Report No. R-104

A SPATIO-TEMPORAL ANALYSIS OF RAINFALL IN THE CANAL COMMAND AREAS OF THE INDUS PLAINS

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IWMI International Water Management Institute

"."And it is He Who sends the winds as heralds of glad tidings, going before His Mercy (rain). Till when they have carried a heavy-laden cloud, We drive it to a land that is dead, then We cause water (rain) to descend thereon. Then We produce every kind of fruit therewith

(Surah Al-A'râf, Al-Qur'an)

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ABBREVIATIONS

ACZ	Agro Climatic Zone
bcm	Billion Cubic Meters
BER	Basic Effective Rainfall
DMA	Double Mass Analysis
ETP	Evapotranspiration
FAO	Food and Agriculture Organization
GTZ	German Technical Cooperation
IBIS	Indus Basin Irrigation System
IBM (Revised)	Indus Basin Model (Revised)
IIMI	International Irrigation Management Institute
IWMI (IIMI's new name)	International Water Management Institute
Km	Kilometer
m	Meter
mm	Millimeter
NESPAK	National Engineering Services of Pakistan
NWFP	North West Frontier Province
O&M	Operation & Maintenance
PGC	Punjab Groundwater Consultants
PID	Provincial Irrigation Department
PMD	Pakistan Meteorological Department
PWD	Public Works Department
RAP	Revised Action Programme
RS/GIS	Remote Sensing/Geographical Information Systems
SWBM	Surface Water Balance Model
WAPDA	Water And Power Development Authority
WMO	World Meteorological Organization
WRMD	Water Resources Management Directorate
WSIPS	Water Sector Investment Planning Study
USBR	United States Bureau of Reclamation
USDA-SCS	United States Department of Agriculture – Soil Conservation Service

FOREWORD

IWMI consider this report as a timely input to the debate on capturing monsoon floods within the Indus Basin for productive use. Arithmetically, a third of the Indus River flows, goes to the sea. But, how much of it could be captured within the plains for agricultural and environmental purposes? The debate goes on!

The report complements an earlier report by Asim Khan titled 'An analysis of the surface water resources and water delivery patterns in the Indus Basin'. This report analyses the spatial and temporal variation of rainfall across the Indus Basin, and estimate net (effective) rainfall available in the canal commands of the Indus Basin Irrigation System. It also highlights the importance of probability analysis in considering rainfall as a reliable source for irrigation.

IWMI hope that the analysis presented in the report will contribute positively to the debate.

This study forms a part of IWMI's initiative to study water resources at selected reference basins. Asim Rauf Khan and Saim Muhammad are congratulated for producing this report.

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Lastly, we extend our thanks to Dr. S. A. Prathapar, Director IWMI-Pak, who has always been very supportive of this work. It was his persistent buoying-up that we have finally managed to complete this report.

ABSTRACT

The annual precipitation ranges between 100 mm and to over 750 mm in the Indus Plains. Most of the rainfall (almost two-thirds) is concentrated in the three summer months of July–September. There are two major sources of rainfall in Pakistan, the Monsoon Winds and the Western Disturbances. The Monsoons originate in the Bay of Bengal and usually reach Pakistan, after passing over India, in early July and their activities continue till September. The Indus Plains receive most of their rainfall from the Monsoons. The entire Indus Plains may be divided into eight distinct zones with respect to rainfall.

The areal rainfall gives a more representative picture rather than point rainfall assumed to be representative of rainfall over an entire canal command area. Furthermore, instead of using long-term averages, as has been the practice in the Indus Basin, it is more appropriate to use rainfall figures expressed with a certain level of probability.

It is only the canal commands in the upper most part of the Upper Indus Plain (Punjab) where rainfall seems to be making a somewhat significant contribution towards the total irrigation supplies to crops along with canal and subsurface water. This contribution is noteworthy only during the Kharif season. There are only seven Canal Commands, out of a total of forty-two in the whole of the Indus Plains, that fall within the zones of moderate to high rainfall (greater than 350 mm). .

As we move from north to the south, in the plains, the variability increases as the mean annual rainfall decreases. The region of maximum rainfall variability is around Jacobabad and Sukkur. All of the main canal commands of Guddu Barrage and some of the Sukkur Barrage fall within this region. Therefore, these Canal Commands need protection not only from droughts but also from potential damages that may result from excessive rains.

A comparison of four methods suggests that the USBR method would provide good enough estimates of effective rainfall at the Canal Command level. It requires only rainfall data and involves very simple computation procedure. The other three methods used in the comparison were the IBM (R) method, the ETP –Precipitation Ratio method and the Renfro Equation.

The temporal imbalances in rainfall occurrences have a great impact on the effectiveness of rainfall. Rainfall during July that is the month with maximum amount of rainfall is reduced to the lowest degree of effectiveness. In such cases, it would be more appropriate to use the monthly time-step and estimate the areal rainfall using the procedure described earlier.

The time series analysis of rainfall data for Mianwali, Faisalabad, and Bahawalnagar in Upper Indus Plain (Punjab) suggests that hydrometeorological time series from different climate stations within the Indus Plains need to be studied in detail in a climate change perspective.

Chapter 1

1 INTRODUCTION

1.1 THE INDUS PLAINS

The Indus Plains in Pakistan contain the world's largest contiguous irrigation network. These Plains form major part of the Province of Punjab and the whole of the Sindh Province (Figures 1.1 and 1.2). The Indus Plains have been formed by the alluvium laid by the Indus River and several of its tributaries. The general slope of the plains towards the sea is gentle, with an average gradient of one meter to five kilometers (Kureshy 1995). In the Upper Indus Plain, constituting central and southern parts of Punjab Province, the major tributaries of the Indus River namely, Jhelum, Chenab, Ravi and Sutlej divide the land surface into several interfluves or Doabs (Doab: Land between two rivers). In the lower Indus Plain, that constitutes the Sindh Province, there is one large river, the Indus itself. The lower Indus Plain is very flat with an average gradient of only one-meter in ten kilometers.

The climate varies from subtropical arid and semi-arid to temperate sub-humid in the plains of Sindh and Punjab provinces. Annual precipitation ranges between 100 mm and 750 mm. The Indus Plains receive most of their rainfall (more than two-thirds) during the period July–September from the Monsoons. The winds from the west bring all the winter precipitation. October and November receive the least amount of rainfall during winters whereas April, May and June are the driest months of the summer season.

1.2 OBJECTIVES OF THIS REPORT

The objectives of this report are to:

- Look into the spatial and temporal variation of rainfall across the Indus Plains.
- Study some of the characteristics of rainfall in the plains through a time-series analysis.
- Estimate the total and net (effective) rainwater availability in the canal commands of the Indus Plains.
- Update and improve upon the existing information/databases regarding rainfall available at the canal command level.

1.3 NEED FOR THE STUDY

The surface and ground water components, due to their relatively large proportions, seem to overshadow the role of rainfall in the total water consumption for irrigation. Although the Provincial Irrigation Departments (PIDs) are required to maintain a record of the climatological conditions in all the canal commands, proper procedures are not followed (PWD 1961). As a result, reliable information regarding the amount of rainfall at the canal command level is not available. Some major studies relating to water sector development, however, do provide information regarding rainfall received by the canal commands of the Indus Basin. In one of such studies conducted in 1979 the annual effective rainfall volume for all the canal commands has been estimated to be 9.3 bcm (RAP 1979). Another source gives a figure of 30 bcm for total rainfall volume (16 bcm effective rainfall) in the Indus Plains (CEAO 1993). In another basin level study conducted in 1990 the effective rainfall canal command-wise has been estimated using the Massland Method (WSIPS 1990) for canal commands in Punjab, while that for the Sindh canals, has been estimated using the methods adopted by the Lower Indus Project studies (1966). The results, with reference to rainfall estimation in the Indus Basin canal commands, in case of all these studies, were either based on rainfall data for one particular year or on long term averages.

It was felt necessary to estimate the availability of rainfall at the canal command level and improve upon the information/database that was already available using modern GIS techniques. Furthermore, the results of this study would provide an important input to any research or planning activity aimed at:

(i). Estimating spatial variability of water stress by comparing the net water availability and demand.

(ii). Evaluating equity and reliability at the canal command level, in context of net water availability and current water allocation and regulation procedures.

Figure 1.1 The Indus River System and the Indus Plains (Central & Southern Punjab, Sindh).

