | Undetectable odour | |

*Source: PCRWR, 2007*

## 7.4 Irrigation Water Quality Standards

There are mainly two irrigation water sources in semi-arid and arid regions such as canal water and tubewell water pumped from aquifer. Water from these sources contains considerable amount of unnecessary or unwanted substances dissolved in water that may deteriorate soil fertility and crop growth andcrop yield. These unwanted substances have come from natural or manmade (domestic and industrial effluents) sources and its severity depends upon the type of substance and its quantity which resulted in deteriorated water quality. Followings are the main characteristics to assess the quality of irrigation water:

- Electrical Conductivity (EC)
- Residual Sodium Carbonate (RSC)
- Total Dissolved Solids (TDS)
- Sodium Adsorption Ratio (SAR)

There are various water quality standards by different organizations. The US Regional Salinity Laboratory and Food and Agriculture Organization (FAO) have given the quality of irrigation water as shown in Table 7.8. Irrigation water quality standards given by Water and Power Development Authority (WAPDA) are given in Table 7.9. Similarly, the irrigation water quality standards set by Punjab Irrigation Department are represented in Table 7.10.

**Table 7.8** Irrigation Water Quality Standards (US Regional Salinity Laboratory and FAO)

| Water Quality Classification | Salinity Hazard | | SAR (meq/L) | RSC (meq/L) |
|---|---|---|---|---|
| | EC at 25 °C (Micromhos/cm) | TDS (mg/L) | | |
| Excellent | <250 | <160 | Upto 10 | <1.25 |
| Good | 250-750 | 160-500 | 10-18 | 1.25-2.5 |
| Medium | 750-2250 | 500-1500 | 18-26 | >2.5 |
| Bad | 2250-4000 | 1500-2500 | >26 | - |
| Very Bad | >4000 | >2500 | >26 | - |

**Table 7.9** Irrigation Water Quality Standards

| Water quality classification | Salinity Hazard | | SAR | RSC (meq/L) |
|---|---|---|---|---|
| | EC at $25^0$ C (Micromhos/cm) | TDS (mg/L) | | |
| Usable water which can be used directly for irrigation without dilution | Upto 1500 | 1000 | Upto 10 | Upto 2.5 |
| Marginal water useable after dilution with canal water with 1.1 ratio | 1500-2700 | 100-1700 | 10-18 | 2.5-5.0 |
| Hazardous water that is difficult to use without damaging crop or soil | >2700 | >1700 | >18 | >5.0 |

**Table 7.10** Irrigation Water Quality Standards (Punjab Irrigation Department)

| Water quality classification | TDS (mg/L) | SAR | RSE (meq/L) |
|---|---|---|---|
| Useable/safe | 500 | 0-6 | 0-1.25 |
| Marginal | 500-700 | 6-10 | 1.25-2.5 |
| Hazardous | >700 | >10 | >2.5 |

## 7.5 Water Quality in Pakistan

In Pakistan, generally groundwater and canal water are the source of water for drinking and irrigation water supplies. The farmers related to areas of saline groundwater are restricted to use canal water only for irrigation and domestic use. Generally, the canal water is good quality for irrigation but not for drinking purpose, so its routine monitoring is necessary but there is no routine testing of canal water. The disposal of untreated sewage water and industrial wastewater are of the main reasons of deterioration of groundwater and surface water quality (Chilton, 2001). Furthermore, In Pakistan, there is lake of detailed study to investigate biological, chemical and physical characteristics of waters. During flood and high flow seasons the river waters have very high suspended solids. The water quality characteristics of some major rivers in Pakistan (Aziz, 2005) are presented in Table 7.11.

**Table 7.11** Surface Water Quality of selected Rivers of Pakistan

| Parameters | Unit | River | | | | |
|---|---|---|---|---|---|---|
| | | Indus at Kotri | Haro at Khanpur | Soan at Chira | Ravi at Balloki | Chenab at Rakh Branch canal |
| pH | - | 7.1–7.5 | 7.7–8.2 | 7.5–8.0 | 7.4–8.35 | 7.0–8.0 |
| Sulfates | (mg/L) | 6–140 | 16–77 | 5–34 | 27.6–39.3 | 28.6–46 |
| Faecal coliform | (/100mL) | 150–400 | – | – | 1200-15000 | 1050–5000 |
| EC* | (mµmhos/cm) | 257–487 | – | – | 280–430 | 125–286 |
| TDS* | (mg/L) | 154–315 | 156–204 | 116–256 | 98–250 | 149–213 |
| Chlorides | (mg/L) | 6–100 | 7–13 | 7–25 | 20–30 | 30–50 |
| Suspended solids | (mg/L) | 10–2000 | 16–4320 | 11–6130 | 156–605 | 137–340 |
| Magnesium | (mg/L) | 3–29 | 12–23 | 7–28 | 8–22 | 13.5–40 |
| DO* | (mg/L) | 1.5–6.9 | – | – | 6.3–8.2 | 6.8–7.9 |
| Nitrates | (mg/L) | 4.2–10.5 | – | – | 0.53–6.0 | 2.0–3.6 |
| BOD* | (mg/L) | 1.5–5.0 | – | – | 2.3–3.9 | 1.4–2.5 |
| Calcium | (mg/L) | 12–46 | 28–44 | 24–36 | 29–59 | 35–53 |
| COD* | (mg/L) | 7.0–19.0 | – | – | 16–80 | 11.0–30.5 |

**EC = Electrical Conductivity, *TDS = Total dissolved solids, *DO= Dissolved oxygen, BOD= Biochemical oxygen demand, COD= Chemical oxygen demand*

*Source: Aziz, 2005*

Due to constrained canal water supplies, the demand of irrigation and domestic are being fulfilled from groundwater sources in most areas of Pakistan (Chilton, 2001). In Punjab, around 90% of domestic water including drinking purpose is coming from groundwater. Presently, the utilization of groundwater is increasing drastically. On the other hand, about 27% area of Punjab and 73% of Sindh province has hazardous quality, which is not fit for drinking as well as for irrigation use. Groundwater in Pakistan is continuously being contaminated by sewage seepage and industrial effluents disposal to land and heavy application of fertilizers and pesticides. The increase in tubewell installation and over exploitation of groundwater is reason of salt water intrusion into the fresh water areas which ultimately deteriorate groundwater quality. The groundwater has fresh quality near major rivers and saline is away from river. The groundwater quality of major cities of Pakistan is given in Table 7.12.

**Table 7.12** Groundwater Quality in Major Cities of Pakistan

| City | pH - | TDS (mg/L) | Hardness (mg/L) | Chlorides (mg/L) | Iron (mg/L) | Arsenic (μg/L) |
|---|---|---|---|---|---|---|
| Lahore | 7.6–7.8 | 260–290 | 192–196 | 14–95 | 0.2–0.5 | 0–50 |
| Faisalabad | 8.2–8.4 | 220–600 | 74–186 | 21–52 | 0.1–0.4 | 0–10 |
| Peshawar | 7.5–7.8 | 300–342 | 90–120 | 18–50 | 0.5–0.6 | 0–10 |
| D.G. Khan | 7.7–8.0 | 230–240 | 140–152 | 17–20 | 0.2–0.9 | – |
| Multan | 7.5–8.1 | 400–1160 | 170–370 | 40–220 | 0.1 | 0–>50 |
| Islamabad | 7.0–8.3 | 190–589 | 130–400 | 3–25 | 0.03–1.53 | 0–10 |
| Mardan | 7.2–7.4 | 230–320 | 140–170 | 26–30 | 0.2–0.4 | 0–10 |
| Karachi | 7.3–7.6 | 211–467 | – | – | – | 0–10 |
| Kohat | 7.4–7.7 | 500–560 | 280–330 | 46–64 | 0.1–0.2 | – |
| Hyderabad | 7.1–8.2 | 167–1140 | 105–600 | – | 0.03–0.2 | 0–10 |
| D.I. Khan | 7.4–7.5 | 230–300 | 143–160 | 14–30 | 1–8.7 | – |
| Rawalpindi | 7.0–8.3 | 209–1042 | 150–540 | 5–163 | 0.03–0.07 | 0–10 |
| Khushab | 7.4–7.6 | 300–500 | 138–160 | 8–11 | 0.2–0.6 | – |
| Quetta | 7.6–8.6 | 400–950 | 170–480 | 24–121 | 0.2–0.4 | 0–10 |
| Jhelum | 7.4–8.3 | 500–540 | 160–182 | 5–14 | 1.0–1.2 | – |
| R.Y. Khan | 7.3–7.5 | 300–500 | 150–170 | 12–20 | 0.2–0.9 | – |

*Source: Hashmi and Shahab, 1999; Aziz, 2001*

## 7.6 Irrigation Water Quality and Agriculture

Water quality for irrigation depends upon salts type and their dissolved quantity. As the total salt concentration increases in various soils caused the crop developing problems resulting in crop yield reduction. The suitability of water to use for particular purpose is decided on the bases of its long term effect and severity. The soil problems such as salinity, sodicity, alkalinity, toxicity and water infiltration rate are discussed in the following sections:

### 7.6.1 Salinity

When salts start accumulating in upper soil profile (root zone) in excess amount, salinity problems appear. In saline area, crop is unable to extract the required amount of water from soil resulting in crop water stress for a significant period. These salts are soluble in water and mostly transported by water. To get higher crop production, high weightage must be focused on proper availability of water for consumptive use. In areas of high salts the practice of leaching of accumulated salts from the root zone is necessary to reduce the level of salts.

### 7.6.2 Sodicity

The soils containing the large amount of sodium ions are known as sodic soils. In sodic soils the positively charged sodium ions attached with negatively charged clay particles. The soil swells and the clay particles disperse when excess in sodium ions is attached to clay particles. When water is added to the soil has sodium ions, resulted the soil structure to slump and collapse rather than sticking together. Similarly, in sodic soil the surface of the soil becomes hard and impervious layer vulnerable to water-logging also reduce aeration which is necessary for biological activity in soil. All these parameters are the reasons of reduction in crop growth and ultimately the crop production.

### 7.6.3 Alkalinity

The ability of water to neutralize the added acids is known as alkalinity, the most important factor determining root media pH. Over the time, the pH is adversely affected by the water having high alkalinity. Alkalinity can be assessed with the measure level of calcium bicarbonate or calcium carbonate. Undesirably, acid is injecting into the water to neutralize the level of high level of bicarbonate or application of ammonium comprising fertilizers. The crops grown in cool areas have low tolerance against ammonium, so especial attention is required for those crops.

### 7.6.4 Toxicity

As water take nutrients when missed with water and on the same time when crop take water containing ionic constituents the toxicity problems raised. The high concentration of toxic elements can reduce crop growth and resulted in low crop production. The primary ionic constituents are boron, sodium and chloride. It is not necessary that the high concentration cause the damage even small quantity respond the same. The water infiltration and salinity problems can also be due to toxicity. Without transpiration, the plant is unable to live as this is the basic need of plant. In this transpiration process, the dissolved ions in water move and accumulated to the leaves. These ions block the stomata in the leaves and reduce the transpiration process which adversely affects the plant growth. It is also to note that the direct application of adsorbed toxic ions from overhead sprinkler can create toxicity problems. Toxicity from both sodium and chloride or from any one is dangers to sensitive crop such as citrus.

### 7.6.5 Water Infiltration Rate

Infiltration rate or intake rate of water is very necessary process to provide water to root zone from the soil surface and reduce salinity through leaching. The problems related to infiltration arise when infiltration rate is reduced to some extent which is not desirable. Due to less infiltration rate, very less water is available to plants roots or remains on the surface of the soil. Because of this problem, the necessity such as water and nutrients are unavailable to plants. Beyond this scenario, the water infiltration rate in soil also varies widely and is affected by soil structure, soil compaction, available organic matter, water quality and chemical constitutes of soil.

### 7.6.6 Management of Water Quality Problems

Leaching is useful to reduce the soil salinity and its problems. The salinity level in the soil can be determined with water having no salts in it, especially the sodium. The soil of good structure and proper drainage is demanded for efficient leaching. For a soil having salinity, it is needed to determine the amount of salts free water to reclaim it. Some time, in soil, having high salinity level needs various application of fresh water to leach the salts below root zone with proper drainage. In the areas of shallow groundwater level, the leaching is impracticable; in such situation, the artificial drainage is recommended. The artificial drainage has some advantages to remove salinity from soil even with low quality water (Cardon et al., 2014).

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Chapter 8

# Irrigation Pumping Systems

**Kashif Mahmood and Tajammal Hussain***

## Abstract

Pumping systems play important role in providing energy to the fluids in domestic, commercial and agricultural services. In addition, they are extensively utilized in municipal water and waste water services as well as in the industrial services for food processing, chemical, petrochemical, pharmaceutical processing and mechanical industries. The focus in this chapter, however, remains on the use of pumping systems in irrigation and agricultural production. Therefore, emphasis has been given on basic concept of pumping, components of a pump, various types of pumps impellers used for irrigation, need of pumping system in agriculture, pump characteristics, pumping efficiency, affinity laws, pump selection, Trouble shootings and solutions, pump maintenance and pump industry in Pakistan. The readers will therefore be benefitted with basic concepts related to operational characteristics of irrigation pumps, their design, selection, installation and diagnoses with possible remedies.

**Keywords:** Pump, Pump Characteristics, Pump Selection and Installation, Pumping Energy, Pumping Efficiency

## Learning Objectives

- To provide an overview about pumping industry in Pakistan and various types of pumps used for irrigation.

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- To familiarize the reader with basic concept related to operational characteristics of irrigation pumps, their design, selection, installation and diagnoses with possible remedies.
- Use of pumps in tube wells and other installations for industry and domestic purposes.

## 8.1 Introduction

Groundwater has been a source of irrigation water since ancient times. Even after the introduction of canal irrigation in the Indus Basin groundwater has played an important role in supplementing the available water supplies. With the growth of population, the increasing demand for irrigation water to accelerate agricultural production could only be met with the use of groundwater. Controlling water logging in the country has further emphasized the need for pumping groundwater.

Over the time the method of extraction of groundwater has changed from digging wells and manual techniques to mechanized pumping using tubewell technology powered by engine or electric motors. Installation of tubewell in the Indus Basin started primarily in the public in the early 20$^{th}$ century to control the problem of water logging. In 1994 installation of about 1800 tubewells were initiated in Rechna Doab under Rural Tubewell scheme to control water logging (Planning and DDvelopment Division, 1991). At the time of independence, Pakistan had only a few thousand of tube wells mainly in Rechna and Chaj Doabs. About 200 tubewells were installed by Soil Reclamation Board from 1952 to 1960. The Salinity Control and Reclamation Project (SCARP) was the first reclamation project where high capacity deep well turbine pumps were installed. By 1992 almost 40 SCARP'S have been completed. The numbers of public tubewells installed in the country have been estimated to about 15650 (Planning and Development Division, 1991).

A significant growth in the number of tubewells has been observed particularly in private sector. In 1964 about 23,000 tubewells were operating which increased to more than 183,000 by 1981 indicating an increasing of about 9,500 private tubewells per year. About 2, 86,300 private tubewells are estimated to be operating in the country by 1988 (Planning and Development division, 1991). These tube wells include both shallow tubewells (up to 30 m depth) with smaller capacity 14 to 28 lps as well as deeper tubewells (54 to 60 m depth) with capacity ranging from 28 to 140 lps. The shallow tube wells which are mostly privately owned by the farmers are centrifugal pumps and are operated by diesel engines, tractors P.T.O or electric power. About 56 percent of private tubewells are diesel operated while the remaining are electric operated (Ahmad and Choudhry, 1988 and Planning and Development Division, 1991).

According to an estimate from one of the canal commands in the Punjab, out of 36.5 percent of the requirements were met from canal water while 20.6 percent from rainfall and 42.9 percent from groundwater. Therefore, groundwater serves as a major source of irrigation water in sweet water canal commands. Moreover, pumping has been found to be indispensable for profitable agriculture in the Indus Basin (Choudhry, 1987). According to an estimate, the total number of tubewell in Pakistan are more than one million (12, 29,000) in which some are diesel operated (5, 45,000), electricity operated (84000) and tractor operated tubewells are 600000 to meet the water requirement of different crops.

There are mainly two types of irrigation systems for providing water to crops. The gravity flow irrigation system and pressurized irrigation system. In gravity flow irrigation system, water is conveyed to the crops under gravitational forces and no pumping is required. In pressurized irrigation systems, water is conveyed through some external pressure and pumps are an integral part of this system. Tubewell irrigation, lift irrigation systems, sprinkler irrigation system and drip irrigation system are its typical examples.

### 8.1.1 Concept of a Pump

The primary function of a pump is to impart energy to the fluid. The power source is supplied by a separate unit, which may be a motor or an engine. A pump is a device, which converts mechanical energy (in case of engine) or electrical energy (in case of motor) into hydraulic energy (Karassik, 2001).

### 8.1.2 Energy

According to Bernoulli's theorem, the energy at any point of the system relative to datum can be expressed as:

$$H = \frac{V^2}{2g} + \frac{P}{r} + z \qquad (14)$$

Where

H = Total energy or head, m

$\frac{V^2}{2g}$ = velocity head, m

$\frac{P}{r}$ = pressure head, m

z = potential or elevation head, m

$r$= unit weight of liquid being pumped

The energy developed by the pump indicates the work done by the pump on the fluid, which may include the increase in elevation ($h_e$), pressure ($h_p$) or velocity ($h_v$) of the fluid being pumped. Thus, total energy or total head (H) produced by the pump may be given as:

$$H = h_e + h_p + h_v$$

The corresponding examples may include rising of water from ground level to the top of a building, operating sprinklers at a given pressure or converting pressure into a high velocity jet.

## 8.2 Components of a Pump

There are several components of a pump as given in Fig. 8.1 and are explained below:

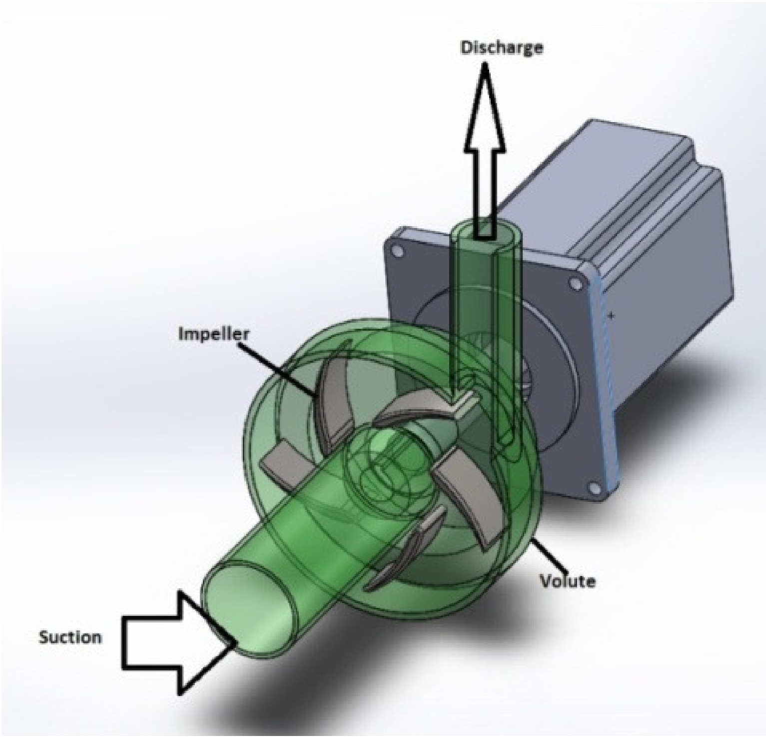



**Fig. 8.1** Components of a Pump

### 8.2.1 Impeller

It is rotating part of pump or turbine that provides centrifugal acceleration to the fluids and is called an impeller. Thus, an impeller is a circular metallic disc with a built-in-passage for the flow of fluid.

An impeller can be further classified as closed, Semi Open and Open impellers.

#### 8.2.1.1 Semi-open Impeller

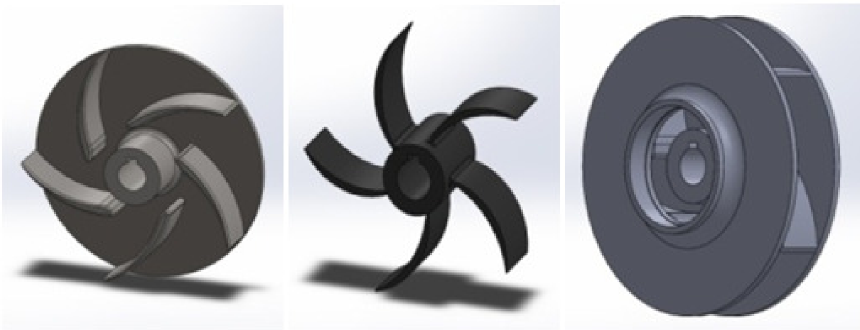
If the vanes of the impeller are enclosed by shrouds only on back side then it is termed as semi-open impeller, as shown in Fig. 8.1. It can work at higher speed. Such impellers must be adjusted so that the clearance between the open side of impeller vanes and bowls or volute face is within a tolerance of 0.1 mm.

#### 8.2.1.2 Open Impeller

If an impeller has no shrouds on its both ends, it is known as open impeller, as shown in Fig. 8.2. The open impeller is less likely to be clogged with solids, but if it does, it is easy to clean it. Therefore, they are suitable to pump liquids carrying organic matter, paper pulp or other dense material such as sewage water.

#### 8.2.1.3 Closed Impeller

If the vanes of the impellor are surrounded by shrouds on both sides then it is called closed impeller, as shown in Fig. 8.2. These impellers can clog if solids or "stringy materials" are pumped. It's difficult to clean out these solids from between the shrouds and vanes. Therefore, these are used to pump clear fluids such as clean water.



Semi-Open Impeller Open Impeller Closed Impellers

**Fig. 8.2** Types of Impeller

## 8.2.2 Shaft

The shaft transfers the torque from motor to the impeller during startup and operation of pump.

## 8.2.3 Eye of Impeller

When the pump operates, water from the source enters the Eye of Impeller. It is located at the end of suction line before the start of wanes of impeller.

## 8.2.4 Stuffing Box

The portion of pump that houses the packing or mechanical seal is called stuffing box. It is usually referred to as dry portion of pump. The stuffing box is in the back of the impeller and around the shaft.

## 8.2.5 Casing

The main function of casing is to enclose the impeller from suction to delivery and therefore, it forms a pressure vessel for the fluid being pumped. The other function includes the provision of support and bearing medium for the shaft and impeller.

There are two types of casings:

(i) Volute casing has impellers that get fitted inside the casings. Its main purpose is to help balancing the hydraulic pressure on the shaft of the pump.
(ii) Circular casing has stationary diffusion vanes surrounding the impeller periphery that converts speed into pressure energy. These casings are mostly used for multi-stage pumps and can be designed as solid casing (one fabricated piece) or split casing (two or more parts together)

## 8.3 Need of Pumping System

A pumping system is required at various places for different purposes such as to:

- Lift water from one elevation to another elevation
- Move water from one point to another point.
- Circulate water around the cooling system.
- Develop pressure to operate sprinklers or Drip Irrigation System.

## 8.4 Pumping System Environment

Pumping Systems are operated to provide municipal water and wastewater services, and industrial services for food processing, chemical, petrochemical, pharmaceutical, and mechanical industries.

## 8.5 Classification of Pumps

The classification of pumps may be based on the following factors:

- Energy imparted to the fluids
- Position of pump
- Number of stages
- Geometry of impeller
- The materials or liquids being handled

### 8.5.1 Method of Imparting Energy to Fluids

#### 8.5.1.1 Positive Displacement Pumps

A pump in which measured quantity of fluid is physically entrapped in a space, its pressure is raised and then it is delivered through the delivery pipe, is called as positive displacement pump. Hand pump is a good example of positive displacement pump. These pumps may be categorized as Reciprocating pumps and Rotary Pumps. Under reciprocating type, the displacement of water takes place by reciprocation of piston plunger. These pumps discharge the same quantity of water independent of head against which they operate. Reciprocating pumps are of 2 types *viz.*, 1) Single Suction Impeller, 2) Double Suction Impeller

An impeller that allows the liquid to enter the center of the vanes from only one direction or if suction takes place with one forward or backward stroke of the piston, it is termed as single suction. An impeller that allows the liquid to enter the center of the vanes from both sides simultaneously or if suction takes place with two forward and two backward strokes of the piston, it is termed as double suction. A double suction impeller is preferred because greater suction area permits the pump to operate with less net absolute suction head. If the displacement of water is by rotary action of gears or lobs, it is called a rotary pump.

#### 8.5.1.2 Centrifugal Pumps

The Centrifugal Pumps utilize Centrifugal force to impart energy to the fluid, which is created through rotation of the impeller, which in turn moves the fluid in radial direction imparting centrifugal force to the fluid. These pumps are mostly used in lift irrigation systems. The prime mover, which may be an engine or an electric motor, provides rotational speed to the impeller. When the impeller rotates the fluid, accelerating it radial direction outward to the surrounding volute casing, creates centrifugal force in the fluid. The Principle of operation of a centrifugal pump may be explained as: The liquid is forced into the eye of the impeller by atmospheric pressure. Then vanes of the impeller pass Kinetic energy to liquid, thereby causing the liquid to rotate. The liquid leaves the impeller at high velocity. The impeller is surrounded by volute casing which converts kinetic energy into pressure energy. Centrifugal pump can be classified as single stage pumps and multistage pumps. Both types of pumps will be explained in section 8.5.3.

#### 8.5.1.3 Jet Pumps

Jet pumps are low capacity pumps, which are seldom used for irrigation purposes. It combines two principle of pumping – that of the centrifugal pump and that of an injector (nozzle and venturi assembly) as shown in Fig. 8.3. Under jet action, some of the water discharged by the impeller passes out of the pump. The rest is re-circulated through the drive line to the injector in the well where the nozzle and venturi create vacuum, which draws water from the lower depth of well, through foot valve. As the water passes through the venture tube into the suction line, the pressure is increased sufficiently to force the water to the pump impeller.

### 8.5.2 Position of Pump

#### 8.5.2.1 Deep Well Turbine Pumps

One impeller rotating inside a bowl and mounted on a vertical or horizontal shaft is called as a stage or a bowl assembly of the turbine. When a number of such bowl assemblies are coupled together on a line shaft such that the lower impeller imparts energy to the fluid and move it upward to the upper impeller that adds to the total head generated by the pump, it is called Multistage Deep Well Turbine Pump as shown in Fig. 8.4.

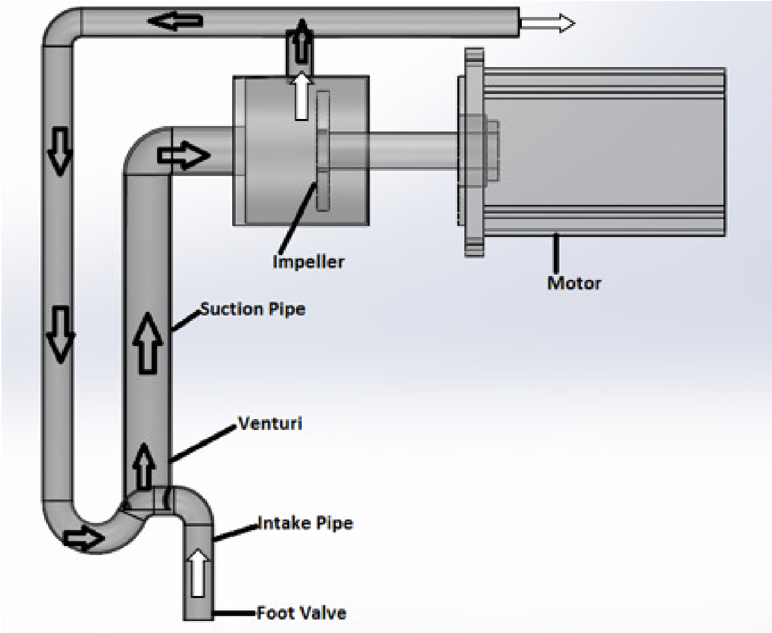



**Fig. 8.3** Working principle of Jet Pump

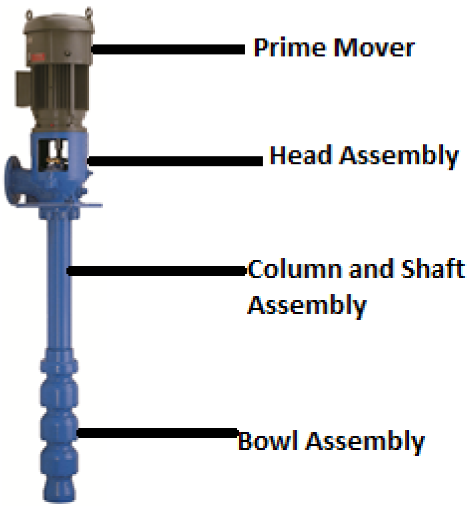



**Fig. 8.4** Schematic Diagram of a Deep Well Turbine Pump

#### 8.5.2.2 Submersible Pumps

A submersible pump is a device which has a sealed motor close-coupled to the pump body. The whole assembly is submerged in the water to be pumped. The main advantage of this type of pump is that it prevents pump cavitations. Submersible pumps are more efficient than jet pumps.

### 8.5.3 Number of Stages of Pumps

As each bowl assembly connected in series to the other bowl assemblies indicates the number of stages of the tubewell, the pumps may be classified as single stage or multistage depending on the number of bowl assemblies as given below. The purpose of increasing the bowl assemblies is to increase total dynamic head developed by the pump.

#### 8.5.3.1 Single Stage Pumps

One impeller rotating inside a bowl and mounted on a vertical or horizontal shaft is called a stage and such type of the pump is termed as single stage pump.

#### 8.5.3.2 Multistage Pumps

When several bowl assemblies are coupled together on a line shaft such that the lower impeller imparts energy to the fluid and moves it upward to the upper impeller, the pump is called multistage pump.

### 8.5.4 Geometry of Impeller

Based on the geometry of the impeller, the pumps may be classified as Axial Flow, Mixed Flow and Radial Flow as detailed below.

#### 8.5.4.1 Axial flow pumps

These pumps push water along the axis perpendicular to the plane of rotation. These are generally used to pump at high flow rates against low heads. Capacities generally range from 40 to 6000 lps and total dynamic head range from 1 to 10 meters. The specific speed remains above 8000.

#### 8.5.4.2 Mixed flow pumps

These pumps accelerate fluids at some angle or move water in a direction between the axial and radial flow pumps. These pumps can handle wide range of flows with capacity ranging from 40 to 6000 lps. In these types of pumps, there is less danger of cavitation.

#### 8.5.4.3 Radial flow pumps

These pumps push water along the axis parallel to the plane of rotation of impeller. These pumps usually develop high head, low discharge and lower efficiency. They exhibit an efficiency of 50 to 80 percent and specific speed of 500 to 3000.

### 8.5.5 Materials or Liquids Being Handled

#### 8.5.5.1 Irrigation Pumps

These pumps are used in semi-arid areas where the canal supply is insufficient to meet water requirements of various crops.

#### 8.5.5.2 Drainage Pumps

These pumps are utilized in humid areas where water table is shallow which affects agriculture in the area.

#### 8.5.5.3 Sewage Pumps

These are used to displace sewerage water from one point to the other point.

## 8.6 Pump Connections

The multiple pump units may be connected in parallel or in series arrangement depending on whether higher capacity at a constant head or higher head at constant capacity respectively, is required for the system under consideration. In planning such installation, a combined system head-capacity curve must be developed to select the right number of pumping units.

### 8.6.1 Pumps in parallel

Two or more pumps are connected in parallel to discharge into a single pipe line where the system requires wide variation in discharge for approximately same head. A group of pumps operating at a pumping station feeding the same supply line are good examples of pump in parallel. In an irrigation system, it is desirable to vary the discharge by putting limited number of pumps in operations to meet varying water requirements during rainy and dry seasons or operating a limited number of sprinklers in an irrigation system. However, to select such multiple pump units, their combined operating characteristics must be developed and compared with the system head curve to determine the range of head, discharge and efficiency in which the pump will operate. The method of developing a combined TDH-Q curve for the pumps A and B connected in parallel can be explained as follows:

$$\text{Combined discharge } Q_{A+B} = Q_A + Q_B \qquad (1)$$

$$\text{Combined Head } H_{A+B} = H_A = H_B \qquad (2)$$

$$\text{Combined Power } BP_{A+B} = BP_A + BP_B \qquad (3)$$

Therefore, combined efficiency for both the pumps would be given as:

$$E_{PARALLEL} = \frac{(Q_A + Q_B) * H_{A+B}}{102\,(BP_A + BP_B)} \qquad (4)$$

Where $Q_A$ and $Q_B$ are in liters per second (lps), H is in meters and $BP_A$ and $BP_B$ are in kilowatts. The combined H, BP and E are calculated and plotted against Q to develop combined characteristics curves for both pumps A and B as shown in Fig. 8.5 If both pumps are not taking water from the same source, different heads may be developed by each pump. The consequence is that the pump producing higher head would tend to suppress the discharge of the pump producing lower head, thus making its operation inefficient or stop it pumping water. Therefore, it is important that the pump should be selected such that they produce same head under given discharge condition.

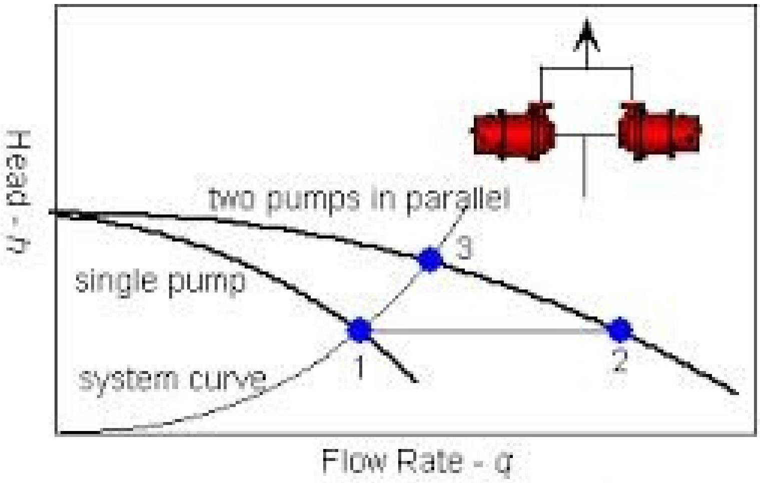



**Fig. 8.5** Pumps in Parallel Combination

## 8.6.2 Pumps in Series

Two or more pumps connected in series may produce different heads but would produce the same discharge as they direct the flow through the same pipe line. However, heads produced by individual pumps would be added up to get the combined head. A good example of pumps in series is the multistage pump or a deep well turbine pump. The centrifugal pumps installed at the boosting stations also considered to be connected in series as the second pump boosts the pressure for use in sprinkler or municipal water supply systems. As shown in Fig. 8.7. The procedure to draw pump characteristics curves for pump A and B is given below:

By selecting several discharge and corresponding head values for both the pumps A and B, the combined discharge, head and power can be calculated using the following equations.

$$Q_{A+B} = Q_A = Q_B \quad (5)$$

$$H_{A+B} = H_A + H_B \quad (6)$$

$$BP_{A+B} = BP_A + BP_B \quad (7)$$

Therefore, combined efficiency for both the pumps would be given as:

$$E_{SERIES} = \frac{Q_{A+B} * (H_A + H_B)}{102\,(BP_A + BP_B)} \quad (8)$$

If all the pumps in series are identical then combined E-Q curve for both pumps would almost be the same as that of pump A or pump B. In case the two pumps are different, the resulting combined E-Q curve would be different than that of each pump as shown in Fig. 8.6.

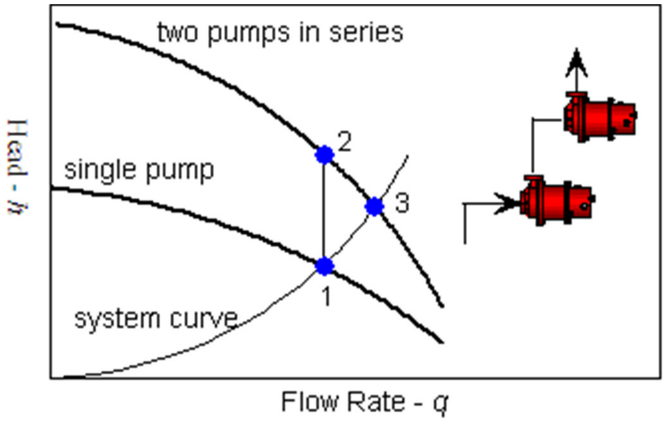



**Fig. 8.6** Pumps in Parallel combination

## 8.7 Affinity Laws

The affinity laws describe the impact of changes in speed or impeller diameter on pump flow, head, and HP. They are useful tools in predicting changes in pump performance when speed or impeller diameter is changed. Such applications are important when variable speed drives are employed or impellers are trimmed. The pump manufactures cannot possibly develop characteristic curves for all ranges of diameter and speed; it would therefore be worth developing one's own curves as desired. The governing laws that provide such relations are called affinity laws which are described below.

### 8.7.1 Affinity Law I

The affinity law I states that flow rate/discharge (Q) will change directly when there is a change in speed (N), heads (H) will change as the square of a change in speed (N) and BP will change as the cube of a change in speed (N). As formulae, Affinity Law I is expressed as follows.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{9}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{10}$$

$$\frac{BP_1}{BP_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{11}$$

Where Q is discharge, N is speed, BP is the Brake horse power and H is the total dynamic head.

The subscript 1 indicates “existing conditions”; the subscript2indicates “new” conditions.

### 8.7.2 Affinity Law II

The Affinity Law II states that flow rate/discharge (Q) will change directly when there is a change in diameter (D), heads (H) will change as the square of a change in diameter (D) and BP will change as the cube of a change in diameter (D). As formulae, Affinity Law II is expressed as follows.

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \tag{11}$$

$$\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2 \tag{12}$$

$$\frac{BP_1}{BP_2} = \left(\frac{D_1}{D_2}\right)^3 \tag{13}$$

Where Q is discharge, N is speed, BP is the Brake horse power and H is the total dynamic head.

The subscript 1 indicates “existing conditions”; the subscriptindicates “new” conditions.

## 8.8 Pumping Energy

The energy that a pump imparts to the liquid during pumping operation is known as pumping energy. The work done by a pump or the amount of energy added into the liquid is the difference of energies between the point where the liquid leaves the pump and the point where the liquid enters the eye of impeller. The energy at any point of the pumping system is measured relative to an arbitrary or selected datum. An incompressible liquid such as water can have energy component in the form of velocity, pressure or elevation. Thus, energy can conveniently be expressed as the force or pressure developed per unit weight of the liquid, such as ft-lbs/s.

## 8.9 Irrigation System Head Requirement

The total system head requirements relate to the total energy or head that must be developed by a pump to overcome static lift, static discharge, good drawdown, operating pressure at discharge point and friction losses through the pumping system. These friction losses include all the losses taking place through pumping system components including well piping, valves, fittings, nozzles, weirs, meters, suction pipe, sprinkler units and pump itself. The total system head is, therefore, site specific and a pump with a given characteristics must be chosen to meet the head-capacity requirements of the system in which the pump must operate.

## 8.9.1 Static Head ($H_{stat}$)

It is the summation of the static discharge ($h_d$) and the static suction heads ($h_s$) or it is different in height between source and destination of the pumped liquid. It is independent of flow rate.

$$H_{stat} = h_s + h_d \quad (15)$$

### 8.9.1.1 Static Suction Lift ($h_s$):

It is the difference in elevation between the static liquid level and the centerline of the pump impeller when pump is not operating. If the pump is located at an elevation below the water surface, the static lift is negative and therefore is sometimes referred as a static head. In case the pump is located right at the water surface the suction lift is zero.

### 8.9.1.2 Static Discharge Head ($h_d$)

It is the difference in elevation between the centerline of the pump impeller and ultimate discharge point. In case the pump discharges directly into atmosphere at the same elevation as the delivery pipe of the pump, the static discharge head is considered zero. It is also independent of flow rate.

### 8.9.1.3 Drawdown

When a pump is installed in an aquifer, a cone of depression in water table develops as the pump operates. The maximum elevation between the static water table and the cone of depression at the well is called well drawdown. The well drawdown depends upon the discharge, aquifer characteristics, well radius and pumping period.

### 8.9.1.4 Operating Head

If the pump discharges into an open channel, the operating head may be considered zero. However, to operate the sprinklers, certain operating pressure is required at the discharge point which is called as operating head. This operating head may be converted into velocity head when sprinklers discharge into atmosphere. The operating head is required to attain the proper drop size and effective coverage of area.

### 8.9.1.5 Friction Losses

When water moves through the pipe system, loss of head due to friction takes place through suction pipe, pump components, pipes, flanges, elbows, joints and drippers. This head loss can be calculated using Darcy-Weisbach equation or William Hazen formula. Estimates of losses through various components of the system can be obtained from the manufacturers specifications as well.

### 8.9.1.6 Pump Size

The size of a pump depends upon the design discharge and head against which it must work. The total head ($H_t$) consists of the following

(a) Elevation Head (Vertical distance from the center line of the pump to the highest field)

(b) Friction losses
(c) Pump suction lift
(d) Minor losses A Fig. of 10% to 15% of (b) above is normally used
(e) Factor of safety

$H_t$ = Suction + Static Lift+Pressure Head+Friction Losses+Factor of Safety

With Q and total head ($H_t$) known, the inspection of pump characteristics curves will indicate the size of pump to be selected.

## 8.10 Pump Characteristic Curves

The pump characteristics relate to operating characteristics of an individual pump independent of the pumping system requirement. These characteristics are built in the design of a pump by manufacturer to meet the given system requirements. These characteristics include the following relationships as shown in Fig.8.7 and 8.8.

- ✓ Total Dynamic Head Vs Discharge Rate (TDH-Q) Curve
- ✓ Break Power Vs Discharge (BP-Q) curve
- ✓ PumpEfficiency Vs Discharge (E-Q) curve
- ✓ Net positive suction head Vs discharge (NPSHR-Q) curve

When a pump is to be purchased, the manufacturers rating of pump characteristics should be consulted to select a pump which should be able to deliver the desired flow rate under given system head. After the most suitable type, the pump has been determined from the available information as described above; a specific pump is selected mating pump characteristics with system head curve. Some manufacturers use tabulated information while others give curves to show relationship between operational variables and the range of their performance.

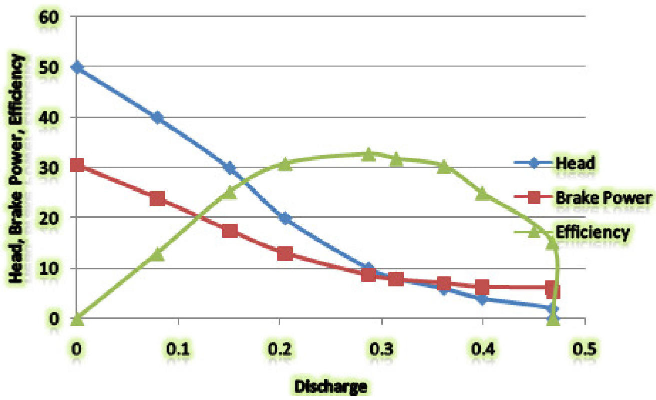



**Fig. 8.7** Pump Characteristics Curves for Turbine Pump

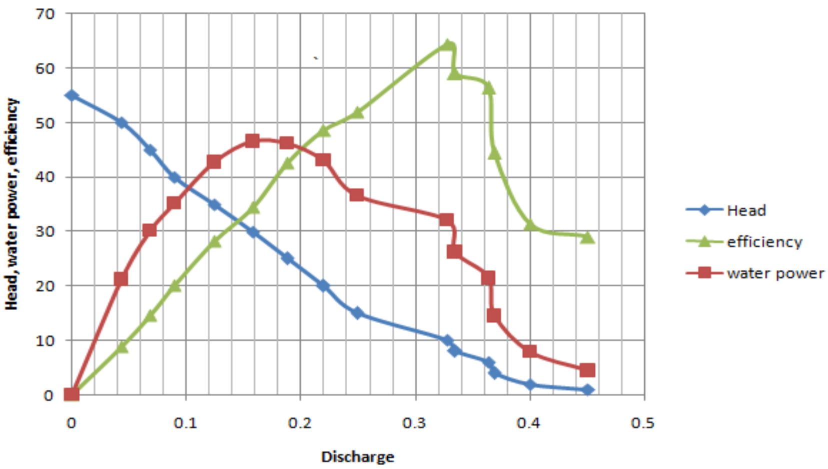



**Fig. 8.8** Pump Characteristics Curves for Gear Pump

### 8.10.1 TDH-Q Curve

This is a curve that relates the head to the discharge of the pump. It shows that the same pump can provide different combinations of discharge and head. It is also noticeable that as the head increases the discharge decreases and vice versa. The point at which the discharge is zero and the head at maximum is called shut off head. This happens when a pump is operating with a closed valve outlet. As this may happen in the practice, knowledge of the shut off head (or pressure) of a particular pump would allow the engineer to provide for a pipe that can sustain the pressure at shut off point if necessary.

### 8.10.2 E-Q Curve

This curve relates the pump efficiency to the discharge. The materials used for the construction and the finish of the impellers, the finish of the casting and the number and the type of bearings used affect the efficiency. As a rule larger pumps have higher efficiencies.

Efficiency is defined as the output work over the input work.

$$E_P = \frac{\text{Output}}{\text{Input}} = \frac{\text{WP}}{\text{BP}} = \frac{\text{Q}*\text{TDH}}{\text{C}*\text{BP}} \qquad (16)$$

$E_P$= Efficiency of pump

BP =Brake power (kW or hp = 1.34 kW), energy imparted by the prime mover to the pump

WP = Water power (kW), energy imparted by the pump to the water

Q = Discharge (l/s or $m^3$/hr)

TDH = Total Dynamic Head (m)

C = Coefficient to convert work into energy units equals - 102 if Q is measured in l/s or 360 and is 360 if Q is measured in $m^3$/hr

Efficiency of motor is the ratio of brake horsepower and input horse power and given mathematically below:

$$E_m = \frac{\text{Output}}{\text{Input}} = \frac{\text{BP}}{\text{IHP}} * 100 \quad (17)$$

$E_m$ = Efficiency of motor

IHP = Input Horsepower measured by voltage and ampere taken the motor.

Efficiency of pumping plant is the ratio of water horsepower and input horsepower and is given by:

$$E_{Pp} = \frac{\text{Output}}{\text{Input}} = \frac{\text{WHP}}{\text{IHP}} * 100 \quad (18)$$

### 8.10.3 BP-Q Curve

The brake power is the output power of the prime mover or the input power to the pump. With increasing discharge, the brake power increases in the beginning and then falls off to some extent at higher discharge. Even at shut off head (zero discharge) same input energy is needed. In some pumps, the brake power will be higher at lowest discharge.

### 8.10.4 NPSHR-Q Curve

At sea level, atmospheric pressure is 100 kPa or 10.33 m of water. This means that if a pipe was to be installed vertically in a water source at sea level and a perfect vacuum created, the water would rise vertically in the pipe to a distance of 10.33 m. Since atmospheric pressure decreases with elevation, water would rise less than 10.33 m at higher altitudes. A suction pipe acts in the manner of the pipe mentioned above and the pump creates the vacuum that causes water to rise in the suction pipe. Of the atmospheric pressure at water level, some is lost in the vertical distance to the eye of the impeller, some to frictional losses in the suction pipe and some to the velocity head. The total energy that is left at the eye of the impeller is termed the Net Positive Suction Head.

The amount of pressure (absolute) or energy required to move the water into the eye of the impeller is called the Net Positive Suction Head Requirement (NPSHR). It is a characteristic of the pump and a function of the pump speed, the shape and the discharge of the impeller. Manufacturers establish the NPSHR-Q curves for the different models after testing. If the energy available at the intake side is not sufficient to move the water to the eye of the impeller, the water will vaporize and the pumps will cavitate. To avoid cavitations, the NPSHA should be higher than the NPSHR required by the pump under consideration.

## 8.11 Pump Selection

Pump characteristics curves can be used as a basis for selecting the pump to provide the required head and capacity for the range of operational conditions at or near maximum efficiency. It is not always possible to select a pump, which meets the required head- capacity needs at high efficiency because there is only one capacity and one head conditions for every pump where high efficiency is obtained. It is also not possible for pump manufacturers to design as many pumps as many operating conditions. They usually design series of pumps covering a range of heads, capacities and efficiencies.

For selection of a specific pump design, the TDH-Q curve should be superimposed on system head curve which determines the head and discharge that can be developed by the pump under consideration. The point where the TDH-Q and system head curves intersect would be the actual operating point (Fig. 8.9).

It is however desirable that the operating point should fall to the right side of the peak efficiency for efficient performance even after sustained operation. At point of intersection of the two curves, the head developed by the pump is equal to the head required by the system at flow rate. If the system demands a different flow rate, a different pump should be tried.

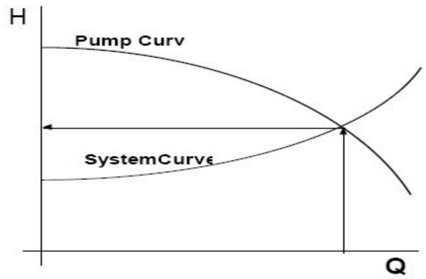



**Fig. 8.9** Selection of Pump by Curves Match

The system head curves are time dependent due to variation in well drawdown, friction, operating conditions, static water level, wear of pumping components and well interface, etc. The pump must be selected to operate efficiently, satisfying the two extremes of low and high system head curves (curves S1 and S2 respectively). If curves A and B are characteristics curves for two different pumps, both pumps produce different ranges of discharge and head for high and low system curves. The pump B with steepest TDH-Q curve will result in least fluctuation in discharge but higher fluctuation in heads. On the other hand, the pump A with relatively flat TDH-Q curve produces higher fluctuation in discharge and least fluctuation in head. The operational requirements (constant head or constant discharge) will however help selecting the right pump design to match the moving system requirements.

# 8.12 Pump Trouble and Solutions

**Table 8.1** Proposed Diagnosis of Trouble Shootings in Pumping Systems

| Observed Troubles | Possible Diagnosis |
|---|---|
| Pump does not deliver water | Pump does not primed |
| | Leakage in suction line |
| | Suction lift too high |
| Insufficient flow rate | Air pockets in suction line |
| | Insufficient priming |
| | Air leaks into pump through stuffing box |
| Loss of pressure | Excessive air in liquid |
| | System head higher than designed head |
| | Speed too low |
| Loss of pressure | Excessive air in liquid |
| | System head higher than designed head |
| | Speed too low |
| Excessive power consumption | Speed too high |
| | Higher specific gravity of liquid |
| | System head lower than pump designed |
| Pump vibrates or noisy | Cavitation occurring |
| | Excessive air in liquid |
| | Food valve partially clogged |
| Pump overheats | Pump not primed |
| | Incorrect Alignment |

# 8.13 Tubewell

A long pipe or tube which is bored or drilled deep into the ground intercepting one or more water bearing stratum. Larger discharge can be obtained by getting a larger velocity and larger cross sectional area.

## 8.13.1 Tubewell Components

Various components of tubewell are given below:

a) Prime movers

A tubewell utilizes diesel engines or electrical motors as power units. A prime mover provides mechanical energy to drive the pump through drive shaft. It is usually placed on the ground surface.

b) Suction Pipe

This is a pipe, which runs from pump to the source of water. It carries groundwater from aquifer to the center line of pump. It consists of two parts.

c) Blind Pipe

The pipe from strainer to eye of impeller is called blind pipe.

d) Strainer

A porous medium used ahead of equipment to filter out harmful solid object from the fluid stream. Important properties of the screen are that it prevents sand and fine material from entering the well during pumping, it has a large percentage of open area to minimize head loss and entrance velocity, supports the wall of the well against collapse, and is resistant to chemical and physical corrosion by the pumped water. The strainer used in Punjab/Pakistan is slotted strainers.

e) Discharge/delivery pipe

This pipe delivers water from the pump to the destination, which may be an overhead tank or a channel. Delivery pipe usually placed above ground to allow free fall of discharging.

f) Check Valve or foot valve:

The function of this valve is to allow the flow in one direction only. This is installed at the food of the pipe to allow entry of water in suction line and prohibit the flow of water back from the pump to aquifer or water body, when pump is stopped.

### 8.13.2 Pump/Tubewell Industry in Pakistan

With the increasing groundwater demand to meet the crop water requirement, several companies have developed, which manufacture different types of pumps in Pakistan. These include KSB, PECO, MECO, Grandfos and Golden Pumps. They produce different sizes of pumps to be used for Irrigation and Drainage purpose. KSB Pump Company is manufacturing a variety of local pumps which include the following:

- ✓ Low pressure Centrifugal Pump
- ✓ Vertical Non Clogging Centrifugal pumps
- ✓ Axial Flow Propeller pumps
- ✓ Multistage High Pressure Centrifugal Pumps
- ✓ Submersible Pumps
- ✓ Deep well turbine Pumps
- ✓ Non Clogging Pumps

## 8.14 Solar Pumping in Pakistan

Pakistan is an energy deficient country, where a large fraction of the population still does not have access to modern day energy services such as electricity. This is due to very limited fossil fuel resources and poor economy, which restrains the import of fossil fuels on a large scale. To overcome energy shortage, Pakistan needs to develop its indigenous energy resources like hydropower, solar and wind. Pakistan lies in an area of one of the highest solar insulation in the world. This vast potential can be exploited to produce electricity, which could be provided to off-grid communities in the northern hilly areas and the southern and western deserts. Applications other than electricity production such as solar water heaters and solar cookers also have vast applications. Solar water pumping also consumes a lot of fossil fuels and electricity.

Solar pumpsare generally designed to operate on DC power produced through solar panels. These pumps are getting popular wherever electricityiseither not available or unreliable. Solar pumps are becoming popular to replace diesel pumps.

### 8.14.1 Advantages

In addition to the environmental advantages of solar power, solar pumps offer the following advantages.

- **Low operating cost:** Since there is no fuel required for the pump like electricity or diesel, the operating cost of solar pumps is minimal.
- **Low maintenance:** A well designedsolarsystemrequireslittlemaintenance except cleaning of the panels once a week and normal maintenance of panels.
- It gives maximum water output when it is most needed i.e. in hot and dry months. Slow solar pumping allows us to utilize low-yield water sources
- The panels need not be right beside the well. Theycanbeanywhereup to 20 meters away from the well, or anywhere you needthewater. So, it offers freedom regarding the placement of panels.
- These pumps can also be turned on and off as per the requirement, provided the period between two operations is more than 30 seconds.

### 8.14.2 Limitation

- Solar pumping is not advisable where water requirement is very high. The maximum capacity available with solar is 2HP. However, the output of the 2HP pump is equivalent to a normal pump of 4HP.
- The water yield of the solar pump is variable and changes according to the sun light.
  It is highest around noon and least in the early morning and evening.
- The submersible pump has an in-built protection against dry run. However, the surface pumps are very sensitive to dry run. A dry run of 15 minutes or more can cause considerable damage to a surface pump.
- As with any other pump, solar pumps work best if the water is clean, devoid of sand or mud. However, if the water is not so clean, it is advisable to clean the well before installation or use a good filter at the end of the immersed pipe.
- The solarpanelscanbe stolen, which may be a problemin remote areas. Therefore, the farmers need to take necessary precautions for security. Ideally, the solar system should be insured against theft as well as natural hazards.

### 8.14.3 Design of Solar Pump

Following are the design steps

- Site Selection and Visit
- Determination of Water table depth
- Water requirements of farmer

- Site location (Latitude/Longitude)
- Shading effect
- Orientation of panels
- Theft protection measures
- Calculation of the Motor HP according to the depth of the W.T.
- Find safe places for Electrical appliances.
- Designed the Possible structure of PV array according to requirements of the site
- Designed the arrays according to the electrical devices.
- Make the connections Of the PV arrays with the electrical devices
- Make use of safety devices

### 8.14.4 Case Study-I

- A solar tubewell was installed at Mari Kot by Energy Alternatives. The following data were collected for installation purpose.
- Depth of water table = 50 ft
- Discharge of tubewell = 0.75 cusec
- Strainer start at 70 ft
- Total bore length = 150 ft
- Total number of pannels = 48 (250 Wp, 24 V)
- Total pannel capacity = 12 kW
- 3 phase Invertor (VFD) of capacity 15 kW
- Safety devices (breaker, fuses and change over)
- Pump type= Centrifugal

### 8.14.5 Case Study-II

- A solar tubewell was installed at Chiniot by Energy Alternatives. The following data were collected for installation purpose.
- Depth of water table = 50 ft
- Discharge of tubewell = 1 cusec
- Strainer start at 70 ft
- Total bore length = 150 ft
- Total number of panels = 80 (20KW, 24 V)
- Total panel capacity = 20 kW
- Number of batteries for back up=40
- 3 phase Invertor (VFD) of capacity 25 kW
- Safety devices (breaker, fuses and change over)

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## Chapter 9

# Land Development and Land Forming

**Muhammad Rafiq Choudhry, Chaudhary Mohammad Ashraff and Lubna Anjum***

## Abstract

Land development refers to working with the waste, undulating or undeveloped land and converting it to a land having smooth topography through draining, dredging, excavating, filling, grading and paving operations etc. by using heavy machinery such as Bulldozers, Scrapers, Graders and Dumpers. Land development process converts a natural or semi-natural land to a land suitable for agricultural production or for housing purposes (J F Ric kman International Rice Research Institute, 2002). It has been estimated that Pakistan's cultivable waste land of 8.2 million hectares can be brought under cultivation through proper land development. The food grain requirements for increasing population demand development of such cultivable waste land for cultivation. The developed land needs further land leveling to facilitate efficient use of costly inputs, especially water and fertilizers. The chapter on "Land Development and Land Forming" has therefore, been designed to summarize the concepts of land development, land forming, land management, sustainable land management and land leveling for the readers involved in agricultural profession. Implementation of these concepts can change the capability of waste land to a productive land. This chapter also includes Land Capability Classification, Land Development Requirements, Development Machinery, Data Collection and Laser Land Leveling procedure. The reader of this chapter may sufficiently update his/her

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knowledge about the concepts, requirement and operational matters related to the land development and land forming to convert barren land into productive agricultural land.

**Keywords**: Land Development, Land Forming, Heavy Machinery, Land Management, Sustainable Land Management, LASER L and Leveling

# Learning Objectives

- To learn about Pakistan's land resources available for agricultural production.
- To understand land classification and land use for irrigated agriculture.
- To equip the reader about technological requirements to develop land and then level it for efficient irrigation.

# 9.1 Introduction

Pakistan covers an area of 79.61 million hectares mainly arid or semi-arid, out of which, 31.0 million hectares are fit for agricultural activities. Out of total area of 21.28 m ha under cultivation, the canal estimated commanded area is about 13.8 m ha. Forest covers 5.3% of the land and about 30% is used for crop production. Out of this, about 7.42 mha are sown more than once in a year. About 5.02 m ha of the cultivable area is fallow primarily because of inadequate supply of water. The rain fed area is estimated as 3.68 mha and the cultivable waste land is extended over 8.2 mha. Table 9.1 shows province-wise land utilization in Pakistan.

**Table 9.1** Province-wise Land Utilization in Pakistan

| S. No. | Particulars | Land Utilization (Million hectares) | | | | |
|---|---|---|---|---|---|---|
| | | Punjab | Sindh | KPK | Balochistan | Pakistan |
| 1 | Geographical area | 20.63 | 14.09 | 10.17 | 34.72 | 79.61 |
| 2 | Total reported area | 17.49 | 14.09 | 8.34 | 17.16 | 57.08 |
| 3 | Forest area | 0.49 | 1.03 | 1.33 | 1.36 | 4.21 |
| 4 | Uncultivated area | 2.95 | 6.77 | 3.90 | 9.83 | 23.45 |
| 5 | Culturable waste | 1.56 | 1.42 | 1.24 | 3.98 | 8.20 |
| 6 | Cultivated area | 12.49 | 4.87 | 1.86 | 1.99 | 21.21 |
| 7 | Current fallow | 1.39 | 2.06 | 0.56 | 0.92 | 4.93 |
| 8 | Net area sown | 11.10 | 2.81 | 1.30 | 1.07 | 16.28 |
| 9 | Area sown > 1 | 5.86 | 1.01 | 0.57 | 0.08 | 7.52 |
| 10 | Total cropped area | 16.96 | 3.82 | 1.87 | 1.15 | 23.80 |

*Source: Agricultural Statistics of Pakistan, 2009*

Agriculture is an economic activity, mainly dependent on natural resources that can be modified to a certain extent through land development and land forming. These natural resources determine the patterns of land use and serve as the basis of agricultural productivity. Out of the categories of culturable waste not available for cultivation, a good part of the area needs land development and land forming before it can be cultivated for crop production. The area comprising rough and undulating terran, particularly the cultivable waste land of 8.2 mha, as given above, requires land development and forming operations to smoothen the topography and make it cultivable.

## 9.2 Land Development

Land development refers to altering land surface from a natural or semi-natural state to relatively a smoother topography suitable for agricultural production or housing purposes. Wikipedia (2009) refers Land Development as altering the landscape in any number of ways such as:

- Changing landforms from a natural or semi-natural state for a purpose such as agriculture or housing
- Real estate into lots, typically for building homes
- Developing property or changing its purpose for useful purposes.

Land Development involves draining, dredging, excavating, filling, grading, paving etc. Heavy machinery such as Buldozers, Scrapers, Graders and Dumpers are used in addition to tractors and plows to loosen the soil at higher locations, and transport to lower elevation points to create relatively a plain surface topography. Fig. 9.1 (a and b) are examples of land development where bulldozers, excavators and scrapers are in action to cut and move the soil to create smoother land surface.

(a) (b)

**Fig. 9.1** (a and b) Land Development Using Earth Moving Machinery

Land development is the costliest operation in farming. It involves jungle clearance, soil opening with deep tillage equipment, moving soil from high to low spots, making farm roads, field bunding and leveling etc. These operations require use of self-propelled and heavy equipment such as crawler tractors with heavy duty ploughs and dozers, high horsepower tractors with dozing arid hoeing attachments. Like scrapers, ditchers, chisel ploughs, subsoilers, terracers, levelers etc. The tillage operations, defined as mechanical manipulation of soil, which are performed to achieve the desired seedbed to provide optimum environment or seed germination and plant growth. Seedbed preparation for sowing / planting of different crops is done through primary and secondary tillage operations. Land development combines the concepts of Land Management and Sustainable Land Management as summarized below:

### 9.2.1 Purposes of Land Development

1. Convertion of barren land into cultivable
2. Utilize the waste or fallow land for agricultural production
3. Expand cropped area in accordance with the available water supplies to ensure food security
4. Make the barren land productive for economic, environmental and agricultural development purposes.
5. Clear the land from unwanted trees and vegetation and smoothen the topography of land for developing housing schemes.

### 9.2.2 Factors Influencing Land Development

Soil factors affecting Land Development activities and the resulting productivity in agricultural systems include soil topography, vegetation, slope, texture, structure, permeability, fertility & salinity, soil depth and degree of undulation etc. Soil fertility refers to the ability of soil to supply nutrients essential for plant growth. Fertility is one of the most important factors that determine the magnitude of crop growth. Soils are known to supply 13 essential nutrients to the plants. Agricultural production is impaired under saline/sodic and waterlogged conditions. Yield reduction up to 70% has been recorded in such problematic soils.

### 9.2.3 Land Development Requirements

The following information must be collected for the development of a land. For this purpose, necessary surveys must be carried out.

1. Location
2. Accessibility
3. Drainage
4. Contouring
5. Grading
6. Surveys
7. Environmental Impact Studies
8. Fees
9. Permits
10. Engineering Services
11. Soil Tests
12. Tree removal (Jungle Clearance)
13. Building of Access Road
14. Drilled Wells

### 9.2.4 Land Development Machinery

Land development is the major and most expensive operation in agricultural farming. It involves forest clearance, soil opening with tillage implements, displacing soil from high to low elevations, making roads, field bunds and leveling etc. to make the land useful for the target purpose. The development of land requires heavy duty machines whether self propelled or mounted such as tractors with heavy ploughs, dozers, scrapers, ditchers, chisel ploughs, sub-soilers, terracers, levelers etc.

The tillage can be defined as mechanical manipulation of soil. It is performed to achieve the desired seed bed for optimum conditions for seed germination and plant growth. Primary, secondary and tertiary implements are used for tillage and inter culture operations. After using the heavy machinery for major earth moving operations, preparation of land for agricultural purposes require following operations.

- Loosening of soil
- Clod size reduction
- Clod sorting
- Smoothening
- Compaction and consolidation may be required for preparing land for construction and housing schemes. The machines that can be used to conduct the above given land preparation operations leading to development and land leveling include the following:

#### 9.2.4.1 Backhoe and Dozer

These are attachments of a tractor. The backhoe (Fig. 9.2a) is mounted in front and dozer (Fig. 9.2b) in the rear of tractor. Both can easily be removed or joined to the tractor. Backhoe is used for excavating soil, making foundations, making trenches for different purposes and removal of bushes and trees. Dozer is used for agricultural land leveling, making bunds in the farms and terracing of farm, road making and site clearance etc.


**Fig. 9.2a Backhoe**

**Fig. 9.2b Dozer**

### 9.2.4.2 Loader

Loader (Fig. 9.3) is used for removal of mud and loose soil, for loading stones, for handling of clay and soil and loading it into truck and trailers. It is commonly used to move a stockpiled material from ground level and deposit it into dump truck for transporting elsewhere. The loader assembly may be a removable attachment or permanently mounted.

### 9.2.4.3 Tractor Mounted Terracer Blade

It is attached toa tractor with the three points hitch system and is hydraulically controlled. The terrace blade is used for grading, leveling of fields, filling of depressions and smoothening of field for irrigation.

### 9.2.4.4 Hydraulic Scraper

The hydraulic scraper is towed behind the tractor as shown in Fig. 9.4. It is used for collecting the soil from one place and unloading at the other. It is used for rough leveling, cutting of high spots and filling of depressions.

### 9.2.4.5 Sheep Foot Roller

The sheep foot roller (Fig. 9.5) is a self propelled heavy machinery which is used to compact soils. The projecting studs on the drum are like a sheep foot, which provide a kneading and high pressure compacting action. These machines are more effective for compacting plastic soils like clay or silt as compared to the granular materials. Sheep foot rollers are available in variety of sizes depending on the nature of the soils. At low moisture contents the resulting compaction is better than other types of compaction machinery. In wet conditions, these are used infrequently. The high contact pressures compact the soil directly beneath the foot tip.


**Fig. 9.3** Loader

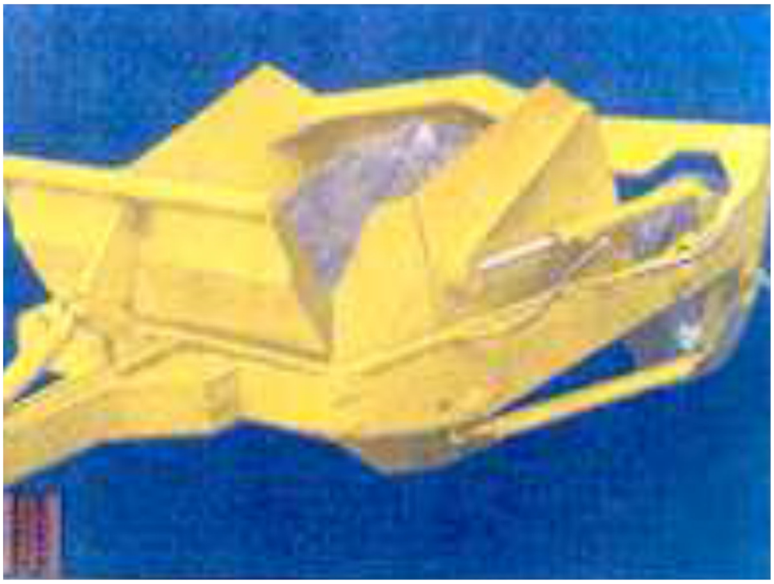

**Fig. 9.4** Hydraulic Scraper


**Fig. 9.5** Sheepfoot Roller

**Fig. 9.6** Ditcher

### 9.2.4.6 Ditcher

It consists of two curved wings with cutting blades, front cutting point, tie bars for adjusting wingspan and hitch assembly with 3- point linkage as shown in Fig. 9.6. It is used for making ditches for irrigation and drainage.

## 9.3 Land Management

It is a broader term indicating the process of managing the use and development of land resources. Land resources are used for a variety of purposes which may include irrigated agriculture, reforestation, water resource management and eco-tourism projects. The United Nations Economic Commission for Europe (UNECE) defines SLM by including the mineral extraction sector, property and estate management in addition to agriculture and forestry as:

"Land management is the process by which the resources of land are put to good effect. It covers all activities concerned with the management of land as a resource both from an environmental and economic perspective. It can include farming, mineral extraction, property and estate management, and the physical planning of towns and the countryside".

Use of land management is a process of managing use and development of land, in which spatial sector-oriented and temporary aspects of urban policy are coordinated. Resources of land are used for different purposes, which may produce conflicts and competitions, and land use management must see those purposes in an integrated way. Land management, therefore, combines the norms and visions driving the policy-making, sector-based planning both in the strategic and more operative time spans, spatial integration of sectoral issues, decision-making, budgeting, implementation of plans and decisions and the monitoring of results and evaluation of impacts.

## 9.4 Sustainable Land Management (SLM)

Sustainable land management is defined as a knowledge-based procedure that aims at integrating the management of land, water, biodiversity, and other environmental resources to meet human needs while sustaining ecosystem services and livelihoods. The term sustainable land management is used, for example, in regional planning and soil or environmental protection but also in property and estate management. It is necessary to meet the requirements of a growing population. Improper land management leads to land degradation and a reduction in the productive and service (biodiversity niches, hydrology, carbon sequestration) functions of watersheds and landscapes. In fact, SLM involves the following activities and procedures:

- Preserving and enhancing the productive capabilities of land in cropped and grazed areas—that includes upland areas, down slope areas, and flat and bottom lands, productive forest areas and potentially commercial and noncommercial forest reserves, and maintaining the integrity of watersheds for water supply and hydropower generation needs and water conservation zones and the capability of aquifers to serve farm and other productive activities.
- Actions to stop and reverse degradation of land or at least to mitigate the adverse effects of earlier misuse, which is increasingly important in the uplands and watersheds, especially those where the destructive

consequences of upland degradation are being felt in far more densely populated areas.

## 9.5 Improved Land Management Practices at Watershed Level

The following practices are known to facilitate upstream-downstream land and water management at watershed leveling terms of costs and benefits:

- All parties in the watershed are given a stake in the management program and in watershed development functions as an equity-enhancing mechanism.
- Because water is often the most valuable resource of watershed management, it is, therefore, essential to develop mechanisms that allow an equitable sharing of the water. This resource sharing can substitute for direct payments to some stakeholders.
- Where common property is involved, especially in the upper catchments, it is essential that local communities collectively protect the common land so that land and water resources are not compromised by illegal deforestation or overgrazing and subsequent land degradation.
- If irrigation water is used to produce greater vegetation biomass on common lands, biomass-sharing agreements are needed, especially for landless stakeholders.
- If water harvesting results in improved recharge of groundwater aquifers, designating groundwater as a common property resource can provide all stakeholders with a powerful incentive to improve natural resources management practices and to promote collective action.
- Following contributing factors have played key role in making land and water resource management programs a successful.
- Local community participation in all aspects of the program.
- Public support for private investment in soil and water conservation.
- Improvement and maintenance of roads.
- Sound macroeconomic management that does not discriminate against agriculture and natural resources.
- Robust local capacity building by nongovernmental organizations and other cooperative-type projects.
- Consistent efforts over at least a decade by concerned governments to increase not only land productivity but also awareness of environmental problems and possible solutions at local levels.

## 9.6 Sustainable Agriculture

Sustainable agriculture is the act of farming using principles of ecology, it is the study of relationships between organisms and their environment. The phrase was reportedly coined by Australian agricultural scientist Gordon McClymont. It has been defined as "an integrated system of plant and animal production practices having a site-specific application that will last over the long term" For Example:

- To satisfy human food and fiber needs
- To enhance environmental quality and the natural resource based upon which the agricultural economy depends
- To make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls
- To sustain the economic viability of farm operations
- To enhance the quality of life for farmers and society as a whole

## 9.7 Land Capability Classification

Various lands may be classified into different capability classes based on their suitability for cropping, grazing, forestry and other useful purposes. Land capability class is determined by the degree of limitation imposed by the land on agriculture (Kenk et al., 1983). Accordingly, eight classes have been established as summarized below:

- *Class I*, is considered very good agricultural land having no limitations for general arable use. This category comprises of loam and silt loam irrigated soils. It is well suited for a wide range of crops. These soils are nearly level, deep and well drained. They show the highest response to good management including the application of fertilizers. They are used for general cropping, vegetables and orchards.
- *Class II* comprises good agricultural land, which imposes minor limitations for general agricultural use. Their soil texture is 75% clay loam to clay and 25% sandy. Soils in this class permit either limited range of suitable crops or this management cost is somewhat high. Generally, the net return from these soils is about 25% less than that from Class 1 soils.
- *Class III* is a moderate agricultural land and puts moderate degree of limitations for agricultural use. Soils in this category may be saline with minor problem of sodicity. Soils in this class permit a limited range of suitable crops and the net return is generally about 50% of less than that of Class 1.
- *Class IV* falls in relatively poor or marginal agricultural land category having severe limitations for agricultural use. Soils in this class have severe limitations because a shallow soil depth or strong salinity and sodicity combined with slow permeability. The net return from this land is generally negligible.
- *Class V* is good forest or range land, which has minor or no limitations for forestry or range land development. The soils are nearly level, deep but stony, and in some places, somewhat imperfectly drained.
- *Class VI* is moderate forest rangeland having a moderate degree of limitation for forestry or range development. Fifty percent of the lands area

have unfavorable relief and the other half to may have sand, gravely or stony soils.

- *Class VII* soil is considered poor forest or rangeland having severe limitations for forestry or range development. Half mountainous and sandy desert and other half, problem of erosion.
- *Class VIII* soils are agriculturally unproductive or non-agricultural lands, which have no potential for any type of agriculture, including forestry and range. This class comprises sand dunes, strong saline/ sodic soils with severe erosion. These are usually forest or grazing lands because of very severe limitations posed by soil erosion, excessive wetness shifting sand or skeletal soils, severe salinity/ sodicity and lack of porosity.

The land classification also ranks soils according to their capacity to respond to improved management. Soils placed in class I are generally responsive to high inputs of water, improved seed, fertilizers, labour, etc. and also to improved management techniques, while the lower classes have correspondingly decreasing response to inputs and management. Consequently, each land class or subclass has a specific set of requirements for land use along with management practices, which would ensure optimal utilization as well as for conservation of available resource. The detailed characteristics of each of the capability classification along with their extent is Pakistan has been given in Table 9.1.

## 9.8 Land Forming /Land Leveling

The present water shortage in the country demands efficient utilization of this scarce resource for its most efficient utilization. About 20 to 25% of irrigation water is lost during its application to the crops because of uneven fields and inappropriate farm designing. This leads to excessive application to low-lying areas and under-irrigation of higher spots. Over-irrigation leaches soluble nutrients out of the crop root zone and on the other hand, under-irrigation of elevated parts of the fields results yield loss due to insufficient moisture availability besides negative impact of accumulation of salts in such patches. This ultimately results in less crop productivity, degrades groundwater quality, causes water stress, and restricts efficient application of agricultural inputs.

Moreover, traditional farm layouts consist of several ditches traversing over two kilometers in an area of one “square” (25 acres) serving numerous small flood basins called “Khal Kiari System”. The fields being not properly leveled, cause excessive wastage of land, water, and other agricultural inputs (fertilizers, pesticides etc.), which result in lower crop yields. Water Management Wing of Agriculture Department has developed a cost effective and sustainable solution in the form of LASER land leveling to address all these problems. The technology is well adopted by the farmers resulting in significant amount of water savings and enhancing crop productivity (Federal Water Management Cell, 1996).

**Fig. 9.7** Laser Land Leveling


**Fig. 9.8** Tractor Mounted Laser Leveler

# 9.9 Laser Land Leveling

Precision Land Leveling is the process of loosening the soil and moving it to achieve a surface with precision of maximum ± 2cm difference between high and low spots of the field. Heavy machinery with laser attachment (Fig. 9.7) or tractor mounted Laser set (Fig. 9.8) can be used to carry out Laser land leveling. The desired leveling accuracy can be achieved by using traditional leveling equipment such as Engineer's level, staff rod and ranging rods for carrying out survey and moving the soil with scraper and land planner. Complete surveying and leveling process is carried out regarding a Bench Mark (BM).

Laser land leveling involves the use of a laser beam emitted by emitter that provides a laser plane as a reference. The survey is conducted by using a Level Eye Detector (Laser supported Staff rod). For carrying out the earth moving and leveling process, the receiver receives the laser beam, which is transmitted to the scraper through hydraulic system of the tractor. Laser guided scraper automatically cuts the high spots in the field and fills the low spots with soil.

## 9.9.1 Advantages of Laser Land Leveling

The LASER land leveling technology has been proved to be highly beneficial because it saves irrigation water, curtails irrigation time, improves efficiency of agricultural inputs, ascertains uniform seed germination and resultantly enhances crop yields. In general, the benefits of LASER L and Leveling include the following:

- Increases productivity of land and efficiency of water use
- Increases crop yields up to 25 percent
- Improves cropping intensity from 35 to 40 percent
- Raises fertilizer use efficiency by 15 to 35 percent
- Enhances irrigated area up to 40 percent by reducing dikes and ditches
- Reduces production costs by enhancing cultivation efficiency and minimizing labor for irrigation
- Makes effective use of irrigation water and agricultural land
- Saves 50 percent of irrigation water
- Increases efficiency of agricultural machinery and curtails 35 percent of labour
- Improves agricultural incomes

## 9.9.2 Use of Laser Land Leveling System in Pakistan

Use of Laser Technology in the precision land leveling was introduced in the Punjab during 1985 through on farm water management (OFWM) program. It was difficult, costly, and cumbersome to achieve the required degree of precision in leveling unleveled fields by the famous "rope operated bucket" scraper. The use of this scarper is, however, necessary for bulk earth movement to make the LASER leveling operation cost effective.

## 9.9.3 Components of LASER Leveling System


**Fig. 9.9** Components of LASER Leveling Equipment

*Source: Directorate General Agriculture (Water Management) Punjab, Lahore, 2013*

A complete LASER Land Leveling System, showing components and in operation at the field, is shown in Fig. 9.9. It consists of the following components:

1. Laser Transmitter
2. Tri pod
3. Elevating Base
4. Telescopic Grade Rod
5. level Eye detector
6. Receiver
7. Mast
8. Control Box (Fig. 9.10)
9. Hydraulic pumps and Horses
10. Solenoid (Fig. 9.11)
11. Cable No.2 from control box to sole mound value
12. Cable No.3 control box to tractor internal battery
13. Laser Scraper
14. Battery

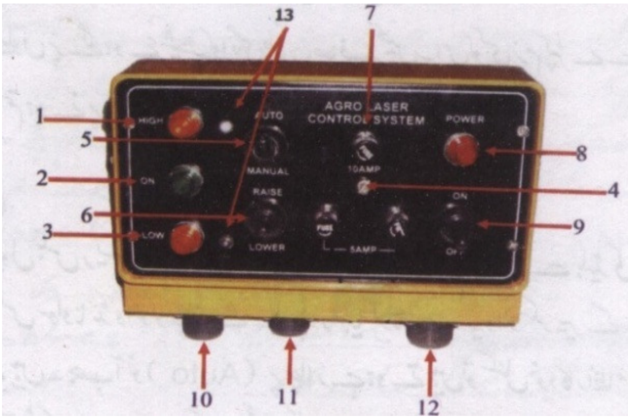


**Fig. 9.10** ControlBox

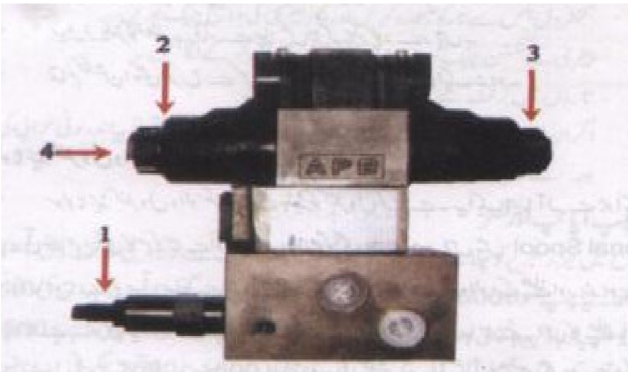


**Fig. 9.11** Solenoid Valve

#### 9.9.3.1 Transmitter

Transmitter is the primary component of LASER Land Leveling System that establishes a reference plan of light above the work area. The beam of light rotates at about 600 revolutions per minute and covers a working radius of more than 300m, depending strength of the transmitter. It is normally mounted on a 3 meters tall tripod. Several scrapers can be guided from one transmitter with the one plane of sight above the field.

#### 9.9.3.2 Receiver

The receiver is an omni-directional device that detects the signals transmitted by the transmitter and conveys to the control box. These signals are processed to indicate the relative position of the receiver to the LASER reference plan in millimeters. It is fitted on scraper and signals are sent via cables to the control panel mounted on the tractor.

#### 9.9.3.3 Control Panel

The control panel is also called as control box, receives and processes signals from the receiver. It displays the same to indicate the relative position of scraper with respect to grade for either manual operation or provide automatic control when interfaced with the tractor's hydraulic system.

#### 9.9.3.4 Scraper

The scraper is bottomless bucket with mechanism for automatic leveling operation. It has a heavy duty cutting edge made for rough and hard conditions. The scraper is attached to the tractor and operates through its hydraulic system. The receiver and solenoid hydraulic valves are mounted on it and receiver is attached to the control box via electric cables whereas valves are connected to hydraulic system through steel or rubber pipes.

## 9.10 Laser Land Leveling Procedure

An engineer should take the following steps to precisely level a given field using Laser Technology (Federal Water Management Cell, 1896).

1. Use Land Capability Classification information before planning any agricultural activity on the land to determine its profitability. Laser leveling is recommended for irrigated land to save water losses.
2. Conduct land development (Jungle clearance, earth moving and smoothening of land surface) before planning for preparing a new land for irrigated agriculture as well as for laser or precision land leveling process.
3. For Laser Land Leveling, visit the field and make a reconnaissance survey to explore lower and higher parts of the field. There should be no bushes, roots of trees, bushes or previous crops, and big clods, which may cause hindrance during leveling. This should be followed by the development of topographic survey map of the field to fully understand locations and degree of cuts and fills. The areas from where soil is to be cut is chisel plowed to loosen the surface for easy movement of earth. All the vegetations and crop residues are also taken out from the field to remove hurdles during leveling operation.
4. It is ensured that tractor, scraper, hydraulic, electrical components etc. are in proper working order before starting the leveling process. The receiver is mounted on the scraper and all connections to the control panel on the tractor as well as hydraulic valves are tightly connected. The LASER transmitter is setup properly to ensure that it is transmitting a horizontal plan of light over the entire operational area. It must be installed at a proper place from where the entire field to be leveled can be covered adequately with laser rays.
5. The transmitter is turned on and the correct field level is established by taking rod reading at the bench mark.
6. Two pieces of timber/brick are firmly set about one meter apart and are dug into the soil so that1 blade of scraper can rest on them in level position. Their top level is set equivalent of the designed field level by taking reading

from the bench mark and scraper is moved over these pieces and its blade is fully lowered onto them. The mast is then moved in upper or lower directions until the "on grade" light is blinked on the control panel. The LASER unit is now ready for the land leveling operation. The tractor is then moved in the field towards cut area. If the receiver is above the LASER beam, the red light at the control panel turns "ON" indicating cut area and scraper starts cutting the soil. The operator moves the tractor towards fill area where yellow light is turned "ON" and blade lifts itself up and starts dropping the collected earth. The tractor is again moved to the high (cut) area and shifts, soil to low (fill) areas. This process is repeated time and again till entire field becomes at one level and the green light turns "ON" all over the area indicating that the field has now leveled.

7. The green light indicates achieving the desired field level. The leveling operation is concluding by moving the scarper across the field to give it final finish.

## 9.11 Status of LASER Land Leveling in Punjab

- The first LASER land leveler was imported and introduced in the Punjab province during 1985.
- Presently, about 80 percent of Laser System components are manufactured locally
- The current price of Laser unit is about Rs. 600,000 or US$ 6,000 (1 US$=Rs.100)
- About 4,000 Laser units, presently working in the private sector, are carrying out precision land leveling of about 1.2 million acres annually in the province of Punjab.
- The Precision Land Leveling followed by Laser land leveling technology has been an important component of water management activities in all the provinces of the country since 1980.
- This activity has created employment opportunities in the Punjab for over 8,000 persons (drivers and mechanics)
- The repair facilities for Laser units are available at almost all the major cities of the province of Punjab.
- Training in Laser Land Leveling has been intensively imparted to the in–service officers of the Water Management wings of the Agriculture Departments at all the provinces of the country by the Training Institutes and Universities (Directorate General Agriculture, 2013).

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# Chapter 10

# Soil-Water-Plant-Atmosphere Relationship

**Lubna Anjum and Muhammad Saffar Mirjat***

**Abstract**

In ordinary circumstances, soil behaves as an inorganic nutrient basin but the soil itself is not essential to plant growth. However, water plays animportantrole for healthy plant growth and development. A healthy plant contains 75-90 percent water. The plants need water to carry out major functions during plant growth, including photosynthesis, transpiration, and transportation of nutrients to different parts of the plant. Continuous water supply is needed to perform these functions. When inorganic nutrients dissolve in the soil water, roots can absorb them. Soil Water Plant Atmosphere Relationship deals with the water movement in the soil, water holding capacity of the soil, water availability and replenishment in the soil and plant characteristics influencing the water movement through the plants under given climatic conditions. Soil water movement and water holding capacity involves pore size distribution of soil particles and their attraction for moisture. The individual pore size is generally larger in sandy soils as compared on to clayey soils, while the porosity of clay soils is greater than that of sandy soils. Variations in potential energy of soil water from one point to another in a soil system causes the water flow within the soil system in the direction of low potential energy. Soil moisture characteristic curve, also known as soil moisture retention curve basically defines the relationship between soil moisture, θ and water potential, ψ; this curve measures the availability of water for plants Value of soil moisture characteristic curve vary for different types of soils. Understanding of these relationships is necessary to assess the crop water

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needs under given soil, water, and climatic conditions. This chapter has been devoted to include basic concepts and soil physical properties and their interaction to water and plants. Understanding of soils types, soil moisture holding capacity, soil water potential, soil moisture characteristics curves and root characteristics in relation to moisture movement in a soil profile, strengthens the basic concepts of the soil-water-plant relationship.

**Keywords:** Soil, Water, Plant, Environment, Water Potential, Moisture Characteristics

## Learning Objectives

- To understand physical properties of soil and their role in irrigation water management
- To learn about the water movement through the soil and plants
- To understand the crop responses to soil, water and environment
- To estimate evapotranspiration and irrigation water requirements

## 10.1 Introduction

Soil acts as a storage pool of water for crop roots. Plants use this water to fulfill its needs through rooting system and in evapotranspiration process. Atmosphere acts as a driving force for water to evaporate from soil surface and transpire through plant leaves. Soil-water-plant-atmosphere relationships involve various physical properties of soil and plants that are responsible for the use of water, its movement and retention for the design and operation of irrigation systems (Fig. 10.1). In planning, designing and managing the irrigation system efficiently, the primary concern is the water intake rate, soil water holding capacity and plant rooting system. The assessment of crop water requirement depends on the characteristics of soil, water and plant as well as the climatic conditions like sun shine hours, temperature, solar radiation, wind, humidity etc.

## 10.2 Soil

Soil is the medium, which supports plant life and mostly provides all the elements such as water and nutrients required by the plants to grow. There are different types of soils depending on their constituents such as percentage of sand, silt and clay. The important physical characteristics of the soil include soil texture, structure, density, porosity, permeability, infiltration, compactionetc. The chemical properties of the soil are known by its reaction i.e. acidic (pH<7), neutral (pH=7) and alkaline (pH>7). The water holding capacity of the soil is also influenced by its type such as sandy, silty, clayey and loamy soils etc. Dominancy of particles determines its class.

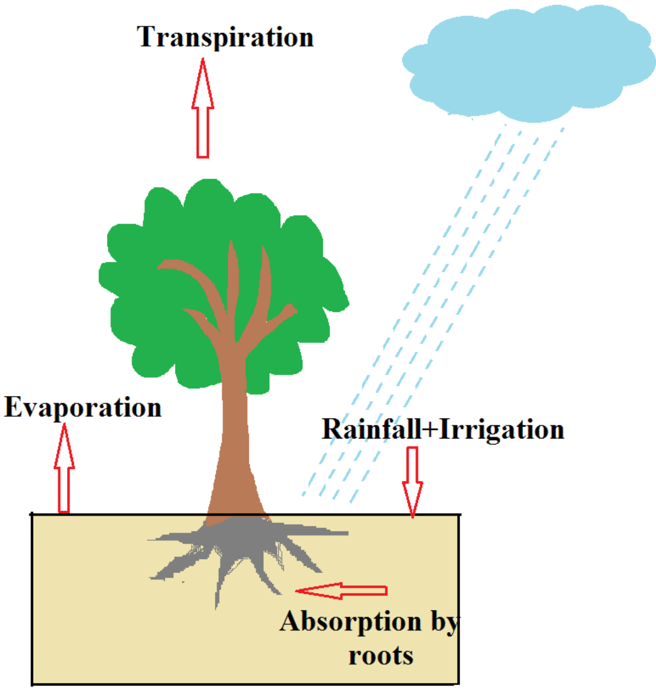


**Fig. 10.1** Soil-Water-Plant-Atmosphere Relationship

If sand particles dominate, the soil is called sand. If clay particles dominate, the soil is called clay. Silty soils have particles between clays and sands. The clayey soil contains 55-80% clay particles and20-45% sand and silt particles; silty soil contains 45-80% silt, 20-55% sand and clay particles; sandysoilscomprises45-80% sand, 20-55% sand and clay particles while loamy soil has equal proportion of sand and silt. If, sand particles dominate soil is sandy loam soil. Similarly, if, silt particles dominate soil is termed as Silty loam. Soil can further be sub classed as clay loam, silt clay, loam, silty clay loam, sandy clay, sandy clay loam, sandy loam, and loamy sand. Size of soil particles and its class has a significant impact on plant growth and crop production. It is particularly important for irrigation farmer, because it determines the depth of water that a soil can store in each soil profile. The Soil Textural Triangle by USDA, describes the detailsonsoil textural classes as per relative proportion of sand, clay and silt particles.

Soil serves as a storage reservoir for plant nutrients and water to meet the crop water requirements and nutrient uptake. However, physical and chemical properties of soil determine how much water a soil can store and further allow for use by plant. This stored water helps in defining the time of irrigation application and amount of water to be applied and ultimately the magnitude of irrigation system required for continuous supply of irrigation water for sustainable agriculture. The physical properties that play role in the soil-water-plant and environment relationship are discussed below.

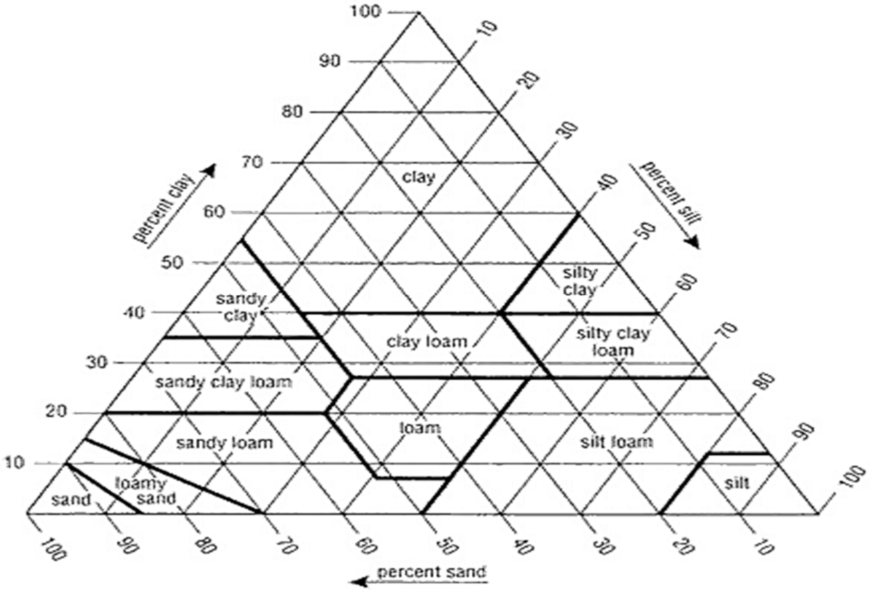


**Fig. 10.2** USDA Soil Textural Triangle

## 10.3 Soil Physical Properties

Soil mainly constitutes inorganic materials (sand, silt and clay particles), organic materials, water, air colloidal materials and accumulation of different substances those form soil layers, called soil profile. The properties of each layer of soil profile influence root penetration, water holding capacity and further movement of water in the soil. The major soil physical characteristics are soil texture, structure and porosity. Soil texture is the relative proportion of sand, silt and clay particles in a specific soil, whereas, soil structure is the arrangement of soil particles within a soil profile (SCS, 1991). Both properties help to determine the porosity of soil, which is the volumetric percent of pore space. Porosity of the soil may in turn be affected by soil compaction. Soil compaction, texture and structure are the main reasons behind changes in soil porosity, root development, irrigation water storage, uptake, transmission and nutrient uptake by the plant. Proper soil aeration is very important for profitable agricultural production.

### 10.3.1 Soil Texture

As described above, soil texture is the relative proportion of various particle sizes in a specific soil i.e. sand, silt and clay. Table 10.1 presents the soil aggregates classification and their range.

**Table 10.1** Particle Size distribution of Soil

| Particle size | Particle diameter (mm) |
|---|---|
| Coarse sand | 1 – 0.5 |
| Medium Sand | 0.5 – 0.25 |
| Fine Sand | 0.25 – 0.1 |
| Very Fine Sand | 0.1 – 0.05 |
| Silt | 0.05 – 0.002 |
| Clay | Less than 0.002 |

*Sources: USDA, 1991*

### 10.3.2 Soil Structure

Soil structure refers as the arrangement of soil particles in each mass of soil. Soil structure plays key role in water and air intake by the soil and influences the water and air movement through the soil profile. Root penetration and nutrient uptake is also affected by specific soil structure. According to USDA, soil structure types refer to the specific type of particle combination that prevails in a soil horizon. For example, single grained and massive soils are less structured. Single-grained soils like loose sand allow the water to percolate very quickly. Similarly, massive soils like clays allow water to move very slowly.

The more promising water relations mostly used in the soils having prismatic, blocky, granular structure and platy structure that impede the downward vertical movement of water. Unlike texture, soil structure can be reformed with the help of tillage machinery up to tillage depth. Soils that contain high organic matter can develop excellent soil structure. Wetting and drying of soils in a rotational manner, improves the soil structure up to tillage depth.

In contrast, tillage operations in medium or fine textured soils with high moisture content, leads to deterioration of soil structure. Irrigation water with large amounts of sodium salts results in undesirable structure formation by dispersing the soil aggregates (SCS, 1991). Various soil structures and their effects on downward movement of water are shown in Fig. 10.3.

### 10.3.3 Porosity

Porosity is a measure of pore spaces in a given soil that commonly varies from 30 to 60 percent of the total soil volume. It is the ratio of volume of pore spaces in a given soil sample to its total volume of soil bulk. Pore spaces in soils are defined by means of an infinite interlinked system of spaces/voids in all directions. The spaces/voids contain gases and liquids and control their movement through a soil profile, and also work as pathways for roots to enter. Porosity of soil can be determined using the following equation:

$$\text{Porosity} = 1 - \left[\frac{\rho_b}{\rho_p}\right]$$

Where,

$\rho_b$ = soil bulk density, g/cm$^3$

$\rho_p$ = soil bulk density, g/cm$^3$

Soil porosity mainly depends on soil texture, root zone activities and amount of gases present in the pore spaces including the activities of insects and other worms in the soil. Inverse relationship exists between particle size and porosity. Generally, porosity decreases with the increase in particle size. Coarse-textured soils are usually less porous as compared to fine textured soils. However, the individual pore size is generally bigger in sandy soils as compared on to clayey soils, while the porosity of clay soils is greater than that of sandy soils. Further, the clay soils have more diverse pore size distribution and have abilities tosh rink and swell during drying and wetting phases/processes.

The bulk density of sandy soils ranges from 1.5 to 1.7 g/cm³ and values of porosity range between 0.36 and 0.43. Similarly, clay soils having bulk density ranging between 1.1 and 1.3 g/ cm³, present porosity values between 0.51 and 0.58. Porosity of subsurface soil is usually lower than that of surface soil due to compaction by gravity.

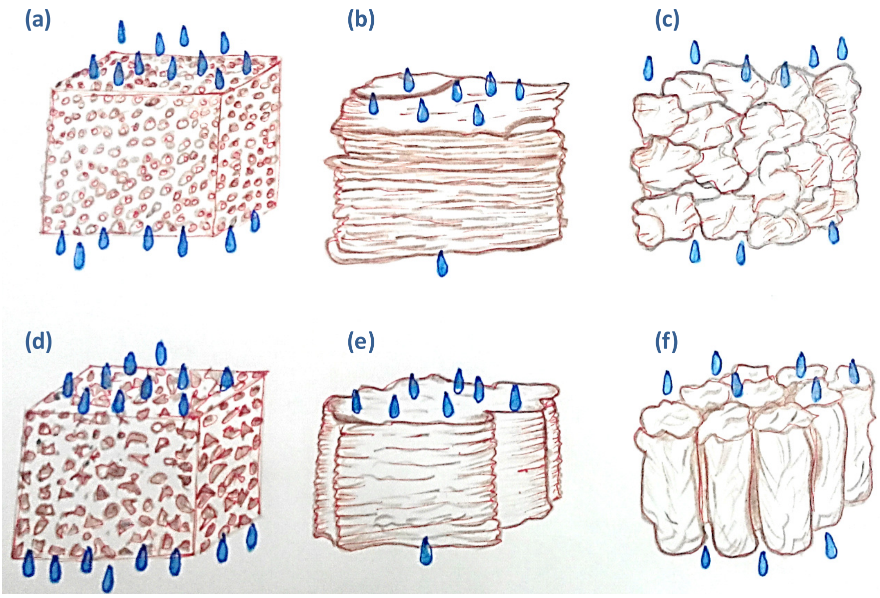


**Fig 10.3** Soil Structure Types and their Effects on Downward Water Movement (a) Sandy soils (rapid water movement), (b) Platy Structures (slow water movement) (c) Blocky structure (moderate water movement), (d) Gravels (rapid water movement), (e) Massive Structures (slow water movement) (f) Prismatic structure (moderate water movement)

### 10.3.4 Soil Bulk Density

Bulk density is defined as mass per unit of total volume of soil (soil particles + pore spaces) and is normally measured using a core sampler of known volume. Soil bulk density mainly depends on the soil texture and the degree of compaction. However, its typical values range between 1.1 and1.6 g/cm$^3$. Mathematically, soil bulk density is expressed as:

$$\rho_b = \frac{M_s}{V_b}$$

$$V_b = \frac{\pi}{4} D^2 L$$

$$\rho_b = \frac{4\ M_s}{3.142\ D^{\,2} L}$$

Where,

$\rho_b$ = soil bulk density, g/cm$^3$

$M_s$ = mass of dry soil, g

$V_b$ = volume of soil sample, cm$^3$

Soil Particle Density ($\rho_p$) is expressed as:

$$\rho_p = \frac{M_s}{V_s}$$

Where,

$\rho_P$ = soil particle density, g/cm$^3$

$M_s$ = mass of dry soil, g

$V_s$ = volume of solids, cm$^3$

Typical values of soil particle density range between 2.6 and 2.7 g/cm$^3$

Bulk density may be further defined in terms of Dry Bulk Density and Wet Bulk Density depending on the moisture content of soil. Dry Bulk Density of soil ranges between 1.0 and 1.6 g/cm$^3$. Soils rich in organic matter may have a bulk density below 1.0 g/cm$^3$. Bulk density determinations are usually done with the help of a metal core samplerofknown total volume ($V_t$) at any desired depth. Core sampler used for measurement of bulk density.

The wet bulk density of a given soil sample is measured by weighing the soil sample in moist condition (*Mt*) and dividing by the total volume (*Vt*). Mathematically, it can be expressed by the equation:

$$\rho_w = \frac{M_t}{V_t}$$

The dry bulk density of a soil sample refers to the density of oven dried soil sample. It is measured by weighing the oven dried mass of soil sample (*Ms*) and dividing by the total volume (*Vt*). Mathematically the dry bulk density is expressed as:

$$\rho_d = \frac{M_s}{V_t}$$

Dry bulk density of a soil sample has inverse relationship to the porosity of the soil. Greater the porosity of a given soil sample, lower will be the bulk density.

### 10.3.5 Soil Compaction

It is a process of applying stress to the soil that triggers densification because air is deported from the soil pores. Generally, compaction is the effect of heavy machinery pressing the soil, the passage of animal feet and consolidation (water deficient stress occurs due to water evaporation that causes internal suction). Compacted soils turn into less absorbent to rainfall, resulting in increased runoff and erosion. Crops also have difficulty to grow due to compression of soil particles causing very little availability of space for water, air and root penetration.

There are several methods to measure compaction of soil. The methods can be categorized as:

1. Static Compaction means to put heavy stress gently to the soil and then release.
2. Impact compaction is the applied stress by dropping a larger mass on the soil surface.
3. Vibrating compaction is a repeatedly and quickly applied stress through a mechanically driven hammer or plate. It is mostly joined with rolling compaction.
4. Rolling compaction is the application of a heavy and large cylinder, rolled over the soil surface. The common example is rolling compactor used over sports pitches. Roller-compactors combined with vibratory devices are used to increase their capacity.

## 10.4 Soil Water or Soil Moisture

The water present in the soil pores of unsaturated zone (micro pores) is termed as soil moisture and in saturated zone (macro pores) is called as soil water (Fig. 10.6). There are many ways to describe the soil water contents. Soil water content or soil moisture content is usually defined as moisture content on weight basis percent (which after multiplication with bulk density is converted into volumetric basis) or equivalent depth of water per unit of soil depth.

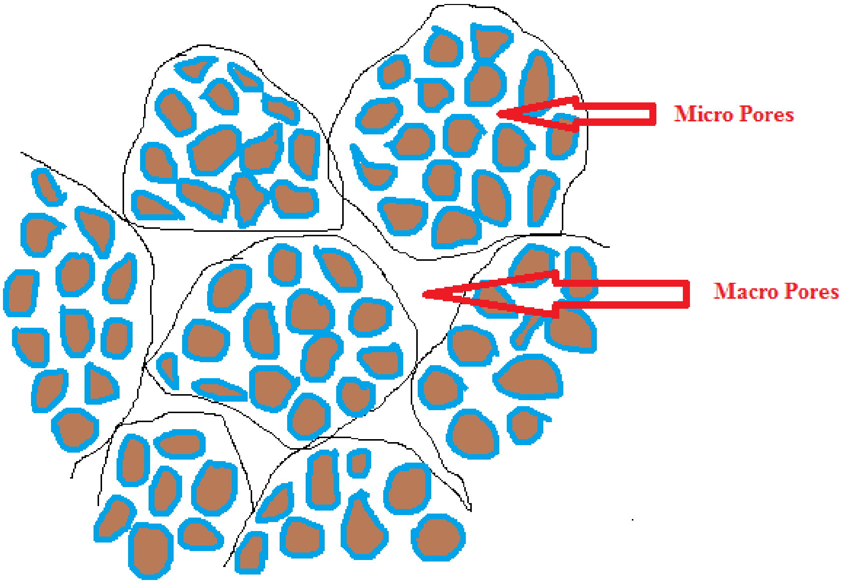


**Fig. 10.6** Soil Macro and Micro Pores

For healthy crop growth, a continuous water supply is needed. An irrigation engineer deals with the water movement in soil, water holding capacity of the soil, water availability to plants and water replenishment in the soil. Soil water movement and water holding capacity involves pore size distribution of soil particles and their attraction for moisture. The amount of water a soil can hold is also influenced by the amount of organic matter present in the soil. Normally, finer the soil particles and larger the amount of organic matter, the more water a soil holds. Soil Water can be further subdivided into three categories as summarized below.

### 10.4.1 Gravitational Water

The soil openings (spaces between particles) develop a system of interlinked spaces of every possible size and shape. When water is applied to soil through irrigation or rain, it is circulated around the soil particles by cohesive and adhesive forces; it removes air from the soil pores and eventually fills up the pore spaces. When all the small, medium and large pores are filled with water, the soil is termed as saturated and is at its highest water holding capacity. The part of soil water that moves downward easily under the effect of gravity is known as gravitational water. This water drains out within 2-3 days out of the soil depending on soil texture. Water drains instantly, out of well-drained soil like sand and is not available for plant use. It can result in shallow rooted plants to droop and ultimately die. The reason is gravitational water holds air spaces to supply oxygen to plant roots.

### 10.4.2 Capillary Moisture

Water available in the micro-pores, in the soil solution, is called as capillary water. When irrigation supply or rain shower to the soil surface is stopped, water depletion starts from the large soil pores and the process continuous for some days. When a well-drained soil is irrigated, free water from the large (macro) pores as well as from soil surfaces drains out due to gravity. Capillary water is held in the soil pores against the gravitational pull exerting on the capillary water. Micro-pores exert more force on water than do macro-pores. Cohesion (attraction between water molecules) and adhesion forces (attraction between water and soil molecule) are responsible for capillary rise. Water in the small (micro) pores shifts due to capillary forces forming capillary fringe. Capillary water movement is slow as compared to downward gravitational water movement; however, it can move in any direction where it finds greater tension. This is the water which is available for plant growth. It is observed that

$$\text{Amount of water held} = f\ (\text{pore size \& pore space})$$

Pore size means cross-sectional diameter of pores.

Pore space means total volume of all pores.

This means that the tension increases as the soil dries out.

### 10.4.3 Hygroscopic Moisture

Water in the soil which is tightly bounded to the soil particles is known as hygroscopic water. It is so tightly held to the soil particles by adhesion forces that plant roots are unable to extract. Soil moisture absorption by plant roots to accomplish different plant needs and evapotranspiration phenomenon causes further water reduction in the root zone to an extent that no more water moves due to capillary action. This water tightly sticks to the soil particles in the form of thin film and cannot be taken up by roots hence it is not available to plants resulting in wilting of leaves and stem. Plants cannot withstand in this situation and eventually will die if irrigation is not applied. Because, this water is not held in the pores but it is tightly held on the particle surface. Which shows clayey soils can retain more hygroscopic water than sandy soils because of surface area differences. However, among all these waters, hygroscopic, capillary and gravitational, irrigation engineers mainly focus on the capillary and gravitational water as hygroscopic water is not available to plants.

## 10.5 Soil Water Potential

Total soil water potential is the amount of work done per unit quantity of pure water to move small quantity of water from a reference point at a defined elevation under atmospheric pressure to the point under consideration. The gradient in potential energy of soil water from one point` to another in a soil system causes the water to flow within the soil system in the direction of lower potential energy. Soil water potential is very important concept regarding crop water needs. Soil water differs spatially and temporally in the soil presenting different potential energies. Soil water potential basically measures the water movement from one point to the other point due to mechanical pressure, gravity, osmosis, and metric impacts like surface tension.

### 10.5.1 Components of Soil Water Potential

Soil water potentials can be categorized into following components:

1. Gravitational potential ($\psi_g$) is the gravity force pull on the water surface
2. Metric potential ($\psi_m$) is force exerted on the water surface by the weight of soil matrix. It is also known as soil water tension.
3. Pressure potential ($\psi_p$) is the force as a result of position of water in the soil
4. Solute potential $\psi_o$) is a result of difference in the salt concentration through a semi permeable membrane like a plant root.

Total potential ($\psi_t$) is sum of gravitational, metric, pressure and solute potential is expressed as:

$$\psi t = \psi g + \psi m + \psi p + \psi o \qquad (10.8)$$

#### 10.5.1.1 Gravitational Potential

Gravitational Potential is mainly dependent on the vertical distance between the point of interest and a reference point, and is independent of soil characteristics.

Gravitational Potential = +ve, if above reference level

= -ve, if below reference level

Gravitational Potential is illustrated in Fig. 10.7c, which shows that there are two points A & B situated at a particular distance from a reference point Z.

Gravitational Potential at point A = 6inches

Gravitational Potential at point B = 4 inches

Difference in gravitational potential between point A & B = 6- (-4) = 10 inches

#### 10.5.1.2 Metric Potential

Metric Potential is a dynamic characteristic of soil and for saturation conditions it is recorded as 0 (zero). The main forces responsible for metric potential are capillary, surface tension and adsorptive forces owing to soil matrix. The forces cause attraction and bound water in the soil resulting in lowering potential energy. Surface tension and soil water contact angle with soil solids develop capillary action. For the reason matrix potential sometimes also termed as capillary potential. Fig 10.11b explains the metric potential, it defines the vertical distance between the points where we want to find potential and the surface of water in a water filled manometer. Ceramic cup is embedded in the soil at the point of interest and is connected to a manometer. Metric potential of the soil water at ceramic cup is the vertical distance

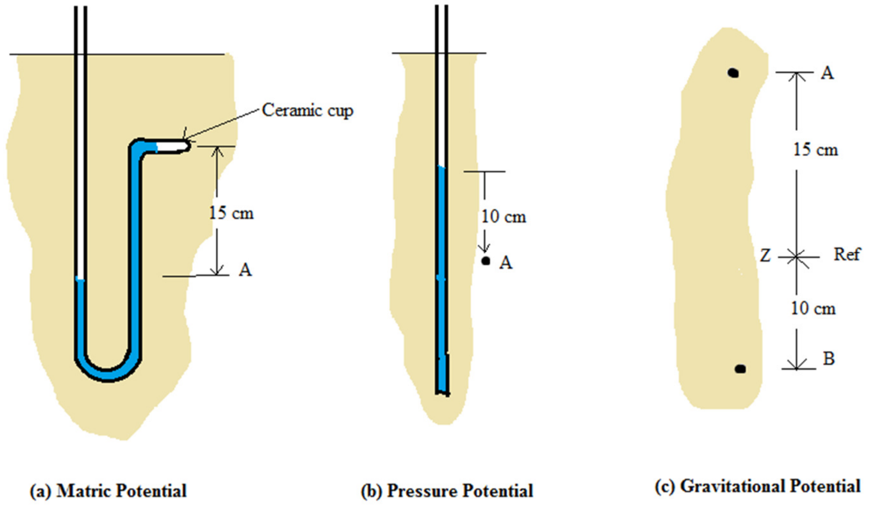


**Fig. 10.7** Types of Soil Water Potential

from the center of the cup to the water level in the manometer which is 6 inch.

#### 10.5.1.3 Pressure Potential

Pressure Potential is mostly applied to saturated soils. Where water is expressed on weight basis, pressure potential is the vertical distance between the water surface and a specified point. In the field, this component is zero above and at the water surface in the piezometer. Below the water level it is always positive. In Fig 10.11c piezometer tube (tube open at both ends) is installed in the soil to a depth below the water table. Pressure potential at point A is the distance between the point and the water level which is 4 inches.

#### 10.5.1.4 Solute Potential

It is also known as osmotic potential. Osmotic/Solute Potential occurs due to soluble salts movement between the soil solution and semipermeable membrane. Two standard membranes in soil-water systems are the cell wall of plant roots and air-water interfaces. Presence of salts may add a considerable osmotic/solute component to the total soil water potential. It is the total potential that decides soil water availability to plants. The solute potential can be approximated from the relation:

$$\text{Solute Potential} = A = R \times T \times C \qquad (10.9)$$

Where,

R = universal gas constant (82 bars $cm^3$/mol°k)

T = absolute temperature (°k)

C = solute concentration (mol/$cm^3$)

Because of the nature of the universal gas constant (R), it is much easier to use SI units in solving for solute potential. With the units illustrated, as values of temperature and solute concentration are placed in the equation, all units cancel except bars. This unit (bar) is now easily converted to another unit as shown in the following discussion. Historically, many units have been used to express tension, suction, potential or stress. A partial list is: bars,

Centimeters (cm) of water,

Centimeters of mercury,

Inches of water,

Atmospheres,

Centibars,

millibars,

Joules per kilogram,

The bar unit is in extensive use; some conversions for this unit are as under:

1 bar = 1020 cm of water

= 75.01 cm of mercury

= 401.5 inches of water

= 0.987 atmospheres

= 100 centibars

= 1000 millibars

= 100 joules/kg

= $10^6$ ergs/g

= $10^6$dynes/cm$^2$

## 10.6 Soil Moisture Characteristic Curves

Soil moisture characteristic curve, also known as soil moisture retention curve basically defines the relationship between soil moisture tension and soil moisture availability to plants. It defines the ability of soils to retain or release water. When continuous suction is applied to the saturated soils, water from the micro-pores start draining at high suctions or tensions except very little water remain in the narrow pores due to metric potential. This pressure or suction also causes reduction in the thickness of layer of water around soil particles. Practically suctions are applied to the saturated soil with suitable equipment. Resultantly a curve is drawn between applied suction and soil moisture content corresponding to a series of applied suctions. This characteristic curve is usually determined for individual soils. Soil moisture characteristic curve for different soil types are shown in Fig. 10.8.

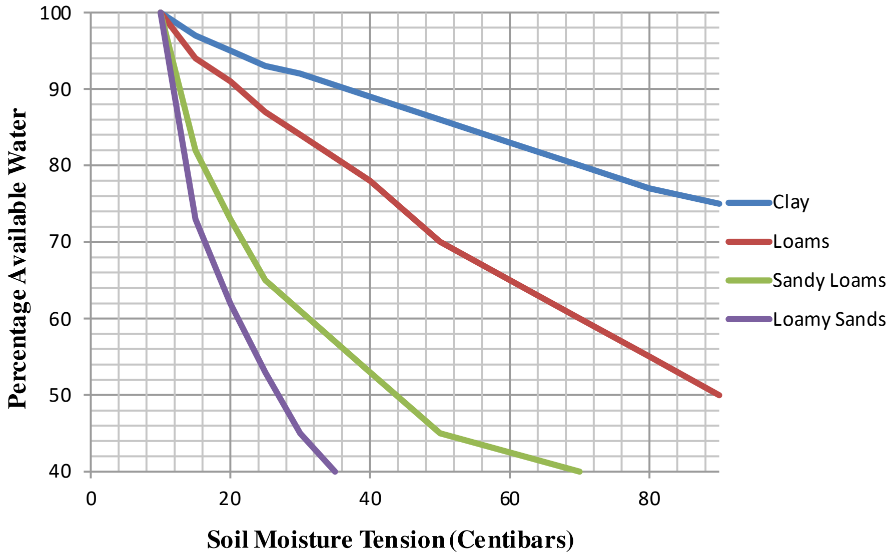


**Fig. 10.8** Soil Moisture Characteristic Curves

## 10.7 Water Movement in Soil

Water movement in the soil is a complex phenomenon because of different forces involved. Forces tend water to move in different directions and states. Gravitational force governs downward movement of water. Cohesive and adhesive forces move water within the pores while heat turns water into vapors that circulates through the air present in the soil. Irrigation water moves from a saturated soil layer towards an unsaturated soil layer and the flow is unsteady. Water movement in wet soils is more uniform than in dry soils.

### 10.7.1 Darcy's Law

An equation known as Darcy law is used to express the flow density (volume of water flowing through a unit cross sectional area per unit time). The equation is expressed as:

$$q = K\,\frac{\Delta H}{L} \qquad (10.10)$$

Where,

q = Flux Density,

(Δ H)/L = Hydraulic Gradient or Slope

K = Proportionality Constant

### 10.7.2 Available Water (AW)

In irrigation system design, one must know how much water is available to plants in the soil. The amount of water applies to a soil to bring it at the field capacity level from wilting point is called the "available water". The amount of water needed to a soil depends on the amount of water a soil can hold. The available water is the difference in the amount of water at field capacity (-0.3 bar) and the amount of water at the permanent wilting point (-15 bars). Generally, available water to plants is measured as the difference between field capacity (FC) and permanent wilting point (PWP). Total available water is calculated as:

$$TAW = (AWC) \times (R_d) \qquad (10.11)$$

Where,

TAW = Total Available water capacity within the plant root zone, (inches)

AWC = Available Water Capacity of the soil, (inches of $H_2O$/inch of soil)

$R_d$ = Depth of the plant root zone, (inches)

If different soil layers have different AWC's, TWS for different layers are summed up as under:

$$TAW = (AWC_1)\times(L_1) + (AWC_2)\times(L_2) + \ldots + (AWC_N)\times(L_N) \qquad (10.12)$$

Where,

L = thickness of soil layer, (inches)

$_{1,\,2,\,N}$: subscripts represent each successive soil layer

### 10.7.3 Field Capacity (FC or $\theta_{fc}$)

The amount of water held in the soil pores after excess gravitational water has been drained away is called field capacity. At field capacity level, soil is not fully saturated but still in a very wet condition. Usually the water content sat this stage corresponds to a soil water potential of -1/10 to -1/3 bar. After irrigation or rain shower, water drains more rapidly in coarse textured soils due to presence of comparatively larger soil pores. Whereas, drainage takes more time in fine textured soils due to their small pore size, it is at faster rate in coars textured oils.

### 10.7.4 Permanent Wilting Point (PWP)

Permanent wilting point is the soil water content beyond which plants cannot recover from water stress and practically become dead. However, some amount of water is available in the soil pool but not sufficient to be extracted by the plants. Plants will wilt if they are not able to take up soil water fast enough to meet the climatic ET demand. If water is not applied, plants will not recover and ultimately die. The water content corresponding to -15 bars is termed as PWP.

Fig 10.9 show the variation in FC and PWP water content by texture. Soil water content in percent by dry weight of soil is shown on the left margin and soil water content in inches of water per foot of soil is shown on the right margin for various soil bulk densities. The Fig. may be used as a general guide for estimating the AWC of soils based on texture until local curves are developed. It applies generally to uniform soil profiles with low salt content.

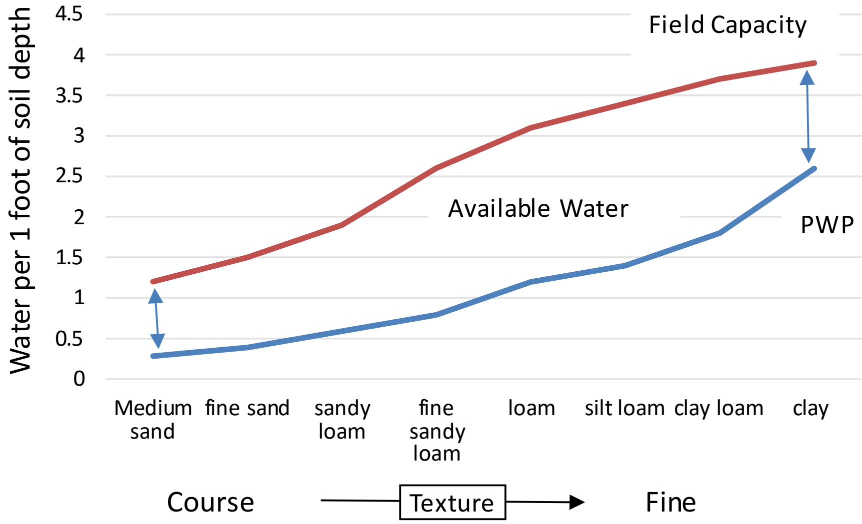


**Fig. 10.9** FC & PWP Variation for Different Soil Types

## 10.8 Plant Root System

Plant roots present the link among soil water, nutrients to plant parts above ground. The two main types of plant root system include Tap Roots and Lateral Roots. The main root emerging from a germinating seed is known as primary or seminal root. The primary root steadily extends and grows radically. Secondary roots developing from the seminal or primary root are termed as lateral roots or branch-roots as shown in Fig 10.10.

With continuous growth of plant roots, nodal roots develop from the under-ground stem nodes. Roots may also appear from above-ground nodes known as crown roots as the brace roots of corn.

### 10.8.1 Plant Root Characteristics

There are two main root characteristics:

1. Rooting Depth
2. Rooting Density

Rooting depth of different crops are given in Table 10.3.

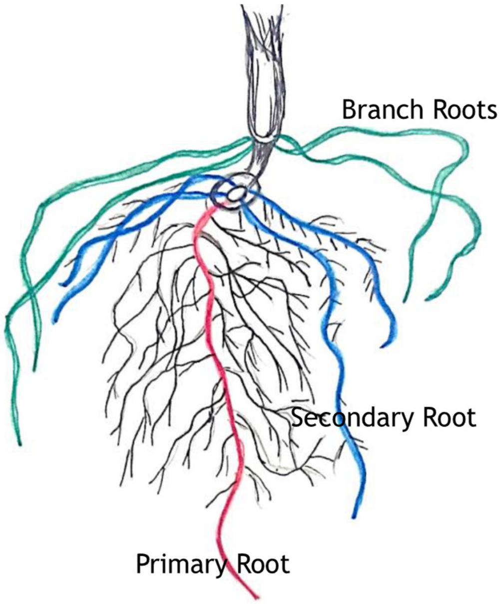


**Fig.10.10** Basic Root Development

**Table 10.3** Maximum Rooting Depth for different Crops

| S. No. | Crop | Root Depth (ft) |
|---|---|---|
| 1 | Wheat | 150 – 300 cm |
| 2 | Cotton | 150 – 300 cm |
| 3 | Rice | 100 – 120 cm* |
| 4 | Sugarcane | 200 – 600 cm |
| 5 | Sweet Corn | 120 – 150 cm |
| 6 | Field Corn | 150 – 180 cm |

*Source: SCS, 1991*

## 10.8.2 Factors Affecting Root Growth

There are many factors affecting root growth rate, maximum rooting depth and rooting density. The major stresses faced by roots in their growth, spread and depth are as follows:

**Chemical** stress is initiated by an unbalanced of nutrient supply, nutrient deficiencies or by presence of toxic substances;

**Physical** stress is caused by anaerobic conditions, mechanical impedance, and unfavorable temperatures and lack of water;

**Biological** stresses are produced by plant pests and diseases.

### 10.8.3 Water Flow into Roots

Water movement through the soil plant atmosphere takes place due to variations in soil water potentials according to their respective positions. Main driving force behind water movement through soil plant atmosphere series is heat energy which causes evapotranspiration.

**Evapotranspiration** is to combine the effect of Evaporation and Transpiration i.e. the combine loss of water from soil and plants.

**Evaporation** is the loss of water from soil surface in the form of water vapors.

**Transpiration** is the loss of water from plant surface in the form of water vapors, mainly from plant leaves.

The Transpiration component of evapotranspiration creates a vacuum (negative pressure or low potential) in the plant leaves, stem and ultimately root system. Because of this water from the soil starts moving towards the roots (xylem), from roots to stem and from stem to branches and from branches to leaves to fill the gap among the three different potential gradients. The two main parameters, determine plant water uptake are:

1. Physical contact of the roots to the soil
2. Intensity of root growth

According to Soil Conservation Services USA, when the upper part of the root zone becomes comparatively dry and water is available in the lower zone, the uptake of water per unit volume of soil takes place and is generally proportional to the rooting density. However, water availability to plants decreases in the presence of salts in the soil. Plant roots have a selective permeable membrane. Water molecules can easily pass through as compared to salts. Availability of water to plants greatly depends on salts presence in the soil water solution. Water movement into roots through semi-permeable membrane present around the plant roots, becomes difficult. As a result, plants show wilting condition linked with water stress. Generally, the root length per unit volume of soil is maximum close to surface of the soil and falloffs with increasing depth to the maximum depth at which roots are observed for a given crop species. This general trend is illustrated graphically in Fig. 10.13.

Extraction of water is most rapid in the zone of greatest root concentration and under the most favorable temperature and aeration conditions. As water evaporates from the upper few inches of soil; it is withdrawn rapidly from the top part of the soil profile. Soils normally show a more rapid loss of water at shallower depths until the potential becomes low enough to limiting rate.

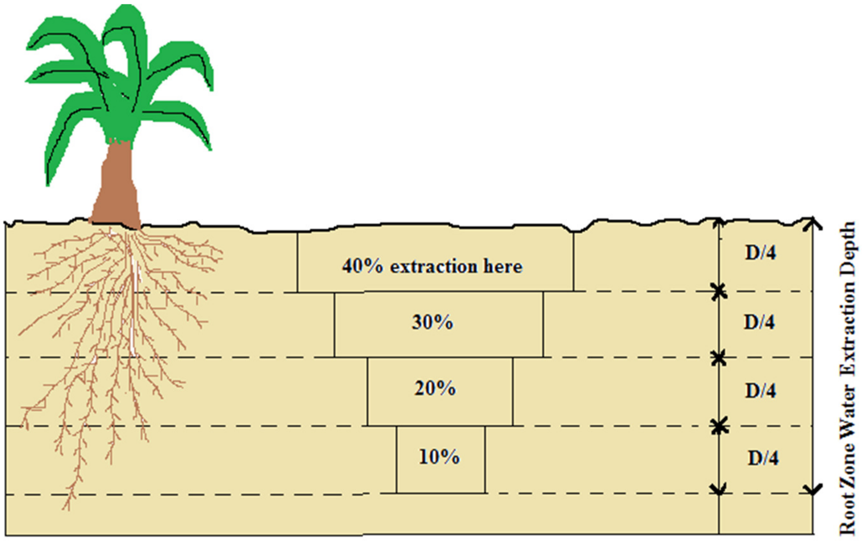


**Fig. 10.13** Water Uptake by Plants

## 10.9 Solved Examples

**Example 1:** Calculate the Dry bulk density ($\rho_b$) of a 400 cm$^3$ soil sample that weighs 575 g (oven dried weight).

Given Data:

Total volume of soil sample= 400 cm$^3$

Total mass of soil sample= 575 g

Required:

Dry Bulk Density=?

Solution: (Formula & Calculation):

$\rho_b$= Mass of solid/Volume of solids

= 575 g/400 cm$^3$= 1.44 g/ cm$^3$

**Example 2:** Calculate the wet bulk density of a 400 cm$^3$ soil sample that weighs 600 g at 10% moisture content.

Given Data:

Total volume of soil sample= 400 cm$^3$

Total mass of soil sample= 600g

Total moisture present in soil sample = 10%

Mass of soil sample without moisture (oven dry weight): 600/1.1 = 545.5g

Required:

Wet Bulk Density=?

Solution (Formula & Calculation):

$\rho_w$= Mass of solid/Volume of solids

= 545.5 g/400cm$^3$= 1.36 g/cm$^3$

**Example 3:** Calculate the volume of a soil sample that has 12% moisture content, weighs 650 g and a bulk density of 1.3 g/cm$^3$.

Given Data:

Moisture present in the soil sample =12%

Mass of soil sample = 650 g

Bulk density of soil = 1.3 g/cm$^3$

Required:

Volume of soil sample =?

Solution (Formula & Calculation):

Oven dry wt. = 650 g/1.12 = 580.4 g

1.3 g/cm$^3$= 580.4 g/vol. = 446.4 cm$^3$

**Example 4:** Calculate the porosity of a soil sample that has a bulk density of 1.35 g/cm$^3$. Assume the particle density is 2.65 g/cm$^3$.

Given Data:

Bulk density of soil = 1.35 g/cm$^3$

Particle density = 2.65 g/cm$^3$

Required:

Porosity =?

Formula & Calculation:

Porosity = (1- ($\rho_b$/$\rho_d$) × 100 = (1- (1.35/2.65)) × 100 = 49%

Thus, Porosity = 49 %

**Example 5:** What is the particle density of a soil sample that has a bulk density of 1.55 g/cm$^3$ and a porosity of 40%?

Given Data:

Bulk density of soil = 1.55 g/cm$^3$ Porosity = 40%

Required:

Particle density =?

Solution (Formula & Calculation):

Porosity = $(1- (\rho_b/ \rho_d) \times 100$

$40 = (1-1.55/ \rho_d) \times 100$

$1.55/ \rho_d = 0.6$

$\rho_d = 2.58$ g/cm$^3$

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# Chapter 11

# Crop Water Requirements

**Allah Bakhsh and Rob Malone**†

## Abstract

With the increase in population and the associated increased demand for food and irrigation, great competition for limited water exists that makes conservation and efficient use of water imperative. Where the water supply is diminishing, and getting scarce or expensive, conservation methods are most apt to be practiced. New sources of irrigation water supplies are limited, and the operating costs for water extraction are increasing. To get the most out of each unit of water, one must know how much water to apply, when to apply it, where to apply it, and how to design and manage an irrigation system optimally. Knowledge of crop water requirements is necessary in planning farm irrigation and drainage systems, for improving irrigation practices, conserving energy, and enhancing irrigation efficiencies. The objectives of this chapter "Crop Water Requirements (CWR)" are to describe relevant parameters that affect CWR, describe climatic effects on CWR, train readers for solving problems related to CWR. Methods to estimate crop water requirements have also been included. Solved examples are also given in the chapter to further elaborate the important concepts and their practical applications in the field. This book chapter will be of value to irrigation specialists, students, faculty members and farmers interested in conserving water and improving irrigation efficiency while maximizing crop production.

**Keywords:** Crop Water Requirements, Evapotranspiration, Production Function, Duty and Delta of Water, Leaching Requirement, Effective Rainfall, Soil Moisture Measurement Irrigation Efficiency.

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# Learning Objectives

After reading this chapter, the reader would be able to understand the concepts of:

- Evapotranspiration, crop factor, crop water requirements, cropping zones of Pakistan, water production function, irrigation scheduling and various methods to estimate crop water requirements.
- Efficient irrigation water application.
- Available soil water, MAD, and Irrigation Efficiency.

# 11.1 Introduction

Crop water requirement (CWR) for a crop is the amount of water required to grow that crop during its entire growing season. The CWR includes the amount of water needed by a crop during its growing period; it further includes the water required for pre-sowing irrigation ("Rouni"), crop growth and all water losses through evaporation, transpiration and water required for metabolic activities. While estimating the CWR, all types of precipitation falling on the crop or soil during its growth period is considered. The knowledge of CWR for a crop especially with its growth stages is important to meet water needs of the crop. As most part of the area of Pakistan lies in arid to semi-arid region, assessment of CWR is very helpful in planning water availability for the crop. The CWR is function of climate, crop type, growth stage, and soil type. Based on annual rainfall, FAO (1986) defined the climatic zones as:

| | |
|---|---|
| Arid | < 400 mm |
| Semi-Arid | 400 to 600 mm |
| Sub humid | 600 to 1200 mm |
| Moist sub humid | 1200 to 1500 mm |
| Humid | > 1500 mm |

Besides considering rainfall as one of the e controlling factors regarding assessment of CWR, the IWMI (2001) has delineated seven cropping zones by considering the crops being grown as well as the climate as the main factors affecting CWR (Fig. 11.1). Cropping zones of the Punjab Districts are given in the Table 11.1. Ullah et al. (2001) made a comparison of the average CWR of different crops sown in Pakistan (given in ranges) with the CWR of Faisalabad. Table 11.2 shows that the CWR of sugarcane, cotton and rice is high as compared to other crops. Hence, the values of CWRin the districts of southern Punjab are comparatively higher as these crops are mostly grown in these districts (Fig. 11.1).

**Table 11.1** Cropping Zones of Punjab Districts

| Cropping Zone | Districts |
|---|---|
| Rice-Wheat | Sialkot, Narowal, Gujarat, Mandi Bahauddin, Gujranwala, Hafizabad, Nankana Sahib, Sheikhpura |
| Mixed | Lahore, Kasur, Okara, Pakpattan, Sahiwal, Toba Tek Singh, Faisalabad, Jhang, Sargodha, Chiniot |
| Cotton-Wheat | Bahawalnagar, Bahawalpur, Rahim Yar Khan, Rajanpur, DG Khan, Muzaffargarh, Multan, Lodhran, Vehari |
| Maize-Wheat-Oil seed | Attock, Rawalpindi, Chakwal, Jehlum |
| Pulses-Wheat | Bhakkar, Layyah, Mianwali, Khushab |

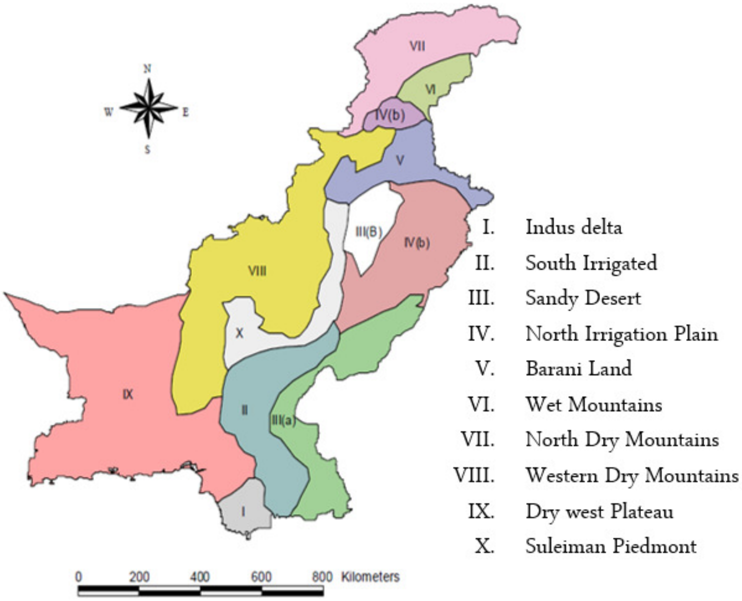


**Table 11.2** Average CWR of Different Crops in Pakistan and at Faisalabad

| Crops | CWR (mm) | Faisalabad (mm) | Crops | CWR (mm) | Faisalabad (mm) |
|---|---|---|---|---|---|
| Wheat | 271-515 | 316 | Sorghum | 370-537 | 406 |
| Maize | 289-367 | 336 | Oil seeds | 247-408 | 284 |
| Sugarcane | 1278-1887 | 1536 | Kharif Minor | 676-1221 | 785 |
| Cotton | 627-1156 | 749 | Rabi Minor | 372-527 | 392 |
| Rice | 587-1323 | 652 | | | |

*Source: Ullah et al., 2001*

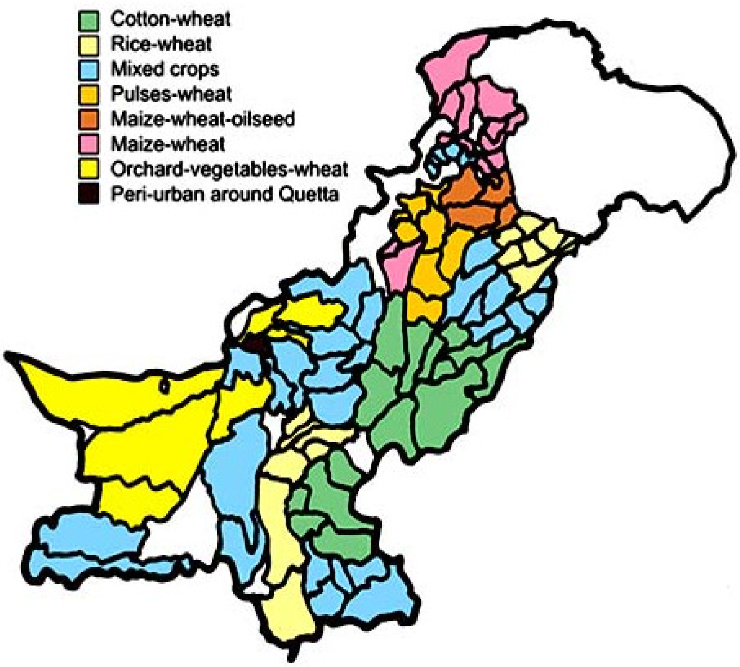


**Fig. 11.1** Agro-Ecological Zones of Pakistan

*Source: Ullah et al., 2001*

## 11.2 Water Production Function

Irrigation water plays a critical role during crop growth and producing crop yields especially in the arid climate regions but its amount has gained significant economic value in wake of the energy crisis. Therefore, it is imperative to quantify the impact of applied irrigation water on the crop yields. The relationship between crop yield and water applied is mostly quadratic. After achieving a certain level of crop yields, the slope of the function becomes flat while it is steep in the beginning. Whereas first derivative i.e. slope can be equaled to zero to determine the optimum amount of water required for obtaining maximum crop yields under environment. Example 11.1 illustrates the applied water and crop yield relationship (Cuenca, 1989).

**Example 11.1:** Under a crop environment, the applied irrigation water and crop yield relationship are described by the following quadratic equation;

$$Y = -2524 + 28.36\ (IW) - 0.015\ (IW)^2$$

Whereas the crop evapotranspiration and crop yield relationship is given as;

$$Y = -3700 + 30.64\ (ET)$$

Where:

Y = Crop yields (kg $ha^{-1}$)

IW = Applied depth of irrigation water (mm)

ET = Evapotranspiration (mm)

Calculate:

a) The ratio of change in yield to the change in depth of irrigation water applied when the depth of irrigation water is changed from 350 to 450 mm and 650 to 750 mm.
b) The efficiencies at 400 and 700 mm of applied water level when it is defined as ratio of ET to IW.

**Solution:**

a) For IW=350 mm:

$$Y = -2524 + 28.36(350) - 0.015\ (350)^2$$
$$Y = 5564.5\ \text{kg ha}^{-1}$$

For IW=450 mm:

$$Y = -2524 + 28.36(450) - 0.015\ (450)^2$$
$$Y = 7205\ \text{kg ha}^{-1}$$
$$\frac{\Delta Y}{\Delta IW} = \frac{7205 - 5564.5}{450 - 350} = 16.36\ \text{kg ha}^{-1}\text{mm}^{-1}$$

For IW=650 mm:

$$Y = -2524 + 28.36(650) - 0.015\ (650)^2$$
$$Y = 9572.5\ \text{kg ha}^{-1}$$

For IW=750 mm:

$$Y = -2524 + 28.36(750) - 0.015\ (750)^2$$
$$Y = 10308.5\ \text{kg ha}^{-1}$$
$$\frac{\Delta Y}{\Delta IW} = \frac{10308.5 - 9572.5}{750 - 650} = 7.36\ \text{kg ha}^{-1}\text{mm}^{-1}$$

b) For IW =400 mm:

$$Y = -2524 + 28.36(400) - 0.015\ (400)^2$$
$$Y = 6420\text{kg ha}^{-1}$$

Rearrange the equation for ET vs. Y

$$ET = \frac{3700 + Y}{30.64}$$

$$\mathrm{ET} = \frac{3700 + 6420}{30.64}$$

$$\mathrm{ET} = 330.31\mathrm{mm}$$

$$\mathrm{Efficiency} = \frac{330.31}{400} \times 100$$

$$\mathrm{Efficiency\ at\ IW400} = 82.58\%$$

For IW= 700 mm:$\mathrm{Y} = -2524 + 28.36(700) - 0.015\ (700)^2$

$$\mathrm{Y} = 9978\mathrm{kg\ ha}^{-1}$$

$$\mathrm{ET} = \frac{3700 + 9978}{30.64}$$

$$\mathrm{ET} = 446.41\mathrm{mm}$$

$$\mathrm{Efficiency} = \frac{446.41}{700} \times 100$$

$$\mathrm{Efficiency\ at\ IW700} = 63.77\%$$

## 11.3 Factors affecting CWR

FAO (1998) described the item wise factors that can influence the CWR, include:

| | |
|---|---|
| ***Climate**:* | Temperature, wind, solar radiation, sunshine hours, humidity, precipitation |
| ***Crop:*** | Crop type, crop stage, crop height |
| ***Soil type**:* | Sand, silt and clay fractions as that affect soil water availability |
| ***OM:*** | Organic matter, its type and concentration |
| ***Topography:*** | Degree and slope |
| ***Drainage:*** | Type of land drainage and sources of excess water |
| ***Irrigation practices***: | Method of irrigation and its efficiency |
| ***Groundwater Level**:* | Depth and quality of groundwater |

## 11.4 Terminologies Related to Use of Water

Terminologies pertaining to the estimated use of water such as Delta and Duty of Water and Base Period of Crop have been described below.