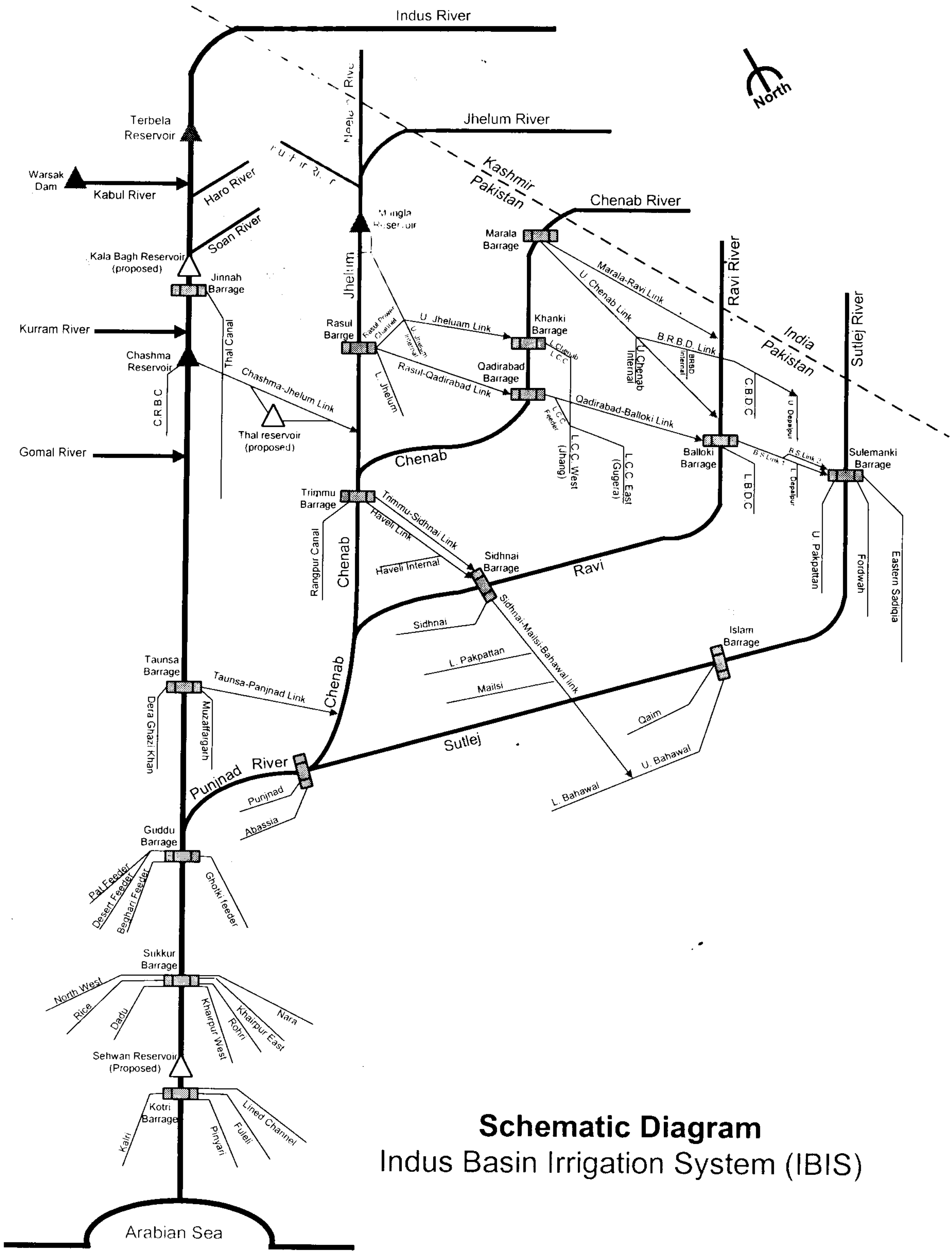

Figure 1.2. The Indus Basin Irrigation System (IBIS), Schematic Diagram.

Chapter 2

2 RAINFALL AND CANAL-IRRIGATED AGRICULTURE IN PAKISTAN

2.1 RAINFALL IN PAKISTAN

The rainfall in Pakistan is markedly variable in magnitude in time of occurrence and in its areal distribution (Figure 2.1). However, most of the rainfall (almost two-thirds) is concentrated in the three summer months of July–September. The mean annual precipitation ranges from less than 100 mm in parts of the Lower Indus Plain to over 750 mm in the Upper Indus Plain near the foothills. There are two major sources of rainfall in Pakistan, the Monsoon Winds and the Western Disturbances. The Monsoons originate in the Bay of Bengal and usually reach Pakistan, after passing over India, in early July and their activities continue till September. The Indus Plains receive most of their rainfall from the Monsoons.

The Western Disturbances coming from the Mediterranean enter Pakistan after passing over Iran and Afghanistan and are responsible for most of the winter precipitation in Pakistan. Since most of the moisture is lost in their long journey over land, they bring small amounts of rainfall to Pakistan. The Western Disturbances begin in December and continue in full strength up to March. The northern highlands of the country receive most of the winter precipitation (mostly in the form of snow) from the Western Disturbances. The Upper Indus Plain receives 125–250 mm of rainfall while the Lower Indus Plain (Sindh Province) remains very dry during the winter season and gets less than 50 mm of rainfall during the winter season.

There are two periods of thunderstorms in Pakistan: (1) April-June (2) October-November. These periods are the driest parts of the year, particularly October and November. During these periods thunderstorms caused by convection bring sporadic and localized rainfall (Khan 1991).

2.1 IMPORTANCE OF RAINFALL FOR AGRICULTURE IN INDUS PLAINS

Agriculture in the Indus Plains is heavily dependent on irrigation supplies from rivers. The Indus Basin Irrigation System (IBIS) withdraws almost seventy-five percent of the mean annual river-inflow in the system. In addition to surface water diversions, groundwater pumpage is another contributor towards irrigation. The rainfall in the Indus Plains (over the canal command areas), when taken into consideration in water accounting procedures at the basin or the canal command level, has its impact in three ways:

(i). As direct rainfall available for crop-use (effective precipitation);
(ii). As recharge to groundwater from rainfall seeping into ground; and
(iii). As surface runoff to rivers.

Due to these reasons, rainfall has always been an important consideration in the designing of all the canal systems in the Indus Basin. Of all the climatological factors that are taken into account in the 10-daily operation/regulation procedures of the canal systems, rainfall is the most important one. It affects the canal withdrawals as well as groundwater pumpage in the canal commands. Rainfall can influence agricultural production in either way i.e., an adequate amount of rainfall can reduce the water stress if canal supplies are not sufficient and an extremely high amount of rainfall may damage the crops. The crop acreage particularly during the *Rabi* season (October-March) is influenced by the amount of rainfall in the preceding month (September) and during the sowing period in October-November (Kazi and Mubasher 1960).

An econometric analysis carried out (Habib et al 1999) for the years 1993-94 and 1994-95 showed that rainfall was an insignificant variable in the former (an year with low rainfall) and a significant one, but with a negative impact on production, in the latter year (an year with higher rainfall). This is an indication of the fact that rainfall is an important variable having multi-dimensional bearing on irrigation and agriculture. Therefore, it must be taken into consideration in any work relating to irrigation planning and management for enhancing the agricultural produce.

The concept of conjunctive water management is gaining more and more importance in the planning and management of water resources in the Indus Basin. Furthermore, the modern water paradigm, describes rainwater as the *green water* (surface water and subsurface water being *blue* and *brown* respectively) indicating its significance, particularly for agriculture, relative to the other sources of water. As such, it is becoming increasingly essential to look into the availability of this precious source of water within the Indus Plains.

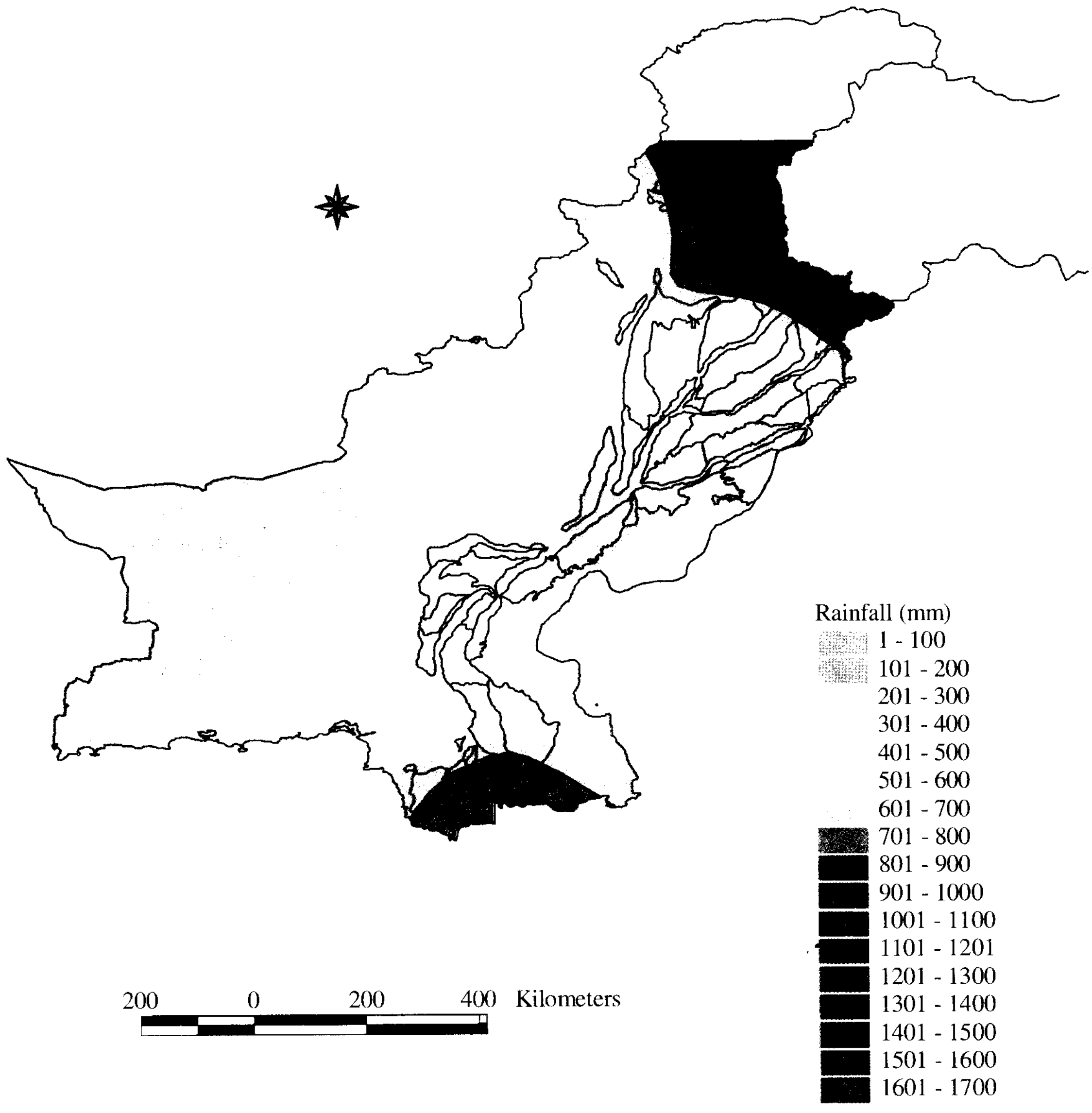

Figure 2.1. Annual Rainfall in Pakistan, the Canal Command Areas of the Indus Plains and NWFP and the Balochistan Plateau, 1994-95.