### 11.4.1 Duty of Water (D)

It is the area to be irrigated using unit amount of flow of water during entire growth period of the specific crop, is called as duty of water for that crop. Duty of irrigation water for growing 1000 hectares of wheat from sowing to harvesting using water supply of 56 liters per second will be 17.86 ha $L^{-1}sec^{-1}$. All those factors, which can affect water application to the field such as soil and topography, stream size, field size, degree of level and irrigation practice, for meeting duty of water can be managed for improving duty of water.

### 11.4.2 Delta of Water (Δ)

It is, in fact, the CWR or amount of water required to grow the crop during its growth period such as 400 mm of water for wheat crop applying 4 irrigations each of 100 mm in depth, including presowing ("Rauni") irrigation. Thus, delta of water in this case amounts to 400 mm of water.

### 11.4.3 Base Period (B)

It is the duration starting from the first irrigation applied to the field for sowing till last irrigation is applied whereas crop period is the duration from sowing till harvesting.

Relationship between duty, delta and base period can be described:

$$\Delta = 864 \times \frac{B}{D}$$

Where:

$\Delta$ = Delta of water, cm.

B = Base period, days.

D = Duty of water, ha per cubic meter of water per second.

**Example 11.2**

A crop requires 50cm of water for its base period of 160 days. What will be the duty of water?

**Solution:**

$$\text{Duty of water (D)} = 864 \times \frac{160}{50} = 2764.8 \text{ ha/m3/s}$$

**Example 11.3**

Water at the rate of 12 $m^3$/sis released at the canal head. Calculate the irrigated area, if duty of water at the field is 1200 ha/$m^3$ sand transit losses are 22%.

**Solution:**

A=D x Q

A=1200 x 12 = 14400 ha

As transit loss is 22%, therefore,

A=14400 x 0.78=11232 ha

**Example 11.4**

An irrigation canal has a Gross Commanded Area (GCA) of 8000 ha and the Cultivable Commanded Area (CCA) is 75%. Irrigation Intensity (II) is 50%. Calculate Delta of Water (Δ) and the outlet discharge (Q) if base period (B) is 120 days and Duty of water (D) is 1600 ha/m$^{3/}$s.

**Solution:**

C.C. A= G.C. A × 75% = 8000 × 0.75= 6000 ha

Irrigated area=C.C. A × I.I = 6000 x 0.50 =3000

As,

$$Q=\frac{A}{D}$$

$$Q = \frac{3000}{1600} = 1.88\ \mathrm{m^3/s}$$

$$\Delta = 864\times\frac{B}{D}$$

Thus, Δ= 864 x (120/1600) = 64.8cm

## 11.4.4 Irrigation Depth

It is the depth of water ($d_n$) required to bring the soil to its field capacity level in the effective root zone for plant growth.

$$d_n = \frac{FC - MC}{100}\times As\times r_z$$

Where,

FC = Field Capacity or the moisture available in the soil at 1/3 atmosphere tension.

MC = Moisture available at the time of irrigation,

As =Apparent specific gravity (i.e. ratio of bulk density of soil in g.cm$^{-3}$to the density of water in the same units as that of bulk density),

$r_z$= Root zone depth in cm.

The gross irrigation depth can be calculated by using the following formula:

$$\text{Gross irrigation depth} = \frac{\text{Net irrigation depth } (d_n)}{\text{Efficiency of irrigation system}}$$

## 11.4.5 Effective Rainfall

It is the rainfall utilized for any beneficial purpose. In different fields, specialists interpret the term in their own way. According to a hydrologist, the rain which directly contributes to the storage reservoirs and indirectly from the surrounding area by surface runoff is an effective part. For a hydro-electrical engineer, a portion of rainfall, which is used for running the turbines to generate electricity is effective. A

Geo-hydrologist defines effective rainfall as aportion which directly contributes to the storage of groundwater. According to FAO (1978), agricultural engineers consider that effective rainfall can be a portion of total rainfall, which is directly used to satisfy crop water needs.

### 11.4.6 Leaching Requirement (LR)

It is the amount of excessive irrigation water applied to the field for passing through the root zone to reduce the concentration of salts in the root zone for reclamation. The leaching requirements can be estimated by the following formula provided.

$$\mathrm{LR} = \frac{\mathrm{EC_W}}{5\mathrm{EC_E} - \mathrm{EC_W}} \qquad (11.5)$$

Where,

LR=Minimum leaching requirement to control salts,

$EC_W$= Salinity of applied water (dS/m),

$EC_E$= Average soil salinity tolerated by crop (dS/m).

The total depth of water to be applied annually to meet both crop water need and leaching requirement can be estimated by the following equation.

$$\mathrm{IW} = \frac{\mathrm{ET}}{1 - \mathrm{LR}}$$

Where,

IW= Depth of irrigation water applied (mm/year),

ET=Total annual crop water demand (mm/year),

LR=Leaching Requirement.

## 11.5 Soil Moisture Measurements

The degree of availability of soil moisture in the root zone is very crucial for ensuring proper growth of the plants because efficiency of other agricultural inputs also depends on the adequate soil moisture availability to the plants. Therefore, soil moisture measurement can help in scheduling irrigations as well as determining the depth of irrigation water required to fill the depleted amount of soil moisture in the root zone. Soil moisture can be measured in different ways and by using different equipment. Some methods are used to measure soil moisture directly from irrigator's point of view whereas the others measure the tension or force required by the plant roots to extract water from the soil, which is held with the soil particles. The following methods are most commonly used to measure the soil moisture in the root zone.

### 11.5.1 Gravimetric Method

The gravimetric method of measuring soil moisture refers to the weighing of soil sample and moisture in it. The soil sample is taken from the soil at the desired depth and is placed in the oven for at least 24 hrs at 105 C° to remove all the moisture contained in the soil sample. The volumetric soil moisture content is determined as below:

$$\mathrm{SMC} = \frac{\mathrm{W}_w - \mathrm{W_d}}{\mathrm{W_d}} \times 100 \text{ x } \mathrm{A_s}$$

Where,

SMC = Soil moisture contents on volumetric basis (%),

$W_w$= Wet weight of soil sample (g),

$W_d$ = Oven dried weight of soil sample the (g),

$A_s$ = Apparent specific gravity of soil i.e. ratio of bulk density of soil (g $cm^{-3}$) to density of water (1 g $cm^{-3}$).

### 11.5.2 Tensiometer

Tensiometer, as apparent from the name, measures tension, which is required by the plants to extract water from the soil. Soil water is held with and within the soil particles because of cohesion, adhesion and surface tension forces resulting in suction forces. A tensiometer is a simple air tight device, filled with water and having porous ceramic cup at one end and a meter on the other end. Water is released from the porous cup to the soil depending on soil moisture status in its vicinity. If the root zone around the cup is dry, water will be released from the cup which will be shown in the form of tension reading in $KP_a$ (bar) or if root zone becomes wet, it will absorb water into the cup and the reading in tension will be lowered. Tensiometers perform better in sandy, loamy sand and coarse textured soils within tension range of 0.0 to 0.8 bar. Clayey soils mostly retain soil water at tension higher than 0.8 bar, which is outside the range of tensiometers, however, in clayey soils, tensiometers can be used if the depletion level is lesser than 50% of available water.

Tensiometer cup needs to be soaked in water overnight to saturate it and then fill the barrel of the tensiometer with water. There should be no air inside the barrel, which can be checked by allowing water to evaporate from the cup and seeing its effect on tensiometer reading. It is preferable to transport tensiometer to the site by keeping its cup dipped in water so that tension remains workable. Tensiometer has different length and can be installed at the desired depth by making a hole in the soil using a steel rod, slightly smaller than the diameter of the cup. Add ¼ cup of water into the hole for moistening the soil before inserting the tensiometer gently into the soil. Care is needed to keep soil moisture within the range of the tensiometer so that it works reliably. If Tensiometer-readings respond to irrigation application and the drying patterns, it means that tensiometer is working satisfactorily.


**Fig. 11.2** Tensiometer

### 11.5.3 Electrical Resistance Block

Electrical resistance block consists of two electrodes, which are enclosed in the porous block or gypsum block. Resistance block works on the principle that water conducts electricity. Therefore, the amount of soil moisture in the root zone is like that in the porous blocks, which affects the flow of electricity within electrodes or in other words resist the flow of electricity depending on the soil moisture availability. Resistance block work better at tension higher than 0.5 bars because it responds poorly for tension lesser than 0.5 bars and are therefore, suitable for fine textured soils such as clayey and silty soils. These resistances are calibrated to measure soil moistures.


**Fig. 11.3** Electric Resistance Block

## 11.5.4 Neutron Probe

Neutron probe provides quick and easy estimates of soil moisture if it is calibrated properly. A two inches vertical aluminum access tube is installed in the field where soil moisture is to be measured. The neutron probe is lowered into the access tube and count of neutron is measured at the counter to relate it with the soil moisture. The neutron probe has a fast neutron emitting source, which emits neutrons that collide with the hydrogen atoms in the soil water and get scattered. These scattered slow moving neutrons are counted by the detector. The count of these scattered neutrons is related with the soil moisture. It is an expansive device and needs care during its operation because of neutron emissions.

### 11.5.5 Time Domain Reflectometer (TDR)

The TDR is relatively new device and consists of two rods, which are inserted into the soil at a certain depth where soil moisture is to be measured. TDR is an instrument which sends electromagnetic wave through these rods, which are conducted through the soil and reached back to the soil surface. The rate of conductance of electromagnetic waves through the soil is related with the soil moisture in the soil. Properly calibrated TDR can provide soil moisture estimates reliably. TDR is an expansive device but is becoming commercially viable.


**Fig. 11.4** Time Domain Reflectometer

### 11.5.6 Soil Moisture Meter

The soil moisture meter has a sensor at its tip, which when pushed into the soil gives readings related to the soil moisture contents in the soil at its digital meter.

**Fig. 11.5** Soil Moisture Meter

# 11.6 Terminologies in Evapotranspiration

## 11.6.1 Evaporation

It is the amount of water, which is evaporated from the soil surface, leaves of the plants or during conveyance of water from the source to the plants. It includes all the water losses, which can occur while meeting crop water needs of the plants.

## 11.6.2 Evapotranspiration (ET)

It is sum of evaporation and transpiration. Transpiration includes that amount of water, which is lost through plant bodies during its growth.

## 11.6.3 Consumptive Use (CU)

It is evapotranspiration plus the amount of water consumed during tissue building process of the plants or the water consumed for plant growth in addition to evapotranspiration. As, the water used by the plants for building tissues is nearly 1% of the total ET, therefore, CU is mostly taken as equivalent to ET.

## 11.6.4 Crop Coefficient ($K_C$)

It is the ratio of actual evapotranspiration ($ET_c$) of the crop to the reference evapotranspiration ($ET_o$). $K_C$ depends on soil type, climate, crop type and growth stages of crop. Some values of $K_c$ of various crops grown in Faisalabad region are given in the Table 11.3.

**Table 11.3** $K_C$ Values for Different Crops in Faisalabad Region.

| Months | 10 days | Wheat | Cotton | Sugar -cane | Maize | Sorgham | Rice | Oil seed | Pulses | Rabi Minor Crops | Kharif Minor Crops |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 1 | 0.91 | | | | | | 1.00 | 0.75 | 1.00 | |
| | 2 | 1.00 | | | | | | 1.00 | 0.94 | 0.98 | |
| | 3 | 1.10 | | | | | | 0.97 | 1.00 | 0.96 | |
| Feb | 1 | 1.10 | | 0.28 | | | | 0.91 | 1.15 | 0.93 | |
| | 2 | 1.10 | | 0.37 | | | | 0.88 | 0.92 | 0.88 | |
| | 3 | 1.10 | | 0.45 | | | | 0.66 | 0.47 | 0.85 | |
| Mar | 1 | 1.00 | | 0.53 | | | | 0.56 | 0.29 | 0.81 | |
| | 2 | 0.88 | | 0.60 | | | | 0.43 | 0.19 | 0.76 | |
| | 3 | 0.71 | | 0.70 | | | | 0.32 | | 0.67 | |
| Apr | 1 | 0.56 | | 0.91 | | | | 0.28 | | 0.63 | |
| | 2 | 0.43 | | 0.99 | | | | 0.23 | | 0.52 | |
| | 3 | 0.23 | | 1.12 | | | | 0.12 | | 0.31 | 0.37 |
| May | 1 | | 0.32 | 1.13 | | | | | | | 0.49 |
| | 2 | | 0.39 | 1.14 | | | | | | | 0.56 |
| | 3 | | 0.52 | 1.15 | | | 0.03 | | | | 0.61 |
| Jun | 1 | | 0.72 | 1.20 | | | 0.05 | | | | 0.68 |
| | 2 | | 0.93 | 1.20 | | | 0.10 | | | | 0.74 |
| | 3 | | 1.09 | 1.20 | 0.09 | 0.18 | 0.21 | | | | 0.80 |
| Jul | 1 | | 1.12 | 1.20 | 0.12 | 0.23 | 0.45 | | | | 0.84 |
| | 2 | | 1.12 | 1.20 | 0.23 | 0.30 | 0.72 | | | | 0.95 |
| | 3 | | 1.09 | 1.20 | 0.32 | 0.38 | 1.03 | | | | 0.95 |
| Aug | 1 | | 1.00 | 1.20 | 0.63 | 0.49 | 1.30 | | | | 0.95 |
| | 2 | | 0.85 | 1.20 | 0.77 | 0.66 | 1.35 | | | | 0.95 |
| | 3 | | 0.74 | 1.20 | 0.79 | 0.80 | 1.40 | | | | 0.95 |
| Sep | 1 | | 0.67 | 1.20 | 0.82 | 0.92 | 1.40 | | | | 0.95 |
| | 2 | | 0.63 | 1.20 | 0.83 | 0.98 | 1.35 | | | | 0.84 |
| | 3 | | 0.51 | 1.20 | 0.82 | 0.97 | 1.13 | 0.12 | | 0.18 | 0.79 |
| Oct | 1 | | 0.47 | 1.20 | 0.72 | 0.93 | 0.96 | 0.19 | | 0.24 | 0.73 |
| | 2 | | 0.42 | 1.20 | 0.56 | 0.83 | 0.69 | 0.28 | | 0.38 | 0.63 |
| | 3 | | 0.36 | 1.20 | 0.33 | 0.68 | 0.55 | 0.35 | | 0.45 | 0.46 |
| Nov | 1 | | 0.30 | 1.20 | | 0.38 | 0.42 | 0.40 | | 0.56 | |
| | 2 | 0.28 | 0.26 | 1.13 | | 0.23 | 0.30 | 0.49 | 0.34 | 0.72 | |
| | 3 | 0.38 | | 1.01 | | | 0.18 | 0.59 | 0.40 | 0.80 | |
| Dec | 1 | 0.45 | | 0.89 | | | | 0.70 | 0.44 | 0.84 | |
| | 2 | 0.54 | | 0.77 | | | | 0.81 | 0.51 | 0.88 | |
| | 3 | 0.71 | | 0.65 | | | | 0.90 | 0.61 | 0.93 | |

*Source: Ullah et al. (2001)*

## 11.6.5 Reference Evapotranspiration ($ET_o$)

It is the rate of water loss in the form of evapotranspiration from a uniform grass, 8-15 cm tall, shading the ground, not suffering from any disease, actively growing and not short of water.

### 11.6.6 Actual Evapotranspiration ($ET_a$)

It is the rate of actual evapotranspiration taking place under the real field conditions considering status of the soil moisture as well as stage of the crop and climatic conditions.

## 11.7 Methods for Estimating ET

The measurement of ET is helpful in planning the depth of water required by the plants or evapotranspired through the plants. It can be measured directly under field conditions and can also be estimated using climatic data.

### 11.7.1 Direct Measurement of ET

Direct measurement of ET has been made through Lysimeters either weighing type or measuring inflow and outflow volumes of water. Weighing type lysimeters provide more accurate data by monitoring periodic measurements of the weight of the lysimeters compared with measuring all types of water entering the lysimeters and leaving the lysimeters. The water budget equation can be used for any closed system to estimate the unknown component while measuring the inflow and outflow components into and out of the system:

$$W_s = W_i + W_p - W_e - W_{dp} + W_{gw}$$

Where,

$W_s$ = Change in soil moisture content over the considered period,

$W_i$ = Water inflow into the system i.e. irrigation,

$W_p$ = Precipitation,

$W_e$ = Evapotranspiration,

$W_{dp}$ = Deep percolation losses i.e. flow out of root zone,

$W_{gw}$ = Contribution from groundwater.

### 11.7.2 Estimating ET from Climatic Data

As climatic variables of temperature, sunshine, wind, humidity and solar radiation affect the rate of ET from the plants or from surface of the earth, therefore, these variables have been used to estimate ET. One of the simplest methods is ET measurement using Pan Evaporation method.

### 11.7.3 Pan Evaporation

It is measurement of evaporation from Class A Pan, which integrates effect of all climatic variables and can be used to estimate the rate of ET by making its adjustment through pan coefficient. The Class A pan is 121 cm in diameter, 25.5 cm deep, made of galvanized iron. The pan is placed in an open field environment not obstructed by trees or buildings or adjacent growing crop on a wooden frame about 15 cm above the ground surface. The water depth inside the pan is carefully maintained at level from 5 to 7.5 cm below the rim of the pan. Water level in the pan is measured regularly mostly in the morning. After taking measurements, water is filled in the pan to keep its level within the desired limits. The ETo can be estimated as below:

$$ET_O = K_p \times E_p$$

Where,

$ET_o$ = Reference evapotranspiration (same units as that of $E_p$),

$K_p$ = Pan coefficient, usually taken as 0.7 but can also be estimated using climatic data of relative humidity, wind speed, and the pan surrounded by dry fallow land or green crop distance.

Evaporation measurements are usually taken after 24 hours i.e. at 7:00 am every day. The difference in water level in the pan over 24 hours is considered as evaporation. In case of rainfall, depth of rainfall is added to the previous water level for determining the depth of evaporation. When water level in the pan approaches the lower allowable level, water is added to the pan to raise its water level in the pan to the upper limit after recording depth of evaporation for that day.

**Example 11.5:** Estimate reference evapotranspiration ($ET_o$) from the pan data and rainfall data given in Table 11.4

**Table 11.4** Daily Pan Evaporation and Rainfall Data.

| Days | Water depth (mm) | Rainfall (mm) | $E_{pan}$ (mm) | Days | Water depth (mm) | Rainfall (mm) | $E_{pan}$ (mm) |
|---|---|---|---|---|---|---|---|
| 1 | 156.0 | - | 5.0 | 17 | 150.3 | 20.0 | 4.6 |
| 2 | 151.0 | 2.0 | 6.3 | 18 | 165.7 | 25.8 | 1.9 |
| 3 | 146.7 | 3.1 | 8.4 | 19 | 189.6 | 32.3 | 3.4 |
| 4 | 141.4 | - | 5.9 | 20 | 218.5/151.2** | 15.8 | 2.0 |
| 5 | 135.5 | - | 9.4 | 21 | 165.0 | - | 5.2 |
| 6 | 126.1 | - | 8.9 | 22 | 159.8 | - | 6.9 |
| 7 | 117.2 | - | 4.6 | 23 | 152.9 | - | 7.2 |
| 8 | 112.6 | - | 6.8 | 24 | 145.7 | - | 8.5 |
| 9 | 105.8 | - | 7.3 | 25 | 137.2 | - | 6.3 |
| 10 | 98.5/157* | 3.7 | 7.6 | 26 | 130.9 | - | 8.4 |
| 11 | 153.1 | - | 5.4 | 27 | 122.5 | - | 6.6 |
| 12 | 147.7 | - | 9.6 | 28 | 115.9 | - | 8.9 |
| 13 | 138.1 | - | 7.2 | 29 | 107.0 | - | 6.6 |
| 14 | 130.9 | - | 6.4 | 30 | 100.4 | 13.6 | 7.6 |
| 15 | 124.5 | 13.9 | 6.3 | 31 | 106.4 | - | 7.4 |
| 16 | 132.1 | 24.1 | 5.9 | 1 (next month) 99 | | - | |

** 58.5 mm of water added.*
*** 66.3 mm of water taken out.*

**Example:** $E_{pan}$ isthe difference in water depth between day 1 and 2 plus the rainfall during day 1.

**Solution:**

$\Sigma E_{pan}$=198.9 mm/month

Number of days in the month=31

$E_{pan} = \Sigma E_{pan}$/ Number of days in the month i.e. 198.9 / 31= 6.42 mm/day

$K_{pan}$=0.70

$ET_o = K_{pan} \times E_{pan}$ = 0.70 × 6.42=4.5 mm/day

## 11.7.4 BlaneyCriddle Method

Blaney Criddle is a simple method to estimate evapotranspiration in case pan evaporation data are not available. This method is not very accurate especially under extreme conditions of dry, windy, sunny, humid and cloudy areas but still gives reasonable estimates in the order of magnitude. $ET_o$ can be estimated as given below:

$$ET_o = p \times (0.46\, T_{mean} + 8)$$

Where,

$ET_o$= Reference mean monthly evapotranspiration (mm/day),

P = Mean daily percent of annual day time hours over the month,

$T_{mean}$ =Mean daily temperature (°C) over the month.

**Example 11.6:** Using BlaneyCriddle method andthe data given in Table 11.5 and 11.6, estimate $ET_o$.

i) Location: Faisalabad, ii) Latitude: 30°N

**Table 11.5** Mean Daily Percentage (p) of Annual Daytime Hours for Different Latitudes.

| Latitude | North<br>South | Jan<br>July | Feb<br>Aug | Mar<br>Sept | Apr<br>Oct | May<br>Nov | June<br>Dec | July<br>Jan | Aug<br>Feb | Sept<br>Mar | Oct<br>Apr | Nov<br>May | Dec<br>June |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60° | | 0.15 | 0.20 | 0.26 | 0.32 | 0.38 | 0.41 | 0.40 | 0.34 | 0.28 | 0.22 | 0.17 | 0.13 |
| 55° | | 0.17 | 0.21 | 0.26 | 0.32 | 0.36 | 0.39 | 0.38 | 0.33 | 0.28 | 0.23 | 0.18 | 0.16 |
| 50° | | 0.19 | 0.23 | 0.27 | 0.31 | 0.34 | 0.36 | 0.35 | 0.32 | 0.28 | 0.24 | 0.20 | 0.18 |
| 45° | | 0.20 | 0.23 | 0.27 | 0.30 | 0.34 | 0.35 | 0.34 | 0.32 | 0.28 | 0.24 | 0.21 | 0.20 |
| 40° | | 0.22 | 0.24 | 0.27 | 0.30 | 0.32 | 0.34 | 0.33 | 0.31 | 0.28 | 0.25 | 0.22 | 0.21 |
| 35° | | 0.23 | 0.25 | 0.27 | 0.29 | 0.31 | 0.32 | 0.32 | 0.30 | 0.28 | 0.25 | 0.23 | 0.22 |
| 30° | | 0.24 | 0.25 | 0.27 | 0.29 | 0.31 | 0.32 | 0.31 | 0.30 | 0.28 | 0.26 | 0.24 | 0.23 |
| 25° | | 0.24 | 0.26 | 0.27 | 0.29 | 0.30 | 0.31 | 0.31 | 0.29 | 0.28 | 0.26 | 0.25 | 0.24 |
| 20° | | 0.25 | 0.26 | 0.27 | 0.28 | 0.29 | 0.30 | 0.30 | 0.29 | 0.28 | 0.26 | 0.25 | 0.25 |
| 15° | | 0.26 | 0.26 | 0.27 | 0.28 | 0.29 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.26 | 0.25 |
| 10° | | 0.26 | 0.27 | 0.27 | 0.28 | 0.28 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.26 | 0.26 |
| 5° | | 0.27 | 0.27 | 0.27 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.27 | 0.27 | 0.27 |
| 0° | | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |

*Source: Jensen, 1981*

**Table 11.6** Mean Monthly Temperature Data

| Month | $T_{min}$ | $T_{max}$ | $T_{mean}$ | p value (30ºN) | $ET_o$(mm/day) |
|---|---|---|---|---|---|
| Jan | 14.6 | 32.2 | 23.40 | 0.24 | 4.50 |
| Feb | 17.9 | 34.8 | 26.35 | 0.25 | 5.03 |
| Mar | 20.4 | 38.3 | 29.35 | 0.27 | 5.81 |
| Apr | 23.8 | 38.9 | 31.35 | 0.29 | 6.50 |
| May | 25.0 | 39.2 | 32.10 | 0.31 | 7.06 |
| June | 26.8 | 36.0 | 31.40 | 0.32 | 7.18 |
| July | 24.2 | 32.1 | 28.15 | 0.31 | 6.49 |
| Aug | 22.3 | 33.0 | 27.65 | 0.30 | 6.22 |
| Sept | 21.9 | 34.6 | 28.25 | 0.28 | 5.88 |
| Oct | 22.7 | 32.4 | 27.55 | 0.26 | 5.37 |
| Nov | 17.9 | 35.1 | 26.50 | 0.24 | 4.85 |
| Dec | 15.3 | 31.6 | 23.45 | 0.23 | 4.32 |

## 11.8 Irrigation Scheduling

It is schedule of applying irrigation water to the plants, which depends on the soil, crop variety and its stage. The irrigation scheduling technique ensures adequate and timely application of irrigation water so that plants don't suffer from water stress and there is no reduction in the crop yields. The question, however, is to determine '*when to apply*' and '*how much to apply*'. Studies have shown that irrigation scheduling can save 15 to 35 percent of the irrigation without reducing yield (Evans et al., 1996). The available water in the root zone can be depleted to a certain critical level, called MAD (Management Allowable Depletion) and when soil moisture approaches to that level, new irrigation water is applied to replenish the water lost as evapotranspiration. The depth of irrigation water to be applied depends on the soil type that stores water to make it available to the plants. It also depends on the root zone i.e. how deep water can be extracted by the plants through their roots. In beginning of the growing season of the crop, root zone is shallow when plants are younger so that at this time it needs lesser water, which can only become possible if the irrigation method offers adequate control over depth of irrigation water to be applied such as through sprinkler or drip irrigation. Whereas flooding or surface irrigation mostly applies heavy irrigation water, which percolates through the root zone and becomes inaccessible to the young plants. Similarly, the depth of irrigation water depends on the type of soil because sandy soil can't store much water in comparison to that stored in the clayey soil.

It is the time when plants need irrigation water otherwise yield can be affected. This stage can be determined by several methods such as monitoring soil moisture in the root zone using soil moisture measuring devices, measuring leaf temperature using infrared thermometer, soil sampling or by observation method. The farmers use observation method to find whether plants need water by observing color of the plants or patterns of the leaves. The depth of irrigation water to be applied can be determined by measuring soil moisture status in the root zone, which can be accomplished by sampling the soil at different root zone depths, which has been elaborated in the following example.

### 11.8.1 Irrigation Scheduling Approaches

Irrigation scheduling may be further categorized as Fixed Scheduling, Flexible Scheduling and Flexible Scheduling Incorporating Rainfall. Each category is explained below.

#### 11.8.1.1 Fixed Scheduling

In fixed method of irrigation scheduling, the following steps are followed:

1. Determine net depth of water required to replenish the lost soil moisture in the root zone by getting soil samples from the field and processing them to estimate the required depth of irrigation water in the field as outlined in the solved example 11.5 OR
2. Calculate $ET_o$ using pan evaporation method or any other method using climatic data and then estimate $ET_c$ by multiplying it with $K_c$, given in Table 11.3
3. Keeping in view the length of growing season or number of growing days, estimate the total crop water requirement (CWR) for the whole growing season.
4. Divide the total CWR by the net irrigation depth to determine the irrigation interval.
5. Apply irrigation depth according to the irrigation interval determined in step-4.

**Example 11.7:** Schedule surface irrigations for tomatoes planted in January under the following conditions. Irrigation Efficiency: 60% for surface irrigation; 75% for sprinkler irrigation; 90% for drip irrigation (FAO, 1986).

Given data

*Crop:* Tomatoes

*Sowing date:* 15 January

*$ET_c$ (mm/month):* Monthly data are given in Table 11.7

Depth of Irrigation applied: Monthly data are given in Table 11.7 = 60

**Solution:**

Net irrigation depth, $d_n$ = 50 mm

Gross irrigation depth, $d_g = \frac{d_n}{E_a} = \frac{50}{0.6} = 83$ mm

Total irrigation water needs = 60+100+120+140+160 = 580 mm

Number of irrigations = $\frac{580}{50} = 11.6 \approx 12$

Total number of growing days = 135 (from Jan 15 to May 31)

Irrigation interval = $\frac{135}{12} = 11.25 \approx 12$ days

The Scheduling procedure is as under:

Net irrigation depth of 50 mm applied after 12 days over the growing season.

***Check Adequacy:*** Irrigation depth applied for 30 days = (50/12) x30 = 125 mm, which would be lesser for the months of April and May and crop may go under stress. Two months of April and May were under irrigated and plants may go under water stress.

**Table 11.7** Data Regarding Monthly Net Irrigation needed and Applied

| Water Depth / Months | Jan | Feb | Mar | Apr | May |
|---|---|---|---|---|---|
| Net irrigation need (mm) | 60 | 100 | 120 | 140 | 160 |
| Irrigation depth applied (mm) | 63 | 117 | 129 | 125 | 129 |
| Difference | +3 | +17 | +9 | -15 | -31 |

Total difference = 3+17+9 – 15 – 31 = -17 mm (17 mm less water was applied) .

The limitations of the Method include:

- Irrigation depth will be same throughout the growing season and it may underestimate during peak CWR.
- The crop may suffer from water shortage. This difficulty can be overcome by determining CWR for each month and adjusting irrigation interval for peak period to avoid soil moisture stress. This procedure is explained under flexible irrigation scheduling method.

### 11.8.1.2 Flexible Scheduling

Repeat the same steps as outlined above except adjusting irrigation interval during peak CWR period as explained in the following example.

**Example 11.8:** Monthly data on net irrigation needed and applied are given in Table 11.8

**Solution:**

Requirement during April& May = 140 + 160 = 300 mm

Number of irrigations = $\frac{300}{50} = 6$

Irrigation interval for these two months = $\frac{61}{6} = 10.2 \approx 10$ days

New Scheme would be same for Jan, Feb and March, while in April and May it would be; application of 50 mm in days.

**Table 11.8** Monthly Data on Net Irrigation Needed and Applied

| Months | Jan | Feb | Mar | Apr | May |
|---|---|---|---|---|---|
| Net irrigation need (mm) | 60 | 100 | 120 | 140 | 160 |
| Irrigation depth applied (mm) | 63 | 117 | 129 | 150 | 155 |
| Difference | +3 | +17 | +9 | +10 | -5 |

Total difference = 3+17+9+10 – 5 = 34 mm

This scheme can work as there is only difference of 5 mm in the last month while overall there is surplus irrigation application of 34 mm.

#### 11.8.1.3 Flexible Scheduling Incorporating Rainfall

This approach has been explained in the following worksheet using water balance approach as given below.

**Example 11.9:** Compute irrigation scheduling for wheat crop under following conditions;

| | |
|---|---|
| Soil Type: | Loamy soil, |
| Field Capacity (FC): | 30% or 90 mm, |
| Bulk Density (BD): | 1.2 g $cm^{-3}$ |
| Root Zone (RZ): | 25 cm, |
| Wilting Point (WP): | 14% or 42 mm, |
| Available Moisture (AM): | 16% or 48 mm, |
| *MAD:* | 50% or 24 mm, |
| *Residual S.M:* | 3% or 16 mm, |
| $ET_o$: | Collected from crop physiology Dept. UAF, |
| $K_c$: | From IWMI report 24 |

**Solution:** Root zone was computed in proportion to $K_c$ values used. Daily SM balance approach was used.

**Table 11.9** Irrigation Scheduling Information

| Month | Days | RZ (cm) | Av SM (mm) | $ET_o$ (mm/d) | $K_c$ | $ET_c$ (mm/d) | Irri-gation (mm) | Rain-fall (mm) | Resi-dual S.M | Used (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1-Nov | 1 | 25.00 | 24.00 | 2.60 | 0.30 | 0.78 | | | 23.22 | 0.78 |
| 8-Nov | 8 | 25.00 | 18.54 | 2.60 | 0.30 | 0.78 | | | 17.76 | 6.24 |
| 15-Nov | 15 | 30.83 | 17.09 | 2.60 | 0.37 | 0.96 | | | 16.13 | 12.61 |
| 22-Nov | 22 | 36.67 | 13.46 | 2.60 | 0.44 | 1.14 | | | 12.32 | 19.71 |
| 29-Nov | 29 | 36.67 | 5.46 | 2.60 | 0.44 | 1.14 | | | 4.31 | 27.72 |
| 3-Dec | 33 | 43.33 | 2.50 | 2.50 | 0.52 | 1.30 | 40.40 | | 1.20 | 32.76 |
| 6-Dec | 36 | 43.33 | 40.30 | 2.50 | 0.52 | 1.30 | | | 39.00 | 36.66 |
| 13-Dec | 43 | 50.83 | 38.13 | 2.50 | 0.61 | 1.53 | | | 36.60 | 46.44 |
| 20-Dec | 50 | 50.83 | 31.98 | 2.50 | 0.61 | 1.53 | | | 30.45 | 57.11 |
| 27-Dec | 57 | 60.83 | 27.32 | 2.50 | 0.73 | 1.83 | | | 25.49 | 69.89 |
| 3-Jan | 64 | 74.17 | 20.40 | 2.00 | 0.89 | 1.78 | | | 18.62 | 83.37 |
| 10-Jan | 71 | 77.50 | 10.15 | 2.00 | 0.93 | 1.86 | | | 8.29 | 95.91 |
| 14-Jan | 75 | 77.50 | 2.71 | 2.00 | 0.93 | 1.86 | 73.55 | | 0.85 | 103.35 |
| 17-Jan | 78 | 77.50 | 74.40 | 2.00 | 0.93 | 1.86 | | 1.50 | 72.54 | 108.93 |
| 24-Jan | 85 | 87.50 | 80.29 | 2.00 | 1.05 | 2.10 | | | 78.19 | 123.15 |
| 31-Jan | 92 | 91.67 | 70.92 | 2.00 | 1.10 | 2.20 | | | 68.72 | 137.95 |
| 7-Feb | 99 | 91.67 | 52.47 | 3.50 | 1.10 | 3.85 | | | 48.62 | 164.90 |
| 14-Feb | 106 | 95.83 | 34.73 | 3.50 | 1.15 | 4.03 | | | 30.70 | 192.90 |
| 21-Feb | 113 | 99.17 | 20.60 | 3.50 | 1.19 | 4.17 | | | 16.44 | 221.22 |
| 25-Feb | 117 | 99.17 | 8.11 | 3.50 | 1.19 | 4.17 | 91.26 | | 3.94 | 237.88 |
| 28-Feb | 120 | 99.17 | 95.20 | 3.50 | 1.19 | 4.17 | | | 91.04 | 250.37 |
| 1-Mar | 121 | 100.00 | 96.00 | 4.50 | 1.10 | 4.95 | | | 91.05 | 255.32 |
| 7-Mar | 127 | 100.00 | 77.75 | 4.50 | 1.10 | 4.95 | | | 72.80 | 285.02 |
| 14-Mar | 134 | 100.00 | 49.58 | 4.50 | 0.93 | 4.19 | | | 45.40 | 316.61 |
| 21-Mar | 141 | 100.00 | 20.29 | 4.50 | 0.76 | 3.42 | | | 16.87 | 345.14 |
| 25-Mar | 145 | 100.00 | 14.75 | 4.50 | 0.76 | 3.42 | 83.88 | | 11.33 | 358.82 |
| 28-Mar | 148 | 100.00 | 91.78 | 4.50 | 0.76 | 3.42 | | | 88.36 | 369.08 |
| 4-Apr | 155 | 100.00 | 70.60 | 5.00 | 0.56 | 2.80 | | | 67.80 | 389.64 |
| 10-Apr | 161 | 100.00 | 53.80 | 5.00 | 0.30 | 1.50 | | | 52.30 | 405.14 |

Number of irrigations = 4

Total depth of irrigation water applied: 289 mm + 28.33 mm effective rainfall = 317 mm = 12.5 inch

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## Chapter 12

# Surface Irrigation Methods

**Muhammad Akhlaq and Muhammad Ashraf***

## Abstract

Plant growth depends upon the adequate water supply in the plant root zone. When rainfall is insufficient to meet water requirement of a plant, water must be supplied to the plant to sustain its life. Therefore, irrigation is the artificial supply of water to crops. In surface irrigation methods, supply of water takes place through open channels under gravity. These may be categorized into basin, border, furrow-ridge, furrow - bed and surge irrigation. Soil characteristics, field geometry, water availability, cropping pattern and climatic conditions are the important factors for the selection of a suitable surface irrigation method. Appropriate selection of irrigation method is an integral part of irrigation scheduling. Application efficiency, conveyance efficiency, irrigation efficiency, water use efficiency, storage or requirement efficiency, distribution uniformity, irrigation time, and advance rate are the criteria to evaluate the performance of surface irrigation method for any field and crop. Atomization may be used to improve the performance and control over the irrigation water application. This chapter on irrigation methods presents basic concepts, irrigation application techniques, flow characteristics and advantages along with the efficiencies to facilitate performance assessment of a given system.

**Keywords:** Irrigation System, Irrigation Method, Infiltration Rate, Field Capacity, Irrigation Evaluation, Irrigation Efficiencies, Surface Irrigation Phases

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## Learning Objectives

- Most of the crop water needs in Pakistan are met through canal and groundwater, using surface irrigation methods such as basin, border furrow and bed and furrow. Therefore, understanding of the on-farm irrigation techniques is very important for the irrigators.
- The available water resources for irrigation are scarce, which unconditionally require that those should be utilized efficiently by minimizing water losses. Understanding of irrigation methods, allow the farmer to utilize the most efficient one under the existing conditions of soil, crop, financial resources and technological advancements for maximizing benefits.
- Use of mechanized farming and productivity enhancement are well connected with the right selection of the irrigation system. Therefore, the mechanization of agricultural farms and precision farming can be achieved by coordinated use of advanced machinery and selected irrigation systems.
- This chapter will help the students and the farm manager for the selection and design of proper irrigation methods.

## 12.1 Introduction

An irrigation system consists of source of water (an intake structure or pumping station), a conveyance system, a distribution system, a field application system and a drainage system as shown in Fig. 12.1 (FAO, 1998).

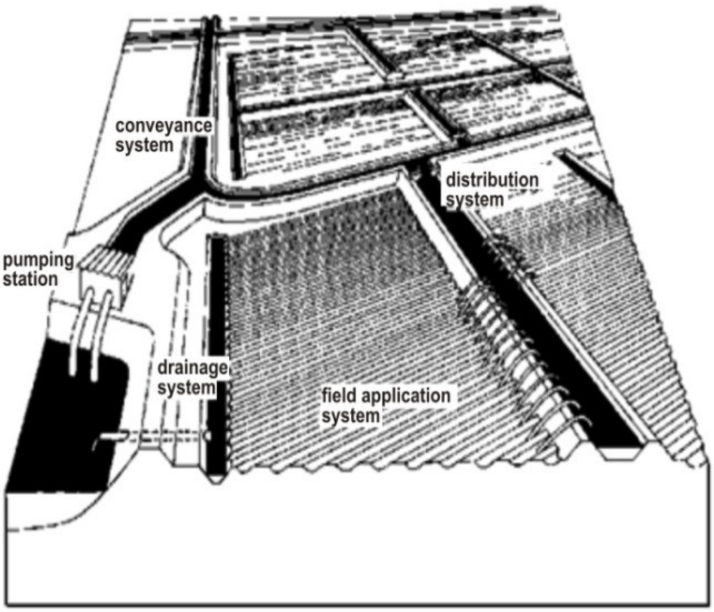


**Fig. 12.1** ASchematic Diagram of Irrigation System

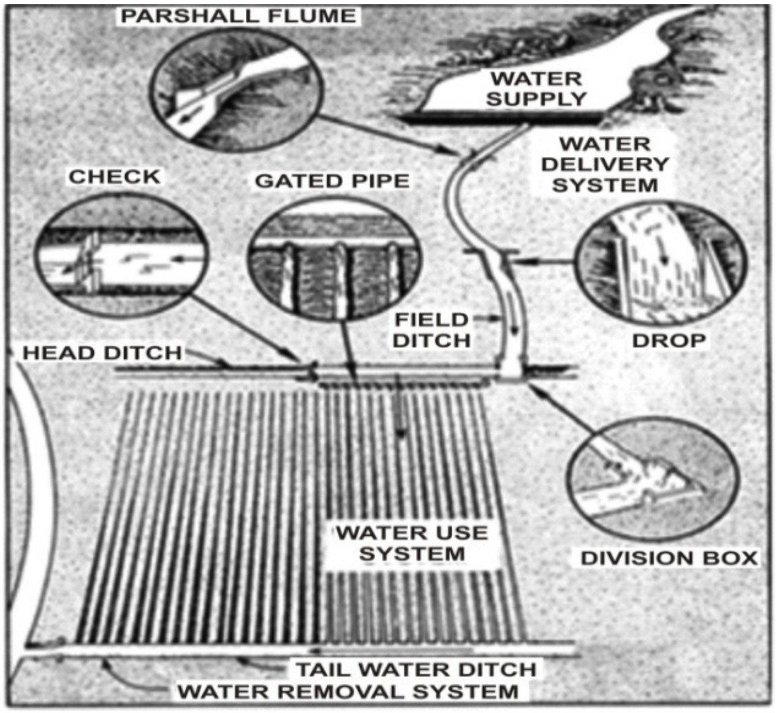


**Fig. 12.2** Types of Surface Irrigation Systems

Different systems are used to supply water to crop. Each one has specific advantages and disadvantages, which should be considered when selecting the irrigation system under the given circumstances such as climate, soil and crop characteristics and availability of water. Appropriate selection of irrigation method is an integral part of irrigation scheduling. In surface irrigation system, water is applied by gravity across the soil surface by flooding or small channels.

There are two main sources of water supply, surface and ground water. Water is supplied from a canal, a pond or a reservoir, or pumped from groundwater and supplied to the field. Some control structures are used to measure and regulate the water supply. Fig. 12.2 (FAO, 1998) shows a schematic diagram of a typical surface irrigation system. Surface irrigation is categorized into several systems, namely, basin irrigation, border irrigation, furrow-ridge irrigation, and bed- furrow irrigation.

It is essential to supply adequate water for plant growth. When rainfall does not fulfill the requirement of crop, water is applied to fulfill the requirement of crop through artificial methods, known as Irrigation. There are two main problems associated with over and under irrigation: If the field is over irrigated, the excess water will be lost as deep percolation. It is not only the loss of water but also results in leaching of the precious nutrients and may also lead to water logging and salinity. If the field is under irrigated, the crop will be under water-stress condition. Both the conditions are not feasible for optimal plant growth. Therefore, proper irrigation is very important to enhance the production of the crop. As rainfall in Pakistan is small as compared to the crop water requirements of the major crops, therefore irrigation is essential for plant growth.

## 12.2 Historical Developments of Irrigation

Ancient Egyptians, before 1800 BC, used the water of the natural lake of Faiyum Oasis as a reservoir to store water for the drier season as shown in Fig. 12.3 (Richard et al., 2008). Basins, bordered by dykes were used to apply water to the fields. Ancient Nubians designed water wheel (sakia) for flood irrigation system between the third and second millennium BC. Firstly, artificial reservoirs were designed by the Sinhalese to store water. Due to their innovation and engineering superiority, they were called 'masters of irrigation'. The Chinese used the Chinese pump which lifted the water to higher elevation during second century AD. The Chinese pump was run by manual foot pedal, hydraulic waterwheels or rotating mechanical wheels driven by oxen as shown in Fig. 12.4 (Richard et al., 2008). Terraces were introduced by irrigation experts of China and America. Irrigation canal system was introduced in the Zana Valley of the Andes Mountains in Peru from the fourth millennium BC.

**Fig. 12.3** Atypical Natural Lake

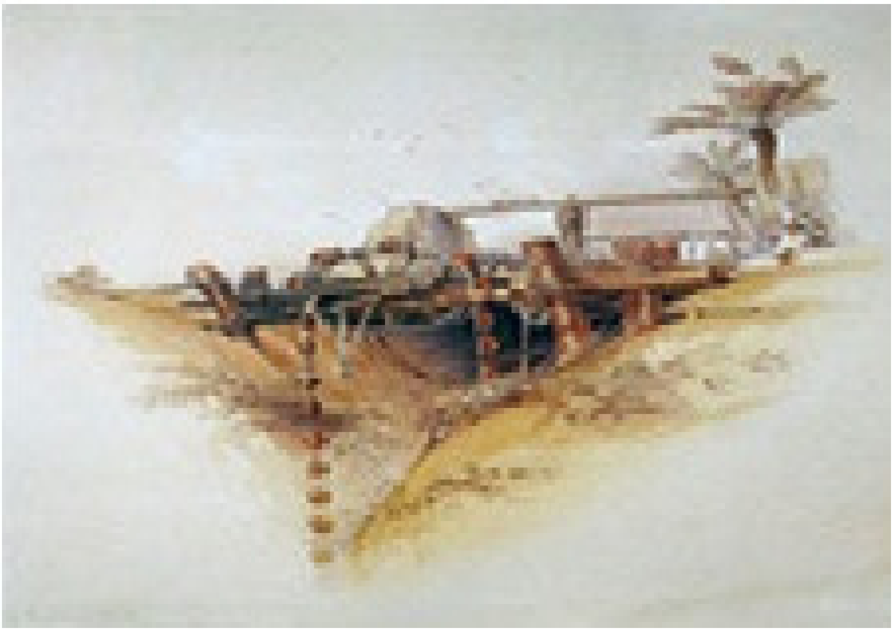

**Fig. 12.4** A Model of Chinese Pump

The Indus Valley has been the host to one of the most ancient civilization of human history. People were settled within the "Doab" (the area between the two rivers) of different river of sub-continent. Population grew all around these regions. Water was insufficient to grow the crops. To reduce the occurrence of low irrigation water supply the British authorities, towards the middle of the 17$^{th}$ century, started modernizing and expanding the irrigation system of the Indus Basin. Different dams and canals were constructed in this valley.

# 12.3 Basic Terminologies

## 12.3.1 Infiltration Rate

The rate at which water is absorbed by soil is called infiltration rate. It is measured in inches per hours or millimeter per hour.

It can be measured by two empirical relations.

- Horton's equation
- Kostiakov equation.

The Horton's equation is written as:

$$f_t = f_c + (f_0 - f_c)e^{-kt} \qquad (12.1)$$

Where:

$f_t$ is the infiltration rate at time $t$

$f_0$ is the initial infiltration rate or maximum infiltration rate

$f_c$ is the constant or equilibrium infiltration rate after the soil has been saturated or minimum infiltration rate

k is the decay constant specific to the soil

t is the time taken by water to infiltrate

The equation of Kostiakov can be expressed by equation 12.2.

$$f_t = akt^{(a-1)} \tag{12.2}$$

$f_t$ is the infiltration rate at time $t$

a and k are the constants

t is the time taken by water to infiltrate

The infiltration can be measured by single or double ring infiltrometers.

### 12.3.2 Moisture Content

Amount of water present in the soil is called moisture content in the soil. It can be measured either on volume basis (volumetric water content) or on weight basis,

The mathematical form of volumetric water content is given in equation 12.3.

$$\theta = \frac{V_W}{V_T} \tag{12.3}$$

Where:

$\theta$ is the volumetric water content (cm$^3$ of water/cm$^3$ of soil)

$V_w$ is the volume of water present in the soil

$V_T$ is the total volume of the soil (soil volume + water volume + air space)

The moisture content on weight basis can be determined by gravimetric method. Equation 12.4 can be used to determine moisture content on weight basis.

$$\emptyset = \frac{M_W}{M_T} \tag{12.4}$$

Where:

φ is the gravimetric water content

$M_w$ is the mass of water

$M_T$ is the bulk mass of soil

### 12.3.3 Saturation

That condition of soil at which all pores of the soil filled with water is called saturation condition. At that condition, the moisture content in the soil is hundred percent.

### 12.3.4 Bulk Density

It is the ratio of soil dry weight of soil to the total volume of the soil. Where volume of soil is the volume of soil particle and pores. It is the indicator of the soil compactness.

The bulk density of the rocks is 2.63 g/cm$^3$ that is ideal condition whereas he medium texture soil has bulk density 1.33 g/cm$^3$.

### 12.3.5 Percolation

The amount of water that flows from the root zone toward groundwater and become a part of ground water is called percolation.

### 12.3.6 Field Capacity (FC)

The volumetric water content of a soil after rapid gravity drainage has ceased. It usually occurs about two days after the soil profile has been thoroughly wetted by precipitation or irrigation. For most the soils, it pertains to -0.33 bars (33 cm) water potential

### 12.3.7 Permanent Wilting Point (PWP)

The soil-water content at which plants wilt and fail to recover is called the permanent wilting point. For most soils, it corresponds to–15 bars water potential.

### 12.3.8 Available Water

All the water in the soil is not available to plant. The water content between the field capacity and the permanent wilting point is called the available water.

## 12.4 Phases of Surface Irrigation Process

There are three phases in the surface irrigation process, as illustrated in Fig. 12.2 (FAO, 1998).

- Advance phase
- Wetting or Ponding phase
- Recession phase

### 12.4.1 Advance Phase

It is the process of the leading edge of water moving across the field either in channel or as overland flow. Advance phase lies between when water is applied to field to the end point of the field as shown in Fig. 12.5 (FAO, 1998).

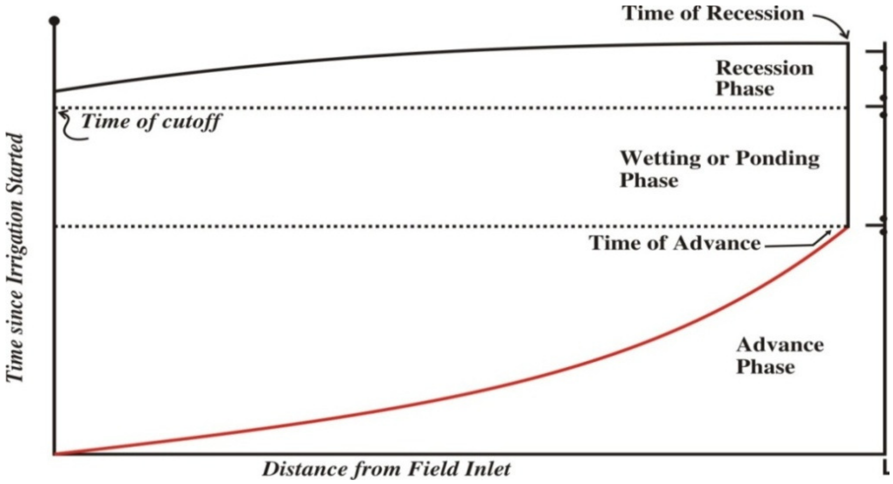


**Fig. 12.5** Phases of Surface Irrigation Process

### 12.4.2 Wetting phase

Wetting phase lies between the water reached to the end point to the shutoff or cutoff time (that time when water is stopped to supply to field). Wetting or ponding phase does not exist until and unless water is advanced to the end corner of the field as shown in Fig. 12.5 (FAO, 1998). Cutoff Time is the time when water is stopped to supply in the field.

### 12.4.3 Recessing phase

After the inflow is stopped, water disappears from the surface of the field by drainage or through infiltration. This is called recession phase. These processes are simulated in all numerical models of surface irrigation methods.

## I2.5 Selection of Surface Irrigation Systems

Selection of irrigation method depends upon climate, characteristics of soil type of crop and stream size. Basin irrigation is used on many different soils. Sandy soils required smaller basins as compared to the clayed soils. Border irrigation is adapted to most soils where depth and topography permit the requirement land leveling at a reasonable cost and without permanent reduction in soil production. Furrow irrigation can be used to irrigate all crops planted in rows, including orchard and vegetables. This method is suitable for irrigation wheat, cotton, maize, sorghum, sugarcane, tobacco, groundnut, potato and other vegetables. Irrigation system may be selected for crops to be irrigated. For example, if rice is the major crop, selection of basin irrigation method may be more appropriate. However, now rice is also being planted on beds to save water. For row crops furrow or bed-furrow irrigation system may be more appropriate.

### I2.5.1 Inlet Discharge Control Practices

Uniformity and efficiency depend upon the relationship of inflow rate and time of cutoff. If inflow per unit width is too small, the water will move along the slope very slowly over the field cause low efficiency and poor uniformity. Large differences in the intake opportunity time to infiltrate the water in the soil will affect the uniformity.

Flow rate for first irrigation of the season through surface irrigation method should be two or three times more than the discharge required for subsequent irrigation to attain the acceptable uniformity. Inlet flow should be higher because of higher infiltration rate during first irrigation of season. Flow rate can be controlled according to crop requirement and soil capacity. Thus, adjustment of the inlet flow is required to get maximum efficiency in surface irrigation method.

### I2.5.2 Changing the Field Geometry and Topography

Field geometry depends upon the soil texture and structure. As soil changes from clay loam and clay to sandy loam and silt loam, the length of the field may be increased to get maximum efficiency of surface irrigation system. Partition of field into parts is an effective way to get maximum efficiency and uniformity.

Slope changes may be avoided for good design of surface irrigation method unless another surface irrigation method is adapted. The range of slopes from 0 to 0.5% is suitable for surface irrigation system. Efficiency of surface irrigation system can be improved by precision land leveling of the fields. It is an integral part of best water management practices.

### I2.5.3 Tail water Recovery Reuse

In order to supply water over the surface of field rapidly to attain maximum system efficiency and application uniformity, the inlet flow should be larger than the soil cumulative intake along the flow direction. Consequently, there is enough amount of water at the end of the field, this tail water can be captured and reused by dikes. Tail water creates problem in different cases like soil erosion for sandy soil and abundant water supply, water logging for heavy soil and salinity. These all problems can be rectified by tail water recovery and reuse it through pumping.

### I2.5.4 Automation and Equipment

The main disadvantage of surface irrigation method is labor requirement. Automation helps the irrigator to regulate the water supply, proper unit flow and cutoff time that is critical parameters in surface irrigation system.

The automation system for basin and border is required single gate off takes, siphons, simple check valve and ditch gates to operate the system. Mechanized and controlled system for every outlet is installed to get uniformity and application efficiency.

Water is applied to the furrow system with the same facilities used in border and basin irrigation system. Ditch gates and siphon tubes are used to supply water in the furrow. In some cases, gated pipes are used for furrow irrigation system. There are two types of gates, one is rigid and other is flexible. Rigid gate is found in form of aluminum and PVC. Flexible gate consists of polypipe.

## 12.6 Types of Surface Irrigation Systems

There are five types of surface irrigation system. The detail of each system and their suitability for different crop and climate is given below.

### 12.6.1 Basin Irrigation System

In basin irrigation system, the water is applied to the leveled land that is bounded by dikes to stop the runoff. The concept of basin irrigation system is illustrated in Fig. 12.6 (FAO, 1998). The detailed description of the Basin Irrigation System is given below:

**Fig. 12.6** An Unleveled Basin with Standing Water in the Field

#### 12.6.1.1 Characteristics

Generally, square field is recommended for the basin irrigation system rather than rectangular field. The shape of field depends upon the stream size and soil characteristic. Advance phase of the basin irrigation system should be minimized as much as possible. In this irrigation system, water is applied to the field less frequently then the border and furrow irrigation system with large depth. Medium and heavy (clay) soil is recommended for basin irrigation system. Clay soil has less infiltration rate and large water holding capacity. If basin irrigation system is adopted for light soils, the water is percolated from root-zone depth, resulting into water and nutrient losses.

Efficiency and uniformity of the Basin Irrigation System largely depend on the relationship of water inflow and soil intake. High inflow in case of light soil and low inflow in case of heavy is required to get the more uniformity and efficiency of the basin irrigation system. With proper design and management, application efficiency exceeding 90% can be achieved for basin irrigation. However, inadequate inflow rate and unleveled basin can reduce distribution uniformity and application efficiency significantly.

In other irrigation systems (Drip and Sprinkler Irrigation), efficiency of system depends upon less water application. But in basin irrigation system efficiency and uniformity depends upon the large depth of water. Duration of irrigation in basin irrigation system depends upon the intake rate, depth of water to be applied and efficiency of system. In this system, short duration of irrigation can be obtained by large discharge.

Basin irrigation system is suitable for most field crops such as alfalfa, cotton, wheat, sugarcane, rice, maize, millet, pulses and oilseed. Basin irrigation system is not suitable for those crops which cannot stand in water logged condition for more than 24 hours. Topography plays an important role in the basin irrigation system. If land is not level, lower parts of field receive more water and upper parts less water, resulting into over and under irrigation. With the help of laser land leveler, it is possible to level the land to achieve efficiency of the basin irrigation system. Table 12.1 (FAO, 1998) shows the suggested maximum basin areas for different soil type and available stream sizes.

**Table 12.1** Maximum Basin Area for Different Soil Types and Stream Sizes

| Stream size (lps) | Maximum Basin Area ($m^2$) Soil type | | | |
|---|---|---|---|---|
| | Sand | Sandy loam | Clay loam | Clay |
| 5 | 35 | 100 | 200 | 350 |
| 10 | 65 | 200 | 400 | 650 |
| 15 | 100 | 300 | 600 | 1000 |
| 30 | 200 | 600 | 1200 | 2000 |
| 60 | 400 | 1200 | 2400 | 4000 |
| 90 | 600 | 1800 | 3600 | 6000 |

#### 12.6.1.2 Methodology

The field is divided into square units and bunds are constructed around these units. These square units are known as basin. Basins are filled to the desired depth and water is retained until it infiltrates into the root zone depth.

#### 12.6.1.3 Advantages

- Basin irrigation is used to leach down the salts
- Easy to operate and manage because of smaller size of fields
- High application efficiency and uniformity can be obtained by proper designing and operation
- Relatively light application of water is possible

#### 12.6.1.4 Limitations

- Ditches create problems in the movement of farm machinery
- It is difficult to drain excess water on clay soil
- Ditches and dikes reduce the cultivated causing reduction in production
- Generally, hard pan of the soil crust is developed when water is applied. This condition creates problem for germination of seed.
- Basin irrigation is time consuming method because it takes more time in different phases of irrigation process
- Whenever, water ponds in the field for a large duration, the carbon dioxide exchanges with the atmosphere. This condition is called scaling. In scaling condition, the roots of the crop are disturbed and ultimately effect the crop production. However, rice can be grown in scaling condition to stop the weed germination
- More water losses due to additional water course to supply water into basin

### 12.6.2 Border Irrigation System

Border irrigation system consists of longer strips of field with strip width of <30 meters as illustrated in Fig. 12.7 (Guisepi, 2001).

**Fig. 12.7** Example of Border Irrigation System

In terraced system, border irrigation is used. Border can be constructed along the contours that system is called contour border irrigation system. This system is illustrated in Fig. 12.8 (Guisepi, 2001). The detailed description of the border irrigation system is given below:

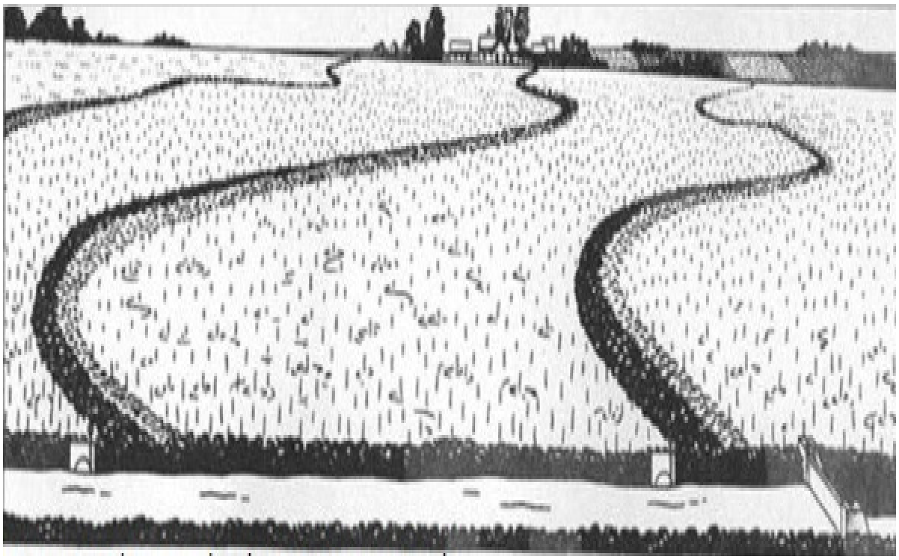

**Fig. 12.8** Contour Irrigation System

### 12.6.2.1 Characteristics

The length and width of the border should be 800 m and 3-30 m, respectively. The dimensions of border irrigation system depend upon type of soil, slope of land, flow rate, cultural practices and farm size etc. The minimum slope of border should be 0.05 % for adequate drainage and maximum slope should be 2%. Dimensions of border with respect to border slope, flow rate and soil type are given in Table 12.2 (Guisepi, 2001).

**Table 12.2** Border Irrigation Geometry with respect to Slope, Flow Rate and Soil Type

| Soil type | Border slope (%) | Unit flow per meter width (l/sec) | Border width (m) | Border length (m) |
|---|---|---|---|---|
| Sand | 0.2-0.4 | 10-15 | 12-30 | 60-90 |
| Infiltration | 0.4-0.6 | 8-10 | 9-12 | 60-90 |
| rate>25mm/h | 0.6-1.0 | 5-8 | 6-9 | 75 |
| Loam | 0.2-0.4 | 5-7 | 12-30 | 90-250 |
| Infiltration rate | 0.4-0.6 | 4-6 | 6-12 | 90-180 |
| of 10-25 mm/h | 0.6-1.0 | 2-4 | 6 | 90 |
| Clay | 0.2-0.4 | 3-4 | 12-30 | 180-300 |
| Infiltration | 0.4-0.6 | 2-3 | 6-12 | 90-180 |
| rate<10 mm/h | 0.6-1.0 | 1-2 | 6 | 90 |

Clay-loam or loamy soils with homogeneous characteristics are recommended for border irrigation system. Because loamy and clay-loam soil have moderate infiltration rate and are for border irrigation system. Heavy soil is not preferred for border because time is required to infiltrate adequate water into the soil. Water is required in border 3 to 5 times greater than furrow flow per unit width and less than basin irrigation system. If furrow with spacing 2.5 ft is irrigated with a flow of 6 gpm /ft and border with the same soil is irrigated with a flow of 20 gpm /ft.

Duration of irrigation depends upon the type of soil. In case of clay-loam soil, inflow is cut off when field is filled 60% with water. Stream flow is stopped when border of loamy soil is covered 70-80% with water. For sandy soil, flow should not be stopped until and unless entire field is filled with water. Border irrigation system is suitable for deeply rooted crops such as alfalfa or pasture. This is not recommended for shallow rooted crops such as vegetables.

#### 12.6.2.2 Methodology

In border irrigation system, large strips of field are formed that are bounded by bunds to stop the runoff. Border may be level or graded at some slope. The slope in transverse direction is zero in both cases. The uniform gentle slope is kept in the direction of irrigation. The essential feature is to provide such a surface that water can flow down with uniform depth. In border irrigation system, each border is irrigated independently by sheet of water.

#### 12.6.2.3 Advantages

- It is economical because dikes of border can be constructed with simple secondary implements
- It is simple to operate
- Adequate surface drainage can be provided at the downstream section if outlets are provided
- Cultivated area can be saved due to reduction of water channel and permanent dikes
- Water losses can be saved by reduction of water channels
- It is suitable for mechanized farming

#### 12.6.2.4 Limitations

- Large irrigation stream is required in border irrigation system because excessive long border take more time to accommodate field
- Proper land leveling and uniform gentle slope are required in border irrigation system
- Wastage of cultivated land due to small channels. However, that may be temporary

### 12.6.3 Furrow Irrigation System

Consecutive small strips of elevation and depression in the field are called furrow irrigation system. These strips of consecutive depression and elevation are also known furrow.

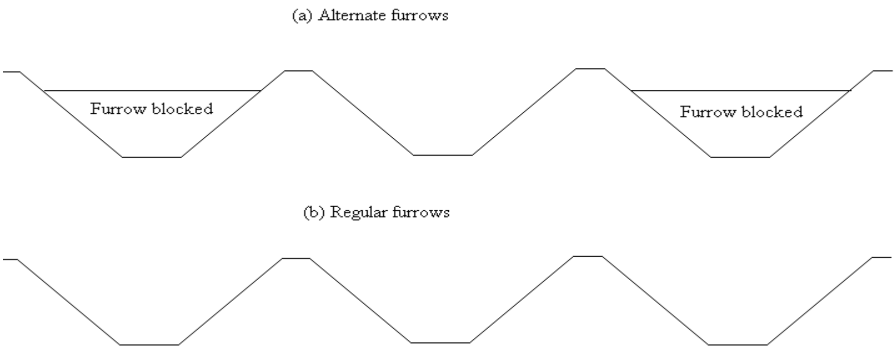


**Fig. 12.9** Furrow Irrigation System

This system of irrigation is illustrated in following Fig. 12.9 (FAO, 1998). The detailed description of the system is given below:

#### 12.6.3.1 Characteristics

The slope of the field is important to select the length of the furrow. If the slop of field is steep the furrow could be longer and vice versa. The maximum slope of furrow should be 0.5% to avoid soil erosion and minimum slope should be 0.05% for effective drainage. If the land is steeper than 0.5% slope, the furrow should be designed at an angle from the slope or along the contours. Furrows along the contours are known as contour furrow. Fig. 12.10 (FAO, 1998) shows the contour furrow. The slope of the furrow should be along the flow of water as well as lateral.

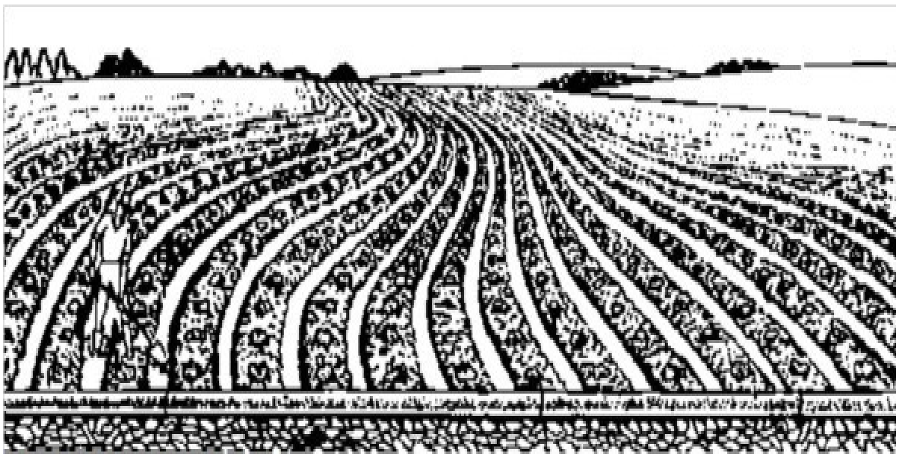

**Fig. 12.10** Furrowsalong Contours

Furrow irrigation can be applied on all types of soils. Water moves with high velocity due to small size of channels. In case of sandy soil, channels of the furrow should be small to supply water at end point. In this way, water losses due to infiltrated can be minimized. On the other hand, channels should be broad in case of clay soil. Furrows are much longer in the clay soil than the sandy soil. The furrow length can be selected with respect to slop and soil type and stream flow as shown Table 12.3 (FAO, 1998).

Saline water is not recommended for the furrow irrigation system because salts cumulate in the furrows that create problem for the germination of the seeds. The flow up to 0.5 L/sec will be applied to the short furrow in the length. The stream flow should be adjusted to avoid the erosion of the soil. It is suggested to use stream sizes less than 3.0 L/sec.

**Table 12.3** Selection of Furrow Length based on Slope, Soil Type and Flow Rate

| Furrow slope (%) | Maximum stream size per furrow (lps) | Clay | | Loam | | Sand | |
|---|---|---|---|---|---|---|---|
| | | Net irrigation depth (mm) | | | | | |
| | | 50 | 75 | 50 | 75 | 50 | 75 |
| 0.0 | 3.0 | 100 | 150 | 60 | 90 | 30 | 45 |
| 0.1 | 3.0 | 120 | 170 | 90 | 125 | 45 | 60 |
| 0.2 | 2.5 | 130 | 180 | 110 | 150 | 60 | 95 |
| 0.3 | 2.0 | 150 | 200 | 130 | 170 | 75 | 110 |
| 0.5 | 1.2 | 150 | 200 | 130 | 170 | 75 | 110 |

Furrow irrigation system is suitable especially for row crops. It is recommended for those crops whose stem will damage due to water in initial stage of growing. Furrow irrigation is recommended for growing almost all types of crops (Fig. 12.11 - 12.13).

### 12.6.3.2 Methodology

In furrow irrigation system, consecutive strips of elevation and depression are formed by furrow planter. These consecutive strips elevation and depression are called ridge and furrow respectively. Furrow should be maintained regularly during irrigation. The uniform gentle slope is kept on both directions (transverse as well as on the direction of the irrigation). The slope and size should be adjusted with respect to crop, spacing between furrow and equipment used for farming. Water moves into the soil laterally and vertically to irrigate the area between furrows.

### 12.6.3.3 Advantages

- Earlier cultivation is possible
- Cultivated can be saved due to less ditch in field
- In furrow irrigation system, minimum evaporation losses because water contacts only one half to one fifth of the land.
- 30% water saving as compare to border and basin irrigation system

### 12.6.3.4 Limitations

- It is not suitable for all crops
- In furrow irrigation system, cultural practices cannot be performed easily
- It required continuous slope to supply
- It is not suitable for sandy soil because of instability of ridge


**Fig. 12.11** A Furrow-bed Planter for Wheat Crop

### 12.6.4 Furrow Bed Irrigation System

About 40-50% of irrigation water is wasted in the fields during its application due to conventional methods of irrigation such as flat basins or inappropriate size of the furrows resulting into loss of precious water, nutrients, energy with overall low water productivity. This precious irrigation water can be saved and crop yield can be increased by growing crops on raised beds using a bed planter illustrated in Fig. 12.11 (Ahmad, 2008). This bed planted was designed by Water Management Research Center, University of Agriculture, Faisalabad.

**Fig. 12.12** Wheatand Sugarcane Planted on Beds and Irrigated through Furrows

**Fig. 12.13** Maize and Cotton Planted on Beds and Irrigated through Furrows

#### 12.6.4.1 Characteristics

Bed and furrow sizes can be adjusted for individual crop. Seed and fertilizer rates can be adjusted as per requirements. Bed planter can be operated by a common tractor driver. Furrow bed irrigation can be applied for different crops as shown in Fig. 12.12 and 12.13 (Ahmad, 2008).

#### 12.6.4.2 Advantages

- It is suitable for different crops
- Water saving up to 50% and yield increase up to 25%
- Higher water and fertilizer use efficiency
- Easy manual and combine harvesting
- Crop intensity increase
- Less weed infestation in sugarcane
- Better drainage of water during rainy season

#### 12.6.4.3 Limitations

- Maintenance of bed planter is required.

### 12.6.5 Surge Irrigation

In this system of irrigation, water is applied through pulses of short duration. Fig. 12.14 (FAO, 1998) illustrates complete cycle of advance and recession phase for surge irrigation system. Instead of six hours of continuous irrigation system, six 40-minuts surges are used to complete irrigation requirement.

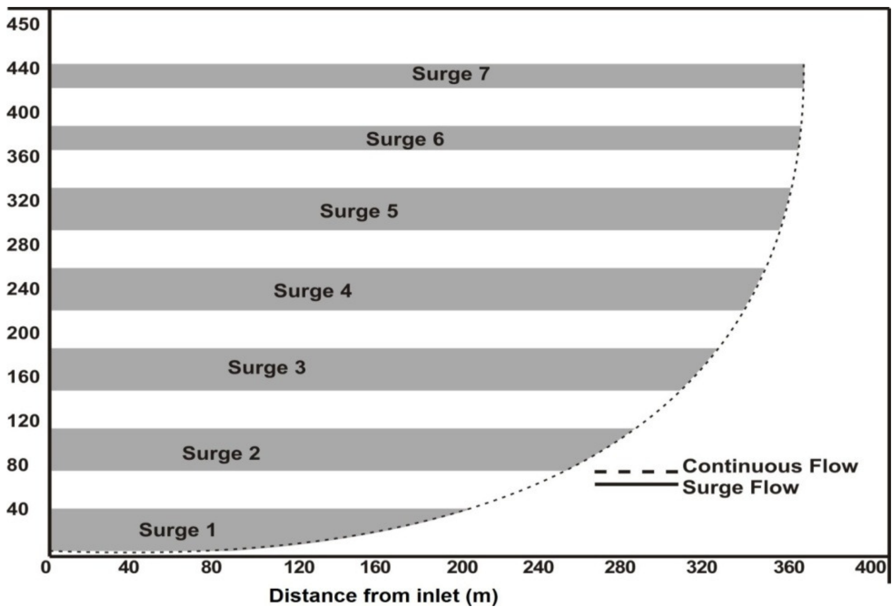


**Fig. 12.14** Surge Irrigation System showing Advance and Recession Phases

The detail of all surge irrigation cycle phases is explained in I2.1.4 section earlier. The ratio of on-time to the total time of cycle is known as cycle ratio. The range of cycle ratio lies from 0.25 to 0.75. Infiltration rate of any type of soil can be controlled by surge irrigation system.

# 12.7 Surface Irrigation Evaluation

Efficiency and uniformity are the most important factors to judge the performance and management of the surface irrigation system. These factors are sub divided into different parts. Evaluation of surface irrigation system illustrates that how much water is stored in the root zone and how much is percolated from the root zone depth.

## 12.7.1 Need for Evaluation

The main purpose to evaluate surface irrigation systems is the identification of management performance and system configurations. Evaluation indicates that more efficient system can be developed by reducing the inflow of water source that can refill water requirement in the root zone.

Evaluation also provides the chances to improve the performance of surface irrigation system by changing in field size and its topography. The evaluation is also useful in different analyses and operations to improve the operation and management of the system. Surface irrigation system is a complex and dynamic hydrologic system. Therefore, the evaluation is an integral part to optimize the utilization of water in surface irrigation system

## 12.7.2 Irrigation Efficiencies and Evaluation Indicators

There are some indices to evaluate the surface irrigation system.

### I2.7.2.1 Application Efficiency

It is the ratio of water stored in the root zone to the total water applied to the field.

$$E_a = \frac{V_s}{V_f} \qquad (12.5)$$

$E_a$ = Application efficiency

$V_s$ = Volume of water stored in root zone

$V_f$= Volume of water applied to the field

### 12.7.2.2 Conveyance Efficiency

The ratio between the water reached at the field to the total water diverted from the source of water. Mathematically it is written as:

$$E_c = \frac{V_f}{V_t} \qquad (12.6)$$

Where,

$E_c$= Conveyance efficiency

$V_f$= Volume of water applied to the field

Vt=Volume of water diverted from the source of water

12.7.2.3 Irrigation Efficiency

It is ratio of water beneficially used to the water applied to the field.

$$E_i = \frac{V_b}{V_f} \qquad (12.7)$$

Where,

$E_i$= Irrigation efficiency

$V_b$= Volume of water beneficially used

$V_f$= Volume of water applied to the field

**12.7.2.4 Distribution Uniformity**

Distribution uniformity may be defined as the average infiltrated depth in the low quarter of the field, divided by the average infiltrated depth over the whole field.

**12.7.2.5 Water Storage Efficiency**

It is the ratio of water stored in the root zone during irrigation to the water needed in the root zone prior to irrigation.

$$\eta_S = \frac{W_S}{W_N} \times 100 \qquad 12.8$$

Where,

$\eta_S$=Percent water storage efficiency

$W_S$=Water stored in root zone during irrigation

$W_N$=Water needed in the root zone before irrigation.

**12.7.2.6 Water Distribution Efficiency ($\eta_d$)**

It is ratio of difference from unity of ratio of the average numerical deviations to the average depth stored during the irrigation. Water distribution efficiency indicates uniformity in distribution of water over the entire root zone.

$$\eta_d = \{1 - \frac{\overline{Y}}{\overline{d}}\} \times 100 \qquad 12.9$$

Where,

$\eta_d$= Percent Water distribution efficiency

$\overline{d}$ = Average depth of irrigation water stored in the root zone during irrigation $\overline{Y}$= Average of numerical deviation from$\overline{d}$.

**12.7.2.7 Crop Water Use Efficiency ($\eta_{cwu}$)**

It is the ratio of crop yield (Y) to the water depleted by evapotranspiration (ET).

$$\eta_{cwu} = \frac{Y}{ET} \qquad (12.10)$$

Where,

$\eta_{cwu}$ = Crop water use efficiency (kg/m$^3$ of water)

Y = Crop yield (kg/ha)

ET = Crop evapo-transpiration (mm).

#### 12.7.2.8 Field Water Use Efficiency ($\eta_{fwu}$)

It is the ratio of crop yield (Y) to the irrigation water applied to the field (IW).

$$\eta_{fwu} = \frac{Y}{IW} \qquad (12.11)$$

Where,

$\eta_{fwu}$ = Field water use efficiency (kg/m$^3$ of water)

Y = Crop yield (kg/ha)

IW = Irrigation water applied in the field (m$^3$)

#### 12.7.2.9 Deep Percolation Ratio

Deep percolation ratio indicates that how much water is percolated below the root-zone depth. Mathematically, it is written as:

$$D_p = \frac{V_{dp}}{V_f} \qquad 12.12$$

Where, $D_P$ = Deep percolation ratio

$V_{dp}$ = Volume of water percolate from the root zone depth

$V_f$= Volume of water applied to field.

#### 12.7.2.10 Irrigation Time

It is the time from advance time to the cut off time.

#### 12.7.2.11 Tail Water Ratio

It is the ratio of the volume of water that drains out from end of field to the volume of water applied to the field.

$$TWR = \frac{V_r}{V_a} \qquad 12.13$$

Where, TWR = Tail water ratio

$V_r$ = Runoff volume at the end of field

$V_a$= Applied volume of water.

**Example 12.6:** A discharge of 100 l/sec is delivered from a canal and 76 l/sec is delivered to the field. Area of 2.5 ha is irrigated in 12 hours. Irrigation is started after depletion of 50% of available soil moisture. The effective root-zone depth is 1.5 m;

available soil moisture holding capacity is 18 cm $m^{-1}$, runoff loss is 400 $m^3$. Water penetration depth is 1.6 m and 1.0 m at head and tail of the field, respectively.

Calculate;

i) Conveyance efficiency.
ii) Application efficiency.
iii) Storage efficiency.
iv) Distribution efficiency.

**Solution:**

i) Conveyance efficiency

$$\eta_C = \frac{W_F}{W_D} \times 100 = \frac{76}{100} \times 100$$

$$\eta_C = \mathbf{76}\%$$

ii) Application efficiency

$$\eta_a = \frac{W_S}{W_D} \times 100$$

$$W_D = \frac{76 \times 60 \times 60 \times 12}{1000} = 3283.2 \text{ m}^3$$

$$W_s = 3283.2 - 400 = 2883.2 \text{ m}^3$$

$$\eta_a = \frac{2883.2}{3283.2} \times 100 = 87.8\%$$

iii) Storage efficiency

$$\eta_S = \frac{W_S}{W_N} \times 100$$

Water holding capacity of the root zone=18 x 1.5=27cm

$$\text{Moisture required in the root zone} = 27 - \left(\frac{27 \times 50}{100}\right) = 13.5\text{cm}$$

$$W_N = \frac{13.5}{100} \times 2.5 \times 10000 = 3375 \text{ m}^3$$

$$E_S = \frac{2883.2}{3375} \times 100 = 85.4\%$$

iv) Distribution efficiency

$$E_D = \{1 - \frac{\overline{Y}}{\overline{d}}\} \times 100$$

$$\overline{d} = \frac{1.6 + 1.0}{2} = 1.3 \text{ m}$$

$$\text{Deviation from mean at the head} = 1.6 - 1.3 = 0.3$$

$$\text{Deviation from mean at the head} = 1.3 - 1.0 = 0.3$$

$$\text{Average deviation} = \overline{\mathrm{Y}} = \frac{0.3 + 0.3}{2} = 0.3$$

$$\eta_{\mathrm{D}} = \left\{1 - \frac{0.3}{1.3}\right\} \times 100 = 76.9\%$$

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Chapter 13

# Pressurized Irrigation Systems

**Junaid Nawaz Chauhdary, Ghulam Shabbir, Shahzad Ahmed and Ahmad Waqas***

## Abstract

Pakistan's cultivable area lies mostly in arid and semiarid climatic regions. Thus, more than 80 percent of its irrigation water requirement is met either through canal system or groundwater pumping. As the population is increasing every year, food requirement is also increasing and thus water required to produce more food is ultimately going higher every year. On the other hand, the per capita water availability is reducing and groundwater extraction is increasing annually. Therefore, the overall available water resources (surface and groundwater) are shrinking. Consequently, there is an imbalance between supply and demand, which demands more efficient utilization of the available water resources. Use of pressurized irrigation systems (Sprinkler and Drip Irrigation Systems), which have performance efficiencies significantly higher than the gravity irrigation system, may help solving the problem. Adoption and successful use of pressurized irrigation systems require that all the stakeholders, practicing irrigated agriculture, including farmers and professionals must update their knowledge about these systems. The Punjab Irrigation and Agriculture Departments have recently launched LBDCIP and PIPIP projects to introduce high efficiency irrigation systems (HEIS) among farmers for row crops, particularly cotton, maize, sugarcane vegetables and orchards on a participatory basis. Thus, it becomes important to provide sound knowledge based

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information to the professionals and users of these systems through books and other printed materials.

**Keywords:** Drip Irrigation, Sprinkler Irrigation, Drippers, Sprinkler Heads, Laterals, Operation Time

# Learning Objectives

1. To introduce the reader about the pressurized irrigation systems.
2. To familiarize the professionals and farmers about the components, design, installation, operation and maintenance of the pressurized irrigation systems.
3. Introducing improved systems to replace the traditional ones may encounter several issues that must be resolved to operate the systems successfully. The purpose of this chapter is to highlight such issues and their solutions.
4. The solved examples and questions to exercise, provide opportunities to the students for a better understanding of the subject.

# 13.1 Introduction

A pressurized irrigation system operates through a piping system where water flows under pressure as compared to gravity systems where water flows due to level difference. The pressurized irrigation system provides opportunities of minimum water losses which otherwise occur due to seepage, surface absorption and through evaporation in gravity flow condition particularly in open channel flow. This system also allows the irrigator to apply more precise quantities of water wherever is needed. Thus, the performance efficiencies are much higher than the gravity irrigation systems. Major types of pressurized irrigation systems include drip or trickle irrigation system and sprinkler irrigation system.

# 13.2 Drip or Trickle Irrigation

Drip irrigation, being a proven technology, has offered special agronomical, economical, and agro-technical advantages for efficient use of water and labor (Keller and Bliesner, 1990; Keller, 2002) and it can replace flood irrigation having 50-60% application efficiency with an efficiency of 90% (FAO, 1988; Leeds-Harrison and Rickson, 1992). Drip Irrigation is the slow application of available irrigation water on or beneath the soil surface as per the field capacity or intake rate of a soil for efficient use in crop production. Water is applied under low pressure through emitters/drippers placed along a lateral line. The device that emits water to the soil is called "emitter" that is either projected on the lateral or may be built in the lateral line. The size, diameter and shape of the emitter affect the operating pressure at discharge point and a small volume of water is discharged. Water flowing out from the emission points infiltrates into the soil and travel further by capillarity and gravity forces.

### 13.2.1 Advantages of Drip Irrigation

1. Highest irrigation application efficiency.
2. Increases yield per unit of water, thereby, increases the water use efficiency.
3. Increases fertilizer use efficiency and therefore, reduces overall production cost.
4. Its operating cost is low as compared to sprinkler irrigation systems.
5. Its operation is not affected by wind speed.
6. Less weeds germination in unirrigated parts of the field, hence, less use of weedicide, less labor requirement for eradication of weeds.
7. Ensure uniform development of crop, excellent quality produce.
8. Less energy cost if farmer previously irrigated his fields by flooding through tube well.
9. Early maturity of crop, early marketing of produce as compare to crop under flood irrigation.
10. Suitable to hilly and unlevelled areas where topography does not allow surface irrigation systems.
11. Daily irrigation keeps land wet and soft for easy penetration of crop roots.
12. Measured and uniform application of chemicals.
13. Reduces irrigation time.
14. Reduces soil compaction.
15. Reduced environmental contamination.

### 13.2.2 Limitations of Drip Irrigation

1. The initial installation cost of drip irrigation system is high.
2. Drip irrigation system operates under pressure that requires additional energy and thus adds to production cost.
3. Regular monitoring and maintenance of drip irrigation system is difficult for common farmer.
4. Salts may accumulate in dry zone area and leaching of salt requirement always exists.
5. Poor quality of irrigation water, arise problems like algal bloom and bacterial slime in the filtration system and may cause clogging of drippers/emitters.
6. Fertilizers and chemicals used for fertigation may corrosive to system parts.

### 13.2.3 Components of Drip Irrigation System

A drip irrigation system comprises of a pumping unit, filters, air release valves, control valves, pressure gauges, fertigation unit, main line, sub-mains, flush valves, laterals and emitters. The main line delivers water to sub-mains and sub-mains into laterals, and finally moves through emitters into the soil. Following are the main components of drip irrigation system:

#### 13.2.3.1 Head Unit

Head unit consists of prime mover (motor or engine), water pump, G.I or PVC pipe fittings, by pass valves, air release valve, filters, flow meter, non-return valve, pressure gages and fertigation unit. All head unit accessories are shown in Fig. 13.1.

#### 13.2.3.2 Field Unit

Field unit consists of main line, sub-mains, manifolds, and lateral lines with emitters, end plugs and flush valves. All field unit accessories are shown in Fig.13.1

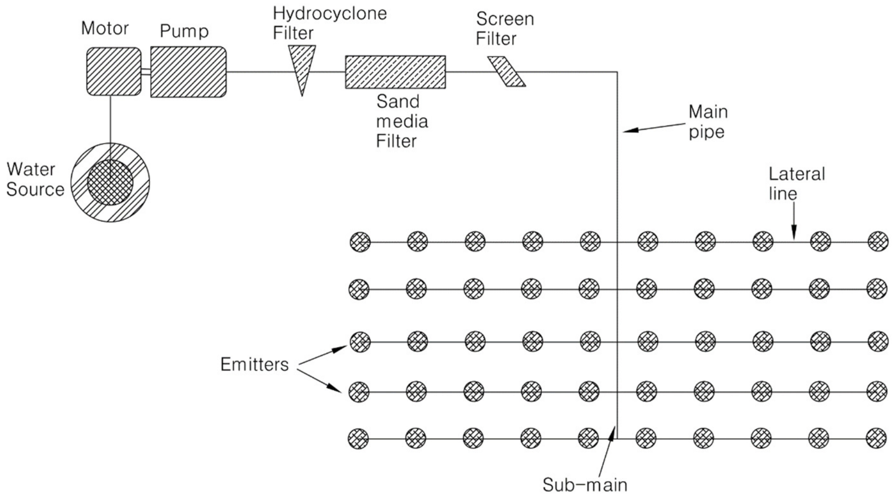


**Fig.13.1** Components of Drip Irrigation System

### 13.2.4 Design of Drip Irrigation System

Following steps are under taken to design drip irrigation system for a given crop, area and water availability:

- Survey of the area
- Water quality consideration
- Soil type
- Emitter selection
- Type of crop and peak water requirement
- Design of lateral, sub-main and main lines
- Selection of Pump
- Selection of Prime Mover

#### 13.2.4.1 Survey of the Area

Survey of the area, where the drip irrigation system is to be installed, requires the following data to be collected:

- Topography of area and relative position of highest point to the pumping unit
- Water quality and quantity of available water and time of irrigation
- Power source available with farmer
- Soil type
- Crop to be grown
- Physical features on ground surface and preparation of a base map.
- Demarcation of the area where mainlines, sub-mainlines and laterals are to be installed. Main-lines, sub-mainlines and laterals should be installed in such a way that they should not interfere with the normal tractor operations.
- Estimated cost (the system must be economical for the farmer).

#### 13.2.4.2 Water Quality Consideration

In drip irrigation system, water comes out from the emitters which have very small openings and can be clogged due to the soil particles, salts, which are always present in water. So, water quality is very important criteria in designing an efficient drip irrigation system for the area under consideration. Analysis of water tells about the presence of chemicals like Calcium carbonate, calcium sulfate, carbonates, silicates, sulfides etc., and suspended solids like sand, silt, clay, algae and bacteria. Calcium and iron precipitates are a potential problem with most of the well water. If bicarbonate level is higher than 2.0 meq per liter coupled with pH > 7.5, it is a major problem for emitter clogging. Iron is present in water in soluble (ferrous) form. It can produce enough slime to plug emitters if the water supply has an iron concentration of 0.3 parts per million (ppm) or greater and the pH of water is between 4.0 and 8.5. Algae are common in most surface water supplies, which can also clog emitters. Filtration system has to be selected according to the quality of irrigation water.

#### 13.2.4.3 Soil Type

In designing of drip irrigation system, soil type is always determined, which helps in the selection of emitters/drippers and their discharge.

The shape of the wetted zone depends on the physical properties of soil:

- In light soils the distribution of the water will be narrow and deeper.
- In heavy soil the distribution of the water will be relatively in spherical shape, wider and less deep.

#### 13.2.4.4 Emitter Selection

Emitter selection in designing a drip irrigation system depends upon the type of soil. The water from the emitter enters the soil and moves downward and sideways forming a cone (wetting pattern). The size and shape of the cone are affected mainly by emitter discharge, type of soil and duration of water application. Cone formation in heavy soils is shallower and wider, whereas, in lighter soils cone is narrower and deeper as shown in Fig. 13.2. In loamy soil, the water will move slowly and water will spread evenly. In heavy soils water is absorbed very slowly and runoff can occur if water is applied quickly because of densely packed particles of the soil profile. Therefore, there will be more lateral movement as compared to vertical movement.

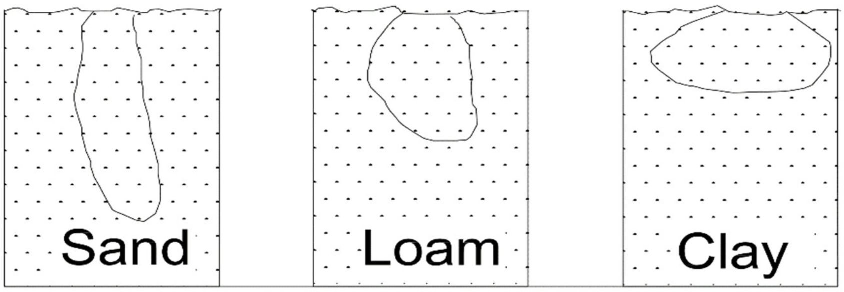


**Fig. 13.2** Cone Formation in different Classes of Soils

The emitter selection mainly depends on the infiltration rate of the soil. The emitter spacing decides the emitter discharge, however, the selection of emitter spacing and discharge for different soil is given in Table 13.1.

**Table 13.1** Recommended Emitter Spacing (cm) for different Soil Types and Emitter Discharge

| Soil Type | Discharge Rates (Lph) | | |
|---|---|---|---|
| | 2 | 4 | 8 |
| Light | 40 | 80 | 120 |
| Medium (cm) | 80 | 120 | 160 |
| Heavy | 120 | 160 | 200 |

Usually, emitter with 2 Lph discharge is used for heavy soils. In lighter soils, which are very loose and absorb water very quickly, no runoff occurs. Sandy soils do not hold water and thus dry out very quickly. For sandy soils 4 Lph discharge emitter can be used. Crop type also influences the emitter selection. There are two types of emitter: pressure compensating and non-pressure compensating. Pressure compensating emitters deliver a constant output of water even with changes of pressure and elevation. In non-pressure compensating emitters, output of water changes with the change in pressure and elevation.

#### 13.2.4.5 Type of Crop and Peak Water Requirement

Drip irrigation system designed for its maximum capacity, should consider type of crop and its peak water requirement. To calculate system irrigation requirement, row to row spacing, emitter to emitter spacing and discharge of emitters for a certain crop are needed to be decided as given below:

$$\text{Total flow (Lph)} = \frac{\text{Area (m}^2) * \text{Emitter flow (Lph)}}{\text{LL Spacing (m)} * \text{Emitter Spacing (m)}} \qquad (1)$$

Application rate is defined as depth of water applied per unit time or flow rate per unit area. It can be calculated by following two methods:

Method-1

$$\text{Application Rate (mm/hr)} = \frac{\text{Total Flow (Lph)}}{\text{Total Area (m}^2\text{)}} \qquad (2)$$

Method-2

$$\text{Application Rate (mm/hr)} = \frac{\text{Emitter Flow (Lph)}}{\text{LL Spacing (m)} * \text{Emitter Spacing (m)}} \qquad (3)$$

### 13.2.4.6 Design of Lateral, Sub-main and Main Pipe

The design of lateral, sub-main and main-line involves selection of required pipe diameter for a given length which can carry the required amount of discharge to the plant or crop in such a way that friction loss (head loss and velocity) should not exceed the designing criteria. The designing criteria is as following:

- The head loss in main and sub main pipe should not exceed 1 m/ 100 m and velocity should not exceed 1.5 m/sec.
- The head loss in lateral should not exceed 20% of operating pressure of emitter.

Availability in the market, affordability of price, and durability of material are also important aspects in selecting an efficient and economic pipe network.

The head loss in lateral, submain and mainline is calculated by using Hazen Williams equation given as following:

$$f = \frac{1222\ (\frac{Q}{c})^{1.852}}{D^{4.865}} \times (L + L_e) \qquad (13.4)$$

Where

f = Friction head loss (m)

c = Hazen-William's roughness constant (given in table 13.2)

q = Flow rate (Lps)

D = Inside diameter (mm)

L= Length (m)

$L_e$= Equivalent length of accessories (given in table 13.3)

Head loss can also be calculated through Darcy Weisbach equation:

$$h_f = 6.377 \frac{FLQ^2}{D^5} \qquad (13.5)$$

Where:

$h_f$= Head loss (m)

F= friction factor for Darcy equation

L= Length of pipe (m)

Q= Flow in pipe (Lph)

D= Diameter of pipe (mm)

**Table 13.2** Hazen-williams Coefficient 'c' for different Materials

| Material | Hazen-Williams Coefficient c |
|---|---|
| Aluminum | 130 – 150 |
| Asbestos Cement | 140 |
| Brass | 130 – 140 |
| Copper | 130 – 140 |
| Fiber | 140 |
| Galvanized iron | 120 |
| Plastic | 130 – 150 |
| Polyethylene, PE, PEH | 140 |
| Polyvinyl Chloride, PVC, CPVC | 150 |
| Smooth Pipes | 140 |
| Steel, welded and seamless | 100 |

**Table 13.3** Equivalent Length of Straight Pipe for Fitting Accessories (m)

| Accessory internal diameter | | 0.5 inch | 1.0 inch | 1.5 inch | 2.0 inch | 2.5 inch | 3.0 inch | 4.0 inch |
|---|---|---|---|---|---|---|---|---|
| Valves | Gate valve | 0.2 | 0.3 | 0.4 | 0.5 | 0.5 | 0.6 | 0.8 |
| | Ball valve | 2.4 | 3.4 | 4.6 | 5.8 | 6.7 | 8.2 | 11.6 |
| Elbows | Regular 90$^o$ | 1.1 | 1.6 | 2.3 | 2.6 | 2.8 | 3.4 | 4.0 |
| | Regular 45$^o$ | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.7 |
| Tees | Line flow | 0.5 | 1.0 | 1.7 | 2.3 | 2.8 | 3.7 | 5.2 |
| | Branch flow | 1.3 | 2.0 | 3.0 | 3.7 | 4.0 | 5.2 | 6.4 |

Friction factor (f) in Darcy equation can be calculated by using equations 13.6-13.8 for different flow regimes and Reynold's numbers.

$$\mathrm{F} = \frac{64}{\mathrm{Re}} \text{ for Re } < 2000 \quad (13.6)$$

$$\frac{1}{\sqrt{\mathrm{f}}} = 1.14 - 2\log_{10}\left(\frac{\mathrm{e}}{\mathrm{D}} + \frac{9.35}{\mathrm{Re}\sqrt{\mathrm{f}}}\right) \text{ For Re } > 4000 (13.7)$$

Where:

f= friction factor

e= internal roughness of pipe

D= inner diameter of pipe (mm)

Re= Reynold's number

$$\frac{1}{\sqrt{f}} = 2\log_{10}\left(\frac{e}{D}\right) + 1.14 \text{ For} Re > 10000 \quad (13.8)$$

f= friction factor

e= internal roughness of pipe

D= inner diameter of pipe (mm)

Re= Reynold's number

#### 13.2.4.7 Selection of Pump

Discharge and head are the two important parameters for the selection of the pump in the design of drip irrigation system. Pump discharge is calculated by multiplying the emitter discharge by total number of emitters in the area. Head developed by the pump should be sufficient to overcome head loss in the system and provide 1 bar head at the exit. Total head loss includes: head loss in laterals, sub-main, main, emitter operating pressure and head loss in power unit and filtration system. Pump size can be selected using pump characteristic curves provided by the manufacturer. A typical pump characteristic curve of the head vs pump for various pump rpm is given in Fig. 13.3.

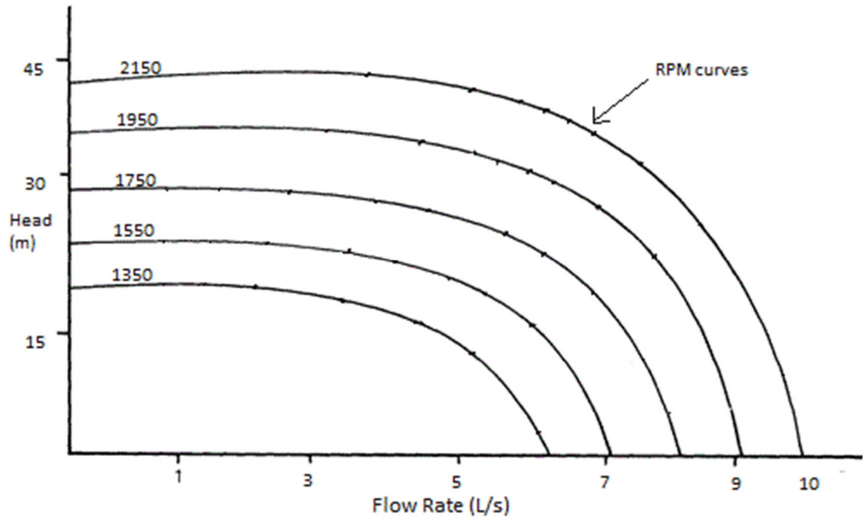


**Fig. 13.3** Characteristic Curves for Pump Selection

#### 13.2.4.8 Selection of Prime Mover

Motor power can be determined by using the equation 13.9.

$$Hp = \frac{Q * H}{76} \quad (13.9)$$

Where:

Hp = Horse power

Q = Discharge (Lps)

H = Head (m)

**Example 13.1:** Determine HP of prime mover if the pump discharge is 25 Lps and the total head against which water is to be lifted is 45 m. Take the motor efficiency as 60%.

Given:

Q = 25 Lps

H = 45 m

$$Hp = \frac{25 * 45}{76}$$

Calculated Hp= 14.8

Actual Hp = $\frac{14.8}{0.6}$ = 24.6→ 25

**Example 13.2:** Design a drip irrigation system for Cotton crop with the following data:

Area = 160 x 120 $m^2$

Plant x Plant= 0.5 m

Row x Row= 1 m

Water source: Both tube well and canal water is used for irrigation.

Suction lift: 2 m

Delivery lift: 2 m.

**Solution**

Field survey is conducted and field layout is developed. To reduce the system capital and operational cost, the whole field is divided into four equal zones as shown in Fig. 13.4. The location of power unit, mainline, sub-main and lateral is also determined. In field survey, it is also analyzed that the soil of the area is sandy loam.

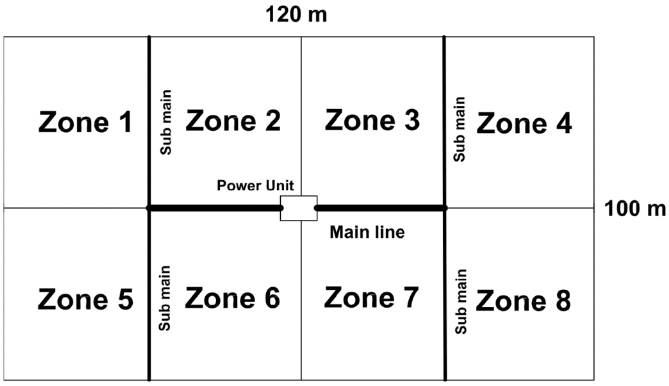


**Fig. 13.4** Field Layout of Case Study

### Water Sampling

Water from canal and tubewell is stored in a settling pond where all impurities like suspended, chemical and biological were present. Hydrocyclone, sand media and screen filters are selected to control and clean the impurities.

### Emitter Selection

The emitter with 4 Lph discharge is recommended for sandy loam soils. The lateral with 4 Lph and 0.30 m emitter spacing is selected as per availability in market.

### Discharge of One Zone

As the drip irrigation system is divided into eight operational zones so the number of plants in one zone is as following:

Dimension of one zone= 30 × 50 $m^2$

Number of laterals in one zone= 50/1 = 50 (as RxR= 1 meter)

Length of lateral= 30 m

Total emitters in one lateral= 30 /0.30 = 100 (as emitters spacing on lateral line was 0.30 m)

Total emitters in one zone= 100 × 50= 5000

Total discharge in one zone= Emitter discharge x No. of emitters

Total discharge in one zone= 5000 × 4= 20000 Lph

Design of Lateral, Sub-main and Main Pipe

The lateral diameter is selected on the basis of head loss, price of lateral and market availability. The lateral with 12 mm diameter is selected.

The head loss was calculated by equation 13.5

$$\mathrm{hf} = 6.377\frac{\mathrm{FLQ}^2}{\mathrm{D}^5}$$

**Lateral Pipe**

The diameter of lateral pipe= 12 mm

The length of lateral pipe= 30 m

Total emitters on one lateral= 30/0.30= 100

Total flow of lateral pipe= 100 × 4= 400 Lph

Head loss in lateral pipe= 1.8 m

By using head loss equation, the diameter of main and sub-main pipe is selected in such a way, so that design requirements are fulfilled.

**Sub-main Pipe**

The diameter of Sub main pipe= 76.2 mm

The length of sub main pipe= 50 m

Total flow of sub main pipe= 50 × 400 = 20000 Lph

Head loss in sub main pipe= 0.5 m

**Main Pipe**

The diameter of main pipe= 76.2 mm

The length of main pipe= 30 m

Total flow of main pipe= 20000 Lph

Headloss in main pipe= 0.3 m

**Pump Selection**

Discharge of pump= 20000 Lph = 5.5 Lps

Total Head of pump= Emitter operating pressure+ Head loss in lateral+ Head loss in submain+ Head loss in main line + Head loss in the joints, turns, filtration unit plus miscellaneous head loss+ suction lift + Delivery lift.

Required Head of pump= 10 + 1.8 + 0.5+ 0.3 +20 + 2+ 2 = 36.6 ≈37 m

Assume Pump efficiency = 60 %

Required Discharge= 5.5 /0.6= 9.16 ≈ 9 Lps

According to discharge, head requirement and market availability, pump is selected with 14.1 Lps discharge and 44 m head.

**Motor Selection**

Motor selection is done by using equation 13.9. Efficiency of the motor is kept at 75 % according to supplier

$$\mathrm{Hp} = \frac{\mathrm{Q} * \mathrm{H}}{76 * \ \mathrm{efficiency}}$$

$$Hp = \frac{9 * 37}{76 * 0.75}$$

Hp=5.84 ≈ 6 Hp

**Example 13.3:** Design a drip irrigation system for the following data:

Area = 180 m x 160m

Soil type = Sandy loam

Crop = Mango plants

Plant stage= Mature

Plant to plant distance = 10 m

Row to row distance = 10 m

Water table is 15 m below from the ground surface in existing dug well

Delivery head is 2 m above ground surface

Given:

Area = 180 m x 160m = 28800 $m^2$

Water source= Dug well

Suction lift (m) = 0 m (Use submersible pump, as the water table 15 m below ground surface)

Delivery lift = 15+2= 17 m

Plant spacing = 10 m

Row spacing = 10 m

Discharge Required

Calculate total no. of plants = 28800/ (10 x 10) = 288

Assume emitter discharge = 8 Lph (As plants are mature)

Calculate total No. of emitters (4 per plant) 288 x 4 =1152

Calculate total flow rate = 1152 x 8 = 9216 Lph = 2.56 Lps

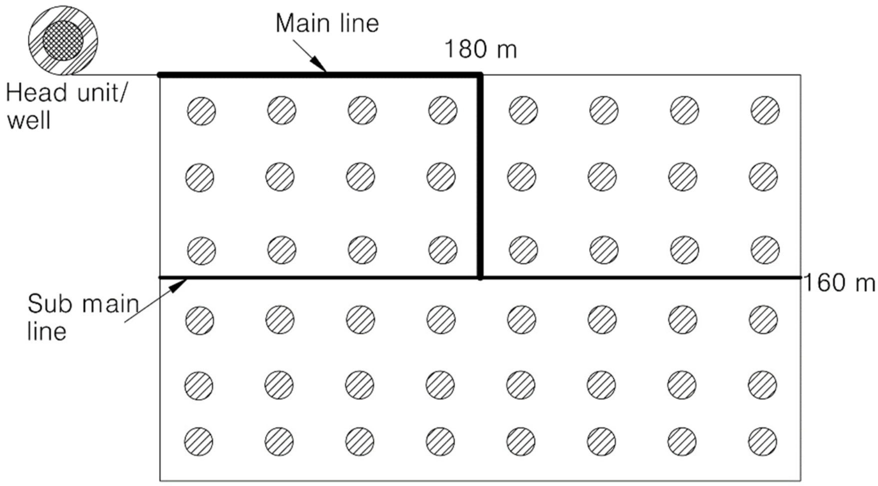


**Fig. 13.5** Layout of Orchard Field

**Lateral Pipe Head Loss**

The diameter of lateral pipe= 12 mm

The length of lateral pipe= 80 m

Total emitters on one lateral= 80/10= 8 × 4= 32

Total flow of lateral pipe= 32 × 8= 256 Lph

Head loss in lateral pipe= 1.9 m

**Sub-main Pipe**

The diameter of sub-main pipe= 63.5 mm

The length of sub main pipe= 90 m

Total laterals on one sub main= 90/10= 9×2= 18

Total flow of sub main pipe= 18 × 256=4608 Lph

Head loss in sub main pipe= 0.4 m

**Main Pipe**

The diameter of main pipe= 63.5 mm

The length of main pipe= 170 m

Total flow of main pipe= 9216 Lph

Head loss in main pipe= 0.9 m

**Pump Selection**

Discharge of pump= 2.56 Lps

Total Head of pump= Emitter operating pressure+ Head loss in lateral+ Head loss in submain+ Head loss in main line + Head loss in the joints, turns filtration unit plus miscellaneous head loss+ suction lift + Delivery lift.

Required Head of pump= 10 + 1.9 + 0.4+ 0.9+20+ 0+ 17 = 40.2 ≈ 41m

Assume Pump efficiency = 60 %

Required Discharge= 2.56 /0.6= 4.26 ≈ 4.3 Lps

**Motor Selection**

Motor selection is done by using equation 13.9. Efficiency of the motor is kept at 75% according to supplier.

$$\mathrm{Hp} = \frac{\mathrm{Q} \times \mathrm{H}}{76 \times \mathrm{efficiency}}$$

$$\mathrm{Hp} = \frac{4.3 \times 41}{76 \times 0.75}$$

Hp=3.09 ≈ 3Hp

## 13.2.5 Fertilizer Application

Nitrogen, phosphorous and potash are important plant nutrients which are supplied to obtain optimum crop production. These nutrients are made available to the crops from different sources like Urea, DAP, Diammonium phosphate, Mono ammonium phosphate, Urea and SOP, etc. but due to the solubility problem of conventional fertilizers, water soluble fertilizers are preferred in drip irrigation to avoid emitter clogging. Following points must be kept in mind before the application of fertilizers in drip irrigation

- Fertilizer must be fully water soluble and does not make precipitates
- Should not increase the pH of irrigation water
- Fertilizers must be economical
- Easily available in market
- Readily available to plants

### 13.2.5.1 Fertilizer Injection Methods

Pesticides, herbicides and fertilizer can be injected into the drip irrigation system using (a) By-pass pressure tank (b) Venturi system (c) Direct injection system.

(a) **By-pass Pressure Tank:** In this method, a tank is provided in which dry or liquid fertilizers are placed. An agitator is fixed at the top of the tank for mixing the fertilizer. The tank is connected to main irrigation line with help of a by-pass valve at the entrance of tank for the inflow of irrigation water into the tank to dilute the fertilizer. Another by-pass valve is given at the outlet of the tank to let the fertilizer go into the irrigation system. In this method of fertilizer injection, rate of fertilizer injection changes with time.

(b) **Venturi Injector:** This is a qualitative method of fertilizer injection in which the rate of fertilizer injection remains the same throughout the time of injection. The working principle of the venturi is that the velocity of flow is increased due to small dia of venture at center that causes a pressure drop in flow pipe which creates a vacuum and sucks the fertilizer. The rate of fertilizer injection is controlled by means of valves. This is the cheapest method of fertilizer injection.

(c) **Direct Injection System:** In this method, a pump is used to inject fertilizer solution directly into the irrigation line. The use of this method is limited because it requires an additional source of power to operate the pump. On the other hand, this method can be automatically controlled and convenient to use because of control over the injection rate with less head loss.

### 13.2.6 Emitter Clogging

Clogging of emitters has been a major problem with the use of drip irrigation systems, especially when fertilizers are applied through the system or when irrigation systems are operated under an inadequate pressure. This problem is not unique in Pakistan rather it is a universal characteristic of drip system applications. Clogging of drippers depends upon source of water. The water quality criteria for emitter clogging are given in Table 13.4.

**Table 13.4** Degree of Clogging as Affected by Different Materials

| Potential Problem | Units | Degree of Restriction on Use | | |
|---|---|---|---|---|
| | | None | Slight to Moderate | Sever |
| Suspended solids | mg/l | <50 | 50-100 | >100 |
| pH | | <7 | 7-7.5 | >7.5 |
| Dissolved solids | mg/l | <500 | 500-2000 | >2000 |
| Manganese | mg/l | <0.1 | 0.1-1.5 | >1.5 |
| Iron | mg/l | <0.1 | 0.1-1.5 | >1.5 |
| Hardness as $CaCO_3$ | mg/l | <150 | 150-300 | >300 |
| Bacterial population | mL | 10000 | 10000-50000 | >50000 |

*Source: Storlie, 1995*

Source of water may be surface or groundwater. Bacterial growth and algae are major problems associated with surface water use. These algae content form aggregate that can clog emitters. Groundwater contains a greater concentration of minerals that can clog the system by precipitation. The acidification and chlorination are used to unclog emitters.

#### 13.2.6.1 Filtration

The major problem with drip irrigation is clogging of emitters by chemical and biological materials. Drip irrigation has low flow rates and extremely small passages (emitter) for water these passages are easily clogged with organic and mineral particles carried out irrigation water and by chemical precipitates and biological growth, that develop within the system, clogging adversely affects the performance of drip irrigation system, resulting in less flow than the designed thus affecting the system distribution efficiency. The major clogging contributors are given in Table 13.5.

**Table 13.5** Clogging Contributors in Drip Irrigation System

| Physical (Suspended Particles) | Chemicals (Precipitation) | Biological (Bacteria and algae) |
|---|---|---|
| Organic: Algae, bacteria, diatoms, larvae, fish, snails, seeds, plants parts | a) Calcium carbonate<br>b) Calcium sulphate | a) Filaments |
| Inorganic: Sand, silt, clay | c) Heavy metals hydroxide, oxides, carbonates, Silicates and Sulphides<br>d) Fertilizer, phosphate, aqueous, ammonia, iron, zinc, cooper, manganese | b) Slime microbial deposition, iron sulphur manganese |

*Source: Bucks et al., 1979*

To remove these impurities, some arrangement techniques for filtration and some filters are used.

**Types of Filtration**

**a) Settling Ponds:** These can be used to remove large volumes of sand and silt. Algal growth and windblown contaminants in the pool cause more filtration problem than sediment, therefore, open water from a pond supply should be avoided. If water is drawn from the pool, it must be chemically treated or filtered through a combination of filters and screens. Minimum 15 minutes are required for most in-organic particles larger than 80 microns to settle.

**Fig. 13.6** Settling Ponds

**b) Hydrocyclone Filter:** These filters remove 98% of the sand particles that would be removed by 200 mesh screen. It depends upon the centrifugal force to remove or eject high density particles from the water. Hydrocyclone filters cannot remove organic materials.

**Fig. 13.7** Hydrocyclone Filters

**c) Sand Media Filter**

These filters have graded sand of selected sizes inside a cylindrical tank. As water passes through the tank, the gravel or sand filters out heavy loads of very fine sand and organic materials. These filters are more effective for organic materials as well as for long and narrow contaminants such as algae and diatoms which are caught on multi-layered sand bed than single screen filters. To measure the head loss in the filter, it is recommended that pressure gauges should install at the inlet and outlet of the filter. If the head loss exceeds more than 3.0 kPa, filter needs back washing. To clean the filter, open the drainage valve of filter and reverse the direction of water inflow into the filter until the deposits wash out from the filter.

**Fig. 13.8** Sand Media Filters

**d) Screen Filter**

As most of the impurities in water are filtered by hydrocyclone and sand media filter, screen filters are provided as a safeguard against any physical impurities left unfiltered from hydrocyclone and sand media filter. The screen filter usually contains cylindrical screens, which filters physical impurities and allows only clean water to enter the drip irrigation system. The screens are mostly made of plastic material and non-corrosive metal as shown in Fig. 13.9. The screen filters are available in market with screen sizes ranging from 20 mesh to 200 mesh with different flow rate capacities.

### 13.2.6.2 Chemical Treatment of Drip Irrigation System

To prevent drip irrigation emitters from clogging due to mineral precipitations and inorganic particles, timely and regular application of chemicals is often required. These chemicals included acids and chlorine.

**(i) Acidification**

Treatment of drip irrigation system with acids such as sulfuric, phosphoric or hydrochloric (muriatic) acid is known as acidification. The most common deposits in irrigation water are iron oxides and magnesium or calcium carbonates. To reduce the potential for chemical precipitations, acids are used to lower the pH of irrigation water (below 7.0) because in irrigation water with high pH (above 7.0), precipitation occurs more readily.

**Fig. 13.9** Screen Filters

The injection rate of acids should be adjusted in such a way so that the pH of irrigation water reaches just below 4.0 to prevent magnesium and calcium precipitates from aggregate forming. The amount of acid required to treat a system depends on (a) the strength of the acid being used (b) the target pH and (c) the buffering capacity of the irrigation water. A "titration test" can be used to determine the optimum volume of acids needed to get the desired pH of water and prevent plat roots from any damage.

**(ii) Chlorination**

Treatment of drip irrigation system with chlorine such as chlorine gas or liquid sodium hypochlorite (household bleach) is known as Chlorination. To decompose and remove Bacteria, algae and fungi from drip irrigation laterals and emitters, chlorine is used as a powerful oxidizing agent. When chlorine is dissolved in water, hydrolysis reaction occurs where chlorine molecules combine with water. The hydrolysis reaction produces hypochlorous acid (HOCl) as shown in Eq.13.10.

$$H_2O + Cl_2 = HOCl + H^+ + Cl^- \quad (13.10)$$

Hypochlorous acid further ionized in to hypochlorite:

$$HOCl = H^{+} + OCl^{-} \quad (13.11)$$

The effectiveness of hypochlorite in killing microorganism is about 40 to 80 times lesser than hypochlorous acid (HOCl). Thus, water with high pH will result in a low concentration of HOCl. The active form of chlorine as HOCl at different pH levels of irrigation water is given in table 13.6. The efficiency of chlorination is greatly dependent upon the quantity of bacteria and pH of the irrigation water source. To lower the pH of irrigation water, acids can be used to increase the efficiency of chlorination.

**Table 13.6** Available Form of Chlorine as Active HOCl at different pH Levels of Irrigation Water

| pH of water | Available active chlorine |
|---|---|
| 8 | 24% |
| 7 | 72% |
| 6 | 97% |

# 13.3 Sprinkler Irrigation System

In the sprinkler method of irrigation, water is sprayed into the air and allowed to fall on the ground surface somewhat resembling rainfall. The characteristics of the system include:

- A network of pipelines is used to convey water to the field and distribute to crops through sprinkler heads in the field. The spray is produced by pumping of water under pressure through small orifices or nozzles. With careful selection of nozzle sizes, operating pressure and sprinkler spacing, the amount of irrigation water required to refill the crop root zone can be applied nearly uniformly at the rate less than the infiltration rate of the soil, thereby obtaining efficient irrigation.
- The system provides efficient coverage for small to large areas, for a wide range of crops and soils. However, these are recommended for sandy soils that have a high infiltration rate and not suited for fine textured soils (Infiltration rate less than 4 mm/hr).
- Sprinkler irrigation system is suitable for steep slopes or irregular topography. If soil erosion is a hazard, sprinkler irrigation can be used in conjunction with contouring, terracing, mulching and strip cropping.
- In sprinkler irrigation, land leveling is not essential.
- In sprinkler irrigation system, there is a provision to apply soluble fertilizers, fungicides and herbicides during the irrigation.

## 13.3.1 Advantages of Sprinkler System

1. Sprinkler irrigation permits efficient irrigation and enables judicious utilization of water.

2. It provides better control over water application convenient for giving light and frequent irrigations and water application efficiency approaching 80%.
3. It saves 10 to 16% land by eliminating channels and ridges needed in other methods.
4. Sandy soils (permeable soils) as well as sandy clay soils (Less permeable soils) can be easily irrigated by this method, without any risk of inundation, erosion and seepage losses.
5. The system saves the extra labor required for the application of fertilizers, pesticides and weedicides.
6. It is suitable for irrigating the crops with very high plant population per unit area. It is most suitable for vegetable, oil and cereal crops.
7. The system permits partial or full portability, wherever required.
8. Lesser chances of clogging of sprinkler nozzles as compared to drip irrigation system.
9. The system is flexible to permit very light application of water for less than 1 inch depth, which is not possible with surface irrigation systems

### 13.3.2 Limitations of Sprinkler System

1. High initial cost of equipment.
2. Excessive use of Energy to create operating pressures of the order of 3 to 6 bars.
3. Higher operating cost because of skilled labor.
4. Winds can disturb the water distribution that causes uneven irrigation.
5. Foliar application of saline water may burn the plant leaves.
6. Under certain climatic conditions, diseases may be exhilarated like fruit rotting in strawberry and tomato.
7. The larger labor force needed to move the pipes and sprinklers around the field.
8. Evaporation losses are high as compared to other irrigation methods because of sprinkling.
9. Tall crops may obstruct center pivot or side-roll portable sprinkler systems.
10. Falling sprinkler drops on bare soil can cause soil crusting.
11. The maintenance cost is high.
12. Due to complexity and expertise requirements, the chances of system failure increases.
13. Excessive wetness of plant leaves may develop certain diseases.

### 13.3.3 Components of Sprinkler System

The main components of sprinkler irrigation systems are shown in Fig. 13.10. These components are as follow:

- Pumping unit
- Main and sub-main lines
- Lateral lines
- Sprinkler heads
- Fertilizer applicator

- Fittings and accessories (Water meter, pressure gauges, couples, flanges, nipples, take of valve, flow control valve)

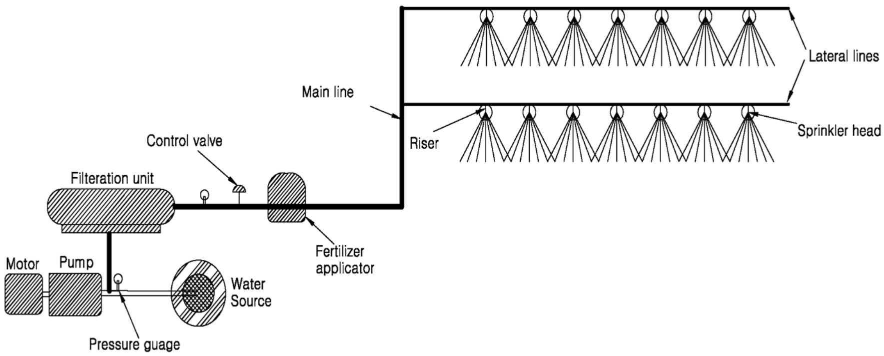


**Fig. 13.10** Component of a Typical Sprinkler Irrigation System.

### 13.3.3.1 Pumping Unit

In sprinkler irrigation systems, water is sprayed over the fields under certain pressure usually provided by a pumping system. It is an essential requirement in the system that the pump should be designed to lift the required amount of water from the water source to the highest point in the field. Centrifugal pumps are commonly used for this purpose, which can be permanent or portable. While the turbine pump is used for deeper water source and it should, generally, be set at a fixed location.

The driving unit may be either an internal combustion engine or electric motor. Electric motors are best for fixed installations. They have low initial and running costs and are easier to maintain. Engines are used when the pumping unit is portable and at places where electricity is not available. The engine maintenance and fuel cost make the system costlier.

### 13.3.3.2 Main and Sub-Main Lines

Main line conveys water from the source and distributes it to the sub-mains. Main lines may be permanent or portable. Mains are generally permanent on the farms with fixed field-boundaries and where crops require full-season irrigation. Portable mains are more economical when a sprinkler system is to be used in several fields on different locations. The material used for pipes can be steel, asbestos, aluminum and PVC. Steel pipes are used for most permanent main lines and for center-pivot laterals. The permanent lines should be buried to be out of the way of farming operations. Light weight aluminum pipes may also be used for portable main lines. Portable mains, generally, have a lower initial cost and do not provide an obstruction to field operations. The laterals/sub-mains are coupled with the mains either through a valve set at each point of junction or in some cases through 'L' or 'T' section that is supplied in place of one of the couplings on the main.

#### 13.3.3.3 Lateral Lines

These pipes are smaller in diameter as compared to main or sub-mains. They receive water from the main/sub-main and deliver it to riser pipes or directly to the field in case of perforated pipe or side roll type of sprinkler systems. Most of the portable laterals are made of light weight steel or high density polyethylene. The lateral lines usually are portable. Buried permanent laterals are, however, used for some orchards, tree nurseries, and for other special sites. Aluminum pipe is best for most portable laterals. The lateral pipes are usually available in lengths of 5, 6 or 12 m. Each length has quick couplings. The rubber gasket in the female portion of these couplings has a U-shape. The water pressure forces the outside of the 'U' to form a water tight seal. When the water is turned off, the seal is broken and water drains from the pipe, making it easier to uncouple and move.

#### 13.3.3.4 Sprinkler Heads

The sprinkler head is the main component of a sprinkler irrigation system. The sprinkler head is responsible for uniform distribution of water over the field without water loss due to deep percolation and runoff. Sprinklers are either fixed or rotating. For a wide range of application and spacing, the rotating type of sprinklers can be adapted. For irrigation of small lawns and gardens, fixed head sprinklers are used. The operating pressure of sprinkler heads ranging from 16 to 40 m depends on the sprinkler type and range of shoot. A typical rotating head sprinkler is shown in Fig. 13.11.

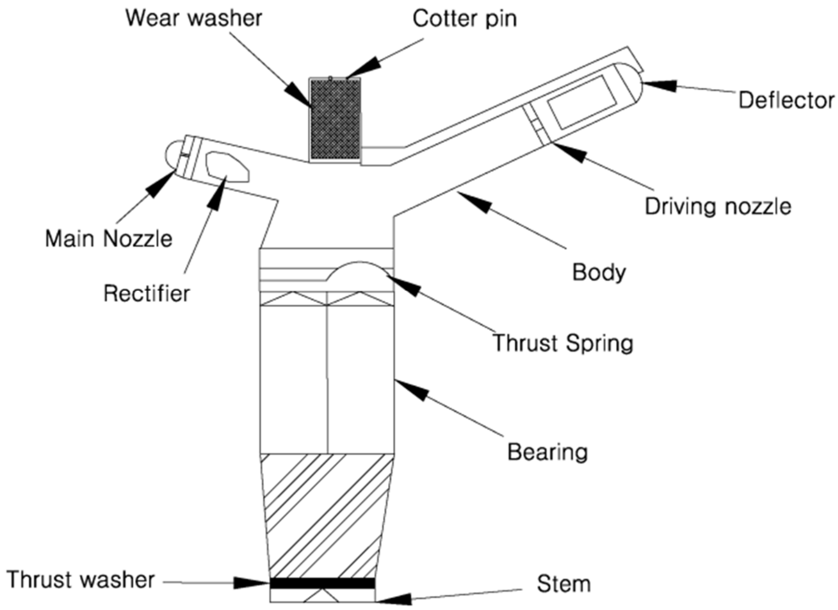


**Fig. 13.11** Details of a Twin-Nozzle Rotating Sprinkler Head.

#### 13.3.3.5 Fertilizer Applicators

It is an optional component that is used to inject soluble fertilizers into the sprinkler system and to apply it to the crops without any danger of being leached away. Both irrigation and fertigation are performed simultaneously in this way, hence, considerable time of the farmer, required for fertigation, is saved. The components of fertilizer applicator include a fertilizer tank, injection pump and a network of pipes and connections. A venturi apparatus can also be used to inject fertilizer directly in the main pipe during irrigation. If the fertilizer is to be injected from suction side of the pump, the pump impeller should be made of corrosion resistant materials. Whenever it is planned to inject fertilizer through sprinkler system, the system should be run long enough to wet the soil and the plant foliage prior to fertilizer application.

#### 13.3.3.6 Fittings and Accessories

The detail of fittings and accessories used in sprinkler system is given below:

a. *Water meter*: It is used to measure volume of delivered water.
b. *Pressure gauges*: These are used to measure system pressure during operation to check that if system is working with desired pressure to ensure application uniformity.
c. *Couplers*: Coupler should provide: a leak proof joint, eases of coupling and uncoupling, flexible connection and durability.
d. *Flanges, couplings and nipples*: These are used for establishing proper connections to the pump, suction and delivery pipes.
e. *Take-off valves*: These are, generally, used to control the lateral line pressures particularly wherever significant differences in main line pressures exist at the various lateral take-off points.
f. *Flow control valves*: These components are needed when non-uniform pressure distribution along the laterals caused by undulating topography of the land is there.

### 13.3.4 Types of Sprinkler Irrigation Systems

Based on the arrangement of spraying and portability of the system, the sprinkler irrigation systems are classified into many types. These systems exist in various sizes, shapes, capabilities and costs. The sprinkler's types which are mostly used are described below:

#### 13.3.4.1 Rotating Head Systems

These systems consist of small size sprinkler nozzles, fitted on lateral pipes at uniform. The lateral pipes are laid in the field usually on ground. These nozzles are rotated through 90°-360° to irrigate crops. In rotating type sprinklers, to rotate the sprinkler heads, commonly a small hammer mechanism is used that is activated by water head.

#### 13.3.4.2 Perforated Pipe Systems

In these systems, perforations are present in the lateral irrigation pipes in a specially designed pattern to distribute water uniformly. Usually, these systems work with low operating pressures of about 0.5 to 2.5 kg/cm$^2$. The pressure required for the system can be attained by connecting the system to an overhead tank. The sprays are directed at both sides of the pipe and can cover a strip of land from 6 to 15 meters wide depending upon the pressure applied. The water is applied at a relatively high rate, and therefore, it is suitable for soils having moderate infiltration rates. These systems are suited for irrigation of lawns, gardens and small vegetable fields and other plants when the crop height does not exceed from 40 to 60 cm. The water should be cleaned through a filter to prevent clogging of the small perforations.

#### 13.3.4.3 Side Roll System

To irrigate rectangular fields, mostly side roll sprinkler systems are used. It consists of a wheel with lateral lines mounted on it with a pipe forming the axle. A driving unit (engine), located near the center of the lateral, is used to move the system during irrigation along the length of field. The height of system is controlled by wheel diameter according to crop height so that system can move without any obstruction.

#### 13.3.4.4 Rain-gun System

These are high performance impact sprinklers designed for a variety of uses and applications where relatively high flows and extended radius of throw are desired. Rain gun systems use large volume sprinklers operating at relatively high pressures (3-6 Bars), mounted on a riser stand or towed through the field (Fig. 13.12). The operating pressure of rain guns usually ranges between 2.0 to 7.5 kg/cm$^2$ and flows of 3 to 30 L/s usually with nozzle diameters ranging from 10 to 30 mm and with a wetting radius of 27 to 60 m (Tajuddin & Somasundaram, 2012). It gives the extraordinary pressure at all operating levels, works smoothly and uniformly over the whole nozzle pressure range. Excellent hydraulic design, large barrel cross section and full size taper bore nozzle allows maximum possible throw and performance. Almost no maintenance is required. It can be adjusted to different stream, break-up frequencies and to various rotation speeds to optimize the water distribution. Variable trajectory angle option allows the changing trajectory angle of various ranges, thus providing more uniformity even in windy conditions. It is mostly recommended for the field crops like Sugarcane, Pulses, Oil Seeds, Cereals, Tea, Coffee and Vegetables, etc.

There are three types of rain-gun sprinkler irrigation system that are: (a) Permanent System (b) Semi-Permanent System and (c) Portable System. In permanent systems, the rain-gun riser stands are installed permanently and fitted to solid set pipeline network. Riser can also be supported by a cement concrete block around it. In semi-permanent system pipeline network, can be permanent and rain-gun riser stand or only rain-gun shifts from one location to another. In this type of systems, the rain-gun riser stand can be detachable. In portable system, entire pipeline network, along with the rain-gun riser stand and rain-gun, can be shifted from one location to another. Easily detachable quick-connect pipes are used for this purpose.

**Fig. 13.12** Rain-Gun Sprinkler Irrigation System

#### 13.3.4.5 Center Pivot Systems

The center pivot system consists of a single sprinkler lateral supported by a series of towers. The towers are self-propelled so that the lateral rotates around a pivot point in the center of the irrigated area (Fig. 13.13). The time for the system to revolve through one complete circle can range from an hour to many hours. The longer the lateral, the faster the end of the lateral travels and the larger the area irrigated by the end section. Thus, the water application rate must increase with distance from the pivot point at the other end to deliver water evenly in the field. A variety of sprinkler products have been developed specifically for use on these machines to better match water requirements, water application rates and soil characteristics. Since, the center pivot irrigates in a circle, it leaves the corners of the field un-irrigated (unless additions of special equipment are made to the system). Center pivots are capable of irrigating most field crops but have on occasion been used on tree and vine crops.

**Fig. 13.13** Center Pivot Sprinkler System

## 13.3.5 Design of Sprinkler Irrigation System

Appropriate flow of water and its pressure in the system are important factors to operate the sprinkler irrigation system successfully. Properly designed, installed, maintained and managed sprinkler irrigation systems greatly reduce the water and pressure losses in the system.

Properly designed piping, with sound hydraulics, can also reduce the maintenance problems of an irrigation system. Keeping the water flow velocity within limits reduces wear of the system components and lengthens service life. Poor hydraulic design results in poor performance of the irrigation system, leading to stressed landscaping, material, or even broke pipes and flood damage.

Following design steps are generally adopted for a typical sprinkler irrigation system:

- Preliminary field survey
- Selection of sprinkler nozzles
- Sprinkler coverage and system layout
- Estimation of system head losses
- Estimation of power requirement
- Calculation of operation time

#### 13.3.5.1 Preliminary Field Survey

The site information required to design the sprinkler irrigation system would include soil type, water supply, crop and its water requirement etc. The detail of these components is given below:

a. **Soil Type:** Soil is natural formation that can absorb water in between its pore spaces. As the pore spaces varies with different soil types, so the water holding and water intake capacity of soil varies with different soil types. The soil infiltration rate (intake rate) influences the type of sprinkler that can be used. The water holding capacity (field capacity) of soil greatly affects the irrigation schedule. The sprinklers are not suitable for soils which have low infiltration rate (clay soils). If sprinkler irrigation is the only method available in that area, then low discharge sprinklers should be used. The larger sprinklers producing larger water droplets are to be avoided to save the soil structure.

b. **Water Supply:** The irrigation practices are influenced by the quality and quantity of the water source. During the growing season, frequent irrigations are suited for small discharge water supplies with low irrigation depth, whereas irrigation frequency should be less for large water supplies with more irrigation depth. The water quality also affects irrigation scheduling. The trace elements like boron or selenium along with water salinity can affect the irrigation scheduling of crops. The application of poor quality water must be frequent and low discharged than the application of good quality water.

c. **Crop and Its Water Requirement:** Sprinkler irrigation is suited for field crops and small tree crops. During irrigation, sprinkler can spray water over or under the crop canopy. However, large sprinklers are not recommended for irrigation of delicate crops such as lettuce because the large water drops produced by the sprinklers may damage the crop.

#### 13.3.5.2 Selection of Sprinkler Nozzles

The sprinkler operating pressure, size of field and shape of field affects the selection of nozzles for irrigation. Rotary nozzle type sprinklers are preferred for pressure less than 40 PSI static. If the area to be watered is greater than 25 ft x 30 ft, rotors may be the best solution. Rotors are not suited for sharp curve edges (less than 20 ft radius). If the area beyond the edge should not get water on it, smaller rotary nozzle or spray-type sprinkler may be adopted. In Table 7, some sprinkler nozzles and their specifications are given.

**Table 13.7** Sprinkler Classification.

| Sprinkler type | Nozzle size | Pressure (m) | Radius (m) | Discharge (Lps) | Area covered |
|---|---|---|---|---|---|
| 20 | 6-8 | 30-40 | 19-23 | 0.66-1.28 | 1584 |
| 30 | 9-12 | 30-40 | 24-29 | 1.38-2.74 | 2584 |
| 40 | 12-16 | 30-45 | 27-36 | 2.64-5.44 | 3960 |
| 50 | 16-20 | 40-50 | 37-42 | 4.97-8.47 | 5544 |

*Source: PARC, 2001*

#### 13.3.5.3 Sprinkler Coverage and System Layout

The area watered by each sprinkler must overlap substantially the area watered by the adjacent sprinkler. This overlap may seem like a waste at first, but it is a very important necessity. Without this overlap it would be impossible to design sprinkler systems that provided uniform water coverage. Sprinkler coverage, crop geometry and pipe spacing influences the layout of the system.

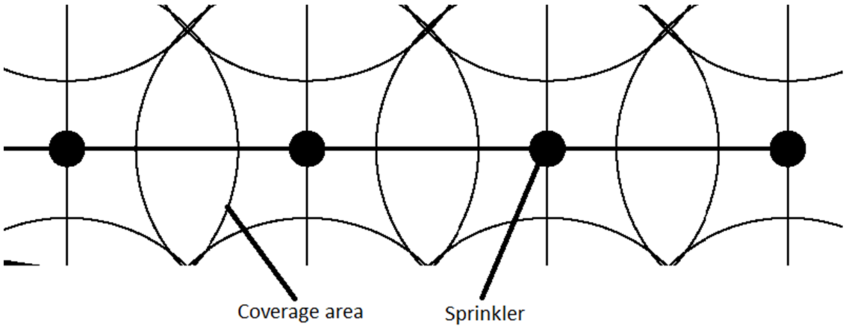


**Fig. 13.14** Sprinklers Spaced Head to Head

#### 13.3.5.4 Estimation of System Head Losses

In the pipe network, the head loss can be calculated by equation 13.4 or 13.5. In case, the pressure losses are very high, the size of pipe laterals may be increased. Larger size of pipes will reduce the pressure but at the same time it may increase the cost of the system. Select the optimum size of main, sub-main and laterals for economic system design.

#### 13.3.5.5 Estimation of Power Requirement

When we know about system discharge and total head loss in the system then we can calculate the power requirement of system by equation 13. 9.

#### 13.3.5.6 Calculate Operation Time

The operation time of a sprinkler irrigation system refers to the time (Minutes) required to cover the area to be irrigated in one pass per day.

$$OT = \frac{I \times 60}{PR \times DA} \qquad (13.12)$$

Where:

OT = Operating time, min/day.

I = Irrigation requirement in the “worst case” season, in/wk.

PR = Precipitation rate, in/hr.

DA = Days available for irrigation per week.

60 = Constant conversion factor of min/hr.

**Example:**

Given:

i. System irrigation requirement: 1.5 inches (38 mm) per week.

ii. Days available for irrigation: 3 days.

iii. Sprinkler performance: 3.5 gpm (0.79 $m^3$/h) full circle, radius = 14 ft (4 m).

iv. Sprinkler spacing: 13 x 15 ft (4 m x 5 m) rectangular.