Chapter 3

3 FRAMEWORK OF ANALYSIS

3.1 RAINFALL DATA AND RELATED INFORMATION

In this study, monthly rainfall data from twenty-six weather stations has been used. All these weather stations are operated and maintained by the Pakistan Meteorological Department (PMD). The stations were so selected that they cover the whole of the Indus Plains (Figure 3.1). The objective was that the network of rain-gauge stations, for which the monthly rainfall data was to be analyzed, provides a representative picture of the areal distribution of precipitation over the canal command areas of the plains. Monthly rainfall data for a 35-year (1960-95) was used in the analysis.

3.1.1 Rain-Gauging Network

The climate stations of the Pakistan Meteorological Department (PMD) are spread all over the country and especially along the aviation routes. The rain gauges installed at these climate stations consist of both the recording and non-recording types of gauges. The rainfall data from these rain gauges is processed at the PMD offices at Lahore and Karachi. A statistical analysis of point rainfall (for all rain-gauge stations) was performed to determine the spatial representativeness of the gauging network. It must, however, be noted that the twenty-six rain-gauging stations constituting this network were the maximum number of stations for which reliable and complete monthly rainfall data (i.e., collected and processed by the PMD) for a 35-year period was available (Figure 3.1).

The total number of rain-gauge stations within and outside the Indus Plains is certainly much greater. According to an inventory of hydrometeorological stations made by the German Technical Cooperation (GTZ) and WAPDA, there are over 1000 precipitation measurement stations spread all over Pakistan. Most of these stations are operated and maintained by PMD, WAPDA and the PIDs. It is, however, not known whether all of these stations are functioning and records of rainfall data being properly maintained. Furthermore, in many cases there are more than one rain-gauge stations at one particular location each operated and maintained by a different public agency. The Pakistan Meteorological Department and WAPDA spend a good deal of effort in the O&M of their respective climate stations and publish the hydrometeorological data in the form of annual reports. The PMD also maintain a web site on the Internet. This was the prime reason for selecting the rain-gauging stations maintained by PMD/WAPDA.

3.1.2 Canal Command Map

The Indus Plains contain 42 canal commands of the Punjab and Sindh provinces. The canal command map used in the analysis was acquired from WAPDA (Figure 3.1). The map was digitized and geo-referenced by the RS/GIS Group of IWMI Pakistan. This map was then used in the estimation of areal rainfall for all the canal commands in the Indus Plains. In this canal command map the command areas of Upper Bahawal and Qaim canals off taking from Islam Barrage (Figure 1.2), on account of their relatively smaller sizes, have been lumped together. On the other hand, one canal command in the Lower Indus Plain has been divided in two portions. This is the Lined Canal sub divided into Lined Canal Tando Bago and Gaja Branch.

3.2 DATA SCREENING

In the words of an expert in the field of hydrology (J. Rodda), "... there is (as yet) no method of measuring the quantity of rainfall at a particular point to a known degree of accuracy". After studying the capture of rainfall by different types of gauge environment he defines true rainfall as "... the amount of rain which would have reached the ground if the gauge had not been there". While discussing sources of error of point rainfall measurements, Baumgartner and Reichel state that "... reliable (rainfall) data scarcely exists". No matter how well planned and well maintained the pluviometry is within a certain area, gauge measurements are subject to a number of sources of error. Some of these are: heavy rainfall splashing out of the gauge, evaporation of rainfall or condensation of moist air, under-catch of a particular rainfall event due to high winds, gauge condition and recording interruptions etc. Therefore, it becomes imperative to screen the rainfall data for quality and consistency prior to carrying out a complete analysis.

Fortunately, the data sets used in this study did not contain missing data for longer periods of time. There were five rain-gauge stations for which data for a 2–3 years period was missing. One reason being that a couple of these climatic stations were set up after 1960. The missing rainfall data was estimated using standard procedures as suggested by the United States Environmental Data Service. The data from two of the climatic stations was discarded since it contained long periods (10–15 years) of missing records within the selected time span of 35 years ranging from 1960-61 to 1994-95. The annual rainfall data was checked for absence of stationarity, consistency and homogeneity. Data that did show some anomaly was further checked to determine its cause.

Figure 3.1 Location of Rain-gauge Stations and the Canal Command Boundaries.

3.3 STATISTICAL ANALYSIS

The statistical properties of the monthly rainfall data for the 35-year period were looked-into for the following purposes:

(i). Checking the adequacy of the rain-gauging network.
(ii). Data screening and quality checking.
(iii). To look into the temporal and spatial variability of rain.
(iv). To study the trends and periodicities in rainfall across the Indus Plains.

A time series analysis was performed for point rainfall with respect to each of the 26 rain-gauge stations. The statistical parameters of the rainfall data that were studied included mean and confidence limits on mean, standard deviation, variability, stability of mean and variance, and cross correlation. Furthermore, the point rainfall data for each station was tested to determine whether it could be adequately modeled by a particular frequency distribution. In addition to the point rainfall analysis, the characteristics of the areal rainfall were also looked into at the canal command level.

3.4 ESTIMATION OF AREAL RAINFALL

The areal rainfall was estimated using the Isohyetal Method. Isohyetal maps showing contours of equal precipitation were drawn and the interpolation of isohyets between stations was done using the *Kriging* method of geostatistics. The application of the *Kriging* method accounts for the spatial structure of rainfall over a region and has been proved to be beneficial for hydrologic balance studies and applications in water resources development (Papamichail and Metaxa 1995, Delhomme 1978, Lenton 1974).

The isohyetal maps thus prepared were then superimposed over the canal command map to obtain the rainfall depth (in millimeters) as well as the rainfall volume (in billion cubic meters) for each of the canal command. In this whole exercise of preparing isohyetal maps from rainfall data and their superimposition over the canal command map, GIS techniques/software (Surfer, Arcinfo and Arcview) were used. The rainfall data used, as described earlier, were monthly totals because when daily rainfall is aggregated over monthly values, correlations are higher. Thus, the monthly level of time aggregation provides a better spatial correlation structure and is considered to be suitable for meaningful interpolation of rainfall data.

3.5 ESTIMATION EFFECTIVE RAINFALL

The concept of effective rainfall has been discussed in chapter 5 of this report. An account of the past studies relating to the estimation of effective rainfall in the Indus System canal commands has also been presented. Different methods were studied and a method suitable to the Indus System canal command areas has been suggested for estimating effective rainfall keeping in view the limitations regarding availability of data. A major consideration in this regard was that the method must be based on simple logic and should not involve complex computational procedures and consequently large data requirements (inputs).

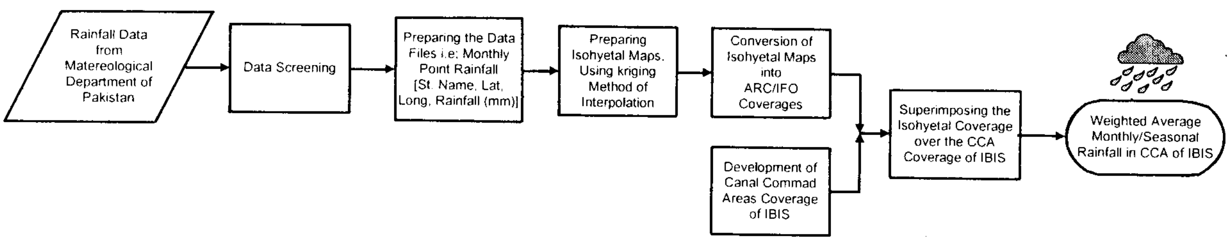

Figure 3.2. The Methodology for the Estimation of Areal Rainfall in the Canal Commands of IBIS.

Chapter 4

4 STATISTICAL ANALYSIS OF POINT RAINFALL

4.1 SPATIAL REPRESENTATIVENESS OF THE GAUGING NETWORK

The density of rain gauges varies greatly from country to country. There are different standards in different countries for the minimum number of rain gauges with respect to topography and variability of rainfall within a certain area. It is not always possible to establish and maintain an 'optimally designed' gauging network because of economic constraints and management problems. Denser networks are certainly preferable since errors in rainfall measurement tend to increase with increasing mean annual precipitation and to decrease with increasing network density, duration of precipitation, and size of area (Linsley 1958). However, the primary objective of setting up a rain gauge network is to obtain from it, rainfall data that gives a representative picture of the areal distribution of precipitation.