Determine the precipitation rate and operation time of the circuit.

$$\mathrm{PR} = \frac{96.3 \times 3.5\ \mathrm{gpm}}{13' \times 15'} = 1.73\ \mathrm{in/hr}$$

$$\mathrm{OT} = \frac{\frac{1.5\mathrm{in}}{\mathrm{wk}} \times \frac{60\mathrm{min}}{\mathrm{hr}}}{1.73\,\frac{\mathrm{in}}{\mathrm{hr}} \times \frac{3\mathrm{days}}{\mathrm{wk}}} = 17.3 \text{ or } \frac{18\mathrm{min}}{\mathrm{day}} \text{ or } \frac{3\mathrm{days}}{\mathrm{wk}}$$

**Example:** Design permanent sprinkler irrigation for a farmer field. The following information was collected after field survey:

i. Total area= 56×42= 0.58 $m^2$ (About half acre)

ii. Soil type= Sandy loam

iii. Crop= Maize

iv. Water source is 3 m deep from G.S

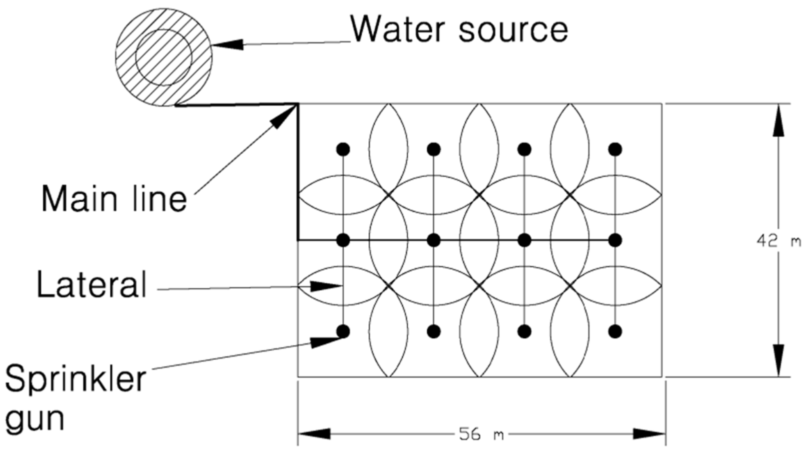


**Fig. 13.15** Layout of Sprinklers in Maize Field

**Solution:**

According to crop (maize) and soil type select sprinkler gun PY-20 (0.66 Lps, 20 m dia throw, 4 bar operating pressure)

Take 30% overlap area (to cover 100% space between sprinkler guns in case of row crops)

Sprinkler in one lateral= 3

Total laterals on main line= 4

Total sprinkler= 3×4= 12

Sprinkler discharge= 0.66 Lps

Total pump discharge= 12×0.66= 8 Lps

Head loss calculation by Hazen-William equation:

Main line= 1.6 (76.2 mm dia) (1.2 m/100 m)

Lateral line= 3.3 (18 mm dia)

Total head loss= Sprinkler operating pressure+ Main line head loss+ Lateral Head loss+ Suction lift+ Delivery lift

Total head loss= 40+1.6 +3.3 + 3+0= 47.9 ≈ 48 m

Power requirement= $\mathrm{Hp} = \frac{Q*H}{76*\ \text{efficiency}}$

$$\mathrm{Hp} = \frac{8*48}{76*\ 60\%}$$

$$\mathrm{Hp} = 8.42$$

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## Chapter 14

# Drainage Requirements of Irrigated Land

**Sikandar Ali and Muhammad Mehboob Alam***

## Abstract

Drainage of agricultural land is as important as irrigation for successful agriculture. Practically no irrigation system can be operated efficiently without a natural or artificial drainage system. Whereas, monsoon rains, obstructed natural drains and widespread irrigation system ceases sources of deep percolation leading to waterlogging of agricultural land, man-made topographic changes accelerate the process of temporary storage and waterlogging. Pakistan's irrigation system comprises a network of rivers, link canals, main canals, distributaries, main watercourse and field channels conveying water from the irrigation channels to the fields. This distribution and conveying system provides a continuous source of recharge, leading to a high water table. Since 1960, Pakistan has implemented several reclamation programs through open drains, pipe drains and more than 50 Salinity Control and Reclamation Projects to control watertable. This chapter identifies the impending problems and agricultural management alternatives in the production, expansion and the disposal of agricultural drainage water. The chapter includes the drainage requirement in irrigated areas of Pakistan, drainage methods, design of drainage projects and drainage models. A summary of major pipe drainage projects implemented in Pakistan has also been included. The chapter discuuses the basic

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concepts related to drainage problems, design, selection, installation of the drainage system with better alternatives.

**Keywords:** Land Drainage, Surface Drainage, Pipe Drainage, Interceptor Drains, Drainage Requirements, Design Depth, Drainage Outlet

## Learning Objectives

- The primary purpose of this chapter is to familiarize the readers about waterlogging problems and their solution through land drainage.
- It gives insight about various needs and types of drainage systems and their expected benefits for reclaiming agricultural land.
- It also updates the knowledge of professionals in the design, installation and operation of the selected drainage systems.

## 14.1 Introduction

Drainage is basically removal of excess water from the field or from the root zone of the crop by creating favorable conditions for the growth of the plant. Sustained accumulation of water over land leads to waterlogging, which necessitates land drainage. Over irrigation and excessive precipitations are most general causes of waterlogging. Pakistan has well distributed structures of main and link canals. Seepage losses from the canals are also contributing to rise of the watertable. In this situation, drainage of water is necessary to create favorable conditions for plant growth. A flood condition in Pakistan is common during the monsoon season, particularly, during the past 4–few years, which may necessitate surface drainage as well as vertical drainage from agricultural as well as from residential, commercial areas etc.

## 14.2 Benefits of Land Drainage

The purpose of agricultural drainage is to remove the excess water from root zone of the plants and permit to achieve following benefits:

- Enhance movement of capillary moisture.
- Improve soil structure.
- Provide aeration within the root zone.
- Make the soil warmer.
- Prevent the erosion hazards.
- Minimize effect of drought conditions.
- Prevent freezing out.
- Minimize rise of alkali.
- Improve the physical condition of the soil to allow farm operations.
- Improve the drainage conditions of the agricultural land and allowing soil, air and moisture favorable for agricultural production.

## 14.3 Types of Drainage Systems

The agricultural drainage systems can be classified with respect to the following categories:

a) Layout (Singular and Composite Systems)
b) Surface and Sub-Surface Installation (Open, Pipe and Mole Drainage Systems)
c) Interceptor (Surface and Sub-Surface Drains)
d) Natural and Artificial Drainage System
e) Horizontal and Vertical Drainage System

### 14.3.1 Singular System

In the singular drainage system, the field drains comprise of buried perforated pipe laterals which discharge into the open ditch collector drains. In the composite pipe drainage system, the collector drain also consists of closed pipe that in turn discharges into the open main drain either by pumping or by gravity (Fig. 14.1). In the singular system, excess surface water may be collected. Lateral pipe length should not exceed 300 m and field width for the singular system should be 300 m and 600 m for single sided and double sided entry, respectively. Further, it depends on drainage requirements design and financial considerations (Lambert et al., 2004).

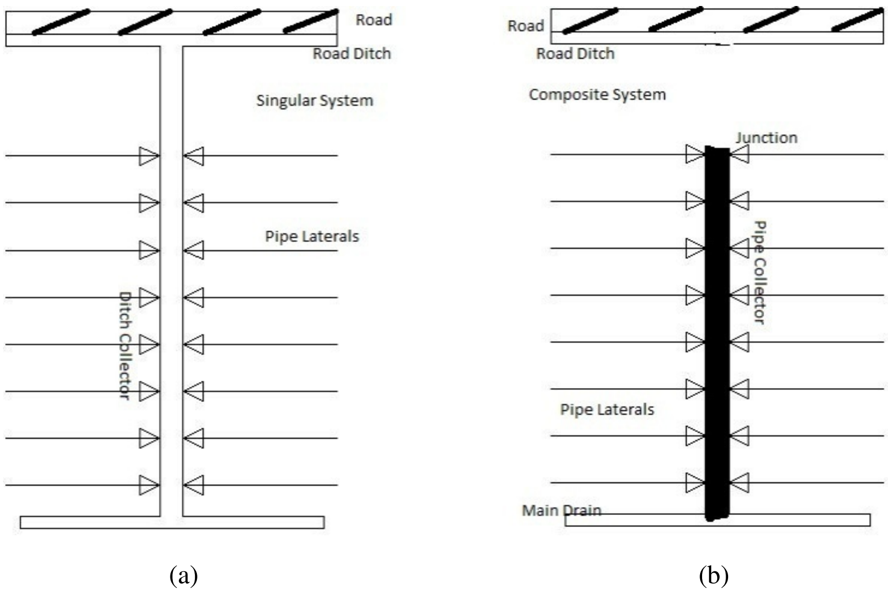


**Fig. 14.1** Pipe Drainage System

### 14.3.2 Composite Systems

In this system, the perforated pipes are used as laterals and closed pipes are used as collector drains which later discharge into the main drain system. The collector drains collect water from field drains and carry it to the main drains for proper disposal to outside of the area to the outlet. The outlet is the terminal point of the drainage system from where drainage water is discharged into the lake, river or sea, etc. Composite systems are preferred in the irrigated areas of arid region because of the greater depth of the field drains as compared to the temperate zone and low discharge rate due to low excess rainfall in arid regions. These are also preferred in the sloping areas to reduce valuable soil erosion (Lambert et al., 2004).

### 14.3.3 Surface or Open Drainage Systems

This type of drainage is achieved by land forming and smoothing for removal of isolated depressions, or by construction of parallel ditches. Ditches and the furrow bottoms are gently graded and discharged into the sub-drains at the boundary of the field. Although the ditches and furrows are projected to convey the excess runoff water, there is also some seepage to ditches depending on position of the existing watertable which is relevant for bed of the draining channels. This may be termed as shallow subsurface drainage. The surface drainage is very important, especially in humid regions, on flat lands with limitation of hydraulic gradients to the nearby rivers. A surface drainage system should be able to remove extra water within 24-48 hours (Zwerman and Coote, 1970).

### 14.3.4 Pipe Drainage Systems

A pipe drain is basically a pipe buried in the soil (irrespective of size, shape, material, etc.) which receives excess groundwater and then conveys to control the existing watertable at any desired depth. The advantages of pipe drainage are:

- ✓ The land can be farmed over the drain without loss of the farming area.
- ✓ Minimum maintenance is required if system is properly constructed.
- ✓ Pipe drainage system is usually installed in soil below 0.70 m depth, and farm operations can easily be performed with pipe drainage system.
- ✓ If overland drainage flow occurs, the shallow open drain is additionally required.

### 14.3.5 Mole Drain

Mole drain is basically an unlined underground drainage water channel which is formed by pulling the solid object, usually the solid cylinder with wedge shaped point located at the end, through the soil at proper slope and depth without a trench. Mole drainage is applied under very specific conditions, mainly, in the stable clayey soils. The mole drainage is the rapid removal of the excess water from surface layers, rather than at controlling of watertable only. However, mole drain has a life span of only a few years and has to be renewed frequently. A typical mole drain is shown in Fig 14.2.

- ✓ Mole drains can be used in areas with high cohesive or fibrous soils which are free of stones and sand lenses.
- ✓ They can also be used as a supplement to the other drains.

Considerations for designing a Mole Drain include:

When planning for a mole drain, consider the factors:

- ✓ Infiltration, deep percolation, potential ground water recharge and runoff to area under consideration.
- ✓ Downstream water use, water temperature, and water quality.

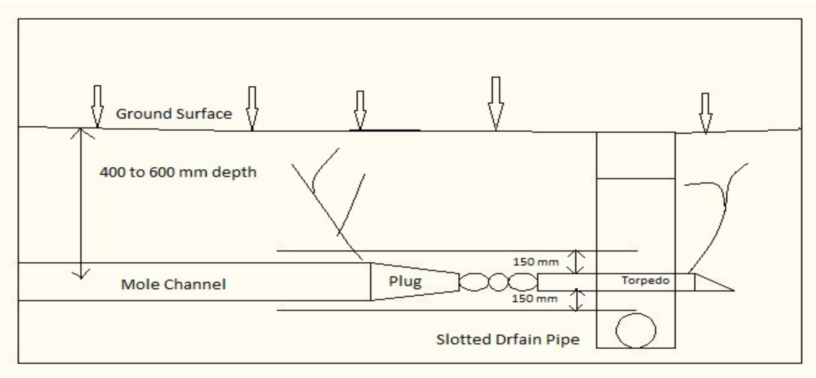


**Fig. 14.2** Mole Drain

## 14.3.6 Interceptor Drains

A drain situated between water source and protected area to intercept the seepage is called the interceptor drain. The interceptor drainage system is used to intercept the surface and subsurface water as shown in Fig 14.3. Interceptor drains are sub-divided into two categories namely Surface water Interceptor and the Groundwater Interceptor Drains.

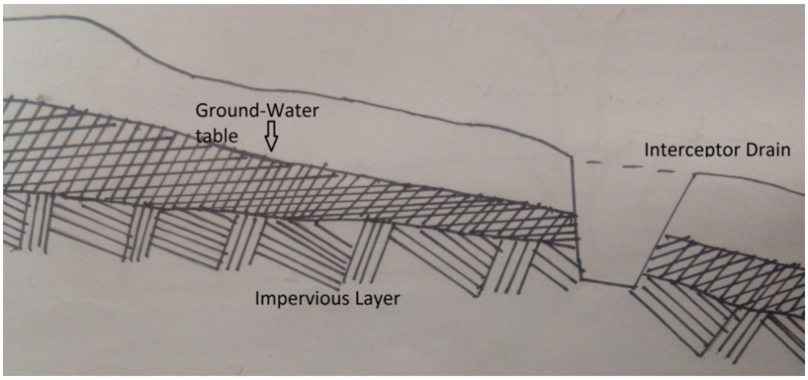


**Fig. 14.3** Interception Drain

### 14.3.6.1 Surface Water Interception

The primary objective of surface water interceptor drains and drainage systems is to remove the surface runoff from footpaths, parking areas, and the roofs of the buildings. These systems are also designed to provide immediate and long term drainage system for gardens, public parks, rural area and yard areas where the surface water runoff is supposed to cause inconvenience.

#### 14.3.6.2 Ground Water Interception

Groundwater interceptor drains are often installed to lower and control the seasonally high groundwater levels, which may adversely affect surface land use.

### 14.3.7 Natural Drainage System

A field in which waterlogging is confined to depressions that is drained off efficiently by aligning the drains in such a way that they pass through and connect these depressions. Such type of regular pattern of drain connection is called as natural system. In the Fig 14.4, there are depressions like wet spots and the drains which connects these depressions and is called as depression drain which passes out from all the wet spots and collects the water and then drains into the main drains.

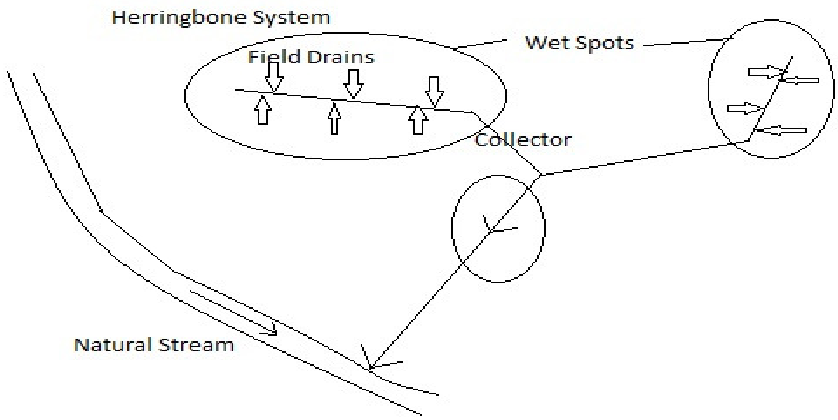


**Fig. 14.4** Natural Drainage System

### 14.3.8 Artificial Drainage System

When the man-made structures such as bridges, buildings are erected in an area, it is necessary to design and construct the drainage systems to offset the extent up to which natural drainage has been upset. Storm sewers are usually the primary feature of ~~an~~ artificial drainage system. Excess water in the root zone of the crop may cause damage to plant growth due to impaired aeration. Crop yield is reduced grown on poorly drained soils and usually plant dies in waterlogged soils because of oxygen deficiency in the root zone. Excess water in the soil which results in high watertablemay come from high precipitation in the humid regions, surplus/inefficient applied irrigation water and canal seepage in irrigated areas. Obstructed drainage tends to introduce the waterlogging which may result in excess of soil salinity.

Artificial drainage is crucial on the poorly drained areas in order to provide the optimum environment which is required by the root zone.

### 14.3.9 Vertical Drainage System

A well, pipe, bore, or pit in porous, underground strata into which the drainage water can be discharged without any contamination in groundwater resources is called a vertical drainage system. It provides an outlet for the drainage water from a surface or subsurface drainage system. The efficiency of vertical drainage is dependent upon many factors like physical properties of the subsurface aquifers and hydrologic conditions of the site. Vertical drains should penetrate the aquifer, which is absorbing the drainage flow. Identification of such aquifer is necessary, whether it is present or absent (Hanns, 2005). The water may carry sediments, debris and salts with it.

It is useful in the areas where underlying strata should receive, transmit, store the designed drainage flow, and where other drainage outlets are not available. This practice is applicable where natural “sinkhole” act as the vertical drains, and erosion control of surface runoff is needed. This is practiced mostly by installing tube wells to create favorable condition in the root zone for crops.

### 14.3.10 Horizontal Drainage

It is the removal of excess water from the field or from the root zone by the action of gravity. It may be surface and sub-surface drainage system. Open ditch may be used for horizontal surface drainage and pipes may be used for the subsurface horizontal drainage. These are preferred in the arid to semi-arid regions for reclamation of saline and waterlogged soil for maintaining long term salt and water balance. Excess water in case of horizontal drainage is more in humid regions as compared to the arid regions, hence required more complications like the inclusion of erosion control practices in the open ditch.

## 14.4 Factors Influencing Drainage Systems

### 14.4.1 Source of Water

Pakistan has annual surface water of 144.9 maf, of which, 46.73 is being wasted in the conveyance system. This wastage is due to deep percolation and may cause watertable to raise thus giving rise to drain that water for better agriculture. Again, in the fields in Pakistan, there are 13.5 MAF application losses of water and mainly contributing to groundwater as deep percolation. In Pakistan, for agricultural use 49 MAF of annual groundwater is being extracted from aquifers again with 13.5 MAF as application losses. Third source we have an average annual rainfall of 13.4 MAF in Pakistan, which also contributes 4 MAF as application losses due to deep percolation.

## 14.4.2 Catchment Area

A catchment is a basin shaped area of the land, surrounded by natural features like hills from which the surface and sub-surface water contributes into streams, wetlands and rivers. Water flows into, and collects in the lowest areas in the landscape. It is an area which receives water and contributes to the development of rivers. The Catchment area is an area of the closed are, which is formed by the contour portion at any given point of topographic surface and two flow lines coming from upslope to the ends of the contour portion.

## 14.4.3 Characteristics of Catchment Area

### 14.4.3.1 Shape of Area

Shape will contribute to the speed with which runoff reaches the river. A long, thin catchment will take more to drain than a circular catchment. Basically, the shape of the area in the drainage system helps to account for the time taken by the precipitation drains from the area.

### 14.4.3.2 Soil Type

Soil type usually helps to find out the amount of water which contributes to the river. Water in sandy soils is likely to be absorbed by the ground. However, clay soil usually poses very less permeability to the water, hence, leads to the formation of runoff which contribute to the flood water. However, in the case of sandy soil, the water may contribute to the surface runoff if soil saturates owing to prolonged rainfall. If the surface is impermeable then the precipitation will create the surface run-off, which will lead to the higher risk of flooding. If the ground is permeable, the precipitation will infiltrate the soil.

### 14.4.3.3 Size of Area

Size will help to determine the amount of water reaching into the river, as the larger is the catchment, the greater is potential for flooding.

### 14.4.3.4 Infiltration Rate

The infiltration rate of soils depends, primarily, on the texture of the soil. A low infiltration area may reflect waterlogged conditions in the cultivated areas. On the other hand, low infiltration rate, usually in relatively impermeable soils, leads to the high runoff volume which is usually looked-for for the catchment areas of the country. For cropped areas, the soils should be sufficiently permeable to allow adequate infiltration and percolation of water to the crop root zone without causing the waterlogging problems. Therefore, the requirements of the cultivated area should always take precedence. Crust formation is a special problem of arid and semi-arid areas, leading to high runoff and lower infiltration rates. Soil compaction as a result of heavy traffic either from machinery or grazing animals could also result in lower infiltration rates.

#### 14.4.3.5 Slope

In design of land grading slope is different in drainage as compared to irrigation. A continuous slope is adequate and type of crop is also considered which is going to be grown.

$$acs = \Delta h / L$$

Where $\Delta h$= Height difference between the catchment outlet and farthest point along the main channel.

$L$= Main channel length

In the area of rainfall, land should have some slope to direct water to the downstream. The degree of slope changes to the conditions and surface of the sites may be as following:

(i) For Turf areas = 2-3%,
(ii) For Paved areas 2%,
(iii) For foundations special requirement

Usually for drainage purposes, the recommended length of slope is 10 ft. having a drop of six inches.

#### 14.4.3.6 Topography

Topographic maps are good for studying drainage problems and factors such as type and location of outlet, degree of land surface preparation and surface slopes. Topographic survey, which indicates existing drainage systems, culverts and other water structures can be helpful for new expected possible drainage structures. The velocity of water, which contributes to the river is dependent on the topography of the area. Clearly, rain that falls in steep mountainous areas will reach the river faster than flat or gently sloping areas. Hence, topographic maps along with aerial photos and ground truth data are very helpful to design new drainage systems.

#### 14.4.3.7 Vegetation

Vegetation of Pakistan varies with soil type, precipitation and elevation. Mostly forests like pine, spruce, cedar and deodar are confined to the mountainous ranges of the northern region. The southern range covers like poplar and willow trees. The plain region of Pakistan, largely dependent on irrigation system, covers major life sustaining crops. These include wheat, rice, maize, cotton, sugarcane, barley, etc.

#### 14.4.3.8 Length of Slope

Length of slope should be in such a way that the velocity of water should not create either silting or scouring effect. In very highly erodible soil, row length of the slope should be limited to 150 m. For less erodible soil, it should be 300 m. Slope and length of slope for various soil types is given in Table 14.1.

**Table 14.1** Slope and Length of Slope as Affected by Soil Type

| Soil type | Grade (%) | Row length (m) | |
|---|---|---|---|
| Coarse-textured soil (sandy) | 0.1 – 0.3 | 300 | |
| Fine-textured soil (clayey) | 0.05 – 0.25 | 200 | |
| Fine-textured soil (clayey) with high organic-matter content | 0.1 – 0.5 | 200 | (flat) |
| Medium-textured soil (loamy) | 0.05 – 0.25 | 400 | (gently sloping) |
| Medium-textured soil (silty loam) with impervious hard-pan at depth | 0.5 | 300 | |
| Medium-textured soil (silty loam) with shallow impervious clay B horizon | ≥ 0.2 | 150 | |
| Moderately coarse-textured soils (sandy loam) with structured clay B horizon at depth | ≥ 0.15 | 60 | |

*Source: Cooter and Warman, 1970*

### 14.4.3.9 Waterlogging

Existence of water and its depth in the subsurface is necessary to indicate at the time of the survey. Sometimes, the soil color proves to be a good indicator of waterlogged conditions. The black and orange mottling of soil is mainly due to manganic and ferric ions which indicates oxidizing and reducing conditions, periodically. The data required for spacing of drains is dependent on the extent and depth of mottling of soil. The existence of blue or blue clay soil is an indication of reducing condition due to continuous submergence under water, hence, indicates waterlogging in the past. Sources of waterlogging may be precipitation, over irrigation, seepage from nearby unlined canals and artesian pressure from hydrostatic pressurized aquifers.

### 14.4.3.10 Drainage Outlet

For proper design of the drainage system, it should have an outlet of proper stability, depth and design. The drainage outlet affects the entire drainage system and it should carry water away from the entire area which is being served by the system. In case of subsurface drainage system, the outlet should be deep enough to drain from low level water of the entire area. The capacity of the drainage outlet should be such that it can drain water quickly of the drainage area. The velocity of water in the drainage system should adequate which don't cause either siltation or erosion. Low values of the velocity will cause siltation effect and will encourage weed growth. The maximum permissible velocity for various soils is given in Table 14.2.

**Table 14.2** Range of Maximum Velocity in the Drainage System

| Soil Texture | Maximum Permissible Velocity (ft/sec) |
|---|---|
| Sandy soil or sandy loam soil | 2.45 |
| Silt loam soil | 3.00 |
| Sandy clay loam soil | 3.45 |
| Clay loam soil | 4.00 |
| Clay soil or silt clay soil | 5.00 |
| Fine gravel, cobbles, or graded loam to cobbles | 5.10 |
| Graded mixture silt to cobbles | 5.60 |
| Coarse gravel or hardpans | 6.20 |

### 14.4.3.11 Depth of Water Table

Depth of the watertable is an important parameter and the upper limit of the waterlogged soil which should be calculated for drainage design. It can be measured by digging the roper hole in soil and water will come into the hole and will provide the depth of the water table. In field conditions, the water table depth can be measured by installation of the observation wells which are partially filled with the gravel. Well should be provided with the perforated pipe and there should be gravels around the pipe for circulation of water into the pipe and the hole. Drainage tubewells provide more depth to water table as compared to the pipe drains which are almost from 3 to 5 ft. But in the tubewell the vertical permeability or infiltration rate should be high enough and in pipe drains it is vice versa. The existence of the impermeable layer in the formation may limit the tubewell drainage and pipe drains can work in these conditions efficiently.

### 14.4.3.12 Design Depth

In humid areas, the designed depth depends upon some factors like soil conditions, soil permeability, depth of water table, spacing, depth to impervious layer, and crops. The drain trench depth changes from 30-60 inches.

In irrigated areas of arid and semi-arid conditions like Pakistan the factors are same like humid areas with additional control over the salinity problems. Depth of drain required usually is from 6-12 feet. Generally, drains should be deep enough so that we should have availability of equipment, and cost of construction and maintenance should be acceptable.

### 14.4.3.13 Drainage Capacity

Design capacity can be based on lower drainage coefficients than those, generally, applied to collection system. Generally, flow from large irrigated tracts is in the range of 2-4 cusec per square mile. It may be 30% less than the return flow due to groundwater export through deep percolation to aquifers, pumping of groundwater for other than agricultural use and consumptive use of trees and other plants.

In Relief Drains, the area served by the drain is equal to spacing time, the length of drain, plus one half spacing.

$$Q_r = \frac{q\,S\,\left(L + \frac{S}{2}\right)}{43{,}200}$$

Qr is the relief drain discharge capacity in cusec

q is the drainage coefficient in inches /hour

S is the drain spacing in feet

L is the drain length in feet

**Example 14.1:** Find out the drain capacity if spacing is 320ft, length is 1500 ft and drainage coefficient is 0.008 inch/hr.

**Solution.**

$$Q_r = \frac{q\,S\,\left(L + \frac{S}{2}\right)}{43{,}200}$$

$$Q_r = \frac{0.008 \times 320\left(1500 + \frac{320}{2}\right)}{43{,}200}$$

Qr = 0.098 cusec.

Drains are not considered as a flow from the pressure and the hydraulic gradient is parallel with grade line and supposed to be an open channel flow. Drain size is dependent on the roughness coefficient and hydraulic gradient. Material commonly used for the drains have a roughness coefficient of 0.011 for good quality clay.

Design criteria have been developed for determining the amount of water necessary to drain from an area.

### 14.4.3.14 Drainage Coefficient

It is defined as the water removal rate used in drainage system design to obtain desired protection of crops from an excess of surface and subsurface water.

For humid areas, it may also be defined as the amount of water drained out in a period of 24 hours. It is related to infiltration characteristics of the soil and climatic conditions (Table 14.3).

It depends on the rate of rainfall, and the amount of drainage water which can be admitted to the existing drainage system. The watershed size greatly affects the value of drainage coefficient.

**Table 14.3** Drainage Coefficients Without Surface Water Inlets

| Soil | Inches to be removed in 24 hours | |
|---|---|---|
| | Field Crops (inches) | Truck Crops (inches) |
| Mineral | 3/8 – ½ | ½ – ¾ |
| Organic | ½ – ¾ | ¾ – 1– ½ |

In irrigated areas, it is the acceptable formula for calculation of drainage coefficient which is based on irrigation application.

$$q = [\{(P+C)/100\} * i]/24f$$

Where

q is a drainage coefficient in inches/hour

P is the deep percolation from leaching requirement and irrigation in percent

C is the field canal losses in percent

f is the frequency of irrigation in days

i is the irrigation application in inches.

**Example 14.2:** Find out drainage coefficient if deep percolation is 22%, field canal losses 9%, irrigation of 5 inches of water with 12 days' frequency

**Solution:**

$$q = [\{(P+C)/100\} * i]/24f$$

$$q = [\{(22+9)/100\} * 6]/24*12 = 0.0064 \text{ inches per hour}$$

# 14.5 Existing Drainage Systems in Pakistan

## 14.5.1 SCARP Programs

In 1958, the Government of Pakistan assigned the responsibility to control salinity and waterlogging problems to WAPDA. Technical solutions of WAPDA focused on improvement of drainage, reduction of seepage from unlined water channels, and enhancement of the efficiencies of farmers' water management strategies. USAID sponsored groundwater survey which started in 1954 and led WAPDA to start SCARP (Salinity Control and Reclamation Projects) with two primary objectives of controlling salinity and waterlogging and to develop extensive fresh groundwater supplies. First project, i.e., SCARP 1 was launched in the 1961, covering about 0.6 million hectares with 2100 public tubewells. The list of major projects is given in Table 14.4.

The main objectives of the SCARPs included lowering of the watertable and to supplement canal water with tubewell water to increase water allowance and cropping intensity as well as to pump out the saline and hazardous groundwater into drains.

**Table 14.4** SCARP Projects in Pakistan

| Sr. No | SCARP Projects | Region |
|---|---|---|
| 1- 8 | SCARP I, II, III, IV, V, VI, VII, VIII | Upper Indus Plain |
| 9 | Hadali | Upper Indus Plain |
| 10 | Paharang Drain | Upper Indus Plain |
| 11 | D.G. Khan (Saline) | Upper Indus Plain |
| 12 | Anti-waterlogging Project along Link Canals | Upper Indus Plain |
| 13 | Tubewell Replacement | Upper Indus Plain |
| 14 | Peshawar | Upper Indus Plain |
| 15 | Bannu | Upper Indus Plain |
| 16 | Chashma Command Area Development | Upper Indus Plain |
| 17 | Mardan SCARP | Upper Indus Plain |
| 18 | Khairpur SCARP | Lower Indus Plain |
| 19 | North Rohri | Lower Indus Plain |
| 20 | Larkana Shikarpur | Lower Indus Plain |
| 21 | Ghotki SCARP | Lower Indus Plain |
| 22 | South Rohri | Lower Indus Plain |
| 23 | LBOD Spinal Drain | Lower Indus Plain |
| 24 | Kotri Stage I & II | Lower Indus Plain |
| 25 | N. Dadu | Lower Indus Plain |
| 26 | East Khairpur | Lower Indus Plain |
| 27 | Larkana Shikarpur Remodeling | Lower Indus Plain |
| 28 | Tubewell Replacement | Lower Indus Plain |
| 29 | Hairdin I&II | Lower Indus Plain |
| 30 | Gogera Khewra Phase_II | PUNJAB |
| 31 | Shorkot kamalia Saline | PUNJAB |
| 32 | 2nd SCARP Transition | PUNJAB |
| 33 | Upper Rachna (Deg Unit) | PUNJAB |
| 34 | Fordwah Sadiqia Phase-I (remaining) | PUNJAB |
| 35 | Fordwah Sadiqia (South) Phase-I | PUNJAB |
| 36 | D.G. Khan Integrated | PUNJAB |
| 37 | Panjnad Abbasia Phase-II | PUNJAB |
| 38 | LBOD Stage-I | SINDH |
| 39 | Kotri Part-II Stage-III | SINDH |
| 40 | Lower Indus Right Bank Stage-I | SINDH |
| 41 | Swabi SCARP | KPK |
| 42 | Fourth Drainage Project | PUNJAB |
| 43 | Mardan Tile Drainage | KPK |
| 44 | SCARP lower Rachna | PUNJAB |
| 45 | SCARP Sukh Bias (CBDC) Phase-I | PUNJAB |
| 46 | Gojra Khewra Phase –I | PUNJAB |
| 47 | Left Bank Outfall Drain Stage-I | SINDH |
| 48 | North Dadu Surface Drainage | SINDH |
| 49 | Bund Kurai Drainage System | |
| 50 | Khushab Sub-Unit | PUNJAB |
| 51 | Tando Adam Tubewell Drainage Project | SINDH |
| 52 | Warah Surface Drainage Project | |
| 53 | Doab Daudzai SCARP | KPK |
| 54 | Pehur SCARP | KPK |
| 55 | Kafur Deri Phase-II | KPK |

### 14.5.2 Fourth Drainage Project (FDP)

1. FDP was executed by WAPDA in 1983-94 to control salinity and waterlogging in south western part of Rachna doab consisting of Faisalabad, Samundri and Jaranwala tehsils of District Faisalabad, comprising a total area of 0.35 million acres. The project was designed in such way to maintain the watertable at an average depth of 4 feet below the natural ground surface. The construction plan consisted of two phases called Schedule I and II, comprising 38 & 41 sumps, respectively, for effluent disposal. WAPDA maintained FDP for 2-3 years and further this project was handed over to Punjab irrigation and power Department (PIPD). The total cost of the project was Rs. 621.37 million.
2. For evaluation of the project, four different indicators were selected and those were groundwater quality, cropping intensity, soil salinity and watertable fluctuations. The groundwater quality was changed from hazardous to usable. The decrease which was observed in surface and profile salinities were 17 and 20%. Annual cropping intensity was increased from 102 to 157%.

### 14.5.3 Khairpur Pipe Drainage Project

This project covered an area of 36000 acres for development of land and water resources in the Sindh Province of Pakistan. The priority was to develop fresh groundwater resources followed by tubewell drainage project in saline groundwater aquifers. The Khairpur pipe drainage project is an integral part of earlier SCARP Khairpur drainage project. The soil of the project area is mainly of medium to fine textured in the northern part with medium drain-ability. The watertable was in depth of 0-5 feet. The construction of the project was started from 1977 and was completed in 1986. PVC and unreinforced concrete pipes were used for laterals and collector drains. Spacing of drains was about 50-150 feet in depth of 1.8 m. The total cost of the project was US$ 28 million and component of the foreign exchange was 50% of the total cost. Government of Pakistan approved the PC-1 of the project in the 1976 at total cost estimate of Rs.372.2 million with component of foreign of about 178.7 million but due to some delay in the project, the costs were revised in 1983 and were approved in 1985 with total of Rs. 630.03 million with component of foreign exchange of Rs. 199.85 million. After finalization of accounts the actual cost was Rs. 575 million and component of foreign exchange was Rs. 189 million. Famous experts commented about the project after their visit that it was constructed in most difficult conditions of the world.

### 14.5.4 Mardan Pipe Drainage System

The Mardan pipe drainage project is, basically, sub-project of the Mardan SCARP project comprising an area of 73,000 acres of land. The objective of the project was intensive development of land and water resources by reclamation of soil salinity and waterlogging and improvement of agricultural production by controlling the adverse situation of soil salinity. Mardan SCARP area is the alluvial plain developed by Swat River originating from the Himalayan foothills bordering the plain in north and northwest. Variation of slope, generally, ranges from 1 to 3 percent. Most of the soil of the project area is of calcareous nature. The site is served by the Lower Swat Canal (LSC) originating from Munda headworks. The area is also served by several lowdensity surface drains running in a south-southwest direction. The agriculture of the area is usually of small scale ranging usually from 1-2 acres with 175-180% cropping intensity. In the project area, crops are adversely affected by the high watertable usually within the range of 3 feet. Twenty percent of the total area is also suffering from excessive soil salinity. Under these conditions pipe drainage was supposed to be the best technique for drainage purpose.

The project plan was completed in 1980 with a total cost for a Mardan SCARP project of Rs. 1.39 x $10^9$ (1390 million). Partly financed by the International Development Agency (IDA) loan of 60 x $10^6$ (60 million) US Dollars and 30 x $10^6$ (30 million) US Dollars by Canadian International Development Agency (CIDA) grant. The cost for pipe drainage system was almost Rs. 9200/acre. The design was such that the laterals were mostly of4-inch diameter corrugated Poly Vinyl Chloride pipes of 600-1000 feet length laid at an average depth of 7.5 feet with gradient of 0.1%. Lateral spacing varies from 100-300 feet. The collectors were of average 4000 feet length, consisting 6-13 inch diameters installed at 10 feet depth.

## 14.6 Design of Drainage System

### 14.6.1 Surface Drainage

The surface drainage system is usually designed for two purposes. One is to minimize crop damage which results from ponding of water on the soil surface, mostly by following a rainfall event and second purpose is to control the intensity of runoff which causes erosion effect. Surface drainage systems which usually start functioning when there is an excess rainfall or irrigation and operate by force of gravity. They can be divided into two categories:

(a) Bedded systems, which is used in the flat lands for crops except rice.
(b) Graded systems, which is used in graded land for crops except rice.

Surface drainage is, basically, suitable for low permeable soils, clay sub-soils and soils with hardpan. The rate of drainage is dependent upon many factors like rainfall, cropping pattern and soil properties. The surface drainage system includes outlet channel, capacity and diameters of lateral ditches or field ditches.

Before designing the surface drainage system, one should have to make a topographic map and draw a contour map of corresponding area using laser techniques, grid surveys and photogrammetric methods. For designing purpose, first check the adequacy of the outfall and its improvement. Verify site levels and develop minor and major field gradients which help in determination of the layout of the drainage and the capacity of the drain. Investigate the seepage and high watertable areas and verify soil conditions and variations for permeability of soil at various depths by deep holes. Verify the topsoil nature, whether subsoil mixing is required or not. Lateral ditches in the field should be deep enough that it should not be a hindrance in the farm machinery operations. The minimum depth of the lateral ditch should be 1 ft. There are two types of field ditches:

**(i) Single Ditch**

It is usually of V-shaped and trapezoidal cross section having a minimum depth of 9 and 6 ft., respectively. Both these sections have a minimum cross sectional area of 5 square feet. As in the Fig. 14.5, side slopes for V-shaped and trapezoidal cross sections should be kept from 10-1 and 8-1 or flatter, respectively.

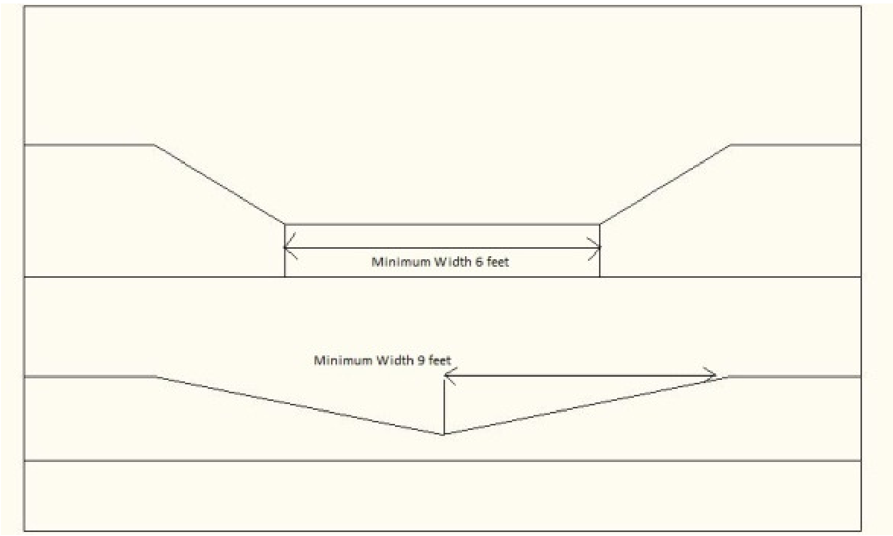


**Fig. 14.5** Single Ditch with Trapezoidal and V-shaped Cross Sections.

**(ii) Double/Twin/W Ditch**

It is preferred that where we have land drainage in both directions and where the slope is very low; row drainage may cause entrance from each side. If the farm machinery operation is not expected in the field, then slope toward the field should be kept from 8:1 and for crowned section it is usually from 4:1. Minimum distance between the two consecutive ditch centers should be 30 ft. Minimum slope is 0.1 percent to avoid siltation effect.

For slow permeable soils, random pattern for ditch alignment is adapted as shown in Fig. 14.6. For very poorly permeable soils, the parallel arrangement of ditches is preferred as shown in the Fig. 14.7.

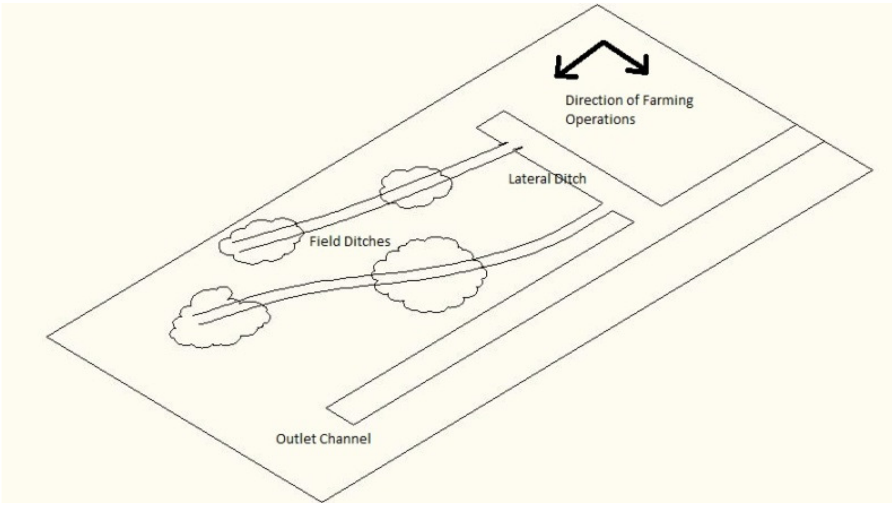


**Fig. 14.6** Random Alignment of the Ditches

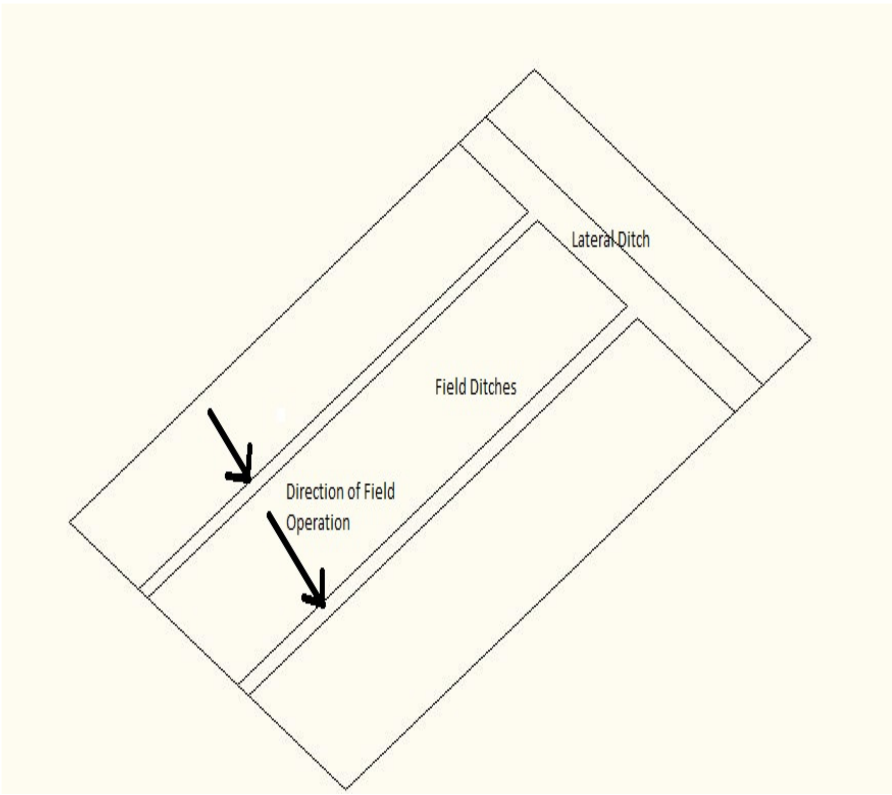


**Fig. 14.7** Parallel Alignment of the Ditches

## 14.6.2 Pipe Drainage

The subsurface drainage system consists of horizontal as well as sloping channels which open in ditches, trenches usually filled with brushwood and soil cap, filled with stones and soil cap, buried pipes, tile drains or mole drains, but they can also include series of wells.

Modern buried pipe drains usually consist of flexible, corrugated and perforated plastic polyethylene or polyvinyl chloride pipe lines wrapped with an *envelope* or filter material to improve permeability around the pipe and to avoid entry of soil particles. The objective of a subsurface drainage system is to drain excess water from the root zone of the plants and lowers the watertable artificially.

### 14.6.2.1 Data Requirement

Subsurface drains consist of outlets (surface or subsurface), subsurface main drains and subsurface laterals. Drain size is also very important and main drain should have size to cover all the lateral drains being discharged into it. The velocity of water should be such that the water should not create erosion or siltation effects. Rainfall and drainage rate of the existing and designed system are also of prime consideration. Placement and slope of pipe material should be adequate to the soil texture. Drain depth and depth of watertable should be known before designing the subsurface drainage. The hydraulic properties of the aquifers vary within a small area and can greatly affect the subsurface drainage.

The field subsurface drainage pipes (or laterals) discharge water into collector or the main system either by pumping or gravity. Subsurface drainage by using wells is often referred as vertical drainage, and drainage by channels is called as horizontal drainage, but usually called as "field drainage by wells" and "field drainage by pipes or ditches" respectively.

### 14.6.2.2 Design Procedure

Planning of subsurface outlets discharging water into surface outlet should be made to avoid damage due to submergence period, damage against floating debris and erosion. An older type of subsurface outlet for the newly installed system should be free from fractures and breakdowns. It should be deep enough to intercept all the outlet main drains and laterals with sufficient capacity to handle large flows during peak periods of rainfall. Topographic conditions of the site along with the depth limitations of the trenching machine and soil cover are of prime importance in the design of subsurface drainage systems.

Drain size is very important and drainage coefficient is required for its determination. For steady state rainfall based conditions, drainage spacing and depth are selected in such a way so that watertable will be steady during steady rain. It means rainfall rate will be equal to drainage rate, in such situations drainage rate is called as drainage coefficient. For transient rainfall conditions, the spacing and depths are selected in such a way that water table will be brought 1 foot down in one day. The drain length of corrugated clay and concrete pipes should be spaced 100 ft. apart with 3/8 drainage coefficient. Critical Velocities of water through open drains for different soil textures are given in Table 14.5.

**Table 14.5** Critical Velocity of Water through Open Drains for different Soil Textures

| Soil Texture | Velocity (feet/sec) |
|---|---|
| Sand and sandy loam | 3.6 |
| Silt and silt loam | 5.2 |
| Silty clay loam | 6.1 |
| Clay and clay loam | 7.2 |
| Coarse sand or gravel | 9.2 |

## 14.7 Drainage Model

DRAINMOD is, basically, a computer based simulation model which is developed by Dr. Wayne Skaggs at North Carolina State University in 1980. It is used for simulation of high watertable and poorly drained soils on an hour by hour and day by day for long periods (e.g. 50 years). The model performs prediction of water management practices and drainage on the soil water regime, watertable depths and crop yields. It can be utilized to determine whether the wetland hydrologic criterion is satisfied for partially drained or drained sites. This model can also be used to estimate the hydraulic capacity of the system for land treatment of wastewater. The model has been applied in different areas. The interface of the model helps to analyze the effect of drainage system design on subsurface drainage, crop yield, nitrogen loss in soil and surface runoff by displaying the results in geographical form.

The original DRAINMOD hydrologic model has been modified into several sub-models on the transport of nitrogen in soil and salinity.

DRAINMOD Inputs:

- Drainage configuration
- Contributing area
- Soils
- Weather
- Vegetation

DRAINMOD Applications

- Agricultural drainage systems
- Controlled drainage
- Sub-irrigation
- Wetland hydrology
- Nitrogen dynamics and losses from drained soil
- Impacts of drainage system and irrigation management on soil salinity in arid regions

- On-site wastewater treatment

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# Chapter 15

# Resource Conservation Technologies

**Allah Bakhsh and R. S. Kanwar***

## Abstract

The world population is likely to increase to 9 billion in 2050. This will require increasing global food production to almost 100% by 2050 to meet the food security needs of an increasing population. To meet the demand for more food supplies, conservation of land and water resources is indispensable. Worldwide, land and water resources are not only shrinking but also degrading fast and therefore, are expected to put additional stresses on both natural resources. Whereas, annual water availability per capita in developing countries like Pakistan has already declined from 5600 $m^3$ in 1950s to less than 1000 $m^3$ in 2014. This situation has placed Pakistan in the list of water deficit countries, adversely affecting its economic growth and wellbeing of the citizens mainly due to water shortage for industry and agriculture. Adequate water availability is a pre-requisite for ensuring food security because on the average, it has an annual rainfall of 240 mm against average annual evapotranspiration of about 2000 mm. Moreover, the country receives about 70% of its annual rainfall during the monsoon season of 70-90 days, whereas water is required throughout the year for growing crops. To cope with increasing food and water requirements of the growing population in the country, there is a crucial need of conservation of land and water resources. This chapter highlights the basic principles of resource conservation technologies including watercourse improvement, laser land leveling, zero tillage, improved irrigation methods, terracing, salinity, skimming well technology, rainwater harvesting and groundwater

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management. Examples of conserving land and water resources have also been presented. After reading this chapter, the professionals, students and other stakeholders will understand the need and importance of conserving the land and water resources using modern technologies to achieve potential food production.

**Keywords:** Food Security, Resource Conservation, Watercourse Improvement, Laser Land Leveling, Rainwater Harvesting, Zero Tillage, Skimming Well

# Learning Objectives

After reading this chapter, readers will be able to learn:

- On-farm resource conservation technologies and their use/prospects
- Water conservation techniques and water harvesting technologies
- Groundwater management and its recharge methods
- Land conservation practices
- Role of Resource Conservation Technologies in Productivity Enhancement

# 15.1 Introduction

The survival of life on this planet depends on the availability of quality natural resources such as land, water and air, which are degrading and relatively shrinking with the passage of time because of their over-exploitation and contamination opportunities because of human activities. Conservation of natural resources will not only assure the availability of these resources for future generations, but also will bring a change in our current thinking that the best practices on sustainable use of water and land resources are the only way for preserving our present and future civilization on this planet. Therefore, there is an urgent need to adopt resource conservation technologies (RCTs) in all watersheds of the world so that optimum crop yields can be obtained for ensuring global food security against increasing population, preserving biodiversity and further improving soil and water quality.

In simple words, the concept of RCTs aims at saving the natural resources to prevent their degradation and loss as well as getting optimum benefits from the resources in such a way that their productivity is not hampered with time rather it is improved for promoting sustainability of the entire eco-system.

One of the best conservation technologies of the 20$^{th}$ century for soil and water conservation has been the use of "conservation tillage system" in agricultural watersheds. Generally, RCTs include several techniques to conserve land and water resources such as contour farming, terracing, no-tillage and chisel plough systems, grass waterways, watercourse improvement and improved drainage systems, laser land leveling, furrow and drip irrigation systems, bed planting, residue management and farm water storage etc. focused at managing water and land resources for promoting their sustainability. Under the umbrella of RCTs, it is desired to promote such practices, which can minimize wastage or less productive use of these resources.

Conservation of water starts from precipitation, which means that all forms of water falling from the atmosphere on the earth originate from precipitation. When water falls on the ground, there are many phases, which may induce losses of water that can be in the form of evaporation, runoff or deep percolation. All these losses are site specific, i.e., depending on local conditions in the watersheds and how well the land surface is managed by farmers, ranchers, foresters, or urban users. This chapter mainly focuses on conservation of land and water resources in agricultural watersheds, primarily at the farmers' fields. When water travels to the farmer's fields, it can be lost during its conveyance and application phases. For improving conveyance efficiency, water can be conveyed through such pathways, which can reduce water losses such as an improved watercourse. Similarly, water application losses in the fields can be managed by controlling water application time and distribution, while ensuring its uniform and desired application of water over the entire field.

## 15.2 Resource Conservation Technologies in Agriculture

Land and water are the two major natural resources that contribute to the potential crop productivity in agriculture. Both the resources are subjected to loss during the crop growing activities unless measures are taken to conserve and make them appropriately available for crop production. The techniques to conserve these resources are discussed below.

### 15.2.1 Water Conservation

Water conservation encompasses all those practices, which can increase the productive use of water while promoting its sustainability for the future. The followings are some of the water conservation practices, which can be adopt at the field level for improving crop productivity.

#### 15.2.1.1 Watercourse Improvement

Watercourse improvement comprises construction of on-farm water channels at predefined waterway and properly designed to convey the sanctioned water from the outlet to tail end of the field and deliver to the shareholders at permissible points. It may be either earthen improvement or the lining of the channel. Renovation or maintenance consists of removing undesirable weeds and silt from the watercourses to conform to the original design standards so that water can be conveyed with minimum losses. Such improvements can be achieved either through profile and topographic surveys and by giving appropriate alignment in accordance with the right-of-way and design specifications or lining with bricks and mortar, or using plastic sheets on the sides and bed of watercourses. After improving conveyance efficiency, the water application efficiency can be improved through measured application and uniform distribution of water in the fields. Watercourse renovation can improve irrigation efficiency from 15 to 25%, depending on the field and farm conditions. For this, land leveling can be a pre-requisite depending on the field conditions.

#### 15.2.1.2 Laser Land Leveling

Conventional methods of land leveling such as using an engineer's level and staff rod, are time consuming, laborious, inefficient, and expensive. Therefore, the Department of Agriculture, Government of Punjab introduced Laser Land Leveling technology to the farmers for leveling their fields precisely. Laser land leveling is a process of smoothing the land surface with criteria of maximum permissible deviation of ± 2 cm from its average elevation using laser-equipped drag buckets. Laser land leveling offers opportunities to level the fields at zero slope so that irrigation water can be distributed uniformly among the head, middle and tail portions of the fields. Large horsepower tractors and soil movers which are utilized for laser land leveling are equipped with GPS and laser-guided instruments. To create the desired slope/level, soil can be moved by cutting high spots and filling low spots as shown in Fig. 15.1.

**Fig. 15.1** Laser land leveling at WMRC, UAF, experimental area.
*Source: Water Management Research Center, University of Agriculture, Faisalabad*

Field studies show that about 20-25% Irrigation water may be lost during its application on the farm because of lack of proper farm layout and unevenness of the fields. This problem is more pronounced in the case of Rice fields. Uneven fields have uneven crop stands, increased weed burden, and uneven maturing of crops. All these factors lead to reduced crop yield and poor grain quality. Using this technique, higher levels of accuracy, water saving and higher crop yields can be obtained. Thus, Laser Land Leveling proves to be one of the effective Water Conservation Techniques.

An unleveled field would face the following problems:

- Traditionally, irrigation application is carried out by the farmers till the high spots are covered, which results in over irrigation, wastage of water and potential water logging at low spots in the field.
- Raised portions of land will get less water and will attract salinity, while the lower areas will be inundated. In both cases, the crop may lose yield.

- In unleveled fields, the soil moisture content will vary spatially in the field. This non uniform distribution of soil moisture will negatively affect the germination of seeds.
- Unleveled fields may require subdivision into smaller portions to minimize the above mentioned problems, which may further obstruct the use of farm implements.

1. Undulated fields have different soil moisture contents at different places in the field and hence fertilizer will not be utilized efficiently.

Thus, it is established through field observations that in case of surface irrigation systems, the field should be leveled and the undulations should be minimized within and between fields.

The Laser Land Leveling as a conservation technique, tends to multiply the benefits in agricultural production. All ill effects of unleveled fields are overcome by laser land leveling, which directly add to the benefits. Thus, directly or indirectly, the following benefits can also be achieved by laser land leveling of irrigated fields.

- Water is uniformly distributed in the field and hence improves irrigation efficiency.
- About 30% water is saved in laser leveled field, therefore, more area can be irrigated with this saved water (Jat et al., 2009).
- The Leveled field will have more uniform germination and hence will produce 20% more yield (Jat et al., 2006).
- Fertilizer will be uniformly distributed, and hence its utilization and efficiency will be improved.
- Erosion hazards would be minimized.
- It improves the machine usage efficiency.
- Land leveling at the farm tends to minimize unwanted watercourses and hence the area under crop may increase.
- Saving of irrigation water as a result of land leveling leads to a less tube well operation that would result in saving of electricity / energy charges and would improve groundwater quality.

To grade a field, laser land leveling is considered the best and viable technology. There are two main parts of the Laser Land Leveling System. The first one is a laser-transmitting unit that emits an infrared beam of light that can travel up to 700 m in a perfectly straight line and the second one is a receiver that senses the infrared beam of light and converts it into an electrical signal. A control box is used to emit electrical signal to activate a hydraulic valve. This hydraulic valve raises and lowers. The blade of a grader is raised and lowered by this hydraulic valve which is being followed by the infrared beam. Laser leveling of a field is accomplished with a dual slope laser that automatically controls the blade of the land leveler to precisely grade the surface to eliminate all undulations tending to hold water. Laser transmitters create a reference plane over the work area by rotating the laser beam 360°. The receiving system detects the beam and automatically guides the machine to maintain proper grade. The field can be leveled or sloped in two directions. This whole procedure is accomplished automatically without the operator touching the hydraulic controls.

#### 15.2.1.3 Zero Tillage

No-tillage or zero tillage is a type of farming practice for which field is not plowed and crop residues are left in the field after harvesting. The sowing of next crop is carried out directly with no-till planters (Zero Tillage Machines). For example, in Rice-Wheat Rotation, wheat is planted with Zero Tillage Drill directly on a rice harvested field without using any tillage machine. Such practices have been found to be very useful to reduce soil erosion either it is in the form of wind or water, especially on the sloppy terrains. Zero-tillage reduces soil erosion because of having roots of the previous crop in the soil and having crop residue on the land surface to minimize the impact of intense rains. It increases organic matter, promotes microbial activity in the soil while conserving the soil moisture and improving soil health in addition to saving fuel cost required for plowing the lands. Zero-tillage, however, may need some other cultural practices for control of weeds (such as crop rotations and integrated pest management) but it is being practiced widely on the lands, which are more prone to erosion.


**Fig. 15.2** Rabi Planter (Raised Bed Technology)

*Source: Water Management Research Center, University of Agriculture, Faisalabad*

### 15.2.4 Raised Bed Planting Technology

Growing of corps on raised beds is one of the improved irrigation methods being practiced all over the world with several benefits. For instance, yield of crops on the bed is improved through better nutrient management, effective aeration around the roots, efficient irrigation and reduced risk of lodging (Syre and Moreno Ramos, 1997). Bed planting has also shown improved water distribution, water use efficiency, fertilizer use efficiency, reduced weed infestation and lodging (Hobbs et al., 2000). This technique also reduces the seed rate without compromising on crop yields as compared to flat sowing. Improvement of root development in bed planting also ensures better crop stand and yields (Peries et al., 2001).

Above all, the bed planting promises a considerable amount of water saving from 35 to 45% as compared to the conventional sowing method, eliminating the formation of crust on the soil surface. (Fahong et al., 2003). Advantages of planting crops on beds become more pronounced when beds are kept “permanent” and are not demolished after the season, rather reshaping for the next crop after wheat. The next crops on the permanent beds have shown better yield and water saving ranging from 20 to 40% compared to those on flat sowing (Cornor et al., 2003).

Since it has been established that bed planting is an important water saving irrigation technique, it has gained momentum in adoption, particularly for row crops such as maize and cotton in the country. The unavailability of a suitable bed planter to grow major crops on the beds, however, was the major limitation with unknown sizes of the furrows and beds on different soils. The Water Management Research Centre (WMRC) at the University of Agriculture, Faisalabad, has been conducting studies on wheat cultivation using different sizes of furrow-bed methods of irrigation since 2002-03. As a result, WMRC has developed a Four Rows Wheat Beds Planting Machine which makes two beds and three furrows along with sowing in a single operation as shown in Fig 15.2. After testing the machine at the experimental area of WMRC for various crops, the machine’s performance has also been tested in farmer’s fields under “University Technology Transfer Program”. The machine has been equipped with three adjustable furrow openers. These openers have the provision to change both the depth and a top width of each furrow, separately, using nut-bolt adjustment mechanism. The provision of this adjustment allows the user to obtain the required size of furrow considering the type of crop, soil, and its seed bed preparation**.** In addition, the machine has also a provision of adjustable seed planting mechanism, which not only allows adjusting the planting depth, but also the spacing within row to row distance of the wheat crop. Furthermore, this planting machine has provision to apply fertilizer in the center of two adjacent rows at deeper depths than the seeds. Kharif Bed planters can be used to sow maize and cotton crops with similar water saving and improved yield opportunities. Fig. 15.3 (a, b, c and) shows successful examples of sowing wheat and cotton crops on beds at WMRC.

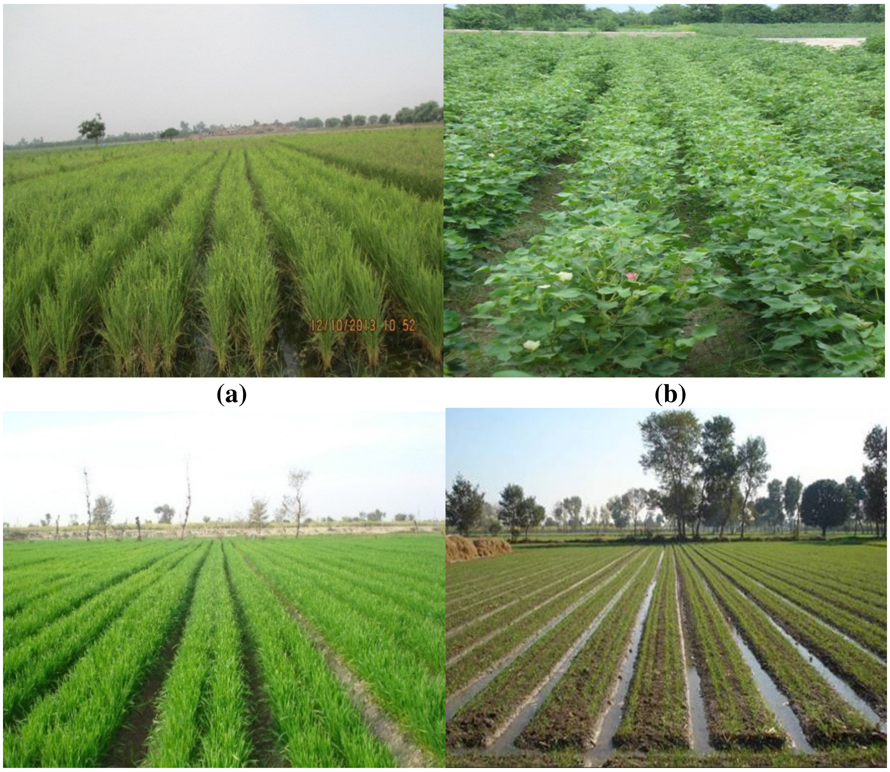
Sowing of wheat seeds in beds can be accomplished successfully by following the tips given below:

- There are two rows from each side of the bed. The first row is at the distance of 3 inches from the edge and the second row is 5 inches away from the first row from both sides of the bed
- There should be distance of 8 inches between the inner two rows of the bed. This distance will minimize water stress as well as salinity problem.
- Seed rate in case of raised bed planting is 10% less as compared to that in the ordinary seed drill planting.

The following are the main benefits of bed planting for wheat crop:

- Water saving from 30 to 50% (Yang et al., 2002).
- 25% increase in crop yield (Wang et al., 2004).
- Higher water and fertilizer use efficiencies
- Less weeds and less lodging of the standing crop

- Good crop response on saline soils and with saline water
- Reduce seed rate by 30-50% as compared to conventional planting
- Conserves rain water through in situ rainwater harvesting
- Saves up to 40% energy used for pumping water (Hassan et al., 2005).




**(a)** **(b)** **(c)** **(d)**

**Fig. 15.3 (a, b, c, d)** Rice, Cotton and Wheat Crops Grown on Bed-Furrow System
*Source: Water Management Research Cente, University of Agriculture, Faisalabad*

In Pakistan, the land and climate are very suitable for rice crop and there is a great chance to increase the yield of rice crop by using bed planting technique. Some guidelines are suggested below to be followed for successful seedbed preparation and planting of rice crop on beds.

I. Prepare the land using conventional method.
II. Use bed planter to make beds of 2 ft width for planting rice seedlings on four rows.
III. Apply irrigation water in the furrows so that beds remain soft. Plant 4 rows of rice crop at 6 inches spacing between rows and plant rice at 6 to 9 inches for plant to plant distance.
IV. Bed planting permits more number of plants than those under conventional methods.

Following Conventional method, if plant to plant distance is kept at 9 inches, then the total no. of plants is about 77440/acre.Research at the Water Management Research Centre has shown that the total numbers of plants using bed planting were more than 100,000/acre. In addition, if one row of crop is grown inside the furrow, then the total number of plants is around 120,000/acre. This will lead to more yield by increasing numbers of plants and more tillering opportunities. Table 15.1 shows that during the years 2008 and 2009, sowing of rice on beds resulted in water saving of 29 and 32 percent, respectively, and average increase in yield of 26 percent.

**Table 15.1** Water Savings and Increase in Yield on Raised Bed System.

| Project area | Year | Area under Rice crop (ac) | Water Saving in % | Increase in Yield % |
|---|---|---|---|---|
| Khurrianwala | 2008 | 71 | 29 | 26 |
| site | 2009 | 80 | 32 | 26 |
| | Average | 151 | 31 | 26 |

Additional benefits given below can be achieved by inter cropping of sugarcane:

- Increase in crop intensity
- Less fertilizer requirement
- Less cost of production
- Water saving for both crops
- Less weed infestation in sugarcane

### 15.2.1.5 On-Farm Water Storage

In Pakistan, water is not available uniformly throughout the year either in the form of canal water or rain water. Therefore, the farmers need to store water whenever it is surplus during any time of the year so that it can be utilized during the dry part of the year. The stored water helps to practice irrigation scheduling i.e. applying the required amount of water at the right time, which is usually not possible without additional storage.

The traditional irrigations are usually heavier, which can be 4 inches or more in depth. This allows the soil to remain wet for about a week depending on the climatic conditions of the region. Nevertheless, many times the farmers want to practice drip irrigation or sprinkler irrigation or any other method to apply lesser amount of irrigation water. In that case, lighter irrigations need to be more frequent, so that the crop water requirements can be met. While the canal irrigation based on warabandi system is a sort of rigid system, which delivers water only after a 7 days' interval. In that case, farmers are urged to store their canal water during their irrigation turn and apply it after two to three days when crops need it. In very hot summer, it is advisable to apply irrigation daily to counter the effects of hot summer, especially when plants and root zone both are short. Under these conditions, it is a better option to have an on-farm water storage, which can also be used for fish farming as well as for recharging groundwater during monsoon season. On-farm water storage pond is shown in Fig. 15.4.

**Fig. 15.4** On-Farm Water Storage at PARS, UAF

*Source: Water Management Research Centre, University of Agriculture, Faisalabad*

#### 15.2.1.6 High Efficiency Irrigation System

High Efficiency Irrigation System usually refers to pressurized irrigation system, i.e., drip irrigation and sprinkler irrigation. Both the systems are considered to have higher irrigation efficiency of 70 to 80% for sprinkler and 80 to 95% for drip irrigation system. Both the systems have their own suitability under specific terrain, soil, water source, and crop specific nature. Both the systems offer better control of irrigation water application and are considered as water conservation methods. Further details about these systems are given in the separate chapters.

**Fig. 15.5** Drip Irrigation System Power Unit installed at PARS

*Source: Water Management Research Centre, University of Agriculture, Faisalabad*

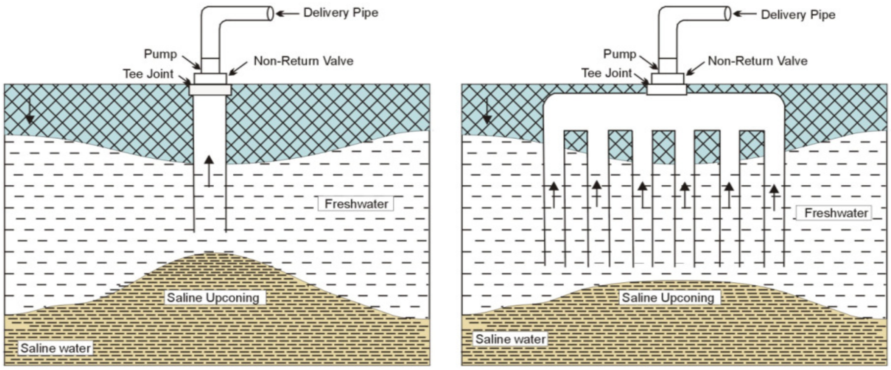
### 15.2.1.7 Mulching

Mulching is a practice in which soil surface is covered with organic material or crop residues so that soil moisture is conserved by minimizing evaporation losses and enhancing infiltration processes. The practice also enhances soil fertility and avoids weed growth. Plastic sheet material is also being used where vegetables or plants grow through the holes provided in the plastic sheet and sheet conserves soil moisture, controls weeds and soil moisture evaporation.

### 15.2.1.8 Skimming Well Technology

Skimming well is a technology in which the top layer of fresh groundwater can be pumped by constructing several bore holes rather than a single bore well. The concept is that a single bore well is usually installed at deeper levels, and therefore, there is a possibility of pumping poor quality groundwater because mostly groundwater quality deteriorates as the well depth goes deeper. For skimming the upper layer of fresh groundwater, the number of bore wells may vary from site to site depending on the aquifer characteristics and groundwater quality. The number of bore wells is usually governed by the drawdown occurring as a result of pumping. The spacing between the bore wells needs to be estimated so that there is a minimum interference of wells on the neighboring wells in terms of their radius of influence and up coning of brackish groundwater. Mostly skimming well depth is installed at 40-50 penetration ratio, i.e., the skimming well can be installed at 40-50% depth of the top fresh water layer after locating interface of the fresh-saline water layer at 3 ds $m^{-1}$.

Fig. 15.6 a and b show the schematic diagrams of a single bore and multiple bore options of skimming well.




(a) (b)

**Fig. 15.6 (a and b)** Schematic Diagram of a Typical Skimming Tubewell

*Source: Water Management Research Centre, University of Agriculture Faisalabad*

### 15.2.1.9 Solar Powered Tubewell

Solar powered tube well works for daytime hours when there is enough power available from the solar panels. Such tube well starts working around 8:00 AM during summer and 9:00 AM during winter depending on the cloudy conditions. Mostly submersible pumps are used as solar powered tube wells because of their improved efficiency and better delivery head. The number of solar panels can be estimated by calculating the required horsepower to run the pump based on groundwater levels. A DC operated motor is coupled at the bottom of the submersible pump, which runs the multistage submersible pump. It is, however, not necessary to use submersible pump. Fig. 15.7 shows a 3-stage submersible pump used for solar tube well installation. Arrangements can be made to run the existing pump by simply converting the DC solar power into AC and running the already installed motor-pump setup. The discharge of solar tube well varies with sun movement throughout the day. The peak discharge of tube well is expected around 12:00-2:00 pm.

The Water Management Research Centre, University of Agriculture, Faisalabad, has installed a Solar Powered Tube well at its experimental area. The three stage submersible pump of the solar tube well needs 4 kilowatt solar energy and delivers around0.5 cusec discharge at peak daily hours. The average discharge of the solar tube well throughout the day for the months of March-June 2013 is given in Fig. 15.8. Such pumping, however, has necessitated the groundwater recharge to maintain the groundwater level within affordable limits.

**Fig. 15.7** Three Stage Submersible Pump for Solar Tubewell

*Source: Water Management Research Center, University of Agriculture Faisalabad*

### 15.2.1.10 Artificial Groundwater Recharge

The increasing demand for water has increased awareness towards the use of artificial recharge to increase ground water supplies. Simply, artificial recharge is a process by which excess surface water is directed to infiltrate into the ground – either by spreading on the surface, by using recharge wells, or by altering natural conditions to increase infiltration – to replenish an aquifer. It refers to movement of water through man-made systems from the surface of the earth to underground water-bearing strata where it may be stored for future use. Artificial recharge, sometimes called planned recharge, is a way to store water during its surplus supplies for its later usage during peak demand period (NCR, 1994). Rainwater can also be used for recharging the aquifer.

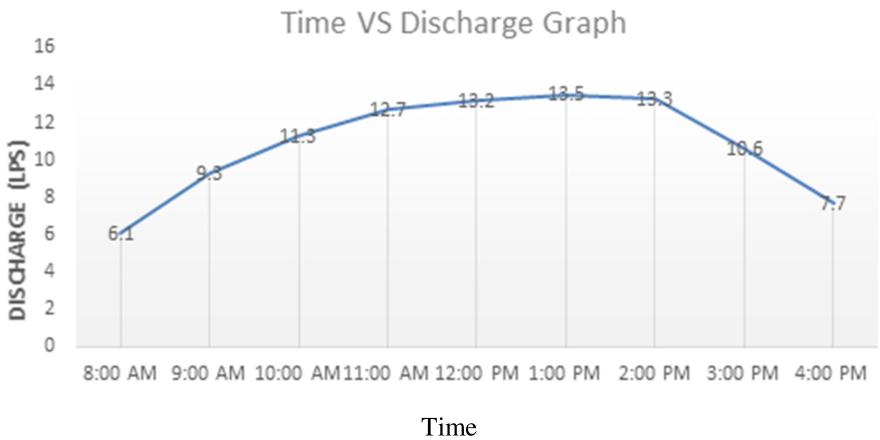



**Fig. 15.8** A Typical Hydrograph for a Solar Powered Tubewell

#### 15.2.1.11 Rainwater Harvesting

This is a technique used for collecting, storing, and using rainwater for landscape irrigation as well as for other uses i.e. ground water recharge and drinking etc. In this technique, the precipitation is collected from various hard surfaces such as roof tops as shown in Fig. 15.9 and/or other types of manmade structures above the ground. This practice is now becoming popular due to increasing water shortage and water demands.

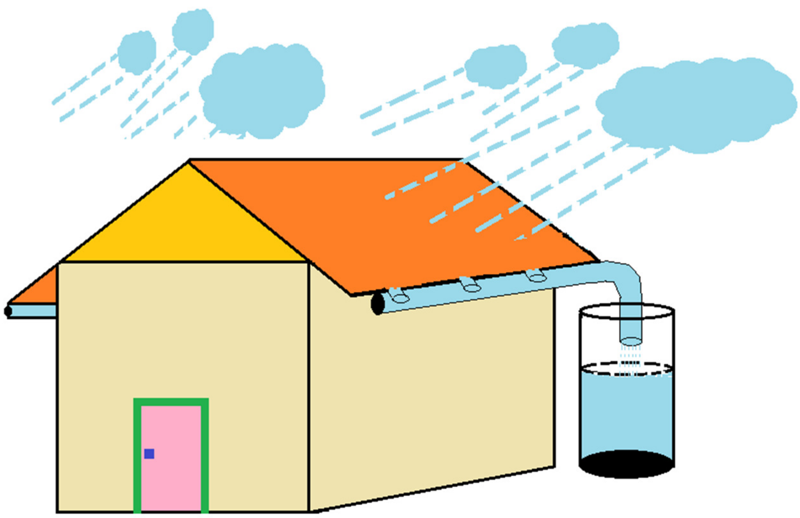


**Fig 15.9** A Typical Rainwater Harvesting Setup from Roof Top of a House

*Source: Water Management Research Cente, University of Agriculture, Faisalabad*

Rainwater collection system mostly includes the following basic components:

The best catchment surface consists of hard and smooth surfaces such as metal roofs or concrete areas (Fig 15.10). The amount of water harvested depends on quantity of rainfall, size of the surface, and slope of the catchment area.

Gutters and downspouts are combined to form distribution system that transports water from catchment area to a storage container such as a barrel, cistern, planted area, etc.

**Fig. 15.10** Rainwater Collection Setup along with Storage Tank and Recharging Well

*Source: Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad*

As the "first flush" of water may contain debris and other pollutants like bird droppings, so it is mostly recommended that the "first flush" should be diverted to an outside area of the storage system. The device which is used for this purpose is called roof washer.

The storage tank, generally, is the most expensive component of a harvesting system. There are numerous types and styles of storage tanks available. Storage can be above-ground or underground. Storage containers can be made from galvanized steel, wood, concrete, clay, plastic, fiberglass, polyethylene, masonry, etc. Examples of above-ground storage include; cisterns, barrels, tanks, garbage cans, above ground swimming pools, etc. To inhibit the growth of algae, storage tanks should be opaque and preferably placed away from direct sunlight. The tanks should also be placed close to the areas of use and supply line to reduce the distance over which water is delivered. Also, consider placing storage in an elevated area to take advantage of gravity flow. The tank should always be placed on a stable and level area to prevent it from leaning and possibly collapsing.


**Fig. 15.11** Storage Tank with Inlet and Overflow Pipes

*Source: Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad*

Appropriate delivery systems are required for the landscape or other end use areas. These can be a gravity-fed based or pump based. Filtration Treatment is needed to make the water safe for human consumption.

**Advantages of Rainwater Harvesting**

1. Makes use of a natural resource and reduces flooding, storm water runoff, erosion, and contamination of surface water with pesticides, sediment, metals, and fertilizers
2. Reduces need for imported / pumped water
3. Excellent source of water for landscape irrigation, with no chemicals such as fluoride and chlorine, and no dissolved salts and minerals from the soil
4. Home systems can be relatively simple to install and operate, it may reduce your water bill
5. Promotes both water and energy conservation
6. No filtration system is required for landscape irrigation

**Disadvantages of Rainwater Harvesting**

1. The capital cost of the system may be too high, especially for sophisticated systems.
2. Requires technical expertise for installation, management and maintenance of the system.
3. If not designed and installed correctly, may attract mosquitoes.

4. Some roof top RWH systems may seep pesticides, chemicals and other pollutants into the water that can harm the plants.

## 15.2.2 Soil Conservation

Conservation of soil means to prevent the soil resource from being eroded and from losing its fertility due to manmade activities. Planting trees and constructing terraces are effective ways to prevent soil erosion. Like this, certain farming practices like contour farming and no-till help prevent loosening of the soil. Preventing pollution of soil helps maintaining soil health and contributes to the conservation of this precious natural resource. The followings are some of the efficient ways to conserve soil.

### 15.2.2.1 Planting Trees

As trees grow tall, the rooting system of trees is more spreader and deeper into the soil layers and hold the soil tightly to prevent it from erosion. Some other management practices like vegetative cover saved soil from wind and water erosion.

### 15.2.2.2 Terracing

Terracing is considered as one of the best methods to conserve soil. A terrace is a leveled section of a hilly cultivated area as shown in Fig. 15.12. Due to its unique structure, it prevents rapid surface runoff of water. Terracing gives the landmass a stepped appearance, thus slowing washing down of the soil. Building firm boundaries is a method used to create terraces in which stone structures are made without using mortar material.

(a) (b)

**Fig. 15.12(a and b)** Terracing for Soil and Water Conservation

### 15.2.2.3 Contour Farming

This practice of farming on sloppy lands considers the slope gradient and the elevation of the soil along the slope (Fig. 15.13). Contour farming is a method of plowing soil across the contour lines of a slope. This method helps in reducing runoff velocity and saves the soil from erosion along the slope. This practice is also useful for better percolation of water in the soil.


**Fig. 15.13** Contour Farming for Soil Conservation

#### 15.2.2.4 Strip Cropping

This consists of growing different crops in alternate strips suchas growing oats, corn, and soybeans in different filter strips as shown in the Fig. 15.14. The crops such as cotton, sorghum (jawar), milo (bajara), etc. allow the runoff water to flow freely within the rows. The erosion resisting crops are mostly legumes like groundnut, alfalfa, clover, peas, beans, lentils, soybeans, and peanuts, etc., which spread and cover the soil and do not allow runoff water to carry much soil with it.Fig. 15.14 gives examples of Strip Cropping. The soil which flows from the strips of erosion allowing by crops is caught by alternative erosion resisting crops. In selecting a suitable legume crop, it should be seen that the maximum canopy and root development of the crop match with the period of high intensity of rainfall.

#### 15.2.2.5 Crop Rotation

When a crop pattern is adopted for a long period, it may cause to build up some pathogens in soil. Repetition of same cropping pattern leads to imbalance in soil fertility. Crop rotation is an effective practice to save soil from these problems. Crop rotation is a method of growing a series of dissimilar crops in an area.

#### 15.2.2.6 Salinity Management

The salinity of soil increases due to excessive accumulation of salts in the soil due to application of saline irrigation water or water logging conditions. This has a negative effect on the metabolism of crops. The salinity of soil is harmful to vegetative growth. The excess salts can lead to reduction in vegetation, which can enhance soil erosion. Hence, salinity management is an indirect way of conserving soil.

**Fig. 15.14** Strip Cropping for Soil Conservation

#### 15.2.2.7 Maintaining Soil pH

Soil pH is an indicator that affects the uptake of nutrients from the soil by plants. Maintaining the correct value of soil pH in the range of 7 is thus essential for soil conservation. Several well established and scientifically proven techniques are available to the farmer for maintaining good pH of the soil. For example, in case of acidic soils, adding lime to the soil is a good practice. Also, for high pH soils, use of gypsum along with green manure is a very good practice.

#### 15.2.2.8 Inter-Cropping

Intercropping is cultivation of two or more crops simultaneously on the same field. It also means the growing of two or more crops in the same field with the planting of the second crop after the first one has completed its development. Fig. 15.15 shows examples of Inter Cropping. The rationale behind intercropping is that the different crops planted are unlikely to share the same insect pests and disease-causing pathogens and to conserve the soil (Boller et al., 2004). It also reduces the cost of production.

**Fig. 15.15** Inter-cropping for Soil Conservation

#### 15.2.2.9 Green Manuring and Cover Cropping

Green manure/cover crops (GMCCs) are plants that are grown to provide soil cover during their growth period and to improve the physical, chemical, and biological characteristics of the soil after plants are harvested and mulched 100% in top 100 to 150 mm of soil. GMCCs such as susbania, may be sown independently or in association with other crops. In general, GMCCs are used to pursue the following objectives (FAO, 2010):

- Provide soil cover for No-Tillage (reduces water evaporation and soil temperature, and increases water infiltration)
- Protect soil from erosion
- Reduce weed infestation
- Add biomass to the soil (to accumulate soil organic matter, add and recycle nutrients, feed soil life)
- Improve soil structure
- Promote biological soil preparation
- Reduce pest and disease infestation

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## Chapter 16

# Remote Sensing and GIS Applications in Water Resources Management

**Muhammad Jehanzeb Masud and Wim G. M. Bastiaanssen***

## Abstract

Availability of data for hydrological and water management analyses is a point of concern, especially in developing countries due to the lack of resource allocations. Remote sensing is being used successfully as an alternative that provides spatially and temporally consistent information required for efficient water resources management. In this chapter, an effort is made to highlight remote sensing (RS) and geographic information system (GIS) and their applicability in data scarce regions for water resources analysis and management. The usefulness of RS for crop classification, rainfall and snow fall estimation, soil moisture analysis, surface and groundwater use is shown that can be used for water resources planning and management in combination with GIS.

## Learning Objectives

This chapter focuses on the potential applications of Remote Sensing (RS) and Geographic Information System (GIS) to many aspects of water resources'

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management at regional and field scale levels, such as rainfall data analysis, soil moisture analysis, irrigation planning and groundwater management.

The reader of this chapter will be able to:

- Develop a sound understanding of RS and GIS technologies
- Learn how to apply RS and GIS in water resources' management studies.

**Keywords:** Geographic Information System, Remote Sensing, Hydro-meteorology, Active Remote Sensing, Passive Remote Sensing and Spatial Land Use.

# 16.1 Introduction

Irrigation system is the largest consumer of fresh water on the earth. About 70% of all water is being used to produce 30% to 40% of the world staple crops (Bastiaanssen, 1998). As water scarcity is becoming a threat that has already initiated a competition among different water users, better irrigation management is needed to achieve higher water use efficiency. To improve water productivity from field to river basin scale, a comprehensive knowledge based management is indispensable. Investments to increase production and making the system to efficiently utilize irrigation water can be economically justified only if the performance can be measured both quantitatively and qualitatively.

Such performance information on scales ranging from farmer's field to canal commands and river basin scale is insignificant as the spatial variation in land use, climatology, soil properties, soil moisture conditions, water usage and cropping conditions occur within an irrigation system. Although it is possible to get this information through field surveys, yet they have a subjective character and it cannot be accomplished for regional or river basin scales. There are also possibilities that field data can become outdated due to frequent changes in land and water management. Therefore, satellites' remote sensing has become an alternative that can frequently provide objective information on hydrological and agricultural situation from field to basin scale. This can enhance the ability of the water managers to properly investigate and design efficient irrigation systems. The development of an adequate monitoring system that can identify the potential threats to sustainability of the system is important for the successful operation of the system.

In this chapter, the ability of multi-sensor satellite to monitor complex hydrological processes, and map water management practices in data, scarce river basins are thoroughly discussed. The internationally shared Indus Basin is taken as an example as it is recognized that reliable data on water resources conditions is insufficient in the Indus Basin. The lack of a dense network of hydro-meteorological observatories is the plausible cause. Remotely sensed information, obtained from satellites, can therefore be an attractive alternative solution.

The scientific methodologies exit that help to efficiently utilize satellite measurements for quantifying conjunctive water use in data scarce river basins. Normally, four knowledge gaps exit that impede a successful basin scale hydrological analysis, including: (i) lack of fundamental data, (ii) lack of knowledge on land use, (iii) missing information on groundwater resources for the entire basin, and (iv) lack of analytical tools to study alternative solutions to combat over-exploitation of water resources and become more climate resilient.

Spatial data, obtained from satellites, can be used for preparing water accounts, prohibiting new upstream water resources development, groundwater restoration plans, developing fair irrigation management practices, providing access to water during droughts, estimating impact of retiring glaciers, reducing non-beneficial water usage, enhancing recycling of drainage water and introducing green water credits in upstream catchments, etc.

## 16.2 Remote Sensing and Geographical Information System

### 16.2.1 Remote Sensing

Remote sensing can be defined as the science and art of acquiring information (spectral, spatial or temporal) about physical objects or areas without coming into physical contact with it. Remote sensing uses electromagnetic spectrum to image the land, ocean and atmosphere by using electromagnetic radiation (EMR) at different wavelengths (visible, red, near-infrared, thermal infrared, microwave) as shown in the Fig. 161. The unique spectral signatures of each object on the earth's surface can be detected at these wavelengths and can be interpreted to generate quantitative information on hydrological processes.

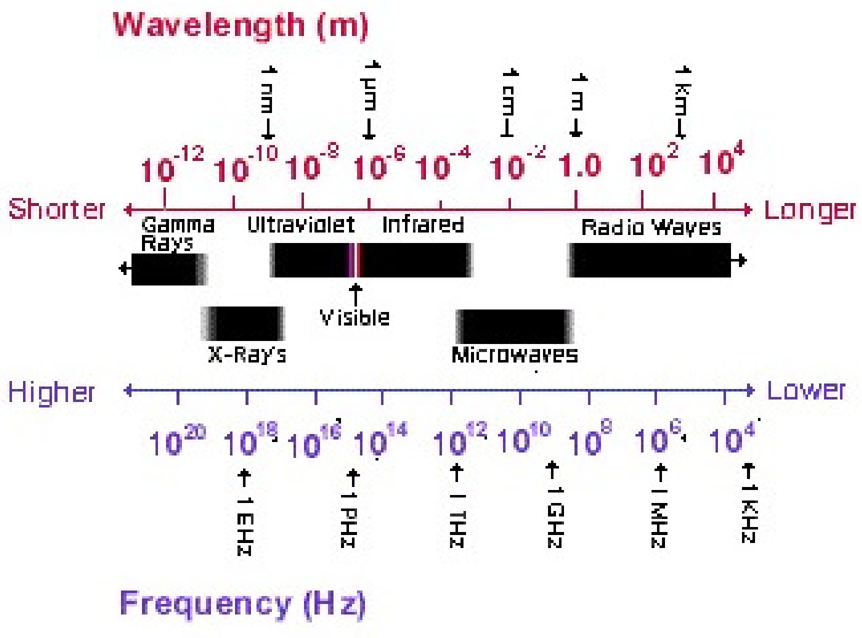



**Fig. 16.1** Electromagnetic Spectrum Categorizing Wavelengths and Frequencies.

There are large numbers of satellites in the earth's orbit, which are being used to acquire information on hydrological and biophysical parameters. Pixel size varies from few metres to kilometres as shown in Table 16.2 and temporal resolution varies from 3-hours to many months. For example, term provides 3-hour rainfall rate estimates at 25 km pixel resolution since 1997. The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) observes atmospheric, land and oceanic parameters. Daily soil moisture estimates at 25 km pixel resolution are available through AMSR-E. Daily evapo-transpiration can be estimated by using AMSR-E and MODIS satellites at 1 km grids. NDVI, LAI, land use, albedo, biomass at 1 km resolution can also be estimated from MODIS, SPOT vegetation etc. Ground water levels can be estimated using the GRACE satellite that provides monthly changes in storage change at 400 km grids. There are two types of remote sensing systems available. First is Active and second is Passive.

#### 16.2.2.1 Active Remote Sensing

In active remote sensing, the sensors have their own sources of energy. They emit radiations towards the target under investigation and detect and measure radiances from objects as is the case of radar (Fig. 16a). Regardless the time of day or season, active sensors have the advantage to take measurement anytime. Active sensors are widely used for the wavelengths that are not adequately provided by the sun. The energy requirements for the better illumination of the target in case of these systems are quite large. Some examples of active sensors are synthetic aperture radar (SAR), LASER and European Remote Sensing Satellite (ERS).

**Table 16.2** Characteristics of Resolution Categories of Polar Orbiting Satellite-based Data

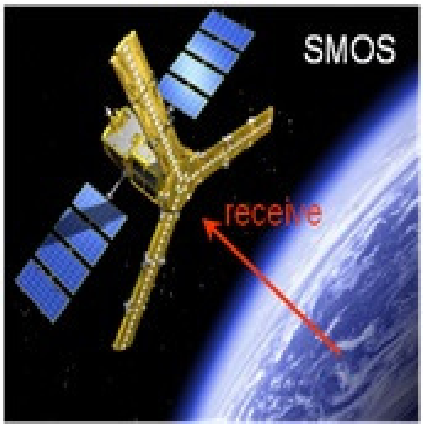
| Resolution category | Pixel resolution (m) | Swath Width (m) | Satellites (selected) |
|---|---|---|---|
| Very high | 0.5 – 2.5 | 5 –40 | Quick bird, Ikonos, GeoEye, Worldview |
| High | 2.5 – 30 | 40 –700 | SPOT, LandSat, Aster, RadarSat, FormoSat, LISS, RapidEye, Chers |
| Moderate | 30 – 400 | 700 –3000 | MODIS, MERIS, AWIFS, FY, ASAR |
| Low | 400 –25,000 | 3000 | MODIS, MERIS, ASCAT, FY, ASAR, TRMM, AMSRE, GRACE |

### 16.2.2 Types of Remote Sensing

#### 16.2.2.2 Passive Remote Sensing

In passive remote sensing, the sensors detect and measure the reflected or emitted EMR from objects that gets energy from natural sources. For remote sensing sun is the primary largest source of energy. The energy is either absorbed or reflected (optical) and then re-emitted, as it is for thermal infrared wavelengths. Earth itself emits radiations that are taken up by the passive sensors e.g. in microwave region of wavelength spectrum (Fig. 16.2).


a) Active remote sensing




b) Passive remote sensing

**Fig. 16.2** Examples of Remote Sensing Types

### 16.2.3 Geographical Information System (GIS)

GIS is used for spatial mapping of objects that integrates space science, survey and the mapping. The GIS can be used to manage data as well as to integrate and analyze spatial data obtained from different sources (field surveys, remote sensing) with diverse structures, resolution and projections.

Remote Sensing and GIS use in the field of water resources management has been increased manifold during the last decade. Data on hydrology can be acquired from satellites. As for irrigation water problems are concerned, high to moderate resolution imagery from satellites give prime information of different hydrological components for water resources management practices.

## 16.3 Remote Sensing and GIS Research in Water Resources Management

Poor Management of water is also big concern for water scarcity as well as unavailability of storages sites. Conventional water resource planning and management is mainly focused on blue water (water in streams, rivers, aquifers, lakes and reservoirs). There is a dire need to incorporate rainfall, especially in arid and semi-aridbasins that infiltrates naturally into the soil and on its way back to the atmosphere in the form of evapo-transpiration. Managing non-beneficial evaporation will result in a significant reduction in water use that can be re-allocated to other users.

Water resources management and planning is always attractive research issue for hydrologists but increasing trend to use up to 50% ground water, there is dire need to manage the groundwater reserves to maximize efficiency at basin level. The mismanagement of the groundwater put harmful impact on ecosystem and ultimately on food security. Hence, sustainable ground water management is more challenging issue than development. Moreover, absence of expert knowledge is a big hurdle of both ground and surface water.

Remote sensing and GIS play a vital role in the conservation and utilization of country's water resources. For achieving optimum planning and operation of water resources, related projects and latest techniques of remote sensing must be combined with the traditional methods of measurement and management of ground water that will last into sustainable groundwater management.

Satellite data is an attractive alternative for data required by hydrological models. It also provides spatial information to decision makers. Satellites provide objective data for database building (for various applications, see Table 16.2), which is politically neutral and cannot be manipulated. Satellite data describes agricultural practices, the observable landscape patterns resulting from socio-economic development, irrigation management, hydrological processes, prevailing jurisdiction and land surface features. Because they are satellite observations, direct measurements are often more reliable source than secondary data. For example, a research carried out by (Bastiaanssen and Prathapar, 2000) in Gediz River Basin in Western Turkey found that satellite data estimated 60% more area than governmental statistics. It is believed that if such uncertain secondary data are used to develop intra-basin water cooperation, conflicts and disputes can increase and ultimately trust will diminish.

Because they are direct measurements, satellite observations are often more reliable than secondary data. For instance, the irrigated area in the Gediz River Basin in Western Turkey appeared from the satellite images to be 60% larger than from the secondary data obtained from governmental statistics (Bastiaanssen and Prathapar, 2000). It is obvious that if such types of secondary data are used to establish intra-basin water cooperation, disputes and conflicts can potentially worsen and trust will fade away.

**Table 16.2** Satellite Measurements for possible Applications in Trans Boundary River Basins.

| Discipline | Application |
|---|---|
| Hydrology | Evapotranspiration, soil moisture, Snow cover, rainfall |
| Agriculture | irrigation performance, Irrigated areas, crop identification, rain fed areas, biomass growth, crop yield, |
| Environment | water quality, salinization, wetlands, Forest area, water logging, rangelands |
| Geography | Land cover, land use, digital elevation, land aspects and land slope |

*Source: Bastiaanssen and Prathapar, 2000*

Many researchers have used satellite data in hydrological models in un-gauged or data scarce regions (Immerzeel et al., 2008). Calibration and validation of these models need long term data series obtained from dense measurement networks. However, in the basins like the Indus, such data is meager, thus causing a high level of uncertainty in the model results. Spatially variable information describing topography, crop types, land use, climatic data, and leaf area index, derived from remote sensing can be used for modeling across basins.

Combination of RS with the Global Positioning System (GPS) and Geographical Information System (GIS) produces politically un-biased knowledge based on land use, soil moisture, rainfall, evapotranspiration, surface and groundwater availability and the use that could be used in the areas of snowmelt-runoff forecasts, irrigation performance evaluation, drought monitoring, watershed treatment, reservoir sedimentation, flood mapping and management.

# 16.4 Spatial Land Use and Land Cover Mapping

A land use database is essential to provide information on the type of water consumers and the returns in terms of food production, wood production, hydropower, environmental services, economic benefits, etc. For judicious allocation of water, the crops grown in the areas have to be identified. This can be accomplished by discerning land uses. Spatially consistent 1 km × 1 km pixel information of various land uses was generated using Normalized Difference Vegetation Index (NDVI) data freely available from vegetation sensors on board the SPOT satellite. The NDVI is calculated from measurements of spectral reflectance acquired in visible (red) and near infrared (NIR) regions of wavelength spectrum as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \qquad (1)$$

The NDVI varies between –1 to +1 representing water and maximum greenness, respectively. Two classification methodologies can be adopted to discern different land use classes.

a) Supervised classification
b) Un-supervised classification

Since collection of ground truth data in the vast river basin is very difficult, therefore un-supervised classification can be used to do initial mapping. In such a classification, the pixels with similar spectral signatures are clustered as a single class ISODATA clustering technique. The knowledge of crop phenology (Table 1) helped to identify crops with specific NDVI temporal profiles. A considerable difference in NDVI patterns helps to identify the land uses (Fig. 16.3).

The irrigated land uses show two peaks in a year while evergreen forests have consistently higher NDVI throughout the year. The rainfed land uses have peaks in phase with rainfall and soil moisture conditions. The phenological cycle thus obtained, supported by expert knowledge and ground information, can be used to identify specific crops and crop rotations. Further classification was based on cropping calendar and dominant crop area. The class cropland was partitioned using NDVI temporal profiles and expert knowledge of cropping patterns. Some classes were merged based on information obtained during ground truth.

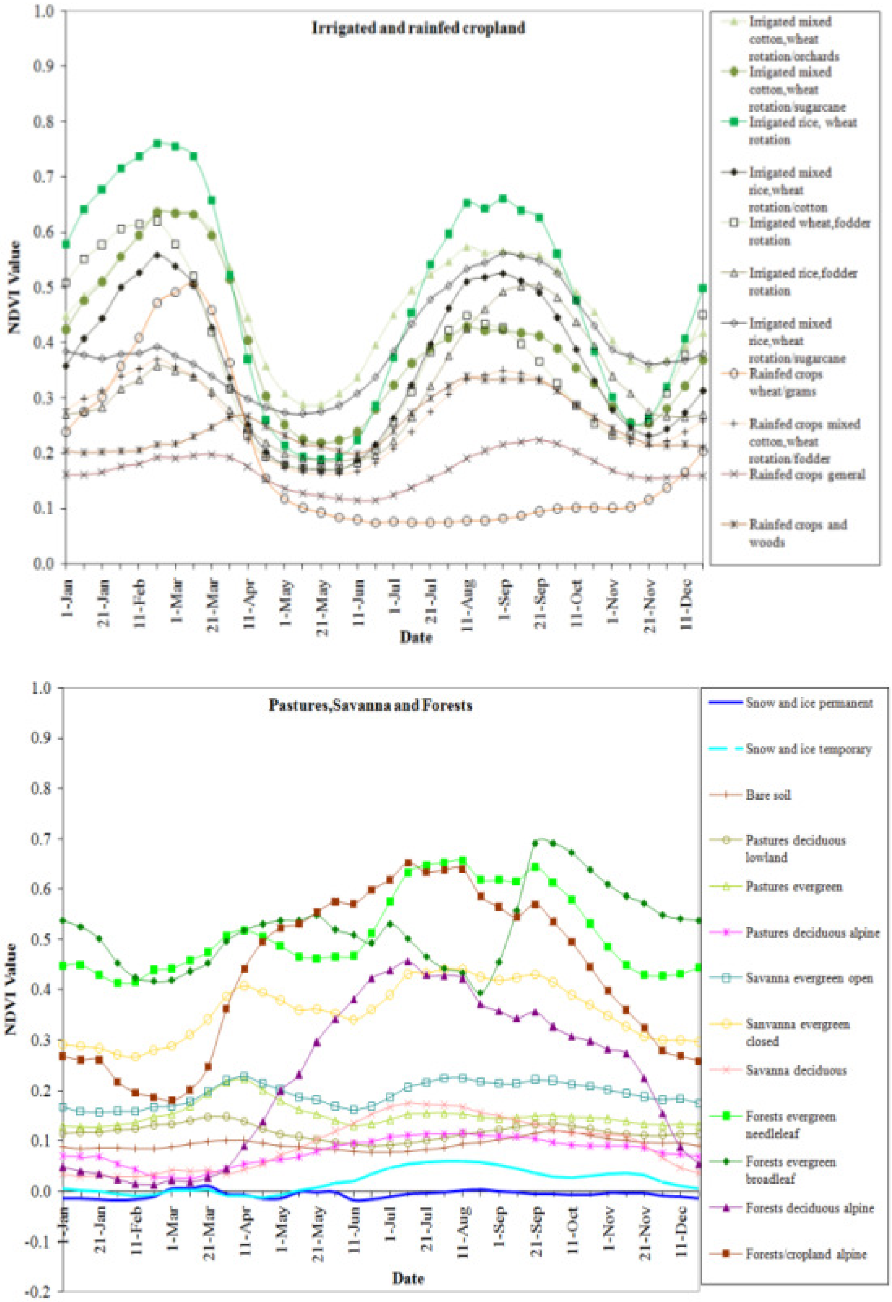



**Fig. 16.3** Mean NDVI Temporal Curves for Irrigated, Rainfed Crops and Forests in the Indus Basin -2007

*Source: Cheema, 2012*

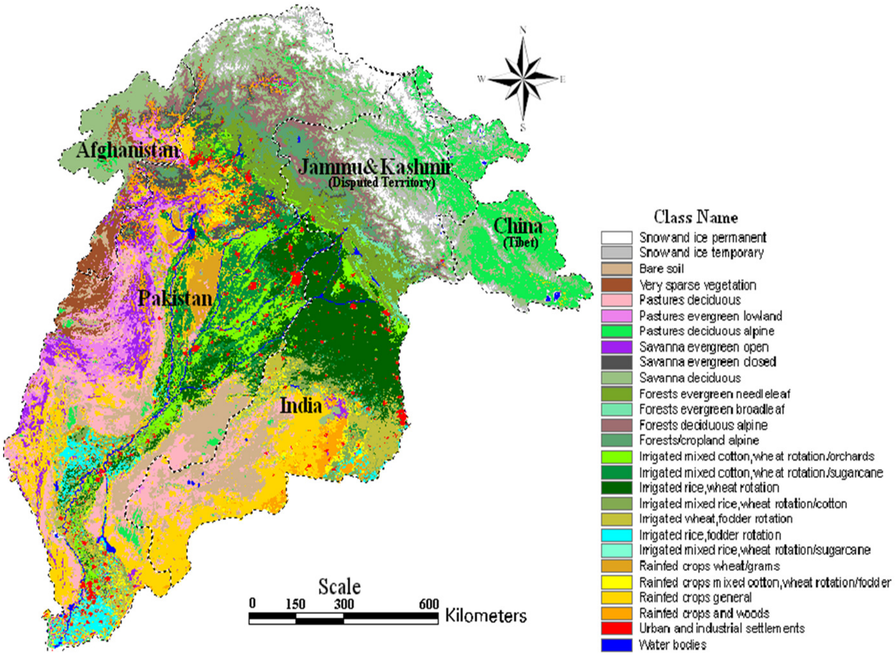



**Fig. 16.4** Land use and Land Cover Map of Indus Basin Developed from 36 SPOT-Vegetation based NDVI Values Covering Annual Vegetation Phenological Cycle of 2007

*Source: Cheema and Bastiaanssen, 2010*

The GIS helps to determine area under various land use classes. Table 16.3 summarizes the classes with their area in the entire Indus Basin. The dominant class in the Indus Basin is irrigated agriculture (23%), followed by pastures (16.2%), rainfed crops (16.1%), savannas (15.9%) and forests (10%).

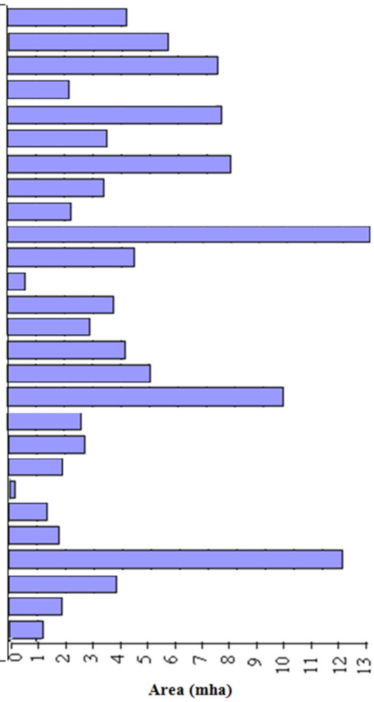
## 16.5 Spatio-Temporal Precipitation

Any water resources analysis starts with quantification of rainfall. Aerial rainfall for catchments and basins is normally interpolated from rain gauge networks. A density of less than four gauges per 10,000 km$^2$, is however insufficient to capture the spatial heterogeneity of rainfall processes. Any small error of a large water balance component such as rainfall can produce significant errors in the smaller components such as runoff. The spatial interpolation of point measurements in heterogeneous landscapes and mountains result in erroneous estimates. Dense networks are needed that are difficult to establish and maintain in developing countries. Rainfall estimation by means of satellites is therefore essential.

Satellite based sensors provide an integrated measurement of rainfall in time and space. They are an excellent alternative for rainfall measurement. Sensors on board the Tropical Rainfall Measuring Mission (TRMM) satellite provide three-hourly global rainfall estimates that can be freely downloaded. However, these estimates are also erroneous (Cheema and Bastiaanssen, 2012). Therefore, such estimates must be corrected before using them in water resources' analysis and management.

**Table 16.3** LULC Types and their Areal Distribution in the Indus Basin

| No | Class Name | Area (mha) | Area (%) |
|---|---|---|---|
| 1 | Snow and ice permanent | 4.18 | 3.6 |
| 2 | Snow and ice temporary | 5.59 | 4.8 |
| 3 | Bare soil | 7.37 | 6.3 |
| 4 | Very sparse vegetation | 2.19 | 1.9 |
| 5 | Pastures deciduous | 7.51 | 6.5 |
| 6 | Pastures evergreen lowland | 3.51 | 3.0 |
| 7 | Pastures deciduous alpine | 7.83 | 6.7 |
| 8 | Savanna evergreen open | 3.37 | 2.9 |
| 9 | Savanna evergreen closed | 2.24 | 1.9 |
| 10 | Savanna deciduous | 12.94 | 11.1 |
| 11 | Forests evergreen needleleaf | 4.42 | 3.8 |
| 12 | Forests evergreen broadleaf | 0.62 | 0.5 |
| 13 | Forests deciduous alpine | 3.69 | 3.2 |
| 14 | Forests/cropland alpine | 2.87 | 2.5 |
| 15 | Irrigated mixed cotton,wheat rotation/orchards | 4.13 | 3.6 |
| 16 | Irrigated mixed cotton,wheat rotation/sugarcane | 5.03 | 4.3 |
| 17 | Irrigated rice,wheat rotation | 9.69 | 8.3 |
| 18 | Irrigated mixed rice,wheat rotation/cotton | 2.59 | 2.2 |
| 19 | Irrigated wheat,fodder rotation | 2.69 | 2.3 |
| 20 | Irrigated rice,fodder rotation | 1.92 | 1.7 |
| 21 | Irrigated mixed rice,wheat rotation/sugarcane | 0.18 | 0.2 |
| 22 | Rainfed crops wheat/grams | 1.34 | 1.2 |
| 23 | Rainfed crops mixed cotton,wheat rotation/fodder | 1.78 | 1.5 |
| 24 | Rainfed crops general | 11.71 | 10.1 |
| 25 | Rainfed crops and woods | 3.78 | 3.3 |
| 26 | Urban and industrial settlements | 1.88 | 1.6 |
| 27 | Water bodies | 1.16 | 1.0 |
| | Total | 116.21 | 100 |




The accuracy of such land use mapping can be done by using error matrix or confusion matrix as described by Cheema and Bastiaanssen (2010).

Two methodologies can be used to calibrate the estimates of the TRMM rainfall (product 3B43) with low density rain gauge measurements. One method is regression analysis and the other geographical differential analysis. Both the techniques sufficiently improve the results with Nash Sutcliffe efficiency by 81% and 86%, respectively. However, the standard error of estimate of the geographical differential analysis was 41 mm lower than the regression analysis for the entire Indus Basin.

The advantage of the geographical differential analysis is that the differences in rainfall are used for spatial interpolation and not for the absolute values of rainfall. The values for the differences reflect certain underlying terrain features, and the corrections at specific locations were thus bigger than in the any other locations. The deviations in measured and estimated rainfall can be reduced considerably to 6%.

This is equivalent to an amount of water of 26 $km^3\ yr^{-1}$, which is 17% of the withdrawals to the irrigation sector, being approximately 150 $km^3 yr^{-1}$. Any small error in rainfall measurement thus affects the calculation of water availability for diversions. The total annual mean rainfall in the basin calculated was 383 mm $yr^{-1}$ (or 445 $km^3 yr^{-1}$). The lowest 5% value was 46 mm $yr^{-1}$and the highest 5% value was 1298 mm $yr^{-1}$. The spatial distribution of the rainfall in the Indus Basin is shown in Fig. 16.

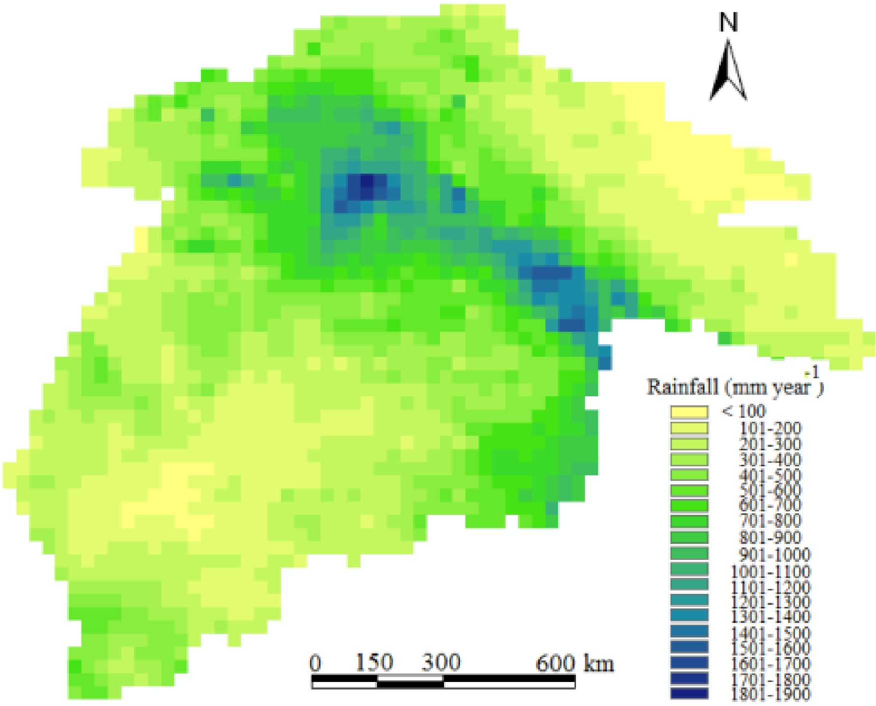



**Fig. 16.5** Spatial Distribution of Calibrated TRMM Rainfall for the Year 2007.

The TRMM provides regional coverage at higher temporal resolution as compared to other gridded products, but at the cost of a low spatial resolution. The indirect measurement of precipitation by onboard sensors also has uncertainties (Hossain et al., 2006). These uncertainties are associated with lack of rainfall detection as well as false detection and bias (Tobin and Bennett, 2010). Both temporal errors (± 8 to ±12% per month) and sampling errors (~30%) can be expected in TRMM rainfall estimates. Such errors can result in erroneous applications if applied without calibration (Gebremichael et al., 2010). Therefore, TRMM satellite estimates need area specific calibration to reduce such errors.

## 16.6 Soil Moisture Mapping for Floods and Droughts

Soil moisture is considered as another state variable that is informative of the water balance. Hydrological processes are very much affected by soil moisture condition.

Water present in the soil unsaturated zone is called as soil moisture while the surface soil moisture is upper soil water present in the top few centimeters of soil. Division of precipitation into surface runoff and infiltration is determined by surface soil moisture. Soil moisture plays an important role in drought predictions, flood forecasting and crop yield predictions.

Presence of water is directly indicated by soil moisture patterns in the arid conditions. Under arid conditions, soil moisture patterns are a direct indication of the presence of water. Wet top soils reflect irrigation water distribution or shallow watertable areas. It is practically impossible to attain soil moisture information at large spatial scales with *in-situ* sensors, and for this reason it is not common to include soil moisture in management decision making. Passive microwave sensors on board satellites such as AMSR-E, SMOS and Feng Yung provide global scale estimates of daily surface soil moisture for free. These sensors provide continuous soil moisture estimates without being affected by weather conditions. That is also the main reason for applying a new evapotranspiration (*ET*) algorithm based on soil moisture measurements.

Surface soil moisture is estimated by applying inversion techniques to the brightness temperature measured by satellites. The technique is not error free; therefore, it was necessary to validate the satellite soil moisture prior to its use in estimating other hydrological processes. Due to the non-availability of *in situ* soil moisture measurements in vast river basins, classical validation techniques are not technically feasible. Therefore, alternative validation approaches were needed to build confidence in using satellite soil moisture products. The reaction of vegetation to soil moisture, and soil moisture to rainfall was studied to explain the soil moisture behavior.

Strong relationships between AMSR-E surface soil moisture and TRMM rainfall in the land use classes “bare soil”, “rainfed” and “very sparse vegetation” were observed. AMSR-E surface soil moisture has a very high relationship with TRMM rainfall events in land use classes. Furthermore, a strong correlation exists between TRMM accumulated rainfall and the AMSR-E mean soil moisture (Spearman’s rank correlation coefficient $r_s$=0.74) rather than NDVI and TRMM accumulated rainfall ($r_s$=0.70). Similarly, NDVI and Mean soil moisture have strong correlation ($r_s$=0.85) as compared to NDVI and TRMM rainfall ($r_s$=0.70).

A time lag between soil moisture and NDVI time series was observed. The late response of vegetation against moisture in root zone is the basic reason of lag. Such a lag was expected due to the delayed response of vegetation against moisture in the root zone. The lag time varied from zero to 60 days, and was generally longer for the wet *kharif* season. For the dry *rabi* season, a Pearson’s $r > 0.60$ was found for 75% of the cases with zero to 40 days lag. For the wet *kharif* season, it was found for 81% cases but with a lag of 20 to 60 days. The maximum surface soil moisture value of 0.35 to 0.45 $cm^3\ cm^{-3}$for a pixel was like the top layer saturated moisture content expected on the basis of soil texture maps and pedo-transfer functions. Higher values occurred in flooded lands and paddy fields. This suggests that absolute AMSR-E values properly describe soil moisture under wet land surface conditions.

Confidence in satellite derived surface soil moisture product will facilitate various applications such as the calibration/validation of spatially distributed hydrological models that can be applied on large scale irrigated river basins with scarce data (Ines and Mohanty, 2008). Accurate soil moisture data is also essential for describing droughts and floods.

## 16.7 Spatially Distributed Crop Water Use Estimation

Water scarcity is a global problem. Therefore, planning and monitoring is required for its efficient management. Consumptive use impact on agriculture, economic, social and environmental development. Urban areas, forests, soil, and natural vegetation are major which consume water through evaporation (E) and transpiration (T). There are two terms which are valuable for effective management of water. Net producer of water resource is a phenomenon where precipitation exceeds ET. Such a land cover class is net producer of water resource e.g. excessive water or non-consumed water feeds aquifer, streams and rivers. However, when rate of ET is greater than net precipitation then it is known as net consumer of water resource e.g. irrigated land is typical example of net consumer of water resource in a land cove class. ET information can be used for irrigation management (Bastiaanssen et al., 1996), drought detection, real water savings, water accounting, water productivity, virtual water trade, model calibration, hydrological model applications and groundwater management.

Evapotranspiration is measured by a number of techniques ranging from traditional point measurement to newly modeling and spatially distributed remote sensing estimates. Lysimeters, Bowen ratio, heat pulse velocity, eddy correlation andsurface renewal are commonly used to measure ET at individual plant and field level. However, the accuracy of these traditional instruments is less than 90% (Teixeira and Bastiaanssen, 2011). Besides, extensive labor, equipment cost and coverage issue are considered as big hurdle to use these techniques at large scale.

The actual rate of evapotranspiration cannot be inferred from routine weather data. Rainfall can be measured easily with cheap gauges, but not *ET* from land surfaces (except at sites equipped for scientific energy balance equipment). Even though water institutions and international river basin commissions have the duty to manage the water resources of river basins, they do not use basin scale evapotranspiration information at all. The financial constraints in the developing countries restrict installation of permanent flux observation towers. There is no single flux tower present in the Indus Basin, while one seventh of the world population lives here and a volume of 496 $km^3$of water evaporates every year.

Therefore, a new methodology (ETLook) has been tested that provides spatial estimates of evapotranspiration from satellite measurements and a surface energy balance.

The surface energy balance can be written as:

$$R_n - G = \lambda E + H \ (Wm^{-2}) \qquad (2)$$

Where:

$R_n$ is net radiation ($Wm^{-2}$),

G is soil heat flux ($Wm^{-2}$),

λE is latent heat flux ($Wm^{-2}$) and

H is the sensible heat flux ($Wm^{-2}$)

λE is associated with ET

The ETLook algorithm uses a two layered approach to solve the Penman – Monteith equation. The Penman – Monteith equation for *E* and *T* can be written as:

$$E = \frac{\Delta\left(R_{n,soil} - G\right) + \rho c_p \left(\frac{\Delta_e}{r_{a,soil}}\right)}{\Delta + \gamma\left(1 + \frac{r_{soil}}{r_{a,soil}}\right)}$$

$$T = \frac{\Delta\left(R_{n,canopy}\right) + \rho c_p \left(\frac{\Delta_e}{r_{a,canopy}}\right)}{\Delta + \gamma\left(1 + \frac{r_{canopy}}{r_{a,canopy}}\right)}$$

Where:

*E* and *T* are evaporation and transpiration respectively ($Wm^{-2}$),

$\Delta$ is the slope of the saturation vapor pressure curve (mbar $K^{-1}$) which is a function of air temperature ($T_{air}$, °C) and saturation vapor pressure ($e_s$, mbar);

$\Delta_e$ (mbar) is vapor pressure deficit, which is the difference between the saturation vapor content and the actual vapor content;

$\rho$ (kg $m^{-3}$) is the air density, and

$c_p$ is specific heat of dry air =1004 J $kg^{-1}$ $K^{-1}$;

$\gamma$ (mbar $K^{-1}$) is the psychometric constant;

$R_{n,\ soil}$ and $R_{n,\ canopy}$ are the net radiations at soil and canopy respectively;

$r_{soil}$ and $r_{canopy}$ are resistances of soil and canopy, while

$r_{a,\ soil}$ and $r_{a,\ canopy}$ are aerodynamic resistances for soil and canopy respectively.

All resistances are in s $m^{-1}$. The *E* and *T* fluxes (W $m^{-2}$) are converted to rates (mm $d^{-1}$) using a temperature dependent function of the latent heat of vaporization.

There are several *ET* algorithms available in the literature, but the advantage of this particular algorithm is that it provides continuous estimates of *ET* throughout the year without being affected by weather. ET look is a two-source model that can infer information on non-beneficial evaporation and beneficial transpiration separately using microwave derived surface soil moisture. Microwave radiometry is least affected by cloud cover and can thus provide continuous surface soil moisture information even in the monsoon periods and for high altitude regions with persistent clouds.

The estimated evapotranspiration at 1 km pixel resolution correlated well with some historic lysimeter measurements, Bowen ratio measurements, and remote sensing studies ($R^2$of 0.70 to 0.76 at annual time scale; RMSE of 0.29 and 0.45 mm $d^{-1}$). It was demonstrated that the pixel scale *ET* fluxes at daily, 8-day, or monthly time scales can be estimated. The total basin wide *ET* in 2007 was 496 $km^3yr^{-1}$ while rainfall was 443 $km^3yr^{-1}$. This revealed that more water is evaporated from the land surface than what was received through rainfall. Multiple line agencies from the region and the gravity mission from NASA also suggested a net storage change related to net groundwater withdrawals, declining groundwater tables, snowmelt, and retiring glaciers. The only solution to make the environment of the Indus Basin more sustainable is to reduce *ET*, and in particular the non-beneficial *ET*.

*ET* information can greatly assist water managers and policy makers with water allocations. It is also important to gain knowledge of net water producing ($R>ET$) and water consuming areas ($ET>R$) (Fig. 16.). The stream flow resulting from net water producing areas can be managed by land used change and adjusted cultivation practices. The concept of green water credits is based on certain agreed upstream ecosystem services to generate sufficient stream flow. Net consuming areas–such as irrigation systems - can be controlled by regulating the water diversions and withdrawals. The irrigation sector is often criticized for inefficient use of water resources. By comparing water diversions to consumptive use, estimates of non-consumed water flows can be made. Irrigation water supply in Pakistan is based on equal access to water for all farmers. Doubtlessly, such aspiration is difficult to achieve anywhere in the world and especially in areas where water resources are limited. Farmer communities often claim that they are not receiving the volume of water for which they are entitled to. Pixel values of *ET* will provide a new source to verify these conditions; not only to certify that they receive water, but at the same time also to verify that they are not using water non-beneficially and non-productively.

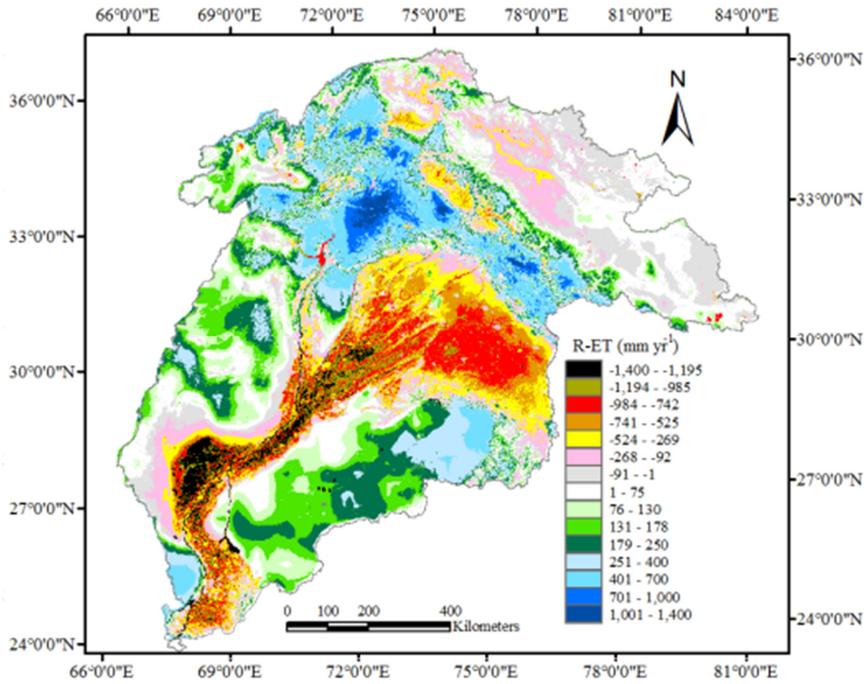



**Fig. 16.6** Rainfall-evapotranspiration difference Map of the Indus Basin for the Hydrological Year 2007

*Source: Cheema, 2012*

estimation of rainfall and *ET*, it is possible to determine the amount of irrigation water supplies that match *ET* rates. A hydrological model (Soil and Water Assessment Tool; SWAT) can be used for this purpose. Pixel information on topography, land use, soils, rainfall, and evapotranspiration provide input data into the SWAT hydrological model. SWAT is a well-known and accepted distributed hydrological model that describes many relevant hydrological, soil physical and bio-physical processes. It is freely available, globally adoptable, and the ability to compute atmospheric land surface, soil, groundwater, and stream flow processes.

The SWAT model parameterization and calibration can be done by using remotely sensed information on land use, rainfall, topography and *ET*. A calibration procedure with variable irrigation water supply and soil physical properties are carried out for each hydrological response unit. The calibrated model thus applied to generate output maps of total irrigation water supply at the farm gate, surface runoff, and combined drainage and percolation. It provides fundamental insights into the breakdown of irrigation water flows into consumed and non-consumed outflows of all irrigated fields present in the Indus Basin in a uniform manner. The spatial water balance of the unsaturated zone read by SWAT is given as:

$$\Delta S_{us} – R_{SWAT} + IRR_{SWAT} + C_r – ET_{SWAT} – Q_{perc} - Q_{surf} – Q_{lat} \quad (3)$$

where:

$\Delta S_{us}$ is the change in storage of the unsaturated zone (mm)

$R_{SWAT}$ is the amount of precipitation (mm),

$IRR_{SWAT}$ is the amount of total irrigation applied (mm),

$Q_{surf}$is the amount of surface runoff (mm),

$ET_{SWAT}$ is the actual evapotranspiration (mm),

$Q_{lat}$ is the amount of lateral flow through the unsaturated zone (mm),

$Q_{perc}$is the amount of percolation (mm) and

$C_r$ is the capillary rise (mm).

The net groundwater depletion ($DEP_{gw}$: amount of water leaving the shallow aquifer) can be estimated for the irrigated areas using information of canal water losses ($LOSS_{cw}$) as:

$$\mathrm{DEP_{gw}} = \mathrm{IRR_{gw}} + \mathrm{Q_{gw}} - \mathrm{Q_{perc}} - \mathrm{LOSS_{cw}} \quad (4)$$

where:

$Q_{gw}$ is the return flow from the shallow aquifer towards the river (mm). Note that the capillary rise is considered as a component of the irrigation water supply.

$IRR_{gw}$ is the gross groundwater that is abstracted from the shallow aquifer.

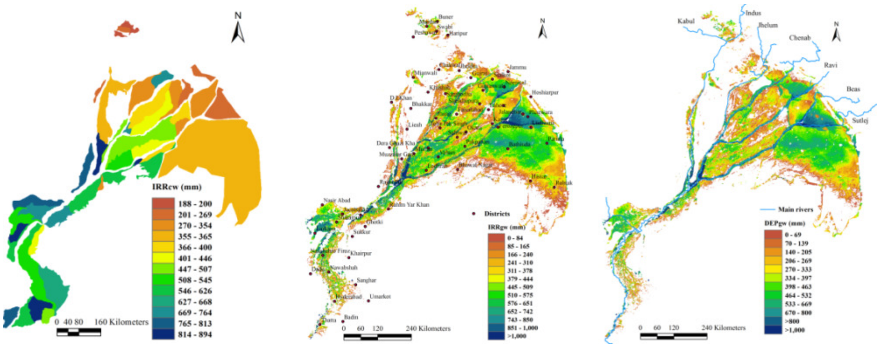
This information can be used to infer the total irrigation water supply at the farm gate for each pixel ($IRR_{RS}$), when being integrated with HRU fluxes obtained from SWAT calculations of Eq. Assuming the capillary rise and storage changes to be the parts of applied water, the analytical expression becomes:

$$\mathrm{IRR_{RS}} = \Delta \mathrm{S_{us}} + \mathrm{ET_{ETLook}} + \mathrm{Q_{surf}} + \mathrm{Q_{lat}} + \mathrm{Q_{perc}} - \mathrm{R_{TRMM}} \quad (5)$$

Irrigation water, diverted to main canals irrigating a specific canal command area (CCA), was aggregated to monthly and annual irrigation volumes. The resulting vector maps of canal water supplies for each CCA were prepared. The supplies were then converted into depths by dividing over the area of each CCA. The map of irrigated land usage was overlaid with the map of CCA to identify the irrigation command areas matching with each HRU. The result is a canal irrigation vector map ($IRR_{cw}$) that has a spatial refinement as compared to the HRU. The total canal water available at the farm gate for each canal command is estimated at 113 $km^3$ (or 434 mm). See Fig. 16 (a). This amount is computed from the reservoir releases and reported conveyance losses. Canal water available at farm gates varies from 200 to 900 mm $yr^{-1}$. This spatial variability in canal supplies is due to the non-perennial system, and variability in water released from the reservoirs.

The overlay helped to part the total irrigation water supply ($IRR_{RS}$) into canal water use ($IRR_{cw}$) and finally gross groundwater abstraction from shallow aquifer ($IRR_{gw}$) (Fig. 16.16.7):

$$\mathrm{IRR_{gw}} = \mathrm{IRR_{RS}} - \mathrm{IRR_{cw}} \qquad (6)$$




(a) Canal water supplies (b) Gross groundwater abstraction (c) Net groundwater depletion

**Fig. 16.7** Spatial Maps of Canal Water supplies, Groundwater Abstraction and Depletion

*Source: Cheema, 2012*

The gross groundwater abstraction can be explored further to quantify the aquifer depletion (Fig. 16. (c). The total depletion of 31 $km^3$ (121 mm $yr^{-1}$) in the aquifer has been computed from $IRR_{gw}$and the return flow $Q_{gw}$. The return flow e.g. base flow from the groundwater to the surface water system, of non-consumed water that is fed back into the river network of 20 $km^3$ $yr^{-1}$ is included in the analysis. The net groundwater abstracted (gross abstraction 68 $km^3$ $yr^{-1}$ minus recharge from leaking fields and canals 57 $km^3$ $yr^{-1}$) became 11 $km^3$ or 42 $mmyr^{-1}$.

The release of surface water from the major reservoirs to the canal command areas was 151 $km^3yr^{-1}$. By integrating irrigation from canal water arriving at the farm gate (113 $km^3yr^{-1}$) with the total irrigation water supply estimated from the SWAT model (181 $km^3yr^{-1}$), it was possible to isolate the total groundwater abstractions for irrigation (68 $km^3yr^{-1}$). Pakistan supplies 40 $km^3$ and India 28 $km^3$ every year. Table 16.5.6 provides an overview of the bulk water balance of the irrigated areas of the Indus Basin.

**Table 16.5** The Water Balance of all Irrigated Areas Combined and considered as being One Single "Big Field" of 26.02 million ha (Cheema, 2012)

| Inflow | $km^3$ $yr^{-1}$ | Outflow | $km^3yr^{-1}$ |
|---|---|---|---|
| Rainfall | 117 | Surface runoff | 25 |
| Canal water supply (Indian part of the Basin) | 36 | Interception evaporation | 5 |

| | | | |
|---|---|---|---|
| Canal water supply (Pakistani part of the Basin) | 77 | ET from rainfall | 99 |
| Groundwater supply (Indian part of the Basin) | 28 | ET from irrigation | 154 |
| Groundwater supply (Pakistani part of the Basin) | 40 | Drainage and percolation from fields | 19 |
| Total | 298 | | 298 |

The vector maps of canal water supplies for every canal command area superimposed on the vector maps of surface runoff and drainage / percolation and the raster maps of rainfall and ET (Fig. 9). This yields a map with 1 km pixels of gross groundwater abstractions for the entire Indus Basin. This is the first map with this level of details. It shows the hotspot areas at a 100 ha resolution. Information on groundwater pumping activities can thus be made public knowledge.

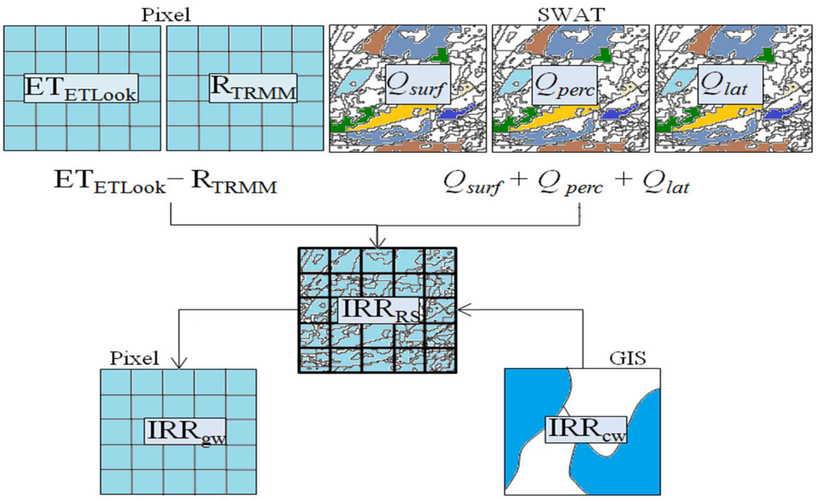



**Fig. 16.8** Schematic Diagram Showing Data Sources to Infer Groundwater Abstraction at 1 km Pixel
*Source: Cheema, 2012*

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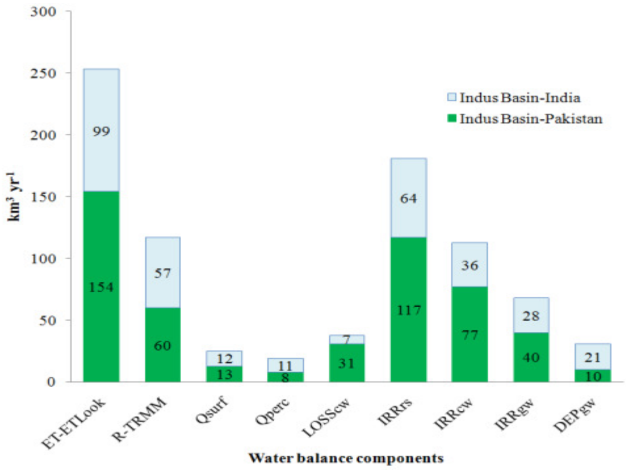


**Fig. 16.9** Water Balance Components in the Irrigated Areas of Pakistani and the Indian Indus Basin
*Source: Cheema, 2012*

The groundwater abstraction can be explored further to quantify the groundwater depletion. The groundwater depletion (gross abstraction 68 $km^3\ yr^{-1}$ minus recharge from leaking fields, amounting to 19 $km^3\ yr^{-1}$, and canals amounting to 38 $km^3$ yr-1) was 31 $km^3\ yr^{-1}$. The groundwater return flow of 20 $km^3\ yr^{-1}$ in the irrigated areas of the Indus Basin was included in the analysis. The actual groundwater depletion is larger due to outflow of groundwater into the river system. Fig. 16.6.9 provides information on various water balance components for irrigated areas of the Indus Basin lying in Pakistan and India separatelyMost of the satellite data at relative coarse resolution, which serves the purpose at basin scale, is freely available. The fine resolution data is also available with a fee. NASA and ESA have new policies to keep prices of images low, so that satellite information becomes everybody's business. The classical sources of data, their use and associated problems with their alternative solutions are summarized in Table 16.6. The use of satellite data as an alternative for getting firsthand knowledge on hydrology, agriculture, environment and geography, was explored. The climatic data available through meteorological departments was measured by using routine weather stations. Space borne measurements made it possible to get these datasets at higher temporal and spatial scales.

The satellite data archives should be explored more often to study the water resources conditions in basins with water and data scarcity. Data on land use, rainfall, soil moisture, and evapotranspiration can be derived. Integration with other data sources such as GIS application for canal water flow and hydrological model application for irrigation supply, surface runoff and drainage / percolation, is preferred. Once properly computed, the spatial dataset has the potential to drastically improve the knowledge based on the hydrology of data scarce trans-boundary basins with high climate variability.

Institutes, organizations, or consultants could process the raw satellite data into water resources information systems across basins with national and international rivers and aquifers. The emerging trends in space technology, geographical information systems, and their applications, coupled with developments in numerical hydrological modeling, should be oriented towards maximizing benefits of all stakeholders.

### 16.9.2 Important Web links for Data Download

Some important links are provided below from where a user can freely download data required for water management and can try it:

- **Finding what your preferred satellite is actually doing:**

The Earth Observation Handbook –

CEOS/WMO Data Base http://www.eohandbook.com/

List of Earth observation

satelliteshttp://en.wikipedia.org/wiki/List_of_Earth_observation_satellites

Finding out what is being measured and how:

The Earth Observation Handbook –

Catalogue of Satellite Instruments http://www.eohandbook.com/

- **Vegetation index**

  http://reverb.echo.nasa.gov/reverb/

  http://free.vgt.vito.be/

  http://glovis.usgs.gov/index.shtml

- **Leaf area index, Albedo, Snow cover, transmissivity**

  http://reverb.echo.nasa.gov/reverb/

- **Rainfall**

  https://wist.echo.nasa.gov/,
  http://neo.sci.gsfc.nasa.gov/Search.html?group=39

- **Soil moisture**

  https://wist.echo.nasa.gov/, http://nsidc.org/data/amsre/_(NSIDC)

  http://geoservices.falw.vu.nl/ (VU, NASA)

  http://earth.esa. Int/SMOS/

**Table 16.6** Applicability of Pixel Information for Database Generation in Vast and Data Scarce International Indus Basin

| Database | Classical data acquisition sources | Associated problems | Alternative Solution and applicability |
|---|---|---|---|
| Land use | Global databases*<br>International organizations§<br>Governmental organizations | Generalised land cover classes<br>No information on specific crop rotations<br>Outdated | NDVI time series at 1 km pixels with intervals of 8 to 10 days |
| Cropped area | Governmental organizations<br>International organizations | No real time information<br>Late dissemination<br>Tabular data | Land use map |
| Biomass production | Global net primary production maps | No data | Advanced algorithms turning raw data into quantified information |
| Crop yield | Governmental organizations' statistics | Late dissemination<br>Administrative unit wise information<br>Absence of spatial data | The pixel information on land use and biomass production can provide crop yield at pixel scale. |
| Rainfall | Meteorological department<br>World meteorological organization<br>Global databases‡ | Point measurements<br>Sparse raingauge networks (<4 gauges/ 10,000 $km^2$)<br>Not proper representation of spatial hydrology | 3-hourly, daily and monthly global estimates of rainfall by TRMM satellite. |
| Snow cover | Global datasets | Not available | Optical and radar satellites |
| Soil moisture | Specific Projects<br>Field experiments | Not available | Passive microwave and radar satellites |
| Evapo - transpiration | Field experiments | No flux tower in the Indus Basin | Advanced algorithms such as ETLook |
| Solar radiation | Meteorological department | Point data available through few stations<br>Not enough for any basin scale study | Geostationary and polar orbiting satellites measuring cloud cover |
| Ground water | Groundwater monitoring organizations | Point data available through sparse piezometer network<br>Only two measurements in a year<br>Data not easily accessible | Pixel information on related hydrological variables can provide spatial estimates of groundwater abstraction. |
| Reservoir levels | Single gauge | Single gauge is insufficient<br>Data not accessible | Radar and lidar altimeters |

*Source: GLCC-IGBP, Glob Cover-ESA, GLC2000, § IWMI, ¶ GMAO-MERRA, ‡ GPCC, CMAP, ERA*

- **Equivalent water thickness**

http://grace.jpl.nasa.gov/data/gracemonthlymassgridsland/ (Texas Uni.)

ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/geotiff/ /

http://lr.tudelft.nl/en/organisation/departments-and-chairs/remote - sensing/physical-and-space-geodesy/data-and-models/dmt-1/ (TUDelft)

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## Chapter17

# Hydrological Models and their Applications to Irrigation Systems

**Syed Hamid Hussain and Akhtar Abbas***

## Abstract

A model refers to mathematical illustration of the physical system. Especially, in irrigated agriculture, application of the models developed for different purposes guides us towards precise irrigation in addition to sustaining the soil and water productivity on longer terms. The use of flow and transport models is rampant in the field of different environmental sciences disciplines. The typical utilization of models is to calculate effectiveness of any remedial work or the movement of contaminations in risk management analysis. The journey from model conceptualization to model documentation guides to quantify significant factors that contribute towards efficient management of irrigation water resources. This chapter covers generic modeling and its types (including numerical and analytical models). The development process, purpose and scope of the model are also conceptualized. The chapterfurther explains how a mathematical model developed on the basis of the selected problem scope and nature. This is followed by the model documentation and use.

**Keywords:** Model, Analytical Model, Mathematical Model, Model Calibration, Sensitivity, Simulation

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# Learning Objectives

- To understand the basic principles of flow and transport phenomena stretching from point to area scale
- To develop basic understanding about model calibration and validation
- To abstract a real system into a conceptual model and vice versa
- Enhancing abilities to understand the complex interactions among soil, plant, water, and climate.

# 17.1 Introduction

Different disciplines of environmental sciences are extensively using the flow and/or transport models. The chapter encompasses different models, their types, operating procedure with documentation, generally in the field of surface water and groundwater. It further covers the performance evaluation of an irrigation system using models.

In general, models are conceptualized description of physical systems and their processes using mathematical equations. The efficiency of a model is estimated by the fact that how closely a model behaves to a physical system to be modeled. A thorough understanding of the system going to be modeled and assumptions is required for evaluating purposes. The outcome of a model depends upon the time, accuracy and frequency of input data, number of parameters included in the input data used in the model calibration. The usefulness of a model to predict the actual behavior of the system also depends how results are interpreted.

# 17.2 Types of Models

## 17.2.1 Analytical models

These models refer to the mathematical equation (s) that express the changes of a physical system in terms of mathematical functions. As an example, a model of personal savings can be expressed as given in Equation1.

$$\frac{d(S)}{d(t)} = r\ (s) \qquad (1)$$

Where, r = Fixed yearly growth rate, S = Savings,t = Time

The analytical solution to this differential equation is:

$$S = S_o e^{rt} \qquad (2)$$

Where $S_o$= initial savings, t = time, and e (x) is Euler's number. This equation is the analytical model of personal savings with fixed growth rate.