An optimal network should provide for at least one rain-gauge station for each homogeneous zone of topographic viewpoint (Jedidi et al 1999). The rainfall, as described earlier, decreases as we move from north to south in the Indus Plains. There are distinct zones with respect to climate and rainfall in particular. The climate varies as semi arid in the north to arid in the middle and sub-tropical in the southern most part of the Indus Plains. Keeping in view the spatial variability of rainfall, a total number of approximately 50 rain gauge stations (presumably in operation) were identified which were considered to be providing reasonably good coverage to the canal command areas in the Indus Plains (Figure 4.1). Out of these 50, there were only 26 climatic stations, all belonging to PMD, for which complete (for a 35-year period) and reliable rainfall data was available. A list of these 50 rain gauge stations has been given in Annex 1.

To ascertain the spatial representativeness of this network comprising 26 rain gauge stations, some statistical properties of the rainfall data recorded at these stations were studied. These properties included mean, standard deviation, variability and lag-zero cross correlation between various stations. Based on these statistical properties of the rainfall data, the entire Indus Plain was divided into eight distinct zones (Figure 4.1 and Annex II). These zones were found to be in close similarity with Indus Basin Agro-Climatic Zones or the ACZs[1] as they are commonly called. The rain-gauge network of the selected (26) PMD stations was found to be adequately covering the canal command areas within the Indus Plains.

4.2 SCREENING OF POINT RAINFALL DATA

Initially, a rough screening of the rainfall data was done to visually detect gross errors and look for any gaps in the data. The Pakistan Meteorological Department (PMD) convention is to use the figure "-1" (or the term "Trace") for very little amount of rainfall (less than 0.5 mm) that can not be measured. For missing rainfall data, the figure "-100" is used. All the "-1" values for monthly rainfall data were replaced by zero. Similarly, the missing data ("-100") and all other gaps in the data were estimated by using standard methods as suggested by the United States Environmental Data Service. The graphical plots of rainfall data for all the rain gauge stations also helped in detecting errors of data-entry through computers, for example misplaced decimal errors. Such errors were removed by checking the original data recording sheets and by comparisons with data from other gauging stations in the same hydrological zone.

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[1] The Indus Basin Model (IBM), which is an agro-economic optimization model used by WAPDA/World Bank, divides the Indus Basin canal command areas into nine different agro-climatic zones based on climate and the cropping patterns in those areas.

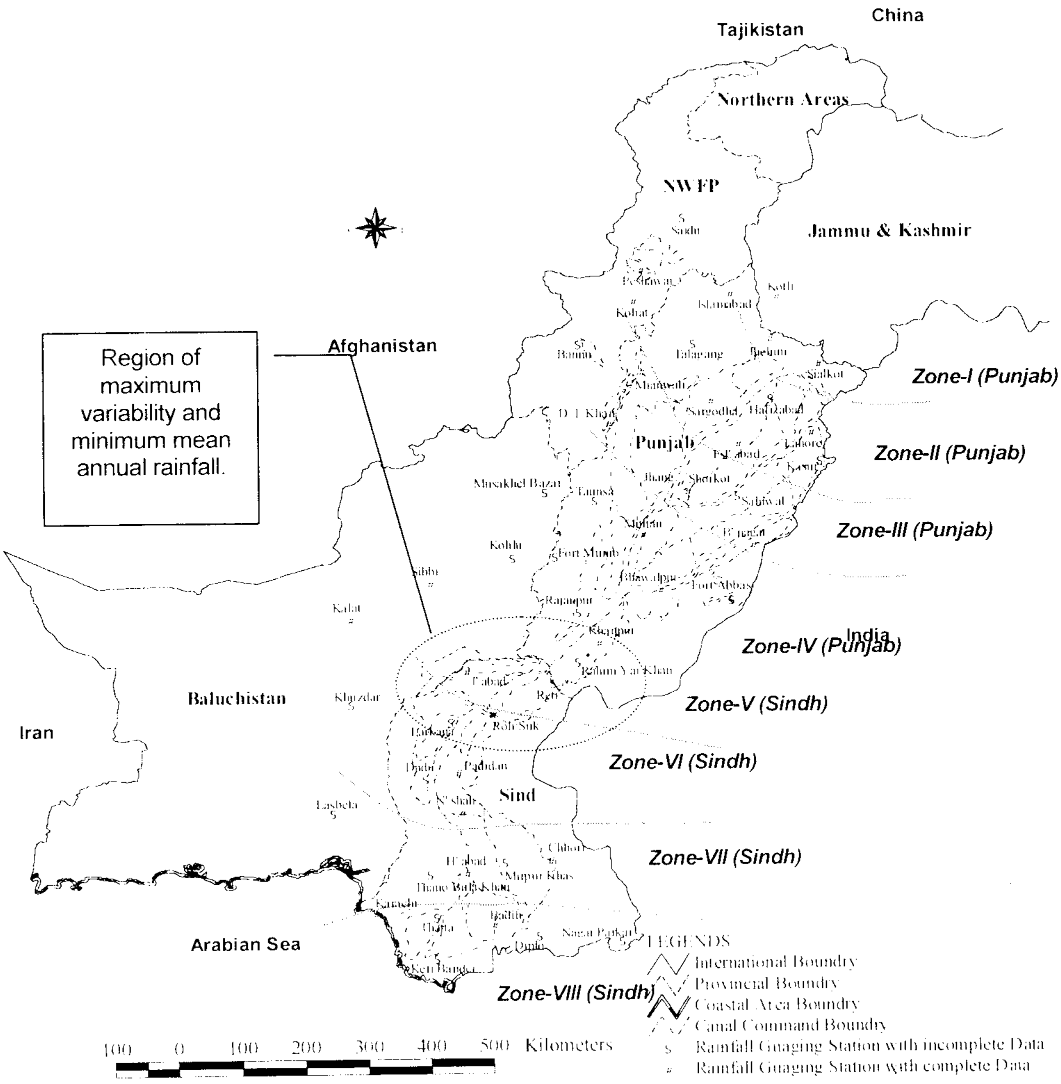


Figure 4.1. The Network of Rain-Gauges, Mostly Belonging to PMD, Covering the Canal Command Areas of the Entire Indus Plains and Peshawar Valley.

The annual rainfall series for all the twenty-six rain-gauging stations were checked for absence of stationarity, consistency and homogeneity (Dahmen and Hall, 1990). The anomalies in hydrological data may be due to observational or other errors in data recording or their causes might be due to some natural or human activity such as, change in land-use pattern, change in location of the rain-gauge, or a meteorological phenomenon. The data screening procedure suggested by Dahmen and Hall, and based on WMO guidelines, helps in detecting the occurrence and to some extent the cause of a certain anomaly in a time series. However, the acceptance or rejection of a data set must be based on concrete evidence regarding any physical and/or meteorological changes.

The procedure adopted for screening of the rainfall data from the twenty-six rain-gauging stations involved:

(i). Test for absence of trend using the Spearman's Rank-Correlation method and the test for stability of variance and mean using the F-Test and the t-Test respectively. The tests check the non-stationarity, inconsistency and non-homogeneity the rainfall series.

(ii). Test for absence of persistence to verify the randomness of the time series by calculating the lag 1 serial correlation coefficients in respect of each of the annual rainfall series.

(iii). Double Mass Analysis (DMA) to determine the relative consistency and homogeneity of the time series. DMA also helps us to verify whether areas covered by certain rain-gauging stations are in the same hydrological region.

The rainfall data generally met the above mentioned criteria and was found suitable for use in further analyses. However, rainfall data from three stations, Mianwali, Fasialabad, and Bahawalnagar (Figure 4.1), did indicate certain anomalies, which were further examined. The annual rainfall series for Mianwali and Faisalabad indicated a significant lag 1 serial correlation coefficient suggesting that the time series might not be completely random. However, the double mass analysis (DMA) of the annual rainfall data from the two stations with other rain-gauging stations in their respective hydrological zones did not show any persistent trends away from the average slope. According to PMD there has been no change either in the locations or the data recording procedures for the two sites. The data sets for the two stations were also compared with their respective original data recording sheets, and there were no discrepancies.

The annual rainfall series was then split into two parts, summer and winter rainfall, and put through the same tests for each of the two stations. The lag 1 serial correlation coefficients were significant both for summer and winter rainfall in case of Mianwali. However, for Faisalabad it was only the summer rainfall series (Monsoon) for which the lag 1 serial correlation coefficient was significant. The winter rainfall series for Faisalabad qualified the test for absence of persistence. Since data sets for these two stations were satisfying other criteria, they were admitted for areal rainfall estimation and frequency analyses. As far as data from the third rain-gauging station, Bahawalnagar, is concerned, the annual rainfall series was found to be meeting the above mentioned criteria regarding absolute consistency, homogeneity and persistence. However, the double mass curve that determines the relative consistency and homogeneity of data, indicated a break. The year was 1985.