One dimension and steady state are the characteristics of analytical flow models. The field conditions, which change with respect to time and space, cannot be estimated by analytical models because they consider specific assumptions and simplifications.

These conditions are flow direction/rate of ground/surface water, chemical/hydraulic properties, hydraulic stresses, and hydro geologic or chemical boundary conditions. Analytical models are developed from the complex differential equations. Sometimes, the differential equations are too complex that analytical solutions are not possible. These models generate only particular exact solutions forhighlystreamlined processes such as yielding production function (Ben-Gal, 2007) and groundwater-flow or transport equation, and TheisEquation. The application of the analytical models are:

- Designing plans for data collection before field activities.
- Well performance impact assessment.
- Crop yield prediction under different quantity and quality of irrigation water.
- Estimating groundwater and surface water fluxes at the boundaries.
- Checking of model simulation results, independently. OR
- Wherever, it is possible to embed the field conditions in simplified way into analytical functions.

### 17.2.2 Numerical models

These models refer to the mathematical models that involve numerical time-stepping procedure. In the example of personal savings (given in previous section), the values are produced for different temporal changes by the Eq. 3.

$$S(t + dt) = S(t) + d(S) = S(t) + rS(t)dt = S(t)\ (1 + rdt) \tag{3}$$

Due to small values of savings d (S) are generated corresponding to each time step, the numerical solution becomes in accordance with analytical solution.

Discretized model domain and time are the requirements of approximations. While discretization, grid cells network shows model domain and time series steps represent duration of simulation.

The models' accuracies depend up on input data, space size and discretization time (inversely related with accuracy) and the numerical methods. These models usually perform the following functions:

- Simulation of one and/or two-dimensional conditions of flow and transport.
- Complex models, two or three dimensional, like water uptake by the plant roots, root zone, sodicity development, surface-water and groundwater flow and solute-transport problems, may be simulated.
- Transient or steady state flows may be simulated.
- Estimate fluxes at simple or complex hydrological and hydro-geologic boundaries
- The problems can be simulated that cannot be tackled by analytical models

MODFLOW, UNSATCHEM, SWAP, SWAT, Groundwater Vista, and HYDRUS are the common numerical models being used now-a-days. Depending upon the set of mathematical equations, input variables, and the way the model runs, modelsaregrouped into following categories:

**(i)** **Linear and Nonlinear Models**: A model is called linear if objective functions and constraints are represented by linear equations and vice versa. Linearity and nonlinearity are defined by the context behind. Some of the linear models may contain nonlinear expressions.

**(ii)** **Static and Dynamic Models:** A static model calculates the system in a steady-state that means that the changes in a system are recorded with equal interval of time. A dynamic model refers to the model that considers temporal variations in the state of a system in terms of differential equations.

**(iii)** **Explicit and Implicit Models:** An explicit model determines output parameters by direct computation of dependent variables in terms of known quantities by an iterative procedure. An implicit model obtains the solution by defining dependent variables in terms of equations with matrix or iterative technique for solving them. Whenever, accuracy of time is considered important, explicit models are preferred over implicit methods. Both models are used in numerical analysis for obtaining numerical solutions of time-dependent ordinary and partial differential equations, as is required in computer simulations of physical processes

**(iv)** **Discrete and Continuous Models:** A discrete model more easily corresponds to the dadt observed, or measurements, and is easier to simulate on computers. Its objects are as discrete as the particles in a molecular model are. Whereas, a continuous model shows objects in continuous way, like fluid velocity in a pipe and temperatures and stresses in a solid.

**(v)** **Deterministic and Stochastic (Probabilistic) Models:** A stochastic model presents randomness. Variations of states are not presented by unique values rather by probability distributions. While in a deterministic model every set of variations of states are uniquely determined by the parameters and by the sets of earlier states of the variables.

**(vi)** **Deductive and Inductive (Floating) Models:** Deductive model refers to a theory based logical structure. While an inductive model is built from empirical relations. The floating model rests on neither theory nor observation, but is merely the supplication of expected structure.

## 17.3 Model Development Process

Model developments for the flow and salute transport of both surface and groundwater models include the following steps:

- Define the importance of models' application to the site
- Characterization of the hydro-geologic framework and the type, and chance of contaminants (Facility Characterization).

- Development of conceptual model (Model Conceptualization).
- Selection of suitable model software (Software Selection).
- Calibration of the model or adjusting the input values (Model Calibration).
- Field data comparison with calibrated model (History Matching).
- Simulation sensitivity of the model with variation of input parameters (Sensitivity Analysis).
- Model simulation to predict outcomes (Predictive Simulation).

### 17.3.1 Purpose and Scope

Along with its limitations and scope, the site specific goals of the model that can be achieved must be stated by the model developer. Along with limitation and scope.

### 17.3.2 Model Conceptualization

The process of testing the data collected during the facility characterization for the determination of suitable model for surface and groundwater flow and salute transport and to assess the uncertainty. For example, in order to conceptualize problems related to salinity in the irrigated agriculture, soil salinity data is gathered and analyzed in the laboratory for diagnosing the problems. A conceptual model is developed to understand the real reasoning of the root zone salt accumulation due the brackish irrigation water by using the mass balance approach of water and salt balance.

### 17.3.3 Model Software Selection

Model selection should be suitable for the simulation of the condition under study. Following guidelines should be kept in mind for the selection of suitable model.

Guidelines for the selection of analytical models are:

- Insufficient field data availability for the development of numerical model
- Field data represents that surface water/groundwater flow is 1D or can be assumed as 1D
- Field data represents the straightforward and simple geochemical and transport process
- A screening of remedial changes for straight forward, romanticized surface water/groundwater stream and contaminant transport conditions is required.

Guidelines for the selection of numerical models are:

- Complexity in the field data direct the involvement of complex surface water/groundwater flow or transport processes.
- Presence of one or more than one aquifers.
- Groundwater/salute movement into the root and stream both vertically and horizontally.
- Rate of change of surface water/groundwater and solute along with the change in direction.

- Presence of many chemicals and hydraulic sinks and sources for surface water/groundwater pollution.
- Degradation of root zone due to salinity and sodicity.
- Geochemical reactions may be relatively complex.

Guidelines for selection of one dimensional groundwater flow models:

- Groundwater flow and contaminant transport complexity is unknown or can be considered simple.
- Only one source of contamination with single chemical and hydraulic sinks or sources.
- Down gradient receptors from the source of contamination.

Guidelines for the selection of two-dimensional flow models:

- Presence of more than one sinks and sources
- Horizontal and vertical distribution of solutes travelling in porous media/root zone
- Wetting patterns visualization of wetting pattern under micro-irrigation systems
- Two dimensional groundwater flow condition
- Prominent hydraulic properties variation in the aquifer
- Distributed hydraulic and chemical sinks and sources within the soil continuum and aquifer
- Lateral distribution of receptors within the aquifer

Guidelines for the selection of three dimensional flow models:

- Both vertical and horizontal groundwater/ solute movement is important.
- The horizontal and vertical movements of contaminants in the root zone are vital.
- The hydro geologic conditions are relatively well known.
- More than one aquifer are present.
- Soil heterogeneity induces to explore the fate of contaminants in root water uptake.
- Comparison of micro-irrigation and macro-irrigation for the wetting patterns in both directions.
- Vertically and laterally distributed sinks and sources in multi aquifers.

### 17.3.4 Model Calibration

Model calibration is the change in input parameters within acceptable range for matching of a given aquifer hydraulic properties, root zone salt concentration, root water uptake, soil degradation status, or solute behavior. This requires the proper field condition characterization. Deficiency in the proper characterization resulted in the model that is calibrated on these conditions may not reflect the actual field condition.

Generally, both steady state and transit condition are involved in the model calibration process. Simulation under Steady state, temporal changes are not observed for hydraulic head and concentration of solute. On the other hand, simulation under transit condition the change in hydraulic head and concentration of solute is considered with time. Input data variation reduced with these simulations, similar steady state simulation can be acquired with the help of many input data choices presents in the model.

Calibration of the model must include the following parameters from field and model simulated values

- Data of hydraulic head.
- Gradient of hydraulic head.
- Mass balance of water.

For solute transport models:

- Concentrations of soluté,
- Rates of contaminât migration
- Direction of contaminant migration
- Rate of degradation.

The above expected output parameters can be mapped in the form of concise pictures of water and solute transport. In order to calibrate the results, critical understanding of the modeler is required. As the modelling of the reality is a complex and non-linear in nature, therefore, difference between simulated and observed results can be reduced by calibrating the predicted results with the simulated results. In order to reduce the errors and biasness, the errors in the predicted model should be distributed randomly. During the calibration process, maximum information helps to reduce the error

## 17.3.5 History Matching

It is considered the second step of calibration and is mentioned as the verification of the model. Selected values of eco-hydrological, hydro-geologic and hydrologic parameters, sinks and sources, and boundary conditions work for matching the field condition within the selected time of calibration. This decision of parameters alludes to us as a realization. Still, the selection of the boundary condition and values of parameter is not constant. There might be a boundless number of factually comparable acknowledgements that give altogether different prescient model results. In this process, historic field conditions are regenerated by the calibrated model, except those used in the process of initial model calibration, for the reduction of variation in simulated values.

The most prominent scenario under history matching is the regeneration of an observed change in the root zone osmotic potential, that is the temporal variation in solute concentration and hydraulic head. For Model verification, the best scenarios are those which performed simulation with calibrated model for the plant water uptake and aquifer under stressed conditions. The model verification process may deem further improvements. With the successful reproduction of measured variations of field conditions (both for calibration and history matching) by a model, it is declared as a perfect model for further predictions.

### 17.3.6 Sensitivity Analysis

It is the process of observing relative change in model results corresponding to different input parameters with a range of values. Generally, the changes are observed in the rate of groundwater flow, variation in hydraulic head and soil physical degradation due to soil salinity and sodicity. The main objective of this analysis is sensitivity provision to model due to the uncertainties in the input parameters. Within parameters sensitivity is also described. Most of the dominated programs of parameter estimation like PEST, SWAP, MODFLOWP, UNSATCHEM, Groundwater vista, performed the quantitative analysis as a component of parameter estimation.

It can be performed at any stage of model development. The most important utilization of the sensitivity analysis is directing the prediction activities. Further characterization is required for the highly sensitive parameters of model. The sensitivity analysis, if conducted during simulations for the prediction of impacts on different parameters, becomes more beneficial.

### 17.3.7 Parameter Estimation

The above three discussed sections described the general concepts about both automated andnon-automated methods of parameters' values estimation during the calibration of a model.

**a) Non-automated method:**

The non-automated calibration procedure is the trial-and-error approach commonly utilized to calibrate models and also, numerous runs are spent changing parameter values, thus time consuming to estimate parameter values.

**b) Automated method:**

The models with conceptual components may involve automated calibration as that does not simulate any specific mathematical expressions to disseminate any physical process and they have large number of parameters involved. Automated methods are also known as the inverse modeling or parameter estimation. Mostly it involves the techniques such as nonlinear least squares regression, as a case, to align a model by altering model parameters to minimize the distinction between measured and simulated root water uptake, root zone salt concentration, rates of groundwater flow and hydraulic heads. This working phenomenon is similar to the trial and error method. Advantages of the techniques are as follows:

- Quickly achieved modeler's calibration criteria with best fit model parameters.
- Measured quality of the calibration.

- Identification of the missing data and importance of the missing data is assessed.
- Determination of parameters sensitivity level.
- Identification of the correlation between model parameter.
- The opportunity to compare the conceptual models quantitatively.

Common calibration processes using the automated calibration routine are PEST, MODFLOWP, and UCODE.

## 17.4 Predictive Simulation

Most common use of the predictive simulations is the estimation of the long term trends of root zone salt concentration and sodicity development, long term average values of climatic parameters, crop prediction, aquifer hydraulic response, solute migration pathway, removal rate of contaminant mass from aquifer. In decision making, simulations are considered as estimates, not certain resultsi.e. predictive simulation for the policy of the remediation of groundwater system.

Another example is the prediction of extraction wells and pumping rates required to seize contamination and to have its concentration in the extracted water. Though, hydraulic heads monitoring and concentrations of contaminant used is compulsory for the verification of hydraulic containment and solution of the pollutant column. As a well-calibrated model if provided with insufficient data or oversimplifications, errors will arise with some uncertainties. Hence, the predictions are expressed into a collection of potential results that reveal associateduncertainties withthe values of most sensitive parameters of model.

## 17.5 Documentation of Models

Each model, whether analytical or numerical, should be properly documented for the ease of the reviewer. In addition, the developed model should be explained by giving some simulated examples of the real case study. For example, the developed software like CROPWAT, SWAT, and SWAP, etc., have complete manual about using these developed software. In SWAP, the examples data are given required to run the model. Furthermore, the boundary conditions about each process are mentioned in the documentation that help the user to input values in a specified range.

## 17.6 Commonly Used Models

Most commonly used modelling software's for the flow and solute transport in both surface and groundwater are listed in the Table 1. First three are freely available for use and the remaining three required the licensing agreement from the developing organization.

**Table 17.1** List of Developed Model along with their Characteristics

| Model | Full name | Model | Flow | Solute |
|---|---|---|---|---|

| | | Type | Dimen-sions | Transport Dimensions |
|---|---|---|---|---|
| SWAP | Soil, water, air, and plant Relationships | Numerical | 1 | 1 |
| HYDRUS | Simulating water, heat and solute movement in one-dimensional variably saturated media. | Numerical | 1,2,3 | 1,2,3 |
| UNSATCHEM | Unsaturated chemistry | Numerical | 1 | 1 |
| RTEC | Soil water retention curve | Analytical | 1 | 1 |
| SWAT | Soil water assessment tool | Numerical | 1 | 1 |
| MODFLOW | Modeling water flow | Numerical | 1,2,3 | 1,2,3 |
| CROPWAT | Crop water requirements | Numerical | 1 | No |
| SPAW Hydrology | Soil, plant, atmosphere, water field, and pond hydrology | Numerical | 1 | No |
| Groundwater Vistas | Modeling groundwater flow | Numerical | 1,2,3 | 1,2,3 |
| ANSWER | Analytical crop yield production model | Analytical | 1 | 1 |
| DSSAT | Decision support system for agro-technology | Numerical | 1 | 1 |

### 17.6.1 Soil Water Air and Plant Relationship Model (SWAP)

SWAP simulates the flow of water, heat and solutes in the vadose zone. The vertical range of the model includes the plant canopy plane to the shallow groundwater plane. All the processes in this domain are vertically one dimensional. SWAP is considered as 1D model. The horizontal range of the model is field scale. The model is available for free at site “www.swap. Alterra.nl” of WageningenUniversity, the Netherlands. Main input files of the models are meteorological data, crop growth and drainage. SWAP reads the ASCII files as input using the TTUTIL library. Binary and ASCII files are generated as output.

Solute transport in the SWAP are on the basis diffusion, convection, root uptake, dispersion, first order decomposition andFreundlich adsorption. PEARL is used in combination with SWAP for the advanced solute transport and kinetic adsorption. Similarly, ANIMO is used in combination with SWAP for the simulation of nitrogen and phosphorus transport.

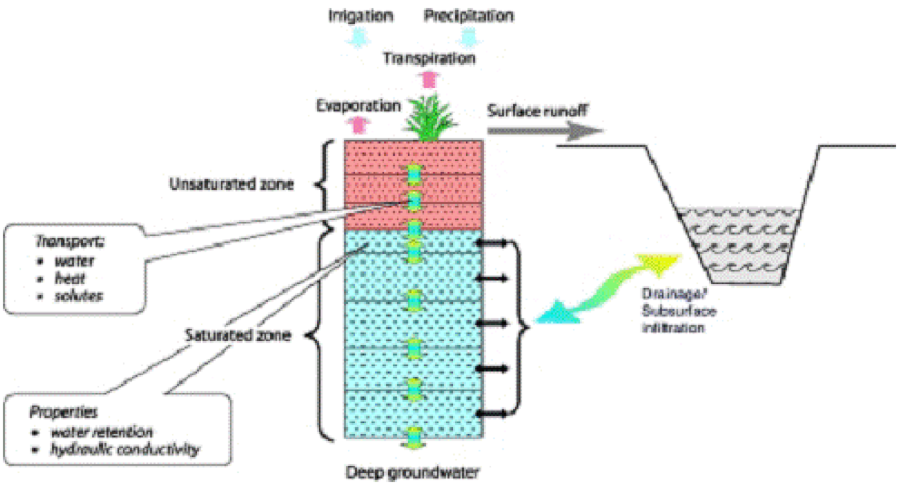


**Fig. 17.1** Overview of the Agro-hydrological Model SWAP

The SWAP input parameters could be categorized into atmosphere, crop, water and soil. Most of the information required could be measured directly in the fields or laboratory. The crop growth parameters with respect to the crop development stage are customized according to local conditions. The relationships of the crop development stage with crop height, rooting depth, leaf area index, yield response factor and rooting density are established and used in the model. The upper boundary is defined by amounts of rainfall, irrigation and their salt concentrations. The potential evapotranspiration is estimated by the Penman- Monteith equation (Abbas, et al. 2006).

## 17.6.2 HYDRUS

HYDRUS-1D simulated the water flow, solute and heat transport in one-dimensional varying saturated media. HYDRUS package consist of computer program, and the HYDRUS-1D/2D/3D graphic user interphase. The working phenomenon of the HYDRUS is based on the Richards' equation for varying saturated flow of water. But for the solute and heat transport HYDRUS worked on the basis of convection-dispersion equations. A sink term is incorporated by the flow equation to measure water uptakes by roots. HYDRUS also include the mobile and immobile model for the water flow. Heat transport is simulated under the conduction and convection along with water flow. In liquid phase the equation of solute transport considered the convective dispersive transport, while in gaseous phase the diffusion is considered. The nonlinear non equilibrium reaction is included in the equation among the solid and liquid phases, among liquid and gaseous phases the reactions are linear equilibrium, zero order production, and two first order degradation reactions. On the other hand, the equations include kinetic addition/removal of solute in solid phase that can be used for the simulation of viruses, bacteria and colloids transport.

HYDRUS also simulated the ions and carbon dioxide movement.$CO_2$ is transported with diffusion, when it is in the liquid and gaseous phase, for the liquid phase just convection. Chemical system included the parameters are Ca, Cl, $CO_2$, Na, K, Mg, $NO_3$, $SO_4$ and alkalinity. The model considered the chemical reaction in equilibrium form between precipitation dissolution, cation exchange and complexation. Both forward and backward reactions are used during the calcite precipitation dissolution and dolomite dissolution, with multicomponent or equilibrium kinetic expressions.

HYDRUS performed the analysis of both water and salute movement in fully saturated, partially saturated and unsaturated medium. The area under study may be consist of heterogeneous soil. Solute movement and water flow can occur in both horizontal and vertical direction and it also occurs in inclined direction. The boundary condition for water flows are the atmospheric condition and the free drainage. Galerkin-type linear finite element schemes are the basis for the solution of equations numerically. HYDRUS also includes a type parameter optimization algorithm for inverse estimation of and/or for solute transport, reaction parameters and soil hydraulic estimation, HYDRUS used the Marquardt-Levenberg algorithm by using measured steady state and transit flow data. HYDRUS is freely available at www.hydrus2d.com or www.pc-progress.cz.

### 17.6.3 Unsaturated Chemistry Model (UNSATCHEM)

The unsaturated chemistry (UNSATCHEM) is a software package for simulating water, heat, carbon dioxide and solute movement in one-dimensional variable unsaturated media. It consists of the UNSCHEM computer program, and the UNSATCH interactive graphics based user interface. It numerically solves the Richards' equation for variably-unsaturated water flow and convection-dispersion type equations for heat, carbon dioxide and solute transport. The flow equation incorporates a sink term to account for water taken up by plant roots. The heat transport equation considers transport due to conduction and convection with flowing water. Diffusion in both liquid and gas phases and convection in the liquid phase are considered as $CO_2$ transport mechanisms.

The major variables of the chemical system are Ca, Mg, Na, K, SO, Cl, NO, alkalinity, and $CO_2$. The model considers the equilibrium chemical reactions between these components such as complexation, cation exchange and precipitation-dissolution. For the precipitation-dissolution of calcite and dissolution of dolomite, either equilibrium or multi-component kinetic expressions are used, which include both forward and reverse reactions. Other dissolution-precipitation reactions include gypsum. The software package can be freely downloaded from www.unsatchem.com.

### 17.6.4 Soil Water Retention Curve (RTEC)

The RETC (soil water retention curve) computer code is used on the unsaturated soil for the estimation of hydraulic conductivity and water retention in the soil. These are considered as the basic parameters for the quantitative description of the water movement in and from the unsaturated soil medium. For the representation of soil water retention curves, the model used the Brooks-Corey and van Genuchtenparametric models. Similarly, for the estimation of hydraulic conductivity it considered the theoretical pore size distribution model of "Mualem and Burdine" on the basis of observed soil water data. Different analytical expressions are explained in detail by the program that are used for the quantification hydraulic conductivity and soil water retention function. Hydraulic models used the nonlinear least square techniques for the estimation of unknown coefficients. The model predicts the hydraulic conductivity on the basis of available observed data of soil water retention by following the assumption of available value of hydraulic conductivity. For the observation of hydraulic conductivity and water retention the code permits analytical function of one to fit.

### 17.6.5 Soil Water Assessment Tool (SWAT)

SWAT (Soil Water Assessment Tool) is a distributed model for large scale studies like a river basin. SWAT was developed for the temporal analysis of different soil management practices on water, sediment transport and agricultural production of large watershed with heterogeneous soil, changing land use and altering management condition. SWAT main components are weather, evapotranspiration, crop growth and irrigation, surface runoff, percolation, transmissionlosses, return flow, pond and reservoir storage, reach routing, loading of pesticide and nutrient, water transfer and groundwater flow.

Salient Features of SWAT model are:

- Long-term simulations with daily time step.
- Basins subdivision on the basis of soils, land use and topography, etc.
- Simulation can be performed on the several thousand square miles basins.
- Ten layers of soil can be developed.
- To route and add flows use of routing command language.
- Grid based or sub basin based subdivision on the basin.
- Spatially displaced output of simulation from hundreds of grids or sub-basins
- Both point and measured data sources are accepted.
- Reservoir and channel water can be transferred.
- Input and output from pesticides and nutrients.
- GIS model can be linked to automate inputs.

### 17.6.6 MODFLOW

Processing MODFLOW for Windows (MPWIN) is three dimensional simulation system for flow and transport of groundwater on the basis of a finite difference model of groundwater namely MODFLOW of the U. S. Geological Survey (McDonald et al., 1988), Windows based Processing Modflow Path (MPATH)for particle tracking (Chiang, 1994) or MODPATH (Pollock, 1988, 1989, 1994), MT3D for solute movement (Zheng, 1990) and PEST, a parameter estimation program (Doherty et al., 1994). PMWIN also consist of particle tracking PMPATH for Windows. Forward and backward semi analytical techniques are used in particle tracking PMPATH (Pollock, 1988) for the calculation of travel time and flow path of the groundwater. PMPATH estimate simultaneously the travel time and flow lines. It consists of many graphical on screen options including velocity vectors, draw down and head contours. In MT3D model for 3Dadventive dispersive reactive transport equation is solved based on the mixed Eulerian Lagrangian approach. The significant flow field cannot occurr with the changes in the concentration field are the assumption of MT3D. This ability provides an independent base for the model calibration. After a flow simulation is complete MODFLOW saved flow terms and hydraulic heads are again estimated by the MT3D. With the help of simple chemical reactions, dispersion and advection are used for the single species change simulation using the MT3D model. Model included chemical reaction are just bound to equilibrium controlled non-linear or linear sorption and biodegradation.

### 17.6.7 CROPWAT

The main purpose of CROPWAT is to calculate crop water requirements and develop irrigation schedules based on data provided by the user. These data can be directly entered CROPWAT or imported from other applications. For the calculation of crop water requirements (CWR), CROPWAT needs data on evapotranspiration ($ET_o$). CROPWAT allows the user to either enter measured $ET_o$ values, or to input data on temperature, humidity, wind speed and sunshine, which allows CROPWAT to calculate ETo using the penman-Monteith formulae. CROPWAT fully supports the. PEN and. CLI files from the CLIMWAT database.

Rainfall data are also needed, and are used by CROPWAT to compute effective rainfall data as input for the CWR and scheduling calculations. Finally, crop data (dry crop or rice) are needed for the CWR calculations and soil data if the user also wants to calculate irrigation schedules (dry crop or rice).

Whereas CROPWAT normally calculates CWR and schedules for the 1 crop, it can also calculate a scheme supply, which is basically the combined crop water requirements of multiple crops, each with its individual planting date (a so-called cropping pattern).

Both for data input and for the calculations CROPWAT offers a wide variety of options that can be set interactively by the user during program execution by clicking on the options button on the toolbar, or through the setting>Options menu.

Program structure:

The CROPWAT program is organized in 8 different modules, of which 5 are data input modules and 3 are calculation modules. These modules can be accessed through the CROPWAT main, menu but more conveniently through the modules that is permanently visible at the left hand side of the main window. This allows the user to easily combine different climatic, crop and soil data for calculation of crop water requirements, irrigation schedules and scheme supplies.

The data input modules of CROPWAT are:

i. Climate/$ET_o$: for the input of measured $ET_o$ data *or* of climatic data that allow calculation of $ET_o$ Penman-Monteith.
ii. Rain: for the input of rainfall data and calculation of effective rainfall.
iii. Crop (dry crop or rice): for the input of crop data and planting date.

iv. Soil: for the input of soil data for (only needed for irrigation scheduling).
v. Crop pattern: for the input of a cropping pattern for scheme supply calculations.

The calculation modules of CROPWAT are:

i. CWR - for calculation of Crop Water Requirements.
ii. Schedules (dry crop or rice) - for the calculation of irrigation schedules.
iii. Scheme- for the calculation of scheme supply based on a specific cropping pattern

## 17.6.8 SPAW HYDROLOGY

The SPAW (Soil-Plant-Air-Water) is a computer model for the simulation of the daily based water budgets of agricultural landson the basis of two procedures, (i) farm fields (ii) wetland ponds or reservoirs. Data files from the field or reservoir projects include vegetation, soil and climate. Multiple reservoir and field project files are presented the data files in various combinations.

Field based hydrology is based on the daily climatic data on temperature, rainfall and evaporation, and soil profile includes separate characteristics of water holding for each layer, and similarly the cropping pattern with detail management practices along with fertilizer and irrigation options. Simulation can be done on the daily vertical, 1D water budget depth of all the factors such as evapotranspiration, infiltration, runoff, percolation and profile of soil water. Field area under study multiplied by the water budget depth resulted the volume of water. Interaction of salinity, soil chemicals with production of crop and soil water are presented. Chemical reaction budget on the daily basis, therefore the process within the crop and soil are neglected. In the analysis of agricultural hydrology these informations on budgets are very important for defining the possible effects.

The SPAW model can be modified for hydrologic analyses according to the available data and programmed methods. In agriculture, some applications are:

- Evaluation of levels of crop water on daily basis under irrigation and rainfall.
- Estimation of rate of seepage and runoff from agriculture lands.
- Irrigation scheduling.
- Assessment of deep percolations which results in the form of losses in nutrients and water.
- Description of wetland inundation based on duration, frequency and depths.
- Agricultural wetland and reservoir designing and performance evaluation for water management and water supply, and waste management.
- Estimation of soil salinity and nitrogen budgets and salinity hazards and concentrations for crop production.

The Soil - Plant - Atmosphere - Water (SPAW) can be obtained from barsusda.gov/SPAW/SPAWDownload.html

### 17.6.9 Groundwater Vista

Groundwater Vistas (GV) is a sophisticated Windows graphical user interface for 3-D groundwater flow & transport modeling. GV couples a powerful model design system with comprehensive graphical analysis tools. GV is a model-independent graphical design system for MODFLOW, MODPATH (both steady-state and transient versions), MT3DMS, MODFLOWT, MODFLOW-SURFACT, MODFLOW2000, GFLOW, RT3D, PATH3D, SEAWAT and PEST. Following link can be used to have moreinformationabout these softwares.

http://www.scisoftware.com/environmental_software/product_info.php?products_id=43.

### 17.6.10 DSSAT

The DSSAT Cropping System Model (CSM) stimulates growth and development of a crop over time, as well as the soil water, carbon and nitrogen processes and management practices. Collectively, these components simulate the changes over time in the soil and plants that occur in a single land unit in response to weather and management practices. DSSAT-CSM incorporates models of all crops within a single set of code. This design feature greatly simplifies the simulation of crop rotations since soil processes operate continuously, and different crops are planted, managed, and harvested according to cropping system information provided as inputs to the model.

### 17.6.11 ANSWER

The arid and semi-arid climates are water scarce and salt concentration is relatively higher. Leaching requirement is the tool used to reduce salt concentration and increase crop yield. The water content of leaching fraction becomes the integrated part of the surface and groundwater, depending on the geological structure. The effect of leaching becomes dominant on the next farmer. Keeping in view the amount water used by plants and mapping of groundwater quantity and quality available for the next user, an analytical implicit yield prediction model based on the soil, water quantity, water quality, vegetation and climatic parameters is developed named as ANSWER. The ANSWER model is capable of predicting yield based on the water scarcity, losses due type of irrigation method for a specific crop, soil, and climate conditions. The model is applied to Capsicum annum on Arava Sandy Loam soil, which predicts analytically how water available for irrigation can be distributed efficiently among the number of farms to optimize the system yield. Based on the model output, water market can be developed that can be used to trade water based on the mutual interests. The results obtained by (Shah et al., 2010) represent that trade based on coupled agro-economic model will improve efficiency except when loss levels are low.

### 17.6.12 IQQM

In order to investigate the water sharing issue, Integrated Quantity Quality Model (IQQM) is developed by the Department of Land and Water Conservation (DLWC), New South Wales, Government in Australia (Hameed and Podger, 2001). The model is used to simulate the river behavior on a longer term basis and is based on a node-link concept. The movement and routing of water between nodes is carried out in the links. Water quality and routing processes are investigated using the daily time step. The model can also be scaled down to have more data of fluctuation on hourly time step. The major processes include routing of flow, water storage modeling, water storage operation, hydropower modeling, water course modeling, and water demand for the crops, modeling wetland, and irrigation water sharing rules of river systems. In order to simulate the maximum and minimum flow, hydrological modeling is applied through the IQQM.

## 17.7 Use and Application of Models to Irrigation Engineering

In order to apply the model to irrigation engineering, an example taken from Ben Gal et al. (2013) is used to optimize the system yield of the number of farmers along the river basin.

### 17.7.1 A Chain Model of Water Use for Irrigation

The developed model considers the network of farms situated in the catchment river on elevation basis. For minimizing misunderstanding, same name was used for both User and Farms, as both carry the same meanings. In this section, interconnection among water, salinity and plant production are described along the network of farms. These interconnections depend on surface water, groundwater and waste water resources of water mostly present in moderate climates areas (Bhutta and Velde, 1992; Ahmad Mobin-ud-Din 2002; Vervoort and van der Zee 2008).

In this study, only one source of surface water (river) was considered, and the network of farms that uses the same water coming from the river. Further, it was assumed that return flow becomes part of river water. This return water is the leached water coming from the root zone.

Following the idea of Ben Gal et al. (2013), Ideal condition was considered that only river water is available to the network of farms. In Fig. 1, the system conceptualization is shown. N number of farms were considered that are prearranged beside a river. The u/s farm/user is represented by i and d/s farm/user by j and number of farms beside the river is *n*.

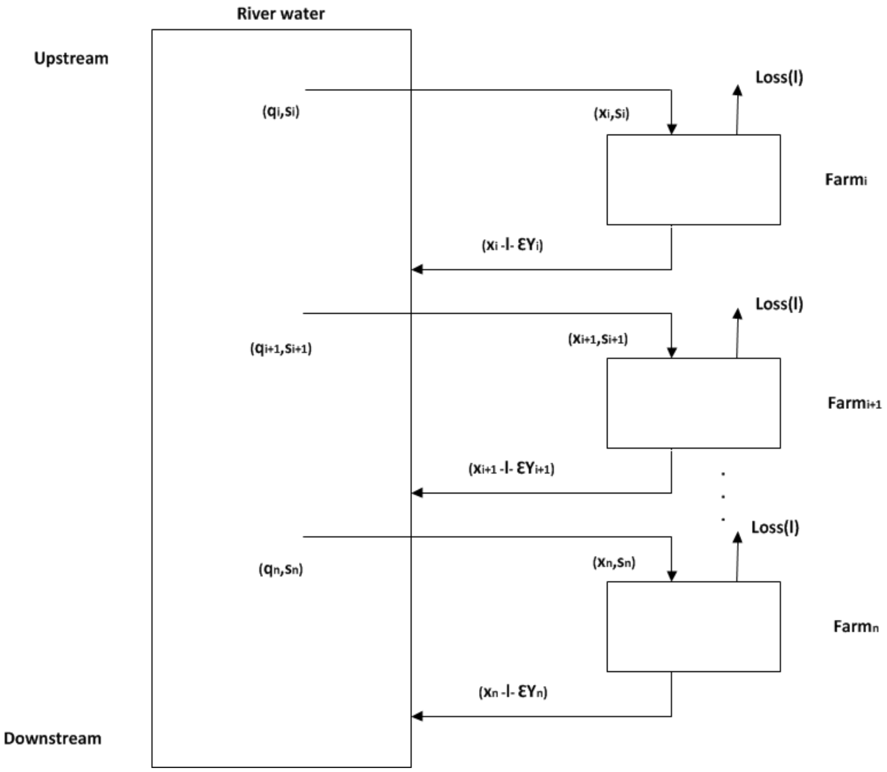


**Fig. 17.2** Conceptual Upstream to Downstream Farm Chain Model.

Fig. 17.2. A theoretical model of farm network along a river

*Source: (Ben Gal et al., 2013)*

The amount of water available in the river for u/s farm/user *i*is represented by *q* along with the quality of available water *s* and collectively represented by ($q_i$,$s_i$). The water utilized by farm *i*, is represented by $x_i$ and this will help to calculate the amount and value of water to the next farm ($q_{i+1}$,$s_{i+1}$) (Fig. 17.2).

As the source of water is only single therefore water quality decreases with the increase use of water, specified as $q_i \geq q_{i+1}$ and $s_i \leq s_{i+1}$ and, such that water availability (*q*) decreases and salinity (*s*) jumps down from higher elevation to lower elevation. All accessible water in the river is utilized for irrigation and all the farms have same climate, soil, and crop except for the amount and value of water. This postulation leads to having the same dependency on the production function for all the farms. The plant maximum yield is a function of the amount of water used for plant growth (Shani and Dudley, 2001; Shani et al., 2007; Shani-et al., 2009; Ben-Gal et al., 2013) without considering other climatic factors. Therefore, water used for crop production is fruitful if the transpiration climbs up due to availability of enough water. It is further supposed that crop yield is a function of salinity. Due to osmotic effect, plants cannot extract water, therefore, the supposition made is feasible

(Homaee et al., 2002). The poor quality water restricts the plant growth due to the presence of high osmotic potential.

Relative yield is a function of the amount and value of water and can be expressed as:

$$Yi = Y(x_i, s_i) \qquad (1)$$

It is sensible that the initial amount and value of water are key constraints for simulation of the model. The water quantity and quality depend on the amount water used by the upstream farmer, amount of water used and leached. Water utilized by Farm i affects the water amount and value. Out of total used water, some amount of water is used for plant growth, remaining leached out of the root zone and contributes towards surface water. Due to the use of water, the salt remains in the root zone and hence salinity increases downstream.

Water amount and value accessible to Farm i can be explained just like loop. The out of Farm i becomes the input of next Farm.

$$q_{i+1} = q_i - x_i + (x_i - \varepsilon Y_i), \quad i = (2,\ldots,n),\ q_1 \qquad (2)$$

where $q_1$ = Initially Available River Water

$$s_{i+1} = \frac{q_i - x_i}{q_{i+1}} s_i + \frac{q_i - Y_i}{q_{(i+1)}}, \quad i = (2,\ldots,n),\ s_1 \qquad (3)$$

The mass balance is:

$$q_{i+1}\ s_{i+1} = (q_i - \varepsilon Y_i)\ s_i \Rightarrow \varepsilon\ Y_i\ s_i = x_i\ (x_i - s_i^r) + \varepsilon\ Y_i s_i^r \qquad (4)$$

Where $\varepsilon$ is the evapotranspiration in a unit amount of plant biomass and $s_i^r$ is the leached water salinity $x_i - \varepsilon Y_i$.

### 17.7.2 Analytical plant yield expression

The (primary) production function depends explicitly on the amount of water *x* and salt concentration *s* as explained in equation 1. The ANSWER model is applied on each Farm i to predict the crop yield at the expense of the amount of water available to plant (Shani et al., 2007; Shani et al., 2009; Ben Gal et al., 2013). This model is smooth and analytically sound, and, is well-suited for the evaluation of more complex nonlinear differential equations (Shani et al., 2007; Tripler et al., 2012; Ben Gal et al., 2013).

The ANSWER model adopted from Shani et al. (2009) shows yield versus quantity *x* and quality of *s* of irrigation water.

$$Y_i = \frac{\min\left\{T_p, \left[\left[\psi_{root} - \frac{\psi_w}{\left[\frac{(x_i - Y_i)}{K_s}\right]^{\frac{1}{\eta}}}\right](x_i - Y_i)\, b\right]\right\}}{1 + \left[\frac{s_i x_i \left[\theta_r + (\theta_s - \theta_r)\left[\frac{(x_i - Y_i)}{K_s}\right]^{\frac{1}{\delta}}\right]}{EC_{50}\,(x_i - Y_i)\,\theta_s}\right]^p} \qquad (5)$$

for soil hydraulic properties ($\psi_w$, $\theta_r$, $\theta_s$, $K_s$, $b$, $\delta$, $\eta$), plant sensitivity attribute ($ECe_{50}$, $p$, $\psi_{root}$), and climate attribute ($T_p$) as explained in Table 17.2. Equation (5) thus simulates unique climate, plant, and soil explicit attributes. It is further supposed that attributes as mentioned in below Table are constant throughout the simulation.

**Table 17.2** The Attributes for Soil type and Plant type to be Used in the Model

| Soil | Millville Silt Loam |
|---|---|
| $K_S$ (mm/d) | 600 |
| $\delta$ (unit less) | 10 |
| $\beta$ (unit less) | 0.25 |
| $\theta_s$ ($m^3/m^3$) | 0.46 |
| $\theta_r$ ($m^3/m^3$) | 0.05 |
| $\psi_w$ (mm) | -300 |
| Plant | Zea mays L. cv. Jubilee |
| $\psi_{root}$ (mm) | -6000 |
| $ECe_{50}$ (dS/m) | 5 |
| $T_p$ (mm/d) | 8 |

## 17.7.3 Irrigation Application Efficiency

Water can be applied to fields in different ways ranging from macro-irrigation to micro-irrigation, and each irrigation method has its own benefits and losses. The application efficiency is a key term to evaluate the different irrigation methods. To understand in more detail, it can also be explained that how much water applied and how much water is consumed by plant for photosynthesis and remaining how much water is evaporated. Irrigation application efficiency laying between 0% and 50% was considered, as evaluation of different irrigation technique is not the main focal point of this paper. The first one is considered drip irrigation and the latter flood irrigation. A loss term was introduced (l), because all water accessible to plant is not used for transpiration. The loss (l) term relates to performance of irrigation technique. This yield:

$$q_{i+1} = q_i - x_i + (x_i - l - \varepsilon Y_i) \qquad (6)$$

The loss of water leached from the root zone increases the root zone salt concentration.

$$s_{i+1} = \frac{q_i - x_i}{q_{i+1}} s_i + \frac{x_i - l - \varepsilon Y_i}{q_{i+1}} s_i^r \qquad (7)$$

### 17.7.4 Crop Yield Function Explanation

The model has the capacity to produce different production curves under different amount available irrigation water and corresponding salinity. Fig. 17.3A shows the plant relative yield of Farm 1. The curve shows the normalized yield versus normalized irrigation. It means that both plant production and amount of water are converted into a dimension less number by dividing the potential transpiration. Relative irrigation is the ratio of the applied amount of water needed to get maximum crop production.

Fig. 17.3A shows the marginal yield for Farm 1. In case of no salinity, two linear lines and for non-zero salinity, smooth production curves form. It means that the production curve shows relatively less yield due to the increase of salinity (Ben Gal et al., 2013).

Farm 2 also shows the same production curve depending on the decision made by Farm 1. In this way, family of production curves can be obtained and the shape of the curve depends on the quality of drained water from Farm1 and the amount of water available for Farm1 as shown in Fig. 17.3B.

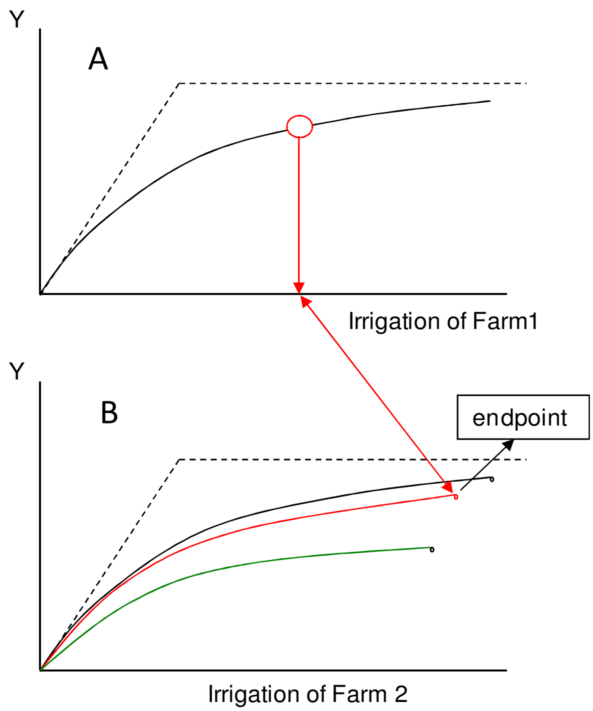


**Fig. 17.3** (A) Relative Yield with respect to Irrigation of Farm1 and Farm 2

B). The Relative Yield of Farm 2 based on the Decision of Farm1.

An important aspect to consider is that the decision made by Farm 1 in Fig. 2A produces a new production curve in Fig. 2B. For two farms network, Farm 2 will use that water after the return flow from Farm 1. Therefore, the last point on the production curve is (also shown in Fig. 2B) is noticeable. The criteria for selecting optimum irrigation water, keeping in view the maximum system yield are developed in R software.

## 17.7.5 Management options

The amount and value of water coming in and out of farm do not change. In addition, the irrigation regime ($x_1,\ldots,x_n$) is also constant. The inputs other than water quantity and quality are not considered in this study.

In order to evaluate the irrigation among the number of farms located along the river, different management options were focused. One of the options is to focus on uncontrolled river water. The other option is to divide the river water equally among farms. The last option is to focus on the optimal water management under different amount of quantity and quality of water.

Without water rate application, each farm uses maximum amount water to get maximum crop production and hence maximum benefits. The amount of water that gives maximum crop production is represented by $\hat{x}_i$. It is worth saying that $\hat{x}_i$ depend on the salinity level $s_i$. Amount and value of water for each farm is determined by using Eqs. (2) – (4).

In no water scarce situation and uncontrolled water usage, the last farm, Farm *n* consumes maximum amount of water for the maximum crop production. Water shortage shows that last farm faces problems to fulfill their crop water requirements. In this paper, extreme condition of water shortage was focused. Under water deficit condition, the distribution of uncontrolled water may be unproductive. This indicates that upstream farm does not receive any increase in marginal productivity compared to downstream user who receives a positive increase in yield. In this situation, the reallocation of water among upstream and downstream users would optimize the system production and eventually the profits. The use of excess water by an upstream user will have two demerits. The first drawback is that less amount of water will be available to the next farm and second demerit will be in the form of increase in salinity to the downstream farm.

The role of an agency was considered that allocates the water to the users in order to optimize the system yield keeping in view the return flow and its salinity. The track for sustainable use of available water is represented by ($x_1^*,\ldots,x_n^*$), and the following equation along with constraints can be used to determine the optimal solution:

$$Max \sum_{i \in N} Y_i \qquad (9)$$

subject to

$$q_{i+1} - q_i = -\varepsilon Yi \qquad (10)$$

$$s_{i+1} - s_i = -\frac{q_{i+1} - q_i + x_i}{q_{i+1}} s_i + \frac{x_i - \varepsilon Y_i}{q_{i+1}} s_i^r$$

$x_i \leq q_i$ , $q_1$ given, $s_1$ given.

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## Chapter 18

# Irrigation System Issues and Options

**Rashid Mehmood and Zahid Mahmood Khan***

## Abstract

Like other irrigation systems of the world, Pakistan's surface irrigation system, which is the largest constructed surface irrigation system, has been facing several problems related to the water use efficiency and system management such as system operation, maintenance, interaction between stakeholders and warabandi (On Farm water distribution system). These issues can be generally divided into five main categories:1) international, 2) national/provincial, 3) river reach, 4) canal reach and 5) farm level. Before independence, water disputes existed mostly between upper Punjab and lower riparian of Sind province. The national problems in some form existed till the Water Apportionment Accord 199, while the issues of management still exist to be solved among the provinces. The issues of water sharing at provincial level, among the provinces of Pakistan, were addressed and solved through Water Apportionment Accord of1991. To monitor the river water distribution, the Indus River System Authority (IRSA) was established in 1992. The canal and farm level problems include improper maintenance of canals, distributaries and watercourses, improper monitoring of irrigation water discharge and distribution, low irrigation efficiencies, inequitable distribution among users, over-exploitation of surface and groundwater, water logging and salinity and desertification of valuable fertile land are some of the issues that need to be considered and resolved for achieving the true benefits of the irrigation system.

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Water sharing problems of international level emerged after the division of the subcontinent into India and Pakistan, mainly because of Indian violation of disrupting water supplies to the command areas of eastern rivers. To resolve these issues between India and Pakistan, the Indus Water Treaty was signed in 1960 with the technical and financial help of the World Bank. These problems not only originated but also intensified when India started building many controversial dams such as hydropower projects of Salal Hydroelectric, Baglihar Hydroelectric Dam, Kishanganga Hydroelectric project on the rivers that were assigned to Pakistan under the Indus Water Treaty 1960. This chapter focuses on the historical developments, nature and gravity of the irrigation water issues between India and Pakistan, provincial water sharing issues, operational and management as well as performance issues. Some suitable options towards dispute resolution, remodeling and upgrading of the system, capacity building of managers and stakeholders, use of marginal water sources such as reclaimed wastewater and rainwater harvesting etc. are also discussed

## Learning Objectives

- To learn about irrigation water issues and their solution options at international, national, and provincial levels.
- To summarize the system's operational problems and solution options at the river, canal farm and watercourse levels so that the readers may be facilitated with sufficient information to plan, design and improve the system to its potential efficiency.

## 18.1 Introduction

Pakistan's Indus Basin Irrigation System is the unified and the largest irrigation system on the earth. The system comprises of 3 major reservoirs (Chashma, Tarbela and Mangla), 18 headworks and barrages (Ferozepur, Sidhnai, Islam, Panjnad, Kalabagh, Balloki, Sukkur, Sulemanki, Marala, Trimmu, Kotri, Guddu, Chashma, Mailsi, Qadirabad, Taunsa, Maralaand Rasul), 12 link canals and 45 irrigation canals. This also contains over 107,000 watercourses and millions of farms and field ditches. The main canal system has an estimated length of 585,000 km and the length of watercourses and field channels surpasses $1.62\times10^6$ km (Rizwan, 2008).

The irrigation system has been operating for more than a century and has been a source of water for domestic and agricultural needs of civilization settling for the huge Indus Basin. With the development of civilization, human intervention to manage the system from inundation to weir controlled system and to operate from flood irrigation to the advanced systems of border, furrow and bed irrigation, has always faced a number of problems at all levels such as basin, river, canal, distributary, watercourse and field. The problems mainly related to the water storage in reservoirs, diversions at the barrages, conveyance through the canal system and the application to the cropped fields. Conflicts also existed in sharing this important natural resource among neighbor countries, provinces, regions as well as the end users. The problems and issues may relate to the engineering structures' performance, deliveries, system management and its professional, legal and social aspects and obligations. The most affected stakeholders may include government functionaries, farmer organizations and individual water users. As a part of the overall system each organizer, engineer, system manager as well as end-user farmer face such problems and almost all of them wish and attempt to find feasible solutions to run the system beneficially. Therefore, it is important for each stakeholder to be aware of the actual issues and possible options for successful operation of the system. Therefore, the major issues and problems relevant to the operation and management of the large and complex irrigation system of Pakistan are highlighted in the subsequent sections.

# 18.2 Issues of Irrigation System Scale Wise

## 18.2.1 International Issues

There are a number of water rights and sharing issues between India and Pakistan – the neighbor countries. The mutually agreed water sharing formula through the historical Indus Water Treaty 1960 and the Indian violations of the mutually agreed treaty have been discussed under the river based issues.

### 18.2.1.1 Historical Background of the Water Rights and Sharing Issues

Since the beginning of the civilization, water of the Indus River system has been used for the purpose of irrigation in the Indus Basin. In the earlier times, the demand for water was conspicuously less than its availability in the river due to smaller population. The demand for water increased with increasing population, which in turn raised more issues both at the provincial and domestic levels. During British rule in the mid of the 19th century, water clashes were mostly between lower (Sindh) and upper (Punjab) riparian, mainly because of lack of confidence between the two provinces. Sindh was afraid that Punjab would encroach upon water shares of Sindh and establish water rights over Indus river water (Sridhar, 2008).

After the creation of Pakistan, more and more disputes of international dimensions erupted between India and Pakistan, mainly due to India's attempts to gain more control of water resources of the Indus Bain. Firstly, during the partition of Punjab, Radcliffe unjustly drew the dividing line across Punjab, giving the most rich water streams of the Indus River to India (Siddiqui, 2010). Secondly, within a year of the partition of the subcontinent, in April 1948, India stopped the water supply of Dipalpur Canal originating from Ferozepurheadworks, built in 1920 on Sutlej River. Pakistan criticized India for this action and sent its delegation to New Delhi to seek resumption of the water supply. On the 4thof May 1948, Pakistan and India signed an agreement, the Inter-Dominion Agreement. According to the contract, India agreed to continue water supply for irrigation until Pakistan would be to accomplish an alternative (Sridhar, 2008).

After that, Jawaharlal Nehru, the Indian Prime Minister, asked an American professional, David Lilenthal, to review the condition. He supported Pakistan's arguments but his observations were rejected by Delhi. From 1952 to 1960, the World Bank supported a series of talks in Washington, and finally India and Pakistan agreed to sign the Indus Water Treaty in 1960. According to this Treaty, it is not permissible for India to build dams for water storage on the Jhelum, Chenab and Indus rivers. However, India was permitted only a limited use of these rivers' water and was allowed to develop run-of-the-river projects for hydropower if required for meeting dire civilian goals. Disregarding all these observations, India continues to make an excessive use of the waters of the Indus and Jhelum rivers, and that remains an issue of discord between the two countries (Sridhar, 2008).

#### 18.2.1.2 The Indus Water Treaty1960

The Treaty is themutualagreement between Pakistan and India to share the water of the Indus River. The Pakistanis' president, M. Ayub Khan, the Indian Prime Minister, Jawaharlal Nehru, and the President of World Bank, W. A.B. Illif, assigned the treaty in September 1960 in the city of Karachi. The Treaty explains the water rights and obligations for both countries. Under this Treaty, Pakistan has the full rights of using the Jhelum, Chenab, and Indus Rivers' water. This According to this, Pakistan was allocated about 75% of the water of the Indus system, and India was allowed, under judiciously specified conditions, to use water of three western rivers before entering into Pakistan (Nosheen and Begum, 2013).

i. The agreed Principles for Water Sharing between India and Pakistan

The following two are the main principles of water sharing between the two countries:

- "All the waters of the 3 Eastern Rivers shall be available for the unrestricted use of India. Pakistan was permitted by way of exception to take water for domestic use, non-consumptive use and certain limited agricultural use".
- "Pakistan shall receive unrestricted use of all water of the Western Rivers, which India is under obligation to follow and shall not permit any interference with these waters except for the domestic, non-consumptive agricultural use, generation of hydroelectric power and storage works" (Akhtar, 2010).

ii. The Principles of Cooperation according to the treaty

According to Treaty, both countries were agreed to exchange of the following daily data for proper development of the rivers, and to cooperate and collaborate with each other. These data have to be shared by both parties on monthly basis.

- Discharge data at all observation stations.
- Releases (withdrawals) from reservoirs.
- Extractions at the heads of all irrigation and link canals.
- Escapades from all irrigation and link canals.
- Deliveries from link canals.

(Akhtar, 2010)

iii. Merits of the Treaty

The following were the major advantages of this treaty:

- Both the countries started improving the water uses (supplies) of rivers according to their shares.
- The Indus basin system became more consistent and reliable source of water.
- The treaty provides good opportunities to the countries to use water in a better way.
- It helped reduce the tension between both the countries.
- A great institution, the Indus Commission, was also the result of this treaty to solve water disputes in future.
(Nosheen and Begum, 2013)

iv. Demerits of the Treaty

The followings were some disadvantages of the Treaty:

- According to Pakistan's point of view, only 75% water allocation of 90% of irrigated land was the destruction of "appreciable harm" principle.
- According to India's perspective, 75% water allocation to Pakistan was a violation of the "equitable utilization" principle.
- Pakistan had to sacrifice an entire flow of 24 MAF from the eastern rivers, which was used for irrigation of the command areas of these rivers.
- Irregular flow in the eastern rivers caused silting inthechannels, resulting in frequent floods in Pakistan during higher flow periods; in addition, causing bad environmental impacts.
- Due to an irregular flow of the eastern rivers, the traditional flood irrigation disappeared in the command areas of the Ravi, Sutlaj and Bias Rivers in Pakistanand thus resulting in a large cultivated area into barren land.
- Storing water is not an alternative of continuous flow because water storage has limited life. Pakistan has already been facing silting problems in the major reservoirs (Nosheen and Begum, 2013).

## 18.2.2 Provincial Issues

There have been many interprovincial conflicts related to the use of water of the Indus River System that date back to the times before the creation of Pakistan, and have not been resolved completely yet. Even after the end of the British rule in the subcontinent, water from the Indus River System (IRS) still occupies the same significance and is a source of inter-provincial conflicts in Pakistan.

For the first time, the issue of water conflict between Sindh and Punjab emerged in 1901, when Indian Irrigation Commission banned Punjab to take even a drop of water from the Indus without the endorsement of Sindh. After the partition of the Subcontinent, the major interprovincial conflicts started when Pakistan, under the Indus Water Treaty 1960, acquired funds from different donor countries and the World Bank to carry on various projects to build dams, barrages, canals, etc. for better utilization of its water share. The province of the Punjab was blamed by other provinces that Punjab is using those projects to divert their share of water for its own use. In 1968, the Water Allocations and Rates Committee, under the leadership of

Akhtar Hussain, was established by the Governor of West Pakistan to examine the water allocations from barrages, release patterns from reservoirs, drawdown levels and the use of ground water in relation to surface water deliveries. In July 1970, a report from the committee was submitted, but no attention has been paid to this report since then (Mansur, 2002).

In 1970, Justice Fazl-e-Akbar committee was formed for the water allocation of the Indus River and its tributaries, which submitted its report in 1971 to the government of Pakistan. During the same time, ad hoc distribution of water from Chashma barrage and Tarbela reservoir was ordered among the provinces. No essential decision was taken on the recommendations of the Fazl-e-Akbar committee and water continued to be distributed on an ad hoc basis by the government of Pakistan. In 1977, one more commission was established by the government of Pakistan involving the chief justices of the High Courts of the Provinces, which was headed by the Chief Justice of Pakistan to observe the issue of water allotment. After that, Justice Halim Commission was set up to look into the water allocation matter. The complete recommendations of these commissions were never implemented by the Federal Government, and therefore, the conflicts among the provinces of Pakistan continued (Mansur, 2002; Feyyaz, 2011).

Lastly, in 1991, the Government of Pakistan enforced the Water Apportionment Accord to resolve the conflict related to water sharing among various provinces of the country. This accord was signed on March 16, 1991in Karachi in a meeting attended by the chief ministers of Punjab, Sindh, Balochistan and Khyber Pakhtunkhwa under the leadership of the Prime Minister of Pakistan. In 1992, the Indus River System Authority (IRSA) was established with headquarter at Lahore, for monitoring river water distribution among the provinces. According to the accord, the three reservoirs (Tarbela, Chashma, entangle dams) and inter-river link canals were stipulated as the main structures for the water management of the Indus basin. The water allocation of these reservoirs to the provinces was centralized, using 'Suggested Operation Criteria' established on a 10-daily basis (Ranjan, 2012). According to the adopted formula, the total water available in the Indus River System, 114.35 MAF, was allocated among the provinces as presented in Table 18.1. The Water discharging to the sea remained unresolved (Ministry of Water and Power, 1991).

**Table 18.1 Provincial** Water allocation (MAF), according to Water Accord 1991

| Provinces | Kharif | Rabi | Total |
|---|---|---|---|
| Punjab | 37.07 | 18.87 | 55.94 |
| Sindh | 33.94 | 14.82 | 48.76 |
| Khyber-Pakhtunkhwa | 03.48 | 02.30 | 05.78 |
| Balochistan | 02.85 | 01.02 | 03.87 |
| Total | 77.34 | 37.01 | 114.35 |

*Source: (Rajput, 2011)*

A few years after implementation, the accord became controversial in 1994 when Punjab was allegedly blamed by Sindh, for not releasing its agreed amount of water. On the other hand, Balochistan blamed Sind for not releasing water, Sindh raised allegations that this is a one-sided agreement and Punjab violates the agreement with the support of IRSA, WAPDAand the Federal government (Mansur 2002).

After the 1994 incident, WAPDA and the Ministry of Water and Power (MWP) returned to apportionment based on historical use, rather than accord. However, IRSA stopped working in 1998. After this, the Prime Minister announced to build a dam at Kalabagh on the Indus River which proved to be a controversial plan and was strongly rejected by the KPK and Sindh. In 1999, the IRSA resumed functioning but only after shifting its headquarters from Lahore to Islamabad. It was also attached with the Federal Ministry of Water and Power (Ranjan, 2012).

IRSA had hard time to produce a compromise over water allocation during the droughts of 2001 and 2002. Protests in Sindh forced the Chief Executive (CE) of Pakistan to overturn his decision. Precisely, the solution of such clashes was a matter of the Council of Common Interests (CCI). Since CCI was inactive, the CE had to tackle this problem. Therefore, the CE took some critical decisions in a meeting with the governors of all the four provinces. In 2003, the situation changed again when the president handed over executive responsibilities to the elected governments at the provincial as well as federal levels. On the dispute of opening up of a link canal, the Chashma-Jhelum, in July 2010, Sindh and Punjab again opposed each other regarding their due share of water. Later, the issue was resolved by the interference of the Prime Minister of Pakistan (Ranjan, 2012).

## 18.2.3 River Scale Water Issues

The Indus Water Treaty was followed by Pakistan and India for almost two decades (1960s-1970s). After that, India, as upper riparian,began creating water problems for Pakistan. Since the birth of the treaty, India had been violating rules of the international law many times. On the other hand, Pakistan kept tolerating the Indian violations for many years. Finally, Pakistan complained to the World Bank and asked for intervention, but no worthwhile results could be attained. The following are the major controversial Indian projects, violating the treaty (Nosheen and Begum, 2013):

### 18.2.3.1 SalalHydroelectric Project

This was the first project from India on the Chenab River. Being located in the occupied Kashmir, the SalalHydroelectric Project created several serious conflicts between both the countries. In 1974, some information on the project was disclosed by India: Pakistan actively objected to the storage capacity and design of the dam. In 1976, both the countries started talks to resolve the dispute. The main objection of Pakistan was that India would disturb the flow of the water by building this dam and would cause flooding to the western Punjab. After incessant deliberations, India did show flexibility finally, and shared the details of the project, agreeing in principle to alter the design of the dam. In 1978, both the countries contracted an agreement on this project. In this way, the first major conflict was successfully resolved under this treaty (Siddiqui, 2010).

#### 18.2.3.2 Wullar Barrage Project

The second controversial project from India was the Wullar Barrage (Tulbul Navigation project) which is still unresolved. The location of the project was in the occupied territory of Kashmir on the Jhelum River. India designed to build the barrage atWullar Lake's mouth. No information was provided to Pakistan on the project, as India started construction in 1984. In 1985, Pakistan came to know about the project, and upraising objections demanded to stop the work (Akhtar, 2010). Consequently, the problem was taken up by the Indus Commission, and several meetings were held to resolve this matter. However, the Commission could not resolve the issue and the construction work continuedup till September 1987, when the work was finally suspended. Then, on the Indian appeal, negotiations started at the secretary level. Up to 2008, about 13 rounds of meetings were held, but the matter is still unsolved. Although the work is suspended till date, yet India still harbors intentions to resume it (Siddiqui, 2010).

#### 18.2.3.3 Baglihar Hydroelectric Project

The third major controversial project was construction of Baglihar Project. This was the first project that was sent to neutral experts to resolve because Pakistan raised some technical questions. In October 2008, the project was initiated in district Doda on the Chenab River. It has two stages with 450MW capacity, collectively. Six objections were upraised by Pakistan to the design to base theclaimthat the project did follow the rules of the Indus Water Treaty. Pakistani experts also raised question that India is going to weaken the defense of Pakistan by stopping the flow of the Chenab river (Akhtar, 2010).

In March 2009, the Pakistani minister for Water and Power gave detailed information to the Parliament that Pakistan wanted India either to compensate for the losses or to provide water equal to 0.2 million acre feet, so Pakistan went to the Indus Water Commissioner to raise this issue. India recognized the claim of dropping Chenab's flow during the high flow months, August and September. Two meetings were held between the High Commissioner of the two states, but with no results. India, as usual, showed traditional inflexibility, which caused loss to Pakistan (Siddiqui, 2010).

#### 18.2.3.4 Kishanganga Hydroelectric Project

Another dispute faced by two countries was the construction of Kishanganga project. This issue was taken by Pakistan to the Court of Arbitration for a fair solution. The location of this project is upstream of Muzaffarabad at a distance of 160 km, with 300 MW installed capacity. Pakistan got information about the intentions of India to build the project in 1988. However, it was officially confirmed by India in June 1994, giving some information about the storage work. Pakistan raised some objections to the project. The fundamental objection was regarding the diversion of river water through a 21 km long tunnel towards Wullar Lake to generate power, which was against the provisions of the Indus Water Treaty (IWT). This was not only a serious threat to Neelum-Jhelum Hydropower Project (969 MW) but would also reduce the water supply for agriculture in the areas of Azad Kashmir. It is estimated that about 27% of Neelum river water would be reduced due to this diversion of water towards

Wullar Lake. Pakistan also raised objections regarding design features, specifically the draw-down technology to blush sediments.

In May 2004, due to objection by Pakistan on construction of the project, India agreed to stop all work for six months, and a meeting was arranged between two countries to resolve the issue. In the meeting, Pakistan was provided information that the foundation of the dam and the power-house were under construction. Pakistan strongly asserted that, before resuming the construction work, India must remove Pakistani objections. Five meetings were held under the Commission from November 2004 to November 2005. However, the issue remained unsolved. In addition, no data about water supply was shared with Pakistan (Siddiqui, 2010).

Recently, in 2013, the International Court of Arbitration (ICA) has permitted India to build the dam and gave permission to divert the water towards Wular Lake. Nonetheless, the court ruled that the minimum flow in the river will not be less than 9 $m^3/s$ always, and India can use the remaining water for producing hydroelectricity (Bhutta and Haq, 2013).

### 18.2.3.5 DulHasti Hydroelectric Plant

The fifth issue between the two countries was the building of two-stage DulHasti hydropower project, having aninstalled capacity of 390 MW. It is situated in Doda district on the main Chenab River. India informed that it was just a hydroelectric station but Pakistan argued that it was a full-fledged dam designed to store water for irrigation like Baglihar dam. India initiated this project in 1983 at the cost of Rs. 34 billion. Pakistan got information that it was 180 m long and 59.5 m high concrete gravity dam. As compared to Baglihar and Salal Projects, the impacts of this project on Pakistan were possibly too severe. Although the stoppage of water could prolong from of 1-2 days only, it was, however, essential to discourage India from providing under-sluices type gated spillways in the body of the dam (Ahmad, 2012).

### 18.2.3.6 Uri-II Hydel Power Project

This location of this project is in Baramulla district (Indian occupied Kashmir) on the Jhelum River and at the downstream of Uri-I. In October 2002, India was asked to provide information about this project but no response came. In July 2004, India was again asked to provide the requested information and again no answered from India was forwarded to Pakistan. In March 2005, the same request was repeated, and finally the information about the plant was provided by India. In April 2006, Pakistan showed its objection to India. However, in June 2007, they started construction unilaterally on the project without informing Pakistan, and as usual India rejected the demands of Pakistan to stop work on the Uri-II project. Pakistan also warned India to pursue the World Bank intervention in case of not stopping the construction work. However, India continued the construction work instead of providing any adjustments on Uri-IIproject (Akhtar, 2010; Sharma, 2007). The project has been completed recently in March 2014, with the capacity to generate 240 MW of power (Kashmir-Reader, 2014).

#### 18.2.3.7 NimooBazgo Hydro Project

This project as run of the river scheme is positioned on the Indus River in district Ladakh, with an installed capacity of 45 MW. In a meeting held by the Indus Commissionerson March 29, 2010, Pakistan was given the construction plans and maps of the project. Pakistan objected that this project might hinder smooth water supply to Pakistan. In July 2010, during the meeting with the Indus Commissioners, India stated its inability to discuss the construction plan of this project, saying that it was not part of the ongoing negotiations. Even, they did not allow Pakistan to visit the site (Akhtar, 2010; Nosheen and Begum, 2013). Nonetheless, a delegation from Pakistan visited the project in October 2011, and raised 5 main objections, which were mostly related to the height of spillways and the depth of the dam. However, these objections were rejected by the India authorities (Mustafa, 2012).

“There are two aspects to the Nimoo-Bazgar project: one, that India is guilty of violating the treaty; and second, that India is violating Clean Development Mechanism (CDM) rules and regulations under the rules and modalities of the Marrakesh Accords, article 37 B and C, which talk about stakeholder consultation regarding impacts of the project,” said Shafqat Kakakhel, the former United Nations Environment Programme official and member of the international CDM board (Parvaiz, 2012). The Nimoo-Bazgo hydroelectric project was commissioned in December 2012 and is now in operational form, from where the cheaper supply of electricity is being ensured to the Indian troops in Siachen (Hindustan Construction Company, 2013; Khalid, 2012).

#### 18.2.3.8 Bursar Dam

This is the biggest project that India intended to build on two major rivers Jhelum and Chenab. The construction work was started in 1996 and is expected to complete in 2016. This dam is being constructed on the Marusudar River near Hanzal village in Doda, which is the tributary of the Chenab River. The dam is expected to have a storage capacity of 2.2 MAF and can generate 1020 MW. This dam was considered as a serious violation of the IWT due to its high storage capacity, which is much beyond tolerable limits. The dam is proposed to have a height of about 829 feet, which is even greater than Tarbela dam (485 feet) and Mangla dam (453 feet). The main object of this project is storage of water, which will help regulate the flow to all downstream projects like DulHasti project, Baglihar dam and Salal dam.

This dam was a clear violation of IWT and international environmental convention (IEC). Not only will it result in water scarcity in Pakistan, but can also cause melting of the Himalayan glaciers. It would inundate about 4900 acres of thick forest and would cause the evacuation of the whole population of Hanzal village. The location of the project covers Kishtwar High Altitude National Park, having about 2 million acre feet which is an environmentally protected area. The park covers 15 mammals’ species including the Himalayan black and brown bears as well as the musk dear and some rear birds, which need an environmental impact assessment study. Pakistan’s Indus Water Commissioner hascontinuously asked its Indian counterpart to deliverinformationon this project. However, India said that they were aware of its legal obligations, and that they would inform Pakistan about the project details and offer relevant data six months before the construction activities started, as required under the Treaty (Ahmad, 2012).

**18.2.3.9 Indian Future Plan**

Pakistan is highly reliant on the water available from the Indus river system. On the other hand, Indiahasplans to build 155 water projects on the western river (Indus, Jhelum and Chenab), which belong to Pakistan according to the IWT. However, the Indian authorities have notconfirmed this plan yet.

"The Permanent Indus Commission (PIWC), which provides an on-going mechanism for consultation and conflict resolution through inspection, exchange of data, and visits between the two countries has compiled a list of 155 hydropower projects dams, India plants to construct in violation of the Indus Waters Treaty of 1960" (Bhutta, 2011).

## 18.2.4 Canal Scale Water Issues

- The prime issue of the Pakistani canal system is that approved flow does not reach at the outlets of distributaries and mirrors. Certain issues related to the canal system are given below:
    a) Excess withdrawal of water from upstream outlets
    b) Incorrect seepage loss estimations
    c) Incorrect inflow estimations
    d) Sedimentation
    e) Use of faulty or improperly designed outlets
    f) Limited desilting
    g) Un-coordinated re-establishment of equitable distribution
    h) Lack of efficient management
    i) Sociopolitical pressures
- Lack of standard water measuring devices which can ensure planned distributions of water.
- Scheduling and delivering water in canals without considering the water demands, which leads to water losses and over-irrigation and under-irrigation. These problems can result in low crop yield, salinization, and water logging beside wastage of water.
- Inefficiency of management leads to erratic and unequal water distributions among distributaries and outlets.
- Improper operation of canals either excess or below the designed discharge can create problems in the geometry of canal sections.

- Poor communication and transportation systems can totally fail during emergency cases such as flooding and rainstorms.
- Illiterate or unskilled persons for canal system's operation and regulation can create lots of problems in planned water supply.
- Lack of interests and participation of farmers in all operation and management activities of canal system.
- Poor performance and maintenance standards.
- Frequent breaks of canal and interruptions in water supply, especially at distributaries and minor levels due to inadequate maintenance by farmers.
- Insufficient and poorly defined procedures of monitoring, evaluation, and accountability at all levels of management.
- Lack of administration during preparation of operational and maintenance plans and their implementation (Anver and Haq, 1988)

## 18.2.5 Farm Scale Water Issues

The followings are the major issues related to farmers:

### 18.2.5.1 Water Availability/ Scarcity

Recently, the water availability in Pakistan has dropped to almost 1,100 $m^3$/ capita since 1940-41, a decrease of over 60%. The scarcity of water during the season of the Rabi can badly disturb the Rabicrops, both in the case of productivity and area. In addition, it can also cause bad impactson the plantation of cotton crop especially in Sindh, as the crop is planted there much earlier than in Punjab.

Some significant issues related to water availability are mentioned below:

1. Seasonal and annual variability of surface water and impact of global warming
2. Decrease in storage capacity of reservoirs due to sedimentation
3. Growing crops of demanding high water quantity and giving a low-return
4. Increasing demands in domestic and industrial sectors, resulting in reduction in irrigation supplies
5. Low delivery efficiency of water supply systems, especially municipal and irrigation systems
6. Water quality deterioration due to agricultural drainage effluent and untreated urban sewage
7. Up-coning from underlying saline aquifer causing salt-water intrusion
8. Over exploitation of groundwater, resulting in depleting groundwater table
9. Increasing pumping costs due to deteriorated performance of public tubewells

10. Ecosystem degradation from seawater intrusion resulted due to low flows below Kotribarrage (Ashfaq et al., 2009)

#### 18.2.5.2 Waterlogging and Salinity

The major factors causing waterlogging and salinity in the country are irrigated agriculture mismanagement, seepage from the link and irrigation canals, flat topography, inadequate drainageand poorquality effluent from a drainage system. This problem has already reduced the production of millions of acres of land. In spite of huge investment on Salinity Control and Reclamation Projects (SCRP)assumed since 1960s, the problem is still not completely resolved. In addition, this problem is getting more severe and severe due to the discharge of drainage effluent.

The waterlogging and salinity, currently, has affected 8% of Punjab soil and around 15% of the soil of Sind and a loss of 1/3 annual yields on slightly saline areas and 2/3 in moderately saline areas. According to a soil survey conducted in 1981, it was estimated that salinity has severely affected around 8% of the gross command area, and according World Bank, it was estimated that salt salinity has reduced potential production of about 25% of the major crops of the country. It is estimated that a land of around 2.4 million ha has a water table less than 5 feet. Increasing diversion of water from rivers and canals over the years has directed towards increasing water table, rising problems of salinity in some areas (World Bank, 1992).

#### 18.2.5.3 Over-Exploitation of Groundwater

Since 1970s, the use of groundwater has amplified to agriculture sector. Groundwater not only supply additional water to cope the water requirements of crops but also offer elasticity. The extensive usage of groundwater in the private sector can pollute the freshwater aquifers with saline water by dropping of water tables in fresh groundwater regions. Further, due to unequal distribution of canal water, farmers mostly depend on groundwater, resulting in over extraction of groundwater.

The continued abstraction of groundwater has resulted in over-pumping and consequent depletion of water table in many areas. Recently, this problem has become more serious due to the continued and extended drought faced by the country. The more noticeable areas affected by these problems are Lahore, some parts of Balochistan, some densely populated urban parts of the Punjab as well as of Sind.

It is reported that, in 26 canal commands, the water table is getting lower with various degrees of depletion. Those canal command areas are most affected where water allowance is lower and crops are heavily dependent on tube well irrigation (Ashfaq et al., 2009).

#### 18.2.5.4 Low Irrigation System Efficiency and Water Productivity

A significant amount of the water is lost through seepage and evaporation because the irrigation system of Pakistan comprises of rivers, a network of unlined irrigation and link canals, unlined distributaries, unlined watercourses, and irrigated fields. It is estimated that 25% and 30% is lost through canals and watercourses, respectively, and 25-40% in the fields due to application of old irrigation practices. An overall irrigation efficiency of 30 % is hardly obtained in the whole system (Ashfaq et al., 2009).

#### 18.2.5.5 Inequitable Distribution among the Users

Until the resolution of the water issues among the provinces through Water Apportionment Accord (WAA) of March 1991, the water of Indus Basin Irrigation System was distributed among the provinces on ad-hoc basis. The distributions of water to the provinces are based on two main concepts:

1. Protecting the prescriptive rights of the provinces acquired through actual canal withdrawals under various projects, and
2. Allocating the surplus water fairly for greater development opportunity to relatively backward areas.

WAA was a great institution for water resources policies in Pakistan. The recognition of environmental protection was measured as the most significant area by the Government of Pakistan. A freedom was given to each province to change the water apportionments within different canals system, which was a great step in the direction of allocation rationalization for agricultural productivity. It obviously did not go to cover the entire Basin, but indicated a movement from the rigidity of the historical withdrawals of each canal system to at least a sub-basin. In spite of the good intentions, the extended drought of 1998-2000 disclosed the limits in the Accord when serious differences arose between provinces over the supply of water under reduced flows. Many problems were produced at farm levels during the distribution of the reduced water flows. One of the major problems was that the tail reaches receive much less water as compared to head reaches. Interference by big landholders in the distribution of water and theft of water were the major reasons for the poor state of affairs. Command Water Management (CWM) and On Farm Water Management (OFWM) projects have given emphasis to the need for equitable distribution of supply between the head and tail of distributaries and watercourses (Ashfaq et al., 2009).

#### 18.2.5.6 The surface water and Groundwater Pollution

The quality of ground and surface water is rapidly deteriorating. The undiscriminating domestic and industrial wastewater into all water bodies is the main threat to the water resources of the country. The main reason for this water quality deterioration is the lack of application of legislative measures and standards. The problem is getting more severe due to increasing contamination from industrial, agricultural and municipal wastes into many aquifers and open water bodies like lakes, rivers and streams of the country. It is estimated that the Ravi River 'pollution due to sewage discharge from Lahore city reduces about 5,000 tons of fish every year (Ashfaq et al., 2009).

#### 18.2.5.6 Poor System Operation and Maintenance

The poor operation and maintenance of the whole irrigation system are the major management issues of the water sector, starting from the rim stations and ending up to the farmers' fields. Water and Power Development Authority (WAPDA) manages the operation of the reservoirs, and Provincial Irrigation Departments (PIDs) take care of the operation of the canal and drainage facilities. Accordingly, PIDs, water resources of Pakistan are greatly vulnerable and under high pressure. Discharge observational structures are not of good quality on the major canals. PIDs are also responsible for the maintenance of the Indus Basin Irrigation System (IBIS) down to the watercourse. On the other hand, the farmers are mostly responsible for maintaining the watercourse and the farm channels.

The maintenance efforts for the large Indus system are insufficient. The significant deterioration in the system performance has major adverse implications. For example, the inequity in water distribution has caused salinization in the tail areas. PIDs lack development budgets, which can cover the cost of maintaining its establishments (staff costs) and the cost of maintenance. Since the amount available for maintenance is not enough, some repairs are affected under the Annual Development Program (ADP) including major programs of renovation under Irrigation Systems Rehabilitation Project (ISRP).

PIDs also cover the maintenance of SCARP tube wells and tile drainage pumps. The SCARP tubewellshave many installation problems and also have high operation and maintenance cost. To deal with these problems, the Government started a rehabilitation program knows as Irrigation Systems Rehabilitation Project phase I (ISRP-I) in 1983. In the framework of ISRP-II, the provinces agreed to maintain FY88 levels in real terms, using FY88 funding level as a benchmark for the existing facilities with appropriate increases to cover any new facilities. However, actual expenditure fell short of FY88 level in all provinces except KPK. In Balochistan, it was as high as 90 percent (Ashfaq et al., 2009).

#### 18.2.5.7 Water Pricing and Valuation

In Pakistan, water is traditionally considered a public good. However, it is widely known that the water supply charges are much below than its opportunity value. Recently, water charges in irrigated agriculture are only 5% of the production input values. Further, the main view on price of irrigation water is that, even when it is considered a ‘public good’, its supply should not be subsidized (Ashfaq et al., 2009).

#### 18.2.5.8 Sea Water Intrusion Issues

The Indus river discharges into the Arabian Sea that repels the salt water to encroach into the surface and subsurface water. This issue is getting severe due to a shortage in the water of the Indus River. Salt-water intrusion has been explored up to 100 km. The salt-water intrusion badly affected theLar area of Sindh. Drinking of brackish water resulted in various diseases. For example, throat swelling was observed in the coastal areas due to drinking of brackish water. Furthermore, it caused loss of fertility of agricultural lands, resulting in economic loss. Hundreds of villages in Badin and Thatta districts have been become deserts, and people have been forced to migrate to some other places. Pakistan National Institute of Oceanography (PNIO) and National Science Foundation (NSF)have recognized that salt-water intrusion into the lower Sindh plains is directly linked to reducing the flow of Indus River. Until adequate water is released to Indus downstream of Kotri, seawater intrusion, combined with raised level of Arabian Sea due to climatic changes will convert Badin, Thatta and some southern parts of Hyderabad district of Sindh into waterlogged land (Memon 2002)

**Table 18.2** Main Issues and Possible Remedial Options for Pakistan Irrigation System

| Issues | Possible Remedies |
|---|---|
| Overall scarcity of water | • Enhancement of rainwater harvesting by Collaboration & partnerships with development organizations.<br>• Increasing the Capacity of groundwater recharging system through catchment restoration, Delay action Dam or retarding Damrecharging wells, flood management, and other efficient and effective means of sustainable water infrastructure development.<br>• Define demands and identification of proper ways and means for reduction of high water demands |
| Waterlogging and salinity in irrigated areas | • Through understanding of irrigation systemsandcurrent cropping pattern, keeping in view the economic aspect by carrying or performing the cost-benefit analysis and also adaptation to Better crop water management approaches or practices according to geographical distribution.<br>• Restoration of environmental flows to flush out salts in the Soil |
| Overexploitation of fresh groundwater in upland and desert areas | • Review policies and incentives for over-exploitation, and promote better equity and environmental cost charging systems<br>• Help restore the traditional and natural regime of groundwater Systems |
| Low efficiency in delivery and use in both domestic and agriculture sectors | • Awareness programs for efficient water utilization among farmers,<br>• Capacity building programs should also be devised for partner organizations including the government and civil society to improve the efficiency level in delivery and use |
| Inequitable distribution among water users at the provincial and local levels | • Review economic aspects of distribution policies, carry out cost-benefit analysis, and identify local interests<br>• Promote multi-stakeholder dialogues<br>• Policy level initiatives, which lead through recommendations for incentives to promote equity among all stakeholders.<br>• Solid initiatives or steps to develop local water management systems and reforms. |
| Pollution of fresh water bodies and natural rivers/streams particularly those near urban centers | • Identify pollution sources, type and levels of pollution<br>• Improve the capacity of government institutions to plan and monitor projects and conduct EIA studies<br>• Work with the private sector as well as promote public-private partnership to look for alternatives or to seek remedial action |
| Poor maintenance of the irrigation and distribution system; and insufficient cost recovery from supplies made for irrigation and domestic use. | • Not an IUCN issue, but need to raise awareness in order to improve the systems. Investigate incentive schemes for performance improvement<br>• Look at alternative pro-poor financing mechanisms for aquatic ecosystem management |
| Conversion of natural wetlands into other land use types | • Economic assessment of costs and benefits and recommendations for economic incentives for wetland conservation |
| Floods and droughts | • Improved geo-physical planning and introduction of Flood &Drought management policy initiative |
| Loss of downstream flows in Indus during winter | • Restore environmental flows for maintaining the natural regime of rivers and other water bodies |

*Source: Ashfaq et al. (2009)*

The estimations in this study are partial and ignore a number of substantial environmental subjects because of incomplete data. Perhaps, the most important omission is that of the mangroves of the Indus Delta. The interaction of riverine and deltaic ecosystems created a rich resource that has continued coastal communities. According to a survey conducted by the International Union for Conservation of Nature (IUCN) in two districts of Sindh (Badin and Thata), sea water intrusion may have affected over 135,000 people and resulted in losses in excess of $125 million.

## 18.3 Proposed Solution Options

There are many issues related to irrigation systems in Pakistan as discussed above. Most of these issues relate to the operation and performance of the system. The issues and the proposed options to solve are described in the Table 18.2.

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## Chapter 19

# Economics of Irrigation Water

**Muhammad Ashfaq and Javaria Nasir***

## Abstract

Water stands as one of the very important factors for agriculture, industry, human life, livestock and probably for all phases of life on the earth. Consequently, it may the considered as the key element in the national economy and development. It is a natural resource that supports the agricultural productivity. Agricultural country such as Pakistan cannot think of surviving without ample water resources. Therefore, it must be used efficiently focusing all the management opportunities to minimize water losses. Thus, a working knowledge on economic aspects of irrigation water is a prerequisite for engineers, managers, policy makers and progressive farmers. Farmers in Pakistan have encountered different policies of the Government in pricing of water, such as crop based and area based putting different constraints on the farmers for its profitable use. Water productivity in Pakistan has been lower than advanced countries of the world, which must be improved for improving the economy of the country. Thus, understanding water as a public and private good, its pricing policy framework must be developed. This chapter deals with various aspects of the economics of water, historical developments of pricing of water, water productivity and principles of water pricing, particularly, in relation to the agricultural production, which would set a sound base of knowledge for students, economists, engineers and policy makers.

**Keywords**: Water Pricing, Market good, Water Productivity, Water Use Efficiency

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## Learning Objectives

- To provide a working knowledge on economic aspects of irrigation water for engineers, managers, policy makers and progressive farmers.
- The reader may understand the dual nature of water as public and private good and its consequences for water pricing
- Understanding of the water pricing policy framework in Pakistan
- The readers may learn different approaches of economic and financial analysis for irrigation projects.

## 19.1 Introduction

Economics primarily deals with the allocation of scarce resources in an efficient manner. It is generally associated with the allocation of profit-making goods such as automotive, garments, or petroleum, etc. Thus, economics of water usually requires answer to the following questions:

I. What are the efficient ways of utilizing water in an efficient manner across competing uses?
II. To determine whether the allocation of water recourse is equitable and if not how we can make it both equitable and efficient?

Economics is the science of decision making so it can help policy makers make conversant choices and also ensure that water resource allocation is equitable and efficient across alternate uses. Subsequently mass trading assumes a significant part in deciding the cost of water, the structure of water markets, welfare dissection of water portions, ecological worth of water asset and appraisal of the expense profit examination of different water ventures.

Water is an extremely complex resource because of its unique characteristics. Its economic valuation is difficult because it's both public and private good. Its opportunity cost is difficult to calculate because it has multiple uses. The flaws in institutions and policies also add complexity for the water resource allocation. However, economists have evolved a great deal of literature in this context. Following are some basic concepts necessary to be understood before explaining different aspects of economics of irrigation water.

## 19.2 Market and Non-Market Valuation of Water

Most of the goods/agricultural products are traded in markets and they have market prices, e.g. wheat, fertilizer, seeds, chemicals, etc. Water, on the other hand, is a natural resource and its markets are not perfect or do not exist sometimes. For instance, groundwater in Pakistan has a market where farmers buy and sell water, but the price on which the water is sold does not reflect its true scarcity value. For Tubewell water only, the charged price covers its extraction cost, maintenance cost and some profit. The true price for water may be far more than the existing prices. Same is the case for canal water in Pakistan, which is sold at heavily subsidized prices that are not enough to cover even the repair and operational costs of the irrigation infrastructure. These distorted prices should be kept in mind while going into the economics of irrigation projects.

The benefits and costs of water projects may go far beyond the monetary gains only. For example, to decide on building a large water dam/reservoir, the costs do not include the construction costs only. There may be huge other costs associated with such projects like dislocation costs for moving a sizable population residing in the area, the loss of natural habitat, deforestation, etc. Likewise, the benefits of water projects may include several other benefits than just the increase in agricultural production or electricity generation. These additional costs and benefits are called social benefits. Several methods have been developed to calculate social benefits and costs of a water project.

## 19.3 Water as a Public and Private Good

Private goods are those which are traded in conventional markets. The Public goods are 'enjoyed in common' and must have two characteristics, namely, (i) Non-rivalry in consumption (ii) Non-excludability in consumption

The utilization is non-rivalry if one man's utilization of water does not rival the utilization of whatever viable individual, e.g. the air has the property of non-contention as utilization of one man does not lessen the utilization of others. Private goods do not have this property as the consumption of one person reduces the consumption of another person for the same good, e.g. consumption of wheat stored by a household. Public goods also have a property of non-excludability which means that nobody can be excluded from its consumption, e.g. consumption of air. Everybody can use it. In other words, it implies that if the goods are available for consumption to one person, these are available to all. In contrast, private goods are excludable which makes it possible to physically exclude some persons from using it as in our wheat example.

So, what this theory of public and private goods has to do with water? Water is both a public and private good. It depends on the situation when it is a public good and when it becomes a private good. Flowing water is generally a public good as everybody can use it without significantly harming the consumption of others. But water becomes a private good, e.g. when is stored by a farmer in a reservoir for irrigation. This dialog of water as one of the open goods and private goods has two imperative results, particularly if there should be an occurrence of open benevolence of water. Firstly, Public goods are supplied collectively and therefore they may be undersupplied due to the free rider problem which arises due to the selfishness of some people who think why they should pay the 'cost' of 'resource' when they can use it for free (think of water in a river as 'resource' and of 'cost' in terms of pollution costs)? Secondly, there is a valuation problem as discussed earlier. Private goods are valued for a single user through efficient market mechanism. In contrast, public goods are used by all people so value placed in them is not by all the people but only by the one who care. So, the benefits of the public goods, mostly go to a number of users while only some pay the costs. This dual nature of water poses special problems when one aims at estimating the true costs and benefits of using water, such for irrigation purposes.

## 19.4 Water Productivity

Water productivity index may only express a physical ratio between the yield and the water used to produce it. Yet, there is not a common agreement to use it as an indicator. It is generally defined as the ratio of crop yield harvested in kgs to the amount of water used in cubic meters ($m^3$) to produce that crop. We can calculate water productivity with a simple mathematical formula:

$$WP = \frac{Y\,(Kg)}{WU\,(m^3)} \quad (1)$$

Where:

WP refers to Water Productivity,

Y refers to crop yield in Kg and

WU refers to the volume of irrigation water used in cubic meter.

Most developing and developed nations have a goal to increase the water productivity.

The other way to calculate water productivity is

$$\text{Water productivity} = \frac{GDPinconstantprices}{annualtotalwaterwithdrawal} \quad (2)$$

**Table 19.1** Water Productivity of Top Twenty Countries in the World-Country Ranking

(Constant 2000 US$ GDP per cubic meter of total freshwater withdrawal)

| Rank | Country | Value | Year | Rank | Country | Value | Year |
|---|---|---|---|---|---|---|---|
| 1 | Singapore | 914.78 | 2011 | 11 | Switzerland | 118.49 | 2011 |
| 2 | Monaco | 631.44 | 2007 | 12 | Congo | 113.97 | 2011 |
| 3 | Luxembourg | 447.06 | 2011 | 13 | Finland | 90.89 | 2011 |
| 4 | Equatorial Guinea | 367.36 | 2011 | 14 | Israel | 90.85 | 2011 |
| 5 | Denmark | 260.63 | 2011 | 15 | Malta | 87.17 | 2011 |
| 6 | Antigua and Barbuda | 178.83 | 2011 | 16 | Brunei | 76.34 | 2011 |
| 7 | Ireland | 157.42 | 2011 | 17 | Kuwait | 74.94 | 2011 |
| 8 | Qatar | 152.27 | 2011 | 18 | Slovak Republic | 68.74 | 2011 |
| 9 | United Kingdom | 136.34 | 2011 | 19 | Norway | 67.46 | 2011 |
| 10 | Sweden | 121.52 | 2011 | 20 | Puerto Rico | 67.36 | 2007 |

*Source: Food and Agriculture Organization, AQUASTAT data, and World Bank and OECD GDP estimate*

## 19.5 Water Use Efficiency (WUE)

Water use efficiency in irrigation is the ratio of the amount (volume) of irrigation water actually used by a crop to the volume of actually diverted from a source for that purpose.

$$\mathrm{WUE} = \frac{\mathrm{Vu}\ (\mathrm{m}^3)}{\mathrm{Vd}\ (\mathrm{m}^3)} \qquad (3)$$

Where:

$V_u$ = volume of water utilized, m³

$V_d$ = volume of water diverted or extracted from a reservoir, m³

## 19.6 Pricing of Irrigation Water

Water is an important economic resource and, over time, economic pressure on water resources forced countries to create a mechanism to enhance water use efficiency, especially for irrigation water.

### 19.6.1 History of Irrigation Water Charges in Pakistan

The practice of collecting water charges can be traced back many centuries in the sub-continent. Initially the collection of water charges was informal. Evidence of the collection of water charges from water users started from the period of Feroz Shah, an emperor of India, in the late 14th century. He levied water charges from water users of the Hansli canal. In the period of the Sikh Government in the Punjab (1763-1849), water charges were introduced on fixed rates, based on the type of crops. Water loving crops were charged one fourth of the produce while low water consumption crops were charged one tenth of the produce. The system was further improved later in 1854 by introducing a monetized system of water charges for some crops like sugarcane and cotton.

After the proper canal system building in sub-continent British introduced the productivity based charge system and first time water charges were introduced to a large canal in 1891 and then to other canals, as they became operative. In response to declining prices of farm output the charges were substantially reduced in 1934. Taxes remained compelling work 1953 and water charges were expanded by 50 percent in zones of immersion trenches. The water charges for the arrangement and plantations were likewise multiplied in 1954 in light of the fact that they supplied additional water supplies for the watering system. In 1955 all charges were again brought back to the level of 1924. In 1959 the waterways were appropriated in two gatherings, the composite duty into parts, so that rationalization and revision of water charges can be possible throughout the country. Water charges were increased many times in the period of 1959-1969, resulting in a 10 percent average increase in overall price. Enclosures and plantation were furthermore charged 3 to 4 rupees for every section of land for every year. The reconsidered water charges remain compelling work 1978 which are 14.4 rupees for every section of land. Water charges overhauled a few times from that point forward and, in 1978, arrived at 18-21 PKR for every section of land for wheat, 18-34 PKR for rice, 18-32 PKR for cotton and 18-71 PKR for sugarcane. The recovery rate was just 50 to 60 percent and was covered by government subsidies. Different forms of this charging system remained in practice till the year 2003 when in Punjab, fixed water charges based on area owned were introduced. These charges were separate for cropping seasons and head-tail differentials were also introduced. Water rates have been kept low in Pakistan since 1959 especially for food and fodder crops as compared to cash crops. It was decided as a policy to keep the water charges low for food and fodder crops to ensure food security. This policy principle has become very contentious with the passage of time as governments tried to keep the water charges low to fulfill political motives. It has been estimated in different studies that irrigation charges have only made up to 2 to 6 percent of the total cost of production of different crops and these would have to be raised considerably to have any notable effect on water demand.

## 19.6.2 Water Pricing Markets

Getting right prices of water is to allocate water in an efficient and sustainable way, but ways of water allocation are very responsive to physical, socioeconomic, institutional and political settings, so one should take into account all these important aspects while developing the water pricing mechanism. Rather, all exertions of water valuing for the proficient designation of water assets, there are contrasts on the methods by which we infer the water costs (Kim and Schaible, 2000). The Government has to play an important role to build a strong institutional and organizational mechanism for efficient water allocation, even if we allow the private markets and give them right to exchange water for successful operation of these private markets that depend on institutional arrangements.

## 19.6.3 Principles of Water Pricing

Due to increased population, changing lifestyle and dwindling water supplies, the competition for scarce resources has been increased, Therefore, it is necessary to rationalize the water use. Water is a precious resource so we should use it efficiently and equitably. Consequently, it is important to consider the efficiency and equity issues so that economic efficiency becomes compatible with social objectives.

### 19.6.3.1 Efficiency

We can see the economic point of view of water resource allocation in different sectors as portfolio of investment projects. Considering this precious water resource as capital and with efficient allocation, one can get the maximum profit by equating marginal benefits of all sectors and utilize water until these marginal benefits are equal for all sectors. In the transient for productive designation, it acknowledges most extreme net profits over variable cost and bring about to minor net profits balance from all divisions asset utilization likewise augment social welfare (Dinar et al., 1997). In the long term we also consider the fixed cost optimal utilization. First, the best efficient is an allocation that maximizes net benefits in the absence of distortionary constraints or taxes. Second, the best efficient is that maximization which considers under distortionary constraints (informational, political, or institutional) or taxes (Tsur and Dinar, 1997)

### 19.6.3.2 Equity

The issue of impartial allotment concerned with reasonable portion over all financial gatherings into the general public and may not perfect with investment proficiency (Seagraves and Easter, 1983; Dinar and Subramanian, 1997). At present, the pricing mechanism of water resource may not be effective in redistribution of income (Tsur and Dinar, 1995), however, this may be because of some political and government's enthusiasm to build the accessibility of water for specific segments or residents. It is important to give water procurement at sponsored rate or receive diverse estimating component to record for different pay level to meet the objective of value (Dinar et al., 1997).

### 19.6.3.3 Theory

Water imparted some regular properties of both renewable and non-renewable assets. The surface water has the issue of reallocation of renewable supply around contending clients if the capacity is not accessible. Anyhow ground exhausts with the current withdrawal if the revive rate is in fitting; due to this reason the asset distribution is exceptionally imperative to think about. Allocative proficiency of watering system water might be computed by likening minimal profits of a unit of water to the peripheral expense of supplying that unit of water. Because many distortionary constraints associated with irrigation water practically it is difficult to achieve Allocative efficiency. Considerable attention has been given to these constraints along with efficiency and equity issues. Both partial equilibrium and general equilibrium have been used to evaluate the irrigation projects. Partial equilibrium analysis considers on one irrigation unit, keeping all other things constant while general equilibrium analysis determine the economy wide effects of policy by considering all other sectors in the analysis. Know we start with general society benevolence of water procurement and notice a few flights into the writing of second-best theories.

### 19.6.3.4 Public Goods

Water is often a public good weather we consider water from underground sources or surface sources of water. As we know water is a scarce resource and we have finite water resources that must be shared between different sectors, user and regions. The difficulty of overutilization of these open products alluded as the "**tragedy of the commons**". This happens when a few clients overlook the impact of their movements on alternate clients of asset and on the asset also, and all clients simply pursue their redirections toward oneself. Economist advocates the definition of private water rights and establishment of water markets to devise the proper user rights which are efficient, equitable and also protect the resource from depletion. For example, tube-well irrigation has now become cheaper due to technology and now it is considered as a private good, even for small scale farmers. However, for exhaustible, non-renewable or uncertain resources privatization is difficult.

#### 19.6.3.5 Implementation Costs

Appropriate institutions are required for proper implementation of the pricing methods, such as a central water agency, but these entail costs. The physical, political and institutional environment is manifest in the form of transaction costs. Implementation cost may also render some pricing methods unreasonable and also shrink the list from which to select. It is not a trivial task to value these constraints under various pricing methods and we have no general rules that can be applied in a given situation. Administration costs, which are easy to value and estimate implementation cost, also include such things as compliance costs, which can be quite extensive. Complex pricing scheme which is also efficient may be constrained by the informational and administrative costs needed for implementation in various parts of the world due to complex farming systems.

Tsur and Dinar (1997) found that the effects of implementation costs on the performance of different pricing methods are significant in the sense that small changes in costs can change the order of optimality of those methods. While these remarks may be uncomplicated, very little experiential proof or methodology exists for evaluation of the practical limitations of various implementation costs.

#### 19.6.3.6 Incomplete Information

If there is a situation that water user has complete information about the marginal value of water, but a part of information is confidential and unavailable to the water authority then othercosts rise. In this situation, rational individuals may use their private information to precede their own interests, but water authority has to put more efforts or monitoring and enforcement at society's expense. The text refers to this as asymmetric information and moral hazard. The persistent case of unmetered water and the occurrence of pricing mechanisms on an area basis demonstrate this aspect of incomplete information in a good manner. Here, an authority will often remedy to the use of per unit area pricing due to the high costs of implementation of metering system. Because the authority does not have complete information on the value and use of the irrigation water, farmers might have an incentive to under-report actual usage of water if priced volumetrically.

#### 19.6.3.7 Scarcity

A pricing mechanism can be used in many ways to address scarce water supplies. We can implement high marginal cost prices during seasonal shortages, to ration all of the water and to recover fixed costs during peak demand. To address scarcity, many informal allocation systems have been introduced in the nonexistence of prices or prescribed markets. For many years, these long-established, mutual measures have often operated successfully, but these are not efficient or equitable: for example, the subaki system in Bali, the warabandi system in Pakistan and India, and the entornador-entornador system in Cape Verde. Imparts instead of volumes of water might be dispensed to unique homesteads when streams are questionable, and proficient designations could be accomplished if these shares are tradable. To balance the budget of water authority, we have another mechanism of introducing the fixed charge to cover scarcity costs. The productivity of minimal expense evaluation might be reached out in this way for short-run (utilizing a two-part tax system). In Egypt, this strategy is utilized. Yearly Pigouvian duty can likewise be utilized to handle shortage; it additionally stays away from distortionary influences or other burdened structures and is accordingly equipped for accomplishing long-run proficiency. Decision of water source and watering system framework is additionally identified with unverifiable and this will eventually influence the cost of water. By method for productivity and value criteria Small and Rimal (1996) assessed water shortage impacts on watering system framework execution in Asia. They note that ideal transport methods to record for shortage may decrease financial proficiency and value insignificantly. Thusly, Zilberman (1997) creates an ideal water evaluation, distribution, and transport framework over space to catch diverse upstream and downstream motivations.

#### 19.6.3.8 Other Distortionary Constraints

It is troublesome to accomplish first-best portions because of numerous other distortionary requirements; we talk about a percentage of the institutional and political demands in later areas. Be that as it may, we ought to say that diminishing comes back to-scale and externalities are additionally considered in attaining productive and impartial water designations before we turn to the act of evaluating and assigning water. There are externalities to nature's domain (contamination) or to other vested parties (outsider impacts) connected with water assignment. Economists have customarily upheld the utilization of assessments to address these externalities. On the other hand, the potential for this relies on upon the way of the watering system framework.

The irrigation projects at large scale exhibits increasing return to water production technology and give rise to natural monopoly. The cost of treatment of water and the per unit delivery cost declines the delivered volume of water increases. Negligible expense will be dependably lower than normal cost so peripheral expense estimating won't take care of the full expense. We can recuperate the full cost (variable and settled expense) by utilizing two parts levy evaluating. It could be more proficient for water power to value water underneath its long run peripheral expense if the settled expense connected with waterways, dams and other base surpasses the variable expense of water supply.

### 19.6.4 Water Pricing in Practice

It has been mentioned above that marginal cost pricing of water is difficult for many reasons. There are different methods for pricing of water resources and efficient allocation which depends on natural and economic conditions of the projects. First, though, it is important to have some idea of the actual supplying costs of the water.

### 19.6.5 Assessment of Irrigation Costs

Assessment of the cost that should be recovered from the water users has been a debatable issue for a long time. Financial costs, which are sometimes referred to as the Full Supply Costs are further composed of following four costs: the cost of depreciation, the financial cost of capital, the cost of rehabilitation and the O&M cost at primary and secondary levels.

The financial cost of the capital (the interest rate payable on the costs associated with the development of the irrigation systems) and the cost of depreciation (capital consumption of the fixed assets) are often grouped together and called the capital charges. For the calculation of capital charges there is disagreement, as old methods use old accounting methods and just look for the cost that is associated with repayment of historical stream of investment.

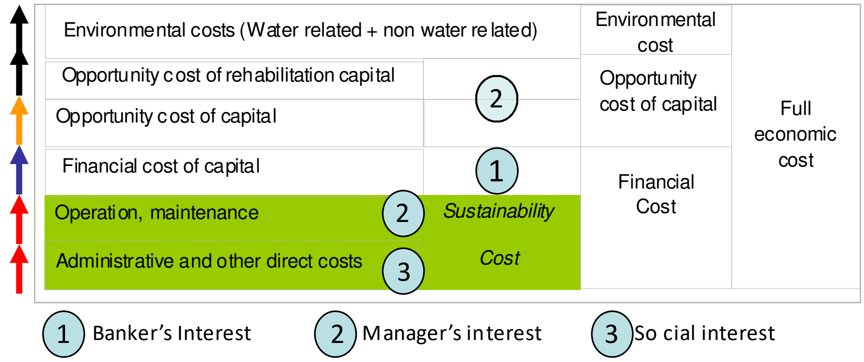



**Fig. 19.1** Components of Surface Water Cost
*Source: Adapted from Peter, 2004*

O&M costs are related to daily running of the delivery system. In these costs, we include typical costs like labor, purchased raw water, repair materials, and other input costs of managing and operating the system at the primary level (i.e., at the reservoir/storage level) and at the secondary level (i.e. at the main canal level). Upgrading or overhauling the system is often called the costs of rehabilitation. In practice, there is typically little dispute as to what are considered as O&M costs or the costs of rehabilitation and how they are to be measured.

Fig. 19.1 depicts the different types of costs involved in the supply of irrigation water. The Fig. also depicts administrative costs along with the operation, maintenance and renewal costs, together which make up the sustainability costs of the system and these should have to be recovered from the users of irrigation services in order to make the system sustainable.

The sustainability costs only make a portion of the full economic costs and most of the time these are not intended to be recovered from the users of the irrigation services keeping in mind the social and political pressures. So most of the time when we talk about cost recovery, it is referring to the recovery of the sustainability cost only. It is important to differentiate between the two terms, i.e., water charge and water price. Although at various occasions, these two terms have been used interchangeably, a distinction has been made by various authors between water tax, water charge and water price. Water tax is generally levied as a compulsory payment to cover the expenses meant for the general revenue raising. No promise of provision of service is made in response to the payment of the tax. A water charge is a payment actually made by the users of a specific service to partly or fully cover the expenses of delivering that service. Water price reflects the value of the commodity determined by the forces of demand and supply and it includes recovery of the full cost.

## 19.6.6 Irrigation Charging Methods

The broad range of categories that have been used for the assessment of irrigation charges include:

- Area based charging system,
- Crop based charging system,
- Volumetric charging system,
- Quota or rationing system,
- Tradable water rights or water markets.

Different characteristics of these systems are described below. While discussing their characteristics the criteria used for the comparison of the above charging systems include: predictability, stability, ease of administration, productivity impacts, and demand management. There might be no single system that can fulfill the requirements of all of the above criteria. Each system is detailed below.

### 19.6.6.1 Area Based Charging System

Area based charging system can be divided further into two procedures;

A. Water charges based on the area of the farm. This type of charging system is not related to the area irrigated, types of crops sown, or the volume of water received; it is rather related to the actual cultivated area of the farm. This type of charging procedure is being used to cover the fixed costs of the irrigation service and these have no impact whatsoever on the productivity, efficiency or demand management. This procedure is very stable, predictability of revenue collection is relatively high and it is relatively easy to administer.

B. Alternatively, fixed charges on the basis of area irrigated may be levied. So the total area of the farm, crops sown or the quantity of the water used has no impact on the level of charges. This procedure differs from the first type in that it has little impact over the demand side, but at the same time it is less predictable than the first method.

Zone based charges, taking into account contrasts in water use via season or product, might have a percentage of the profits of volumetric estimating. Furthermore, it might be the circumstances if, in the wake of conspiring for yield and season there could be almost no progressions being used of water for every hectare. There are still a few issues exist in a range based evaluating on the grounds that the agriculturist at the head of waterway have a tendency to over flood and this issue might be determined by guaranteeing the in time conveyance of the obliged amount of water to the agriculturists, in this situation there will be no purpose behind over watering system.

#### 19.6.6.2 Crop Based Charging System

In crop based charging systems, charges vary with the type of crop being cultivated. The water charge depends on the availability of water for different crops and on the "sweet will" of the policy makers. On the off chance that strategy producers want a productive allotment of water assets they need to permit higher watering system charges for high water expending products, for example, rice and sugarcane might be liable to higher charges for every hectare. With this charging framework if the distinction in charges is more extensive than agriculturist naturally switch to interchange crops. Anyhow if the government has some objective of the low nourishment value strategy, and needs to expand creation of any business crop than these favored yields will be charged more level than different harvests. Nonetheless, the mind must be taken in customizing the subsidies for delicate inputs, for example, water with the end goal of higher creation in light of the fact that subsidies some time prompts inefficiencies and abuse of the rare asset, for the most part with harvests, for example, rice and sugarcane. The product based charging methods have little effect on the interest administration of the watering system water, yet are less foreseeable and less steady than the range based charging techniques.

#### 19.6.6.3 Volumetric Pricing System

The volumetric charging procedures can further be divided into categories described below.

**(i) Charges Based on Marginal Price of Water**

In this method, a fixed rate charging system for each unit of water used is levied. The charges are directly proportional to the volume of the water used by the farmers. Different research studies have concluded that these procedures have a positive impact on productivity and demand. But it is very difficult to assess whether these methods can assure the demand/ supply balance or not. On the other hand, the assurance and predictability of revenue collection are poor with a complicated system to administer.

**(ii) Rising Block Tariff System**

In this case, a variable rate of water levies per unit received is applied. Service charges are directly related to the amount of water received, but these charges are not proportionately distributed. Lower volume water consumers have a lower block of charges, while higher volume users are charged at higher rates. This procedure is relatively more effective in assurance of supply and demand balance as compared to the first type of volumetric method.

Practically, volumetric methods of supply of water to individual farmers are perhaps not practicable in many countries of the developing world. At present the reason is that these require installation of measuring devices and these costly devices are vulnerable to accidental and malicious damage. Volumetric charging procedures can serve as an incentive to reduce demand if an irrigation infrastructure and water distribution methods can allow different volumes of irrigation water supply to serve different consumers.

**(iii) Two-Part Tariff**

Another modification of the volumetric charging procedure is a two-part charge, if we combine volumetric pricing and a fixed charge it will be considered as two parts tariff. It has the advantage of overcoming the weaknesses of block method pricing. The volumetric part dependent upon minimal expense evaluating and empower less utilization of water, while repair part used to make any shortfalls and guarantee the stream of income without recognizing what amount of water is accessible and conveyed. Even there is a part of operational and maintenance cost which is fixed cost and has to be paid even water has not been used in any season. It has also a disadvantage that it is relatively difficult for farmers to understand and hard to calculate. Likewise, the management expenses on a piece valuing plan are prone to be to a degree higher than a solitary charge plan.

#### 19.6.6.4 Quota or Rationing Charging System

This is a widely practiced charging procedure in the field. Quota limits the consumption at a threshold level, but it does not provide any incentive to farmers to utilize the available water efficiently below this limit. Although this system of charging water is quite efficient in the areas where water is scarce, but it also opens a political debate regarding the allocation of quota and its administration is also very difficult to manage.

#### 19.6.6.5 Tradable water rights or Water Markets

Water markets or Tradable water rights are applicable in the countries where water rights can be traded formally or informally between individuals or companies at a particular price. Water markets oblige a decently characterized structure of rights, value to regulate the conveyance of water, wide manages for exchanging, legal body to manage exchanging exercises and focus question for effective working. A well-developed conveyance system for transportation of water to all participants is also required, if all these requirements are in place, supply and demand will be effectively adjusted by market equilibrium prices. This system of water market has very high effects on water productivity and it can manage supply and demand balance very effectively.

## 19.6.7 Global Water Pricing Schemes

Water charging followed by different countries of the world are given in Table 19.2

**Table 19.2** Water Charging and Cost Recovery Conditions in Various Countries

| Countries | Charging Scheme | Cost recovery | Cost recovery rate | Issues/Comments |
|---|---|---|---|---|
| Pakistan | \$0.6 to 3.0 per acre-inch for different crops | About 35%, govt. subsidies cost of O&M | (30 to 35%) | ISC have little impact on efficiency and cost recovery |
| Syria | \$110-190 for permanent irrigation | Fee for investment cost recovered in 30 yrs, Flat fee represent O&M part | 90% of O&M cost | Govt. has not large networks, wells cover 59% of area |
| Cyprus | \$0.108/m3 | Govt. covers 38% of weighted cost | 34% of weighted cost (more than 90% of target) | Calculation of weighted cost is responsibility of govt. |
| Morocco | \$0.02/m3 to \$0.053/m3 as per irrigation method | 100% of O&M cost to be covered from beneficiaries | 58 to 70% | Drought effects recovery rates |
| Turkey | \$22.3 to 76.7 depending upon crop and irrigation method | Capital cost up to 10 yrs, O&M cost for previous year | 55% to 93% depending upon the system | Low capital cost recovery and no inflation adjustment |
| Mexico | . \$40/ha, determined by WUA | User pay 85% of O&M, govt. 15% | 90 to 100% | Transfer prog. Raised charges (39 to 80%) |
| Jordon | ITB system, \$0.01 to 0.05/m3 for 1000 to 3000m3 on monthly basis | Govt. subsidize about 30% of the O&M cost | -- | Costs recovered by the users were not invested back in to the system |
| China | Complex system (Volumetric + crop based), \$27 – 49.5/m3 | Irrigation retain 75%, local management 25% | > 90% | |
| France | Volumetric (partially), \$ 5.27 / 1000 m3 | User pay 100 percent of O&M cost | > 90 % | System of charging recover sustainability costs in some areas |

*Source: Johansson, 2000; Bazza and Ahmad, 2002; Dinar and Mody, 2004; Cornish, 2005*

## 19.6.8 Recent Changes in Pricing Policy

The income gathered from water asset is collected in the common treasury alongside other expense income and they lose their source personality. Consequently, we can't claim immediate relationship of water accuses of operational and support exercises. Cost of upkeep and administration expense of watering system water supply is more than receipts. Receipts have just 30-70 percent of cost on the operation and support of watering system. The remaining sum left in the wake of paying all non-water inputs from the terrible income gathered from the harvests indicates the returns to water and these might be considered as the most extreme sum for an agriculturist to pay. The conclusion for year 2000-01 gave Rs. 121 for every section of land inch for wheat, 57 for rice, 26 for cotton and 66 for sugarcane, correspondingly. These are steady with the conclusion dependent upon the expense of water tube wells. The estimation of peripheral quality item per–inch of water was Rs.70-107 in 1992. On the off chance that we express these pieces in 2000-2001, it compares to Rs.148-226. It demonstrated that negligible quality result of water is much higher than the current and flow water cost.

On the foundation of terrible salary for every section of land evaluations, utilizing the normal yields for year 1999-2000 and the legislature floor costs for that year, the proportion of ebb and flow water charges increased to horrible wage that have changed from 0.57 to 1.22 percent for different harvests. In the event that the rates of water build by two folds, agriculturists would just need to pay from 1.74 to 3.66 percent of their constraint salary, contingent upon the yield rehearsed, for trench water. The sensible and most suited charge for watering system water as a percent of horrible wages is 6% for Asian nations (this proportion is about 6.5 percent for the Philippines, Indonesia and South Korea). We can expand the water costs significantly even than this level can't be attained in Pakistan. On the off chance that we expand water charges by 100 percent than it will bring about degrees of water charges to net ranch wages that are harshly equal to those of various other Asian nations. Be that as it may, the increment in water charges has practically no impact on water use in view of the instrument of value framework. Ranchers will be eager to pay considerably higher water charges for great quality water and better administrations. In Punjab, yearly financial burdon on administration and upkeep of watering system frameworks is over 5 billion rupees. Income gathering of water valuing is much lower than uses, and this consequence in the procurement of huge subsidies to this area.

An expansive sum is additionally used in water charges accumulation, so a fitting water estimating component is the need of time for productive gathering, additionally for recouping the expenses all the more viably. It has likewise some suggestion for money division in country regions. Punjab government took a choice to change the waterway, water charging strategy from yield region cum-product sort based charging to harvest zone based level rate charging in 2013. Under the yield zone cum-harvest based framework, water charges separate by the condition, sort and season of the product and were imposed, depending upon the region trimmed. High charges executed for higher water expending harvests, for example, rice, and low charges for less water devouring yields, for example, wheat (for instance, for every hectare harvest based-water-charges preceding June 10, were Rs 37 for feed, Rs 148 for wheat, Rs 222 for cotton, Rs. 297 for rice, and Rs. 432 for sugarcane).

Under the new even rate framework for each hectare water expenses are settled for Rabi and Kharif seasons, despite the kind of yields created in every one season (new rate for each hectare are Rs 124 for Rabi and Rs 210 for Kharif products, paying little personality to the sort of harvests created).

### 19.6.9 Factors Responsible for the Change

a) The harvest based charging framework was viewed as old fashioned and not in accordance with the changing water and flooded horticulture circumstance;
b) It was thought to be controlled by the powerful agriculturists and government authority, (for example, distorting and miss-recording product sorts and yield zones, e.g., charging for grain rates when high water rate products, for example, rice or sugarcane were really developed);
c) The water charges appraisal was dependent upon the judgment of the income official, so it is generally obvious that it prompts an environment for rent looking for conduct;
d) The past arrangement of water charging was viewed as beneficial to enormous agriculturists and inconvenient to little ranchers that involve the incessant in the cultivating group; and
e) The harvest based charging framework prompts expansion weight on open subsidizes and broaden the hole between watering system costs and income gathering (e.g. as of late aggregate income gathered through water charges in the Punjab territory represented 31.4 for every penny (or Rs 1.6 billion) of the aggregate uses (of Rs 5.1 billion). It additionally uncovered that Punjab government is paying 3 rupees for each one rupee of water charge gathered. There is a blended response for this arrangement, while there are numerous supporters and a few faultfinders additionally for this approach change. There are three principle issues identified due to changes in approach. The new framework did not depend upon farm area and it is dependent upon the homestead region under harvest throughout the Rabi and Kharif seasons (i.e., level rate for every hectare of zone edited in each one season) the homestead range has water benefit or the region getting water.
f) Under the exhibited warabandi framework, portion of water is doneon the measure of homestead landholdings. In aggregate terms, substantial ranchers gather and utilize more trench water than little agriculturists. On hectare support, on the off chance that we consider that little and vast ranchers get an equivalent measure of water little agriculturist who have huge trimming force will pay more than the extensive agriculturists. In the past the flooded region halfway by waterway water and in part by ground water is charge completely for trench water charges. The individuals who use more groundwater and other variable inputs to expand their editing force might need to pay all the more in for every hectare water charges.
g) The most recent product range based level rate methodology, despite the fact that it does not report for intra-occasional harvest distinction, yet it represents between-season crop contrast and like the old framework, water charges in it are duty dependent upon region trimmed and trimming power throughout a season. So, while the new framework will support in tending to the product sort distorting issue, it might not resolve the issue of harvest region misreporting. The even rate for every unit of area is dependent upon the area size, free from product sort and trimming intensities are an improved elective to address both of these issues.

## 19.7 Groundwater Markets in Pakistan

Water showcases that exist in Pakistan are casual and are typically restricted to water markets spotted between contiguous agriculturists. The practice is extremely regular groundwater. Nonetheless, in spite of the fact that it is in numerous parts of Pakistan, the event of groundwater markets is not uniform. The region flooded through water markets, which is regularly recognized to be a substitute for the size of exchange water, shifts by locale and about whether relying upon various components, for example, drizzle, supply groundwater, editing examples, and the expense and accessibility of power. For instance, in water rare pockets of Punjab a significant zone inundated through groundwater markets. No methodical across the country appraisal of the degree of water exchanging.

Groundwater markets are truly normal in Punjab and North Western Frontier areas of Pakistan, where it is soft and fair water quality. Channel gathering and wells frequently utilize both saline and freshwater ranges; in saline zones ranchers blend the water to bring down the level of salt and sweet in the lack and deficiency of supplies strengths agriculturists to proceed with this practice. All head and medium ranchers offer water, while 87 percent of the tail itself, however offers groundwater through tube wells. In this way, groundwater markets are creating in the focal Punjab, where subsoil water is of good quality.

### 19.7.1 Competition between Buyer and Seller

Groundwater markets are not superbly intense markets where purchasers are allowed to browse various sellers - the force for the most part practiced a restraining infrastructure in these businesses. Groundwater rights are not generally characterized, and transaction expenses are a long way from being zero. Since purchasers and merchants are not nameless yet confront one another as neighbors consistently, a larger number of is included in these transactions than a straightforward offer of water.

One of the fundamental demands to rivalry in groundwater markets is that there are not an extensive number of water venders who can serve a specific zone of the area. Under the conditions overarching in a large portion of Pakistan, water tube well watering system is not a product that might be transported far from the source to the provision range. Transport misfortunes between the well pipe and the field, limits purchasers to purchase from wells found in the region of their fields (and confines merchants to those inside a constrained sweep well). The separation is doable and financially feasible to transmit water relies on upon the dirt, geography and channel sort (open or private) that is utilized to transport water. Physical nearness is not just the relationship impacts the improvement of focused markets groundwater. Social and agrarian relationship between the purchaser (and occupant) and the vender likewise limit the deal and buy of groundwater, whether tube well managers are just ready to offer to close relatives or individuals who have different ties. A significant explanation behind the deal between relatives is that relatives frequently have the closest land because of legacy examples.

### 19.7.2 Nature of Groundwater Markets

The altered hourly charge pump is the most well-known manifestation of business contracts groundwater in most market zones of groundwater. This kind of plan happens in different sorts of tube wells. Water in diesel pumping supplies ordinarily sold under an agreement by which the purchaser supplies the diesel and motor oil pump and pays an extra charge for every hour for the manager to blanket the motor wear. Offer development contracts for water are utilized under diesel and electric wells.

Overviews have uncovered that 96 percent of the wells were introduced for particular and business use. Most diesel wells are determined and the number fluctuates from one to three in each one homestead. The force of the tube wells fluctuates from 15 to 20 and the download speed shifts from 0.75 to 1.25 cusecs and the profundity is something like 130 feet with a reach of 100-170 feet. The expense of introducing tube well changes from Rs 300,000 Rs 30,000 relying upon the force supply (i.e. tractor, diesel or power). Yearly using shifts from PKR 15,000. 40,000 tube wells in tractor driven, diesel driven using reaches from PKR 2500 to PKR 21000 and controlled power is in the reach of PKR 4000-20000. The normal time for every section of land differs from 2.5 hours, 2 hours and 2.5 hours on the tractor, diesel and power worked tube wells with a reach of 2-4 hours.

The costs charged rely on upon the pump sort, limit and area, as depicted above. Higher costs for fuel worked water wells reflect the high cost of working this kind of pump. The normal cost of water under the compensation framework is pretty nearly the same for diesel and electric wells, despite the fact that the previous are by and large more costly to work. The normal expense for every hour of water to the buyer of diesel tube wells is marginally higher under the framework purchaser - bring - fuel under the altered charge for every hour. Water merchants' diesel pumps are apparently just recouping its expenses of operation and upkeep under any kind of agreement. Transaction expenses of the merchant in the procurement of fuel and working or administering the operation of the pump are probably higher in hourly load contracts, yet there may be some hesitance to let purchasers work the pumps themselves under the purchaser framework - brings - fuel.

The capability of agriculturists to pay for water might be assessed from the individuals who rely on upon water markets groundwater. Private-wells gave just about 30 percent of the water, leaving the homestead throughout the year 1997-1998. In Punjab, something like 40 percent of the aggregate accessibility of water through tube wells (Government of Pakistan, 2002) Today, the normal offering cost of water from a tube well is about 120 PKR for every hour for introducing a limit of one cubic foot for every second, which is proportionate to more or less one section of land - inch of water for every hour (100 m3/hr). This charge is more than twofold what a rancher depending quite on the trench water pay for the same volume of water for the same products.

## 19.7.3 Problems in Groundwater Markets

Groundwater markets are indigenous establishments generally independent to remain useful without a great deal of government intercession. These plainly assume a significant part in stretching access to groundwater assets discriminating part in Pakistan. Since access to such ground water is free in light of the fact that there is no confinement on the withdrawal of ground water markets and water have additionally expanded the control of ranchers on watering system. In spite of the preference of water markets, there are a few issues, which are in the improvement of groundwater markets.

The primary impediment to market improvement of groundwater is renewable groundwater that forces restriction on the amount of wells that could be introduced and worked in a practical way. Punjab overall surpasses energize pumping in excess of 25 percent. This implies that the supply of a tube well for all ranches is not a reasonable long haul result.

The level of water control gave buys of ground water is not as incredible as that of the tube well holders. Managers of tube wells treated water deals as a remaining classification to help their fields. The offers of groundwater when all is said in done are not an exchanging organization in which dealers have an enthusiasm toward helping their customer base. Accordingly, water purchasers can't hope to get more water they require and when they require it. Consequently, the tube well water is purchased, not as profitable as the water from their wells.

Watercourses lined pipes and guarantee that buyers accept more water from the water from the well-paying tube and offering allows a more extensive field of each one tube potential number. So, transport structures lined run together with the improvement of more aggressive markets groundwater. Regardless of these points of interest in groundwater markets, there has been minimal private financing in the covering or tubes in Pakistan. By and large, the channels are adjusted field just in the initial 20 meters of tube well, which is basically used to assimilate the vitality of water from tube wells being pumped into the channel.

The conduits of agriculturists to utilize water from a tube well regardless of the procurement of the Act seepage channel and that whole make the rate of water utilization are assessed for the waterway watering system. Nespak (1991) study proposes that this law limits the offer of tubewell water. The Canal and Drainage Act further confines the transport of water through tubewells to agriculturists by precluding the transport of water through open water courses.

## 19.7.4 Seller and Buyer Preferences

### 19.7.4.1 Sellers' Preferences

Research shows that there are a number of preferences which sellers of ground water keep in mind while selling water. These include:

- Relatives and friends,
- Timely payments,

- Religious sects,
- Bradrism (caste-centered), and
- Anyone who could pay the price.

#### 19.7.4.2 Buyers Preferences of Purchasing Water

There are different types of preferences indicated by purchasers. The following are the important factors which affect the decisions of the buyer for irrigation water:

- Relatives and friends,
- Quality of irrigation water,
- Location of tube well relative to irrigation requirements,
- Price of water,
- Availability of water at the time of need,
- Provision of tube well on fuel basis,
- Provision for making payment at harvest, and
- Other reasons like religion and Bradari.

## 19.8 Economic and Financial Analyses of Irrigation Projects

An economic analysis is defined as ‘‘a systematic approach to determine the optimum use of scarce resources, involving comparison of two or more alternatives in achieving a specific objective under the given assumptions and constraint”.

The financial analysis only takes the point of view of stakeholders on a project, like investors, be those the government, farmers, NGOs, etc. But economic analysis also incorporates the societal perspective in the analysis and seek weather the project will benefit the whole society. Economic analysis has the objective to maximize benefits at the national level instead of profit maximization of primary stakeholders.

### 19.8.1 Fixed Costs

Fixed Costs are those costs, which in total do not vary with changes in the level of output. It has to be paid even when the firm (or farmer) stops working i.e. when the output is zero. For example, land rent, interest rate on money borrowed from the bank, permanent hired labor etc.

### 19.8.2 Variable Costs

Variable Costs are those costs, which change with the level of output. The increase in variable costs is associated with each one unit increase in output.

**Total Cost:** Fixed and variable costs can be summed at each level of output.

$$TC = TFC + TVC \quad (4)$$

Where;

TC = Total cost

TFC = Total fixed costs

TVC = Total variable costs

### 19.8.3 Gross Margins

This is an important economic concept which may be defined as:

Gross Margin= Total Revenue – Total Variable Cost

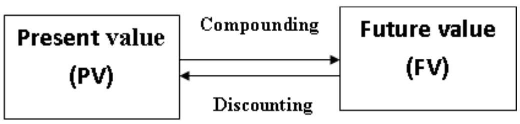
It may be noted that cost has two components, variable cost and fixed cost. In calculating gross margins only variable costs are subtracted from the total revenue. Positive gross margins sometimes indicate that investment/intervention is worthwhile. But this is not a perfect measure to decide on whether to implement the project or not because there may be several other benefits and costs associated with a project. Nevertheless, gross margins provide a rough idea of the usefulness of the project.

### 19.8.4 Marginal Cost

Marginal cost is an economic concept is profit maximization and cost theory. Marginal cost – also called the incremental cost – is defined as the additional amount of money incurred to produce one extra unit of output. In case of groundwater, the marginal cost of using water may be defined as extra dollars spent on using an extra cubic meter of water. For canal water usage, marginal cost may be defined as extra amount of money spent to deliver one cubic meter of water to the field.

### 19.8.5 Net Benefits and Costs

Net benefits are defined as total benefits minus total costs when both are measured in monetary terms. This is a concept used in cost-benefit analysis. For irrigation projects, the net benefits may be calculated by summing all the expected benefits and costs of a proposed irrigation project (in monetary values) and then subtracting the latter from the former. A positive net benefit Fig. may be an indication of an economically feasible project but this measure should be used with care when comparing different projects.




$$\text{Discount Factor} = \frac{1}{(1+r)^n} \qquad (5)$$

$$PV = FV\times \frac{1}{(1+r)^n} \qquad (6)$$

$$FV = PV(1+r)^n \qquad (7)$$

Where:

FV = Future value (total amount payable)

PV = Initial amount borrowed (present value)

r = Interest rate

n = Number of years

### 19.8.6 Costs-Benefit Analysis

Cost-Benefits Analysis (CBA) or Benefit-Cost Analysis (BCA) is used in economic analysis. It makes use of comparing the costs and benefits of a project as the basis of decision before initiating the project.

Cost-Benefits Analysis has two purposes:

- To determine the soundness of an investment
- To compare different competing projects for the choice of the best one

In CBA, expected costs and benefits are usually discounted to assess their present values. This is done using a discount rate. So, CBA actually compares discounted benefits and costs. Therefore, in the CBA, the benefits and costs are brought on the same temporal footing.CBA attempts to measure the benefits and costs of a project which may accrue to users of project, non-users of a project, the externality effects, and social benefits costs.

### 19.8.7 Benefit -Cost Ratio (BCR)

The benefit cost ratio is defined as “the present value of the estimated benefits divided by the present value of estimated costs”.

$$BCR = \sum_{i=1}^{n} Bi/\,(1+r)^{i} \qquad (8)$$

When using BCR, the decision rule is:

- If BCR > 1, then accept the policy or the project.
- If BCR<1 then reject the policy or the project.
- If there are different policies or projects, select the one with the highest BCR value.

### 19.8.8 Net Present Value (NPV)

Net present value is defined as the “present values of estimated benefits minus present value of cost”. Mathematically it can be expressed as:

$$NPV = \sum_{i=1}^{n} \frac{(Bi-Ci)}{(1+r)^{i}} \qquad (9)$$

Where;

NPV = Net Present Value

Bi = stream of benefits

Ci = stream of costs

When using NPV, the decision rule is

- If NPV> 1, then accept the policy or project.
- If there are different policies or projects, select that one with the highest NPV.

### 19.8.9 Internal Rate of Return (IRR)

A good way of using the incremental net benefit stream or incremental cash flow for measuring the worth of a project, is to find that discount rate, which makes the net present value of the incremental net benefit stream or incremental cash flow zero. This discount rate is called the Internal Rate of Return (IRR) and is obtained through an iterative process. It is the average earning power of the resources used in the project over its lifetime. Following are the two types of IRR, which are used to evaluate development projects.

Financial Internal Rate of Return (FIRR)

Economic Internal Rate of Return (EIRR)

$$IRR = LDR + \frac{(HDR-LDR)\times NPVatLDR}{(NPVatLDR-NPVatHDR)} \qquad \text{.............. (10)}$$

Where:

IRR = Internal Rate of Return

HDR = Higher Discount Rate

LDR = Lower Discount Rate

NPV = Net Present Value

IRR must be greater than the cost of borrowing for the project to be feasible.

### 19.8.10 Determination of economic values

To focus the monetary qualities from an undertaking's execution, the budgetary costs are utilized and balanced for different elements that twist the true worth to the general public. The principle components that are incorporated in these alterations are:

- The premium on foreign exchange
- Transfer payments
- Price distortions in traded items
- Price distortions in non-traded items
- Evaluation of land and labor

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# Glossary

**Acidification:** Treatment of Drip Irrigation system with acids such as sulfuric acid, phosphoric acid hydrochloric acid.

**Actual evapotranspirartion:** Rate of Evapotranspiration actually taking place under the real field conditions taking into account status of soil moisture as well as stage of crop and climatic conditions.

**Affinity laws:** Describe the impact of changes in speed and diameter of impeller on the pump flow.

**Alluvial soil:** Fine Grained fertile soil deposited, developed and shaped by the flowing water, is recognized as alluvial soil.

**Analytical model:** Refers to an equation that expresses the changes of a physical system in terms of mathematical function.

**Appropriation doctrine:** System of allocating water rights from a water source that is markedly different from riparian water rights.

**Aquifer:** It is saturated and permeable geologic formation that can store enough water and can yield economical quantities of water through pumping wells.

**Base period:** The duration, starting from the $1^{st}$ irrigation to the last irrigation applied to a cropped field.

**Bed planting:** Planting of crops on raised beds.

**Chlorination:** Treatment with chlorine gas or liquid sodium hypo chloride.

**Coefficient of roughness:** Represents the integrated effect of waterway cross sectional resistance as the irregularity of channel bed influences the velocity of flow.

**Critical velocity:** Flow velocity of a stream, which is neither silting nor scoring during the flow process.

**Critical velocity ratio:** Ratio of the mean velocity to the critical velocity of flow.

**Crop period:** Period from sowing till harvesting of a crop.

**Crop water use efficiency:** Ratio of crop yield to the water depleted by the crop through evapotranspiration.

**Delta of water:** Amount of water required for growing a crop during its growth period.

**Drip irrigation:** Slow application of available irrigation water on or below the soil surface depending on the field capacity and intake rate of soil.

**Duty of water:** Area to be irrigated using unit amount of flow of water during entire growth period of a given crop.

**Effective rainfall:** Component of rainfall utilized for a given beneficial purpose. For example, for agricultural crop, the portion used in evapotranspiration (meeting part of crop water requirement) is effective rainfall.

**Electrical conductivity:** Ability of water to pass the electric current, which depends on the concentration of dissolved salts.

**Field capacity:** Amount of water held in a soil after excess gravitational water has been drained away.

**Permanent wilting point**: Soil moisture beyond which the plants cannot extract water from soil.

**Fixed cost:** Cost which does not vary with changes in the level of output e.g. land rent, interest rate or money borrowed from a bank.

**Flow measurement:** Determination of quantity of fluid flowing per unit of time across any section of the channel and is usually expressed as volume of fluid per unit time.

**Flume:** A device that provides flow control through a constriction in flow geometry, in vertical or horizontal direction, and is used to measure discharge or flow rate in an open channel.

**Full supply level:** Water level in the channel at design discharge.

**Geographical information system (GIS):** Technology used for spatial mapping of objects that integrate space science, survey and mapping.

**High efficiency irrigation system:** Refers to irrigation systems, which result in higher efficiency of water use, usually applied under pressure, such as Drip or sprinkler irrigation system.

**Hydraulic conductivity:** It is coefficient of proportionality describing the rate of fluid flow through an isotropic porous medium per unit hydraulic gradient.

**Hydraulic depth:** Ratio of the flow area to the top width of a channel.

**Hydraulic radius:** Ratio of the cross-sectional area to the wetted parameter of flowing channel.

**Hydro cyclone filter:** These filters remove soil particles from irrigation water. Separates large and heavy particles from smaller and lighter particles through the forces of gravity and centrifuge.

**Hydrological cycle:** Describes the circulation of water in nature starting with evaporation from open surfaces, returning to the earth as precipitation and further entering subsoil and finally coming back to the oceans.

**Institutional reforms:** Reforms focused at improving the management and maintenance of the irrigation system for ensuring its long term physical and financial sustainability.

**Interceptor drain:** A drain situated between water source and are protected from water to intercept seepage or drainage water.

**Inundation canal:** A canal where no weir control system such as a barrage or a head work exists and water supply depends on the periodical rise of water level in the river from which it takes off.

**Irrigation management:** Organization and coordination of activities of an irrigation system in accordance with certain policies and objectives defined by the organization.

**Irrigation scheduling:** Schedule of applying irrigation water to the crop, based on soil, crop variety and its stage. It ensures timely application of right amount of irrigation water.

**Land capability classification:** Classification of land based on its suitability for agricultural and other useful purposes.

**Land development :** Altering the land surface from natural state to relatively smoother topography suitable for agricultural production or housing development.

**Land management:** Process of managing land resource and using it for irrigated agriculture and other useful purposes.

**Leaching requirement:** Amount of excess irrigation water, applied to the field to reduce the concentration of salts in the root zone.

**Laser land leveling:** Process of loosening the soil and moving it to achieve a level surface for uniform application of irrigation water.

**Mathematical model:** A model refers to mathematical representation of a physical system.

**Model calibration:** Involves replacement of the values of input parameters, within a reasonable range, to match the hydraulic state of a given system such as aquifer and water uptake by roots.

**Mole drain:** An unlined underground drainage water channel, which is formed by pulling a solid object such as a cylinder or wedge shaped through the soil at proper slope and depth without a trench.

**Mulching:** A farming practice under which soil surface is covered with organic material or crop residues so that the soil moisture is conserved by minimizing evaporation losses and enhancing infiltration process.

**Numerical model:** These models refer to the mathematical models that involve numerical time stepping procedure.

**Non perennial canal:** A canal, which operates only a part of the year, usually during summer season and at the beginning and end of the winter season.

**Permanentcanal**: Canal which is fed by a permanent source of water such as ice fed river or a reservoir.

**Perennial canal :** A canal, which gets continuous supply of water from a given river through out the year.

**Perched aquifer:** An Aquifer, where an impervious layer exists between the actual watertable and ground surface. It occurs where water is obstructed by an impervious layer in the aquifer above the actual watertable.

**pH of water:** Concentration of hydrogen ions and hydroxyl ions in water.

**Piezometer:** Non pumping well (or a hole in the aquifer) generally of a small diameter that is used to measure elevation of watertable at the point it opens at the bottom.

**Porosity:** Ratio of volume of pores to the total bulk (including solids and pore space) of soil.

**Provincial irrigation and drainage authority:** An autonomous body with mendate to establish, manage and monitor the elected bodies of farmers and promote the farmers' participation in the operation and maintenance of irrigation system.

**Pump**: A power source that imparts energy to the fluid.

**Pump characteristic curves:** Curves relating to the operating characteristics of an individual pump independent system of head requirements.

**Rain water harvesting:** Technique used for collecting, storing and using rain water for useful purposes.

**Reference evapotranspiration:** Rate of water loss in the form of evapotranspiration from a uniform grass, 8-15 cm tall, shading the ground, not suffering from any disease, actively growing and not short of moisture.

**Remote sensing :** Science and Art of spectral, spatial and temporal information about physical objects or area without coming into physical contact with it.

**Regime channel:** An unlined channel in which neither silting nor scoring take place during flow.

**Resource conservation:** Measures to conserve and make the resources such as land and water available for crop production efficiently minimizing the losses.

**Riparian:** Area belonging or relating to the bank of a river. A riparian retains his right to the water of the river regardless of whether or not the use is made of water for irrigation or other purposes.

**Residual sodium carbonate:** It is a measure of sodium contents in relation to calcium and magnesium.

**Right-of-way:** Land officially allocated for conveyance of irrigation water through a channel. It is applicable to every person owning a water right.

**Sand media filter:** These filters use graded sand inside a cylindrical tank to filter out heavy loads of fine sand and organic materials.

**Screen filter:** These filters contain cylindrical screens that provide safe guard against impurities left unfiltered from hydro cyclone and sand media filters.

**Sprinkler irrigation:** Spraying of irrigation water under pressure in the air, which can fall on the ground surface or crop resembling rainfall.

**Skimming well technology:** A technology in which the top layer of fresh groundwater (with lower salinity) is pumped through a well.

**Soil moisture characteristic curve:** Also known as Soil Moisture Retention Curve, which defines the relationship between soil moisture tension and moisture availability to plants.

**Soil structure:** Arrangement of soil particles in each mass of soil.

**Soil texture:** Refers to the relative proportions of various particle (sand, silt and clay) in a soil.

**Soil water potential:** Amount of work done per unit quantity of pure water to move a quantity of water from reference point to the point under consideration.

**Stream gauging:** Recording of flow depth in a channel through a vertical scale at a given section.

**Submergence:** Ratio of the downstream depth to the upstream depth of water at a control section of the flow measuring device such as a flume.

**System head requirement:** Total Head or Energy that must be developed by a pump to meet the head requirement of the system where installed.

**Telemetry system:** Electronic system of flow measurement through sensors.

**Total dissolved salts:** Sum of cations and anions, which indicate the salinity behavior of water.

**Venturimeter:** It is a device that causes reduction in fluid pressure through a constriction in the flow section of the pipe resulting in the increase of fluid velocity.

**Variable cost:** Cost, which changes with the level of output.

**Vertical drainage:** A well, pipe, bore or pit in porous underground strata in which drainage water can be discharged without contamination in groundwater resource. Drainage by a tubewell or recharge well are examples of vertical drainage.

**Warabandi:** A rotational way of equitable distribution of irrigation water at the watercourse command according to a predetermined schedule.

**Water conservation:** Practices, which can increase productive use of water while promoting its efficiency and sustainability for future.

**Water distribution efficiency:** Indicates uniformity in the distribution of water over the entire root zone of crop. It is defined as average infiltrated depth in the low quarter of the field divided by the average infiltrated depth over the whole field.

**Water productivity:** It is an index that expresses a ratio between yield and amount of water used to produce crop.

**Water use efficiency:** Ratio of the amount of irrigation water actally used by a crop to the volume of delivered from the source.

**Water market:** Trading of water formally or informally between individuals or companies at particular price.

**Weir:** A structure or a device that is installed in a channel to measure flow rate by observing head or depth of water over the structure.

**Zero tillage:** A type of farming and plowing practicefor which the field is not plowed and the crop seeds are planted with no till planting machines.

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