The Bahawalnagar rainfall series was again split into summer and winter periods. The summer rainfall did not exhibit a break in the double mass curve but the curve for the winter series did show a significant break. The monthly rainfall data for Bahawalnagar shows an almost doubling of the January-through-March average rainfall (from 24 mm to 48 mm) in the post 1985 period. Nevertheless, data set for Bahawalnagar was admitted for areal rainfall estimation and frequency analyses. After encountering these anomalies in some of the rainfall series, data from all the rain-gauging stations was analyzed to study the different components of each time series: trend, periodicity, and stochasticity (Section 4.3).

4.3 TREND, PERIODICITY AND STOCHASTICITY IN RAINFALL SERIES

A hydrologic time series may be considered to be composed of the sum of two components: a random element and a non-random element (Chow 1964). The non-random element then, may be composed both of a trend, or a long-term movement and an oscillation about the trend. A time series may or may not contain both of these parts. If for any given time series, the sequence of values follows an oscillatory pattern and if this pattern indicates a more or less steady rise or fall, it is defined as a trend. However, *"no matter what the length of the time series is, it can never be stated with certainty that an apparent trend is not part of a long term oscillation, unless the series ends"* (Chow). Therefore, what we might be seeing as a trend towards an increase or decrease in rainfall may well be a part of slow oscillation. Trends in a hydrological time series may be the result of some natural or man-made phenomena. Periodicities are usually due to astronomical cycles such as the earth's rotation around the sun and 11-year sunspot cycle.

Time series and spectral analyses of annual rainfall (Kite 1989) were carried out to study the relative magnitude of apparent components such as trends, jumps, periodicities and autoregression. The results in case of Mianwali (Zones I and II; see Annex-II) and Faisalabad (Zone-II) are of particular interest. The total variance in the annual rainfall series for Mianwali is explained identically (33% each) by the trend component and periodicity and 33% is left unexplained as random residual (Figure 4.2). Similarly, in case of Faisalabad, one-third of the total variance is explained by autoregression and two-thirds remains unexplained as random residual. For Bahwalnagar, the trend component explains around 20% of the total variance (also see section 4.2) and the rest is largely unexplained as random residual.

The rainfall series for Mianwali was then split into three sub-periods of twelve-year each (1960 to 1995) and the analysis indicated that the relative percentage of the periodic component in the total variance of the series was zero. The total variance was explained by about 30–40% by the trend component in case of all the three sub-periods, 7–23% by autoregression and the rest remained unexplained as random residual. This exercise also helped us trace-out the period which was affecting the rainfall series in such manner. In the eight years of period from 1976 to 1983 rainfall has been 25–75% above average (the meteorologist's normal) for the entire Indus Plains and the Punjab in particular.

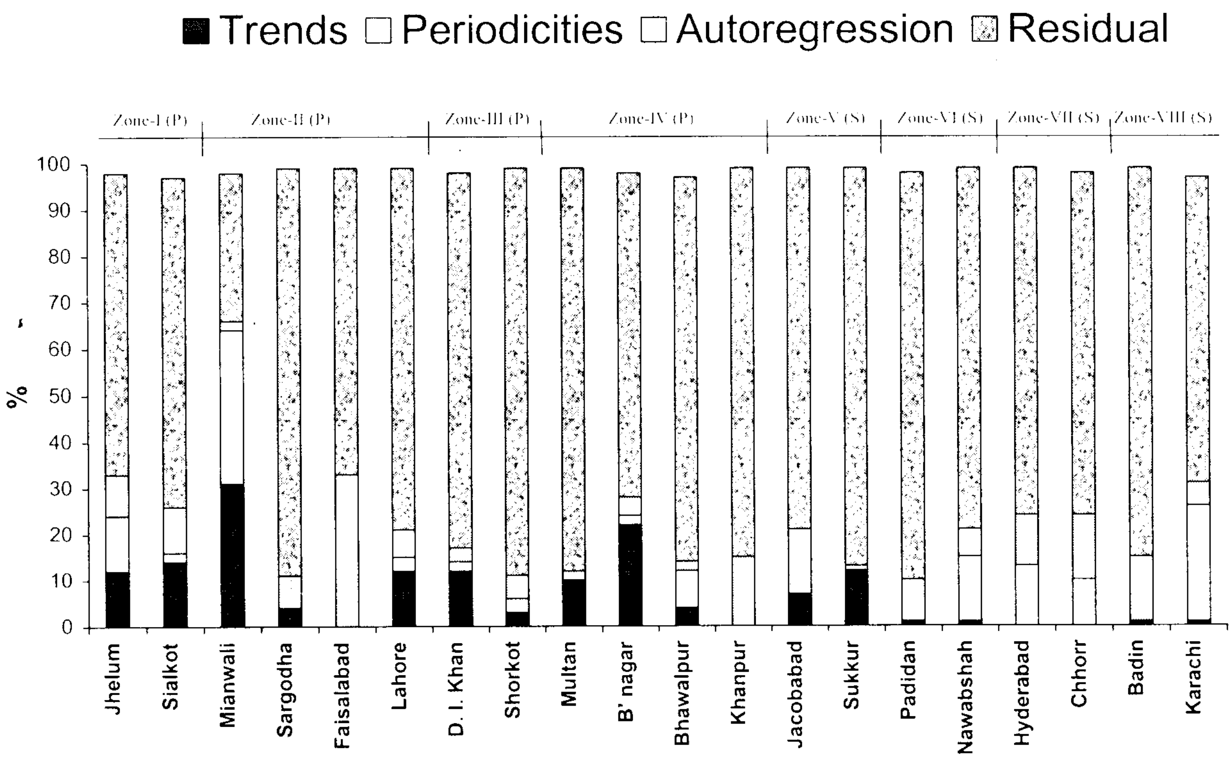


Figure 4.2. Relative Magnitude of Trends, Periodicities, Autoregression and Random Residual in Annual Rainfall Series for Main Rain-gauging Stations within the Indus Plains.

In fact, the years 1976 and 1983, for many of the rain-gauging stations, are years of the maximum (or near maximum) annual rainfall ever recorded in the 35-year period of 1960 to 1995. In the Upper Indus Plain (Punjab), other stations with somewhat significant trend component (≈10%) explaining part of the total variance in the annual rainfall series are Jhelum, Sialkot, Lahore, D. I. Khan and Multan. In the Lower Indus Plain, the rainfall series for rain-gauging stations closer to the coastline in (Karachi; Zone-VIII) show a cyclic component explaining around 20% of the total variance. As we move north and away from the coastline, the percentage of this component in the total variance of the rainfall series reduces to almost half (10%) for stations in Zone-VII and is almost completely diminished in Zone-V and Zone-VI. In this case, Badin, located east of Karachi, seems to be an exception where the cyclic component is insignificant.

There are years with higher rainfall and marked flooding over large areas and other years with rainfall much lower than the normal. However, there is no reliable method of projecting any trend, if present in a hydrologic time series, very far into the future. Therefore, for practical purposes, the emphasis should be on frequency studies of the past and on the extremes at either end of a spectrum rather than trend analyses. No further investigations, in relation to trends and periodicities in rainfall series, were made thereof. In a climate change perspective, trends, jumps, autoregression and periodicities in a climate-related time series such as rainfall must also be studied keeping in view the physical changes taking place as a result of meteorological factors or data measuring and recording procedures. This area, however, did not fall within the scope of this particular study.

4.4 Deciding on the "Right" Percentile

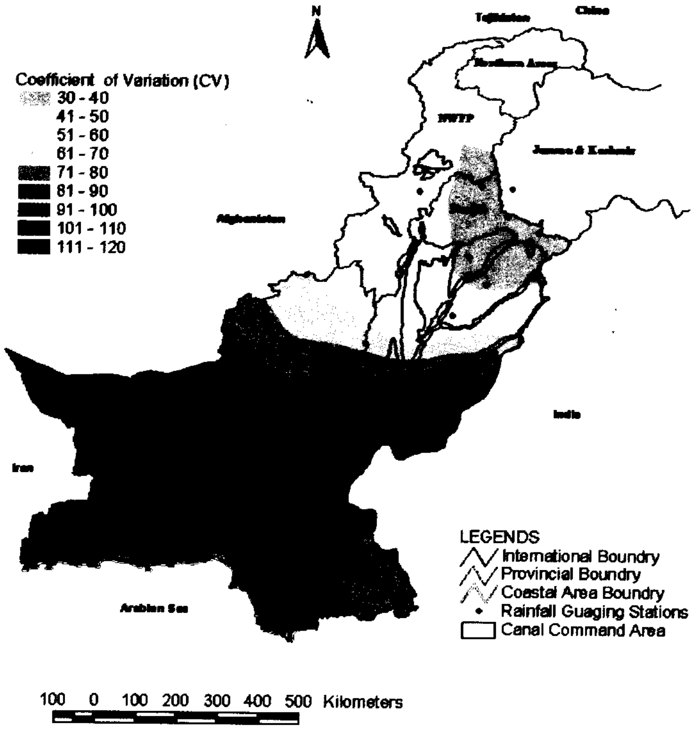
In most of the studies conducted in context of the IBIS for planning purposes in the irrigation/agriculture sectors, it was customary to use the mean annual or seasonal precipitation. Even in research work when it comes to rainfall the common practice is to use long-term averages. This, in a way, indicates that both planners and researchers in the Indus Basin attach little importance to this source of fresh water. The major reason, of course, is its insignificance in quantitative terms, in the Indus Plains, in comparison with the other two sources of water for irrigation/agriculture i.e., surface and ground water. Furthermore, rainfall is relatively more difficult to quantify in its occurrence as well as its effectiveness (usage in agriculture) as compared to surface and ground water. Although long-term averages do provide some information, it is certainly not advisable to use these values in any work, for planning or research, without looking into some other characteristics of rainfall within a certain area as well.

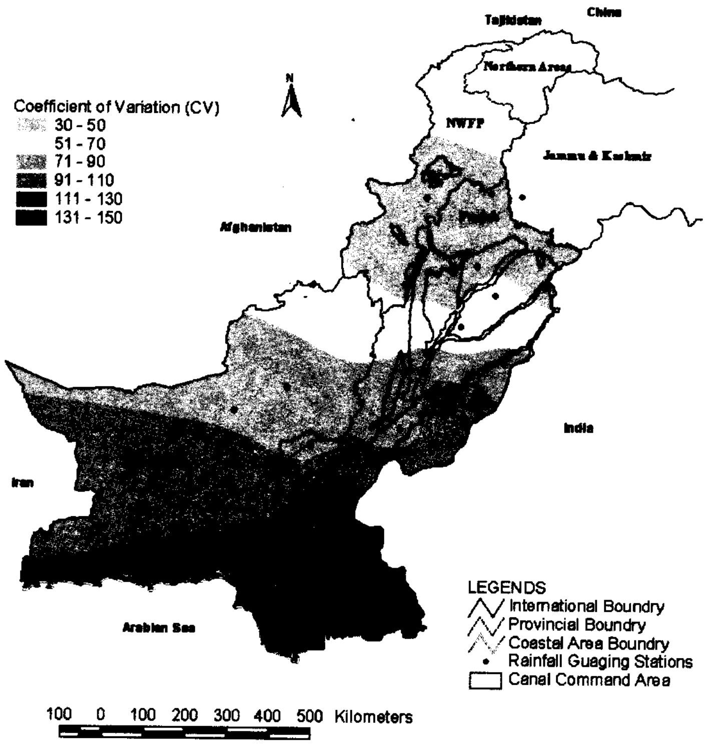
The average *Kharif* season rainfall at Bahawalpur (Lower Bahawal Canal Command Area), for example, is 139 mm. Using this figure in any water accounting procedure may lead to gross over estimation of rainfall in quantitative terms. If we look at the frequency tabulation of *Kharif* season rainfall data for a 36-year period, it shows that in 21 out of the 36 seasonal values, rainfall was below 108 mm. Whereas, rainfall events bringing seasonal rain of 108–217 mm occurred only six times. Such long-term averages, thus, are of little practical value especially in case of the canal commands in Southern Punjab and the whole of Sindh Province (the Lower Indus Plain). For the canal commands in these areas, it is more appropriate to use the median or the 50th percentile (P50) from a long-term (at least 25 years) rainfall series. Therefore, the frequency distribution of precipitation and its variability must also be known.

4.5 Variability of Rainfall Across the Plains

In the arid and semi arid regions, cultivation is not possible without irrigation. Rainfall in such regions is marginal to cultivation. In addition, the high variability of rainfall may pose serious risks to agriculture. The variability of rainfall in time and space is an important factor determining the effectiveness of rainfall. In years of better rainfall, crops are good whereas dry and extremely wet years have an adverse effect on agriculture both in the irrigated and non-irrigated (rain-fed) areas. Although irrigation provides a good deal of protection to agriculture from droughts but the importance of natural supply of water to the crops in the form of rainfall may not be neglected in the Indus Plains. It is, therefore, essential not to underestimate the impact that this natural phenomenon might have particularly in regions with high variability of rainfall both in time and in space.

The long-term average amounts of precipitation for a season (*Kharif* or *Rabi*), or a year, give little information on the regularity with which rain may be expected, particularly for regions where the average amounts are small. This is the case for almost all of the Indus Plains except the extreme north and northeast (Zone-I, Punjab). The variability of annual rainfall is related to the average amounts. Variability tends to be higher where the average amounts are low (Figure 4.3). As we move from north to the south, in the Indus Plains, the variability increases as the mean annual rainfall decreases. It may also be seen that the region of maximum rainfall variability is around Jacobabad and Sukkur. All of the main canal commands of Guddu Barrage and some of the Sukkur Barrage fall within this region.





(b)

Figure 4.3. Variability (C_V) of Rainfall Within the Indus Plains (a) Variability of *Kharif* Season Rainfall; (b) Variability of *Rabi* Season Rainfall.

Chapter 5

5 RAINFALL AT THE CANAL COMMAND LEVEL

5.1 POINT AND AREAL RAINFALL

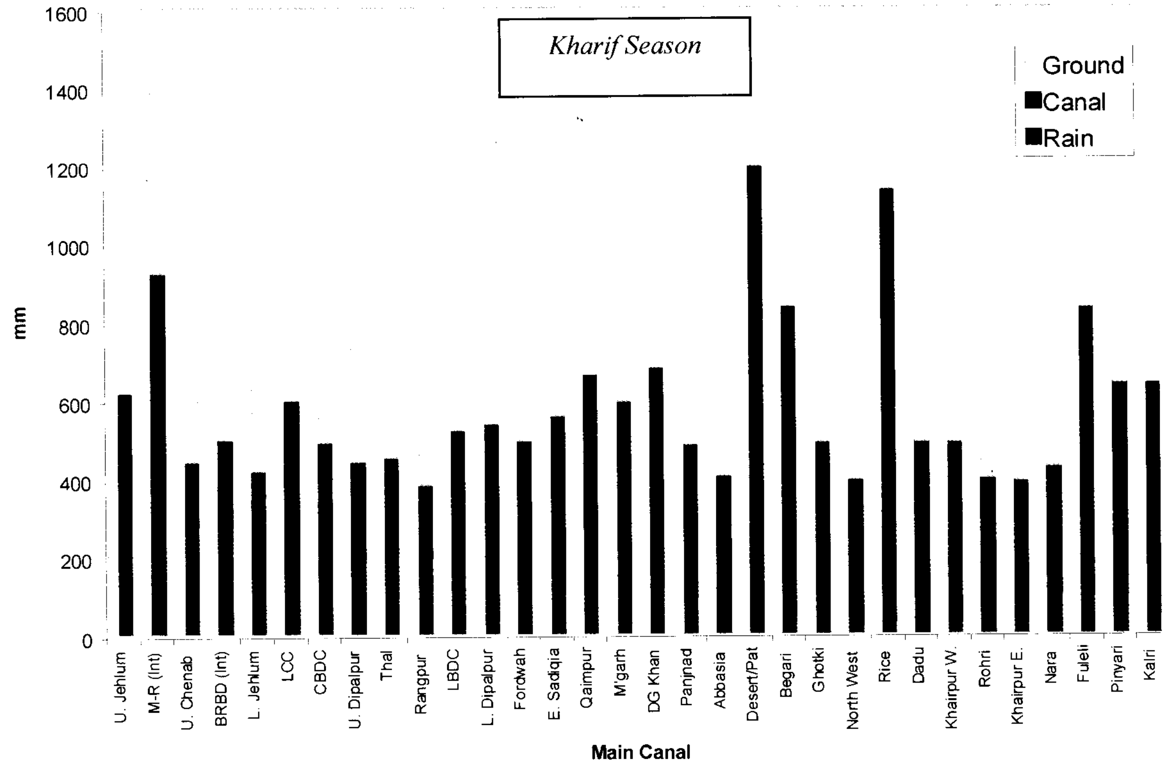
In water resources engineering one is primarily interested in areal characteristics of rainfall rather than point characteristics. Rainfall is a process with high spatial variability in the Indus Plains. It has been shown in the previous chapter that all the canal commands within the Indus Plains fall in an area with above normal (>± 5%) variability both in the *Kharif* and the *Rabi* seasons. As such, point rainfall measured at one particular rain gauge or an arithmetic average of rainfall measurements at two or more rain gauge stations within (or close to) a canal command area, would not adequately represent the rainfall within that canal command.

In case of large areas, such as the Indus Plains, the frequency of rainfall over these areas is of interest, especially with reference to irrigation planning and management. For example, if one is interested in estimating the average rainfall within a particular area (a canal command) from a 25-year rainfall data from say, 3 rain gauge stations, it would be inappropriate to average the 25-year rainfall at the 3 stations. The reason is that unless the different rainfall events can occur simultaneously, this average value will have a return period greater than that of the individual values (Linsley 1992).

The evaluation of the spatial distribution of rainfall, thus, becomes a necessary step for any rainfall analysis particularly in the Indus Plains where the number of rain gauges per square kilometers, for which rainfall data for a sufficient period (25–35 years) is available, is low. There are different methods for estimating areal rainfall using point rainfall data. These methods include; Thiessen Polygon Method, Isohyetal Method, Percentage-of-Mean-Annual Method and the Abbreviated Isopercentual Method (Chow 1964). In this study the Isohyetal Method has been used for this purpose. Furthermore, a canal command has been adopted as the basic unit of area. The areal rainfall was computed, on seasonal basis, (*Kharif* and *Rabi*) from point rainfall data for a 34-year period from 1961-62 to 1994-95.

5.2 RAINFALL IN THE CANAL COMMANDS

The relative contribution of rainfall in most of the canal commands is lower when compared with the other two sources of irrigation water supply i.e., canal water and groundwater. The entire Indus Plains (canal command areas) receive average seasonal rainfall of 212 mm (95% confidence interval ± 28) and 53 mm (95% confidence interval ± 8) in the *Kharif* and *Rabi* seasons, respectively. A synopsis of the water supplies available to crops during the *Kharif* and *Rabi* seasons in the year 1993-94 is presented for comparison (Figure 5.1). In the year 1993-94, the summer rainfall (April–September) across the entire Indus Plains matched the 50th percentile (from long term data) except for some of the canal command areas in zones III and IV (Punjab) where the summer (*Kharif*) rainfall was falling within the upper quartile. Barring the canal commands in Zone-I and Zone-II in the Punjab, where the rainfall was falling in the lower quartile, winter rainfall (October–March) during 1993-94 matched the 25th percentile. The system inflows were 10% below average and the system canal diversions were 4% above the average. It may be seen that it is only the canal commands in the Upper Indus Plain (Zone-I and Zone-II, Punjab) where rainfall seems to be making a somewhat significant contribution towards the total irrigation supplies to crops alongwith canal and subsurface water. This contribution is noteworthy only during the *Kharif* season. The figure very clearly represents the spatio-temporal imbalances in water supplies across the entire Indus Plains. Worthwhile to point out here, with respect to temporal distribution of rainfall, is the fact that most of the *Kharif* rainfall is concentrated in the July–September period and the *Rabi* rainfall in the December–March period.



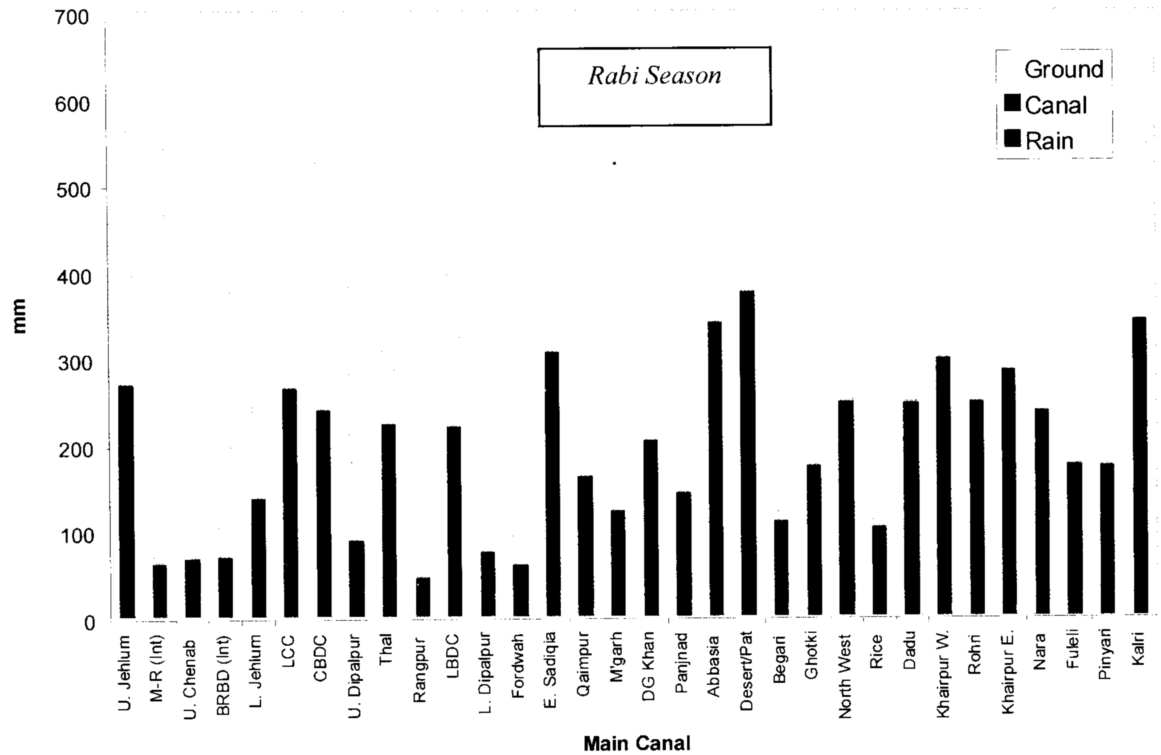


Figure 5.1. Seasonal Effective Rainfall (by USBR method), Canal Diversions at Farmgate and Tubewell Pumpage in the Canal Commands of the Indus Plains in the Year 1993-94 (*Tubewell pumpage estimated by M. Kaleemullah, IWMI-Pakistan, unpublished work*).

In quantitative terms, the canal commands in the Upper Indus Plain (Zones I and II, Punjab) received monthly rainfall equal to or in excess of 25 mm in more than three months (Jan–Mar, Jul, Aug) during 1993-94. On the other hand, the occurrence of the same amount of rainfall in a month, in the canal commands of southern Punjab (Zone-IV) and those on the left bank of the Indus River (Zones VII and VII, Sindh) took place only once; during the month of July (Table 5.1). For most of the canal commands, the months with some noticeable amount of rainfall (≥ 25 mm) are January–April and July–August whereby moisture brought in by the Western Disturbances and the Monsoons, respectively, precipitates over the Indus Plains. The months of October and November are the driest except for the command areas of Kotri Barrage canals on the left bank of Indus in the Lower Indus Plain (Zone-VIII, Sindh). In addition to the rains brought in by the Monsoons in the July–August period, these canal commands receive sporadic rainfall due to thunderstorm activity in October–November.

Table 5.1. Monthly Rainfall Equal to OR in Excess of 25 millimeters in the Canal Commands of the Indus Plains, Based on the Areal Rainfall Estimated for the Year 1993-94.

Annual Occurrences	Month	Canal Command
4–5	Jan-Mar, Jul, & Aug	UJC, LJC, UCC, MRI, BRBDI, CBDC, CRBC.
2–3	Apr, May/Jun, & Jul/Aug in Punjab; Jul, & Oct in Sindh	Thal, LCC, U. Dpr, L. Dpr, Rangpur, Haveli, Sidhnai, LBDC, U. Pakpn, L. Pakpn, Mailsi, U. Bah, L. Bah, Qaim, Ford, E. Sadq, Abbs, Ghotki, Pinyari, Fuleli, Lined C.
1	July	Panj, MGH, DGK, Desert, Beg, Dadu, K'East, KWest, Nara, Rohri, Kalri.
Nil	–	Pat, Rice, North West

The most appropriate way of depicting the reliability of rainfall are the rainfall probability tables (Annex III) showing the least amount of rainfall expected at different probability levels. These probability tables have been prepared from a 34-year (1961-62 to 1994-95) areal rainfall data for each of the canal commands in the Indus Plains. The 2-Parameter Log Normal Distribution has been assumed for all the canal commands except the Guddu Barrage canal commands (Zone-V, Sindh). For the Zone-V (Sindh) canal commands the Log Pearson Type-III Distribution was assumed. According to these probability tables, only four of the canal commands; Upper Jhelum Internal (UJC), Upper Chenab Internal (UCC), Raya Branch (BRBDI) and Marala-Ravi Internal (MRI), may get rainfall in excess of 400 mm during *Kharif* and 100 mm during *Rabi* with a probability level of 50%. An interesting characteristic of rainfall of the entire Guddu Barrage canal commands (Zone-V, Sindh) that less than 25 mm of rainfall can be expected at the 90% probability level in the *Kharif* season. Similarly, barring the canal commands in Zone-I (Punjab), rainfall in the range of 7–25 mm may be expected at the 90% probability level for the entire *Rabi* season.

5.3 EFFECTIVE RAINFALL—THE CONCEPT

The term effective rainfall or utilizable rainfall has been interpreted differently not only by specialists in different fields but also by different workers in the same field. Civil engineers, agriculturists and irrigation engineers and other experts working in the fields of forestry, geohydrology etc do not have identical interpretations of the concept of effective rainfall. In context of the Indus Basin Irrigation System, we shall look into this characteristic of rainfall with respect to irrigation and agriculture. Dastane (1974) in his paper on effective rainfall has provided a fairly elaborate definition of this concept. The paper discusses the concept of effective rainfall and also presents an account of different methods available for its estimation in quantitative terms. According to Dastane, in irrigated agriculture, effective rainfall includes the portion of total rainfall (annual or seasonal):

(i). Intercepted by vegetation;
(ii). Lost by evaporation from the soil surface;
(iii). Lost by evpotranspiration during plant growth;
(iv). Contributing towards leaching, percolation, and
(v). Facilitating other cultural operation either before or after sowing without any harm to yield and quality of crops.

This concept of effective rainfall is suggested for use in planning and operation of irrigation projects.

There are several factors that influence the proportion of effective rainfall such as rainfall characteristics, meteorological parameters, topography, soil characteristics, groundwater conditions, crops and agricultural practices. The rainfall characteristics influencing effective rainfall are its amount, frequency and spatio-temporal distribution. In the Indus Plains, the effective fraction of rainfall is high during winters when the rainfall is low in intensity, frequency and amount. On the other hand, this fraction is low during the Monsoon period (July–September) when the rainfall is high in both amount and intensity. Meteorological factors such as temperature, relative humidity and wind velocity also affect the proportion of effective rainfall. Topography influences the direct surface runoff following a particular rainfall event. According to Barlow's Table (Punmia and Lal), the runoff percentage from rainfall in areas such as the Indus Plains would lie between 15 to 20 percent of the total rainfall.

Soil characteristics that determine the moisture retaining capacity of the soil are also important. The percentage of effective rainfall is greater in areas where depth to ground water table is also greater since the soil moisture deficit is, in part, replenished due to the capillary rise of sub surface water if present at shallow depths. Thus, the proportion of effective rainfall varies inversely with the depth to groundwater table. On the other hand, if the groundwater quality is saline near the soil surface, higher amount of rainfall may help in diluting the salts thus increasing the proportion of effective rainfall. In the canal command areas of the Indus Plains (South Punjab and Sindh Province), the groundwater is generally saline and the climate arid. Taking into consideration both these factors, the proportion of effective rainfall would be greater in such areas particularly during winter. However, the total effective rainfall is certainly not enough to meet the entire or even a considerable proportion of the irrigation/crop-water requirements.

The crop types and their different stages of growth also determine the proportion of effective rainfall. The canal command areas where rice is the major crop such as Upper Chenab (UCC), Marala-Ravi (MRI), Raya Branch (BRBDI), and Lower Chenab (LCC) in the Upper Indus Plain (Punjab), the effective proportion of total rainfall would be higher. These canal command areas also fall in the high rainfall zone. Furthermore, the percentage of effective rainfall would be higher when the crop water requirements are higher for the maturing of wheat in March-April and the sowing of cotton in May-June. Incidentally, this is the period when the two reservoirs, Mangla and Tarbela, are also nearing their minimum levels of conservation. Therefore, in general, any rainfall in the period March through June would have a much higher percentage of effective rainfall, from agricultural as well a irrigation viewpoint, than the rainfall in other months. The agricultural practices, such as tillage, irrigation schedules etc, that have an influence on runoff and moisture retention properties of the soil, also influence the degree of effective rainfall.

In light of the foregoing, it is quite evident that estimation of effective rainfall, keeping in view all the important factors influencing it, might not be practicable. Depending on weather, type of soil and time span considered, the effective rainfall as a percentage of total rainfall may be as high as 90% or as low as 40% (Doorenbos and Pruitt 1975). There are several methods of estimating effective rainfall from irrigation/agricultural viewpoint and Dastane (FAO Paper 25, 1974) has discussed many of these methods. In addition, the paper presents an evaluation of different methods for estimating effective rainfall. A few more methods, apart from some already included in the FAO Paper by Dastane, have been discussed in the next section in context of their applicability in the Indus Basin Irrigation System (IBIS). The different methods for estimating effective rainfall may be categorized as: direct field monitoring techniques; empirical techniques (equations, tables, charts); and soil water balance methods (SWBM).

5.4 ESTIMATION OF EFFECTIVE RAINFALL

The direct field monitoring methods provide the most accurate results for estimation of effective rainfall. These methods include Daily Moisture method, Integrating Gauge method, Ramdas method, the Drum technique and Lysimeters. Out of all these methods, lysimetry provides the best estimates of effective rainfall. These methods, however, are expensive and require some level of technical knowledge on part of the person engaged in this work. As such their applicability in the Indus Basin Irrigation System (IBIS) is unlikely (or very limited). Some empirical formulae are also available for estimation of effective rainfall. These formulae

In quantitative terms, the canal commands in the Upper Indus Plain (Zones I and II, Punjab) received monthly rainfall equal to or in excess of 25 mm in more than three months (Jan–Mar, Jul, Aug) during 1993-94. On the other hand, the occurrence of the same amount of rainfall in a month, in the canal commands of southern Punjab (Zone-IV) and those on the left bank of the Indus River (Zones VII and VII, Sindh) took place only once; during the month of July (Table 5.1). For most of the canal commands, the months with some noticeable amount of rainfall (≥ 25 mm) are January–April and July–August whereby moisture brought in by the Western Disturbances and the Monsoons, respectively, precipitates over the Indus Plains. The months of October and November are the driest except for the command areas of Kotri Barrage canals on the left bank of Indus in the Lower Indus Plain (Zone-VIII, Sindh). In addition to the rains brought in by the Monsoons in the July–August period, these canal commands receive sporadic rainfall due to thunderstorm activity in October–November.

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include the Renfro Equation, the United States Bureau of Reclamation method, Ratio of ET_P to Precipitation method, the USDA-SCS method, and some other empirical relationships for rice and non-rice areas developed in India, Burma, Thailand and some far eastern countries. These formulae and empirical relationships give results with low to medium accuracy and are highly economical in monetary terms. However, their applicability is suggested only in particular conditions (i.e., in conditions similar to those under which they have been developed) and mostly for broad-based planning purposes.

UN ESCAP in one of its research reports (1974) have estimated effective rainfall as the portion of Basic Effective Rainfall (BER: total rain less isolated showers of under 6 mm/day), surface runoff and infiltration into soil. The method, in addition to rainfall data, also requires information regarding water-holding capacity of soil and surface runoff from rainfall. This method was applied in the rice-cultivated area of Thailand. Its applicability is therefore limited to similar areas for which the requisite data would be available. Patwardhan et al (1990) suggest the usage of soil water balance techniques for better estimation since they account for the dynamic nature of soil water and weather conditions in the field. A soil water balance model (SWBM) takes care of all the factors influencing effective rainfall such as rainfall, irrigation, interception, infiltration, runoff, deep percolation and evpotranspiration etc. An SWBM probably gives the best estimates of effective rainfall although data requirements are quite high since data regarding rainfall, solar radiation, air temperatures, and soil conditions is needed on a daily time-step.

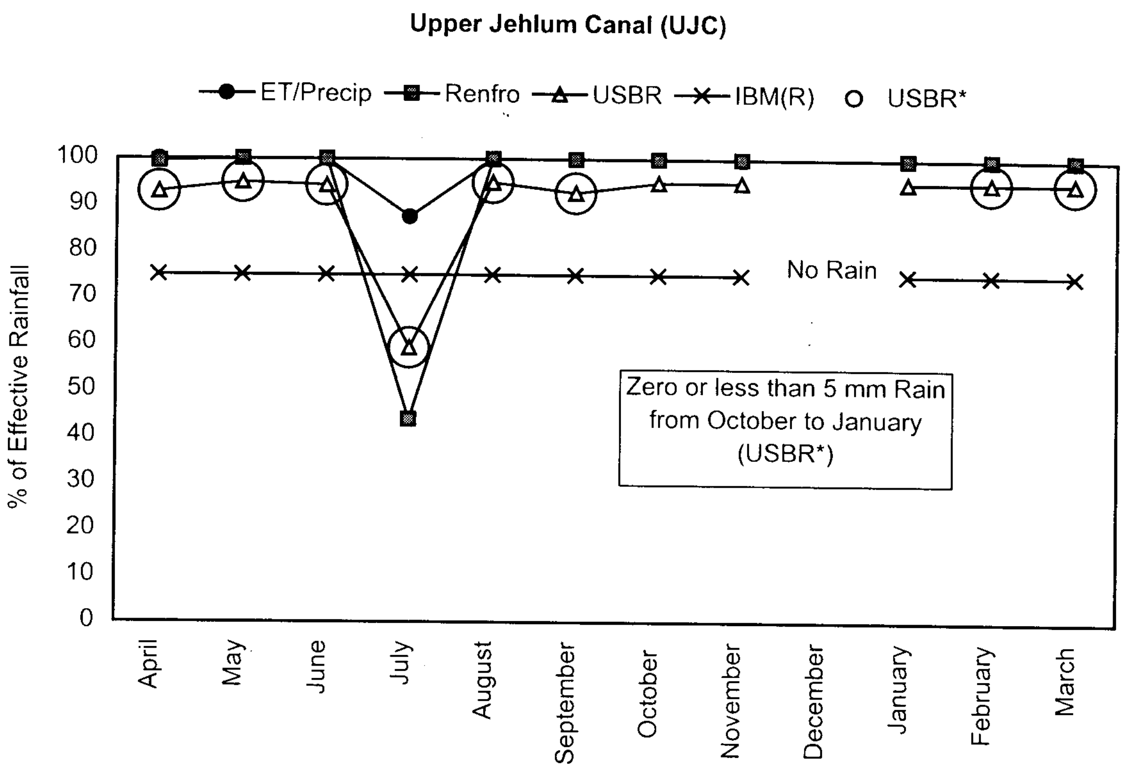
Yashima (1995) has proposed a method for estimating effective rainfall from an irrigation management viewpoint in a supply-based irrigation system. According to his approach, only that portion of rainfall is effective which can reduce irrigation supply requirements. The method is simple and takes into the crop water requirements (evapotranspiration and seepage and percolation losses). The most commonly used method in major water sector studies (RAP 1979, PGC 1998) in the IBIS, has been the USBR method. The method uses monthly rainfall data and has been suggested for arid and semi-arid regions. The method is characterized by indicating that the smaller the rainfall, the higher the effective rainfall ratio. The method is simple, allows rapid calculations and only requires monthly rainfall data.

The Massland method, which was primarily employed for estimating the recharge to groundwater from rainfall in the Water Sector Investment Planning Study (1990), may also be used for the estimation effective rainfall. This method, however, is somewhat complicated and requires detailed rainfall data. The Indus Basin Model (Revised) estimates effective rainfall by taken into account the direct runoff (assumed to be constant at 15% of the mean monthly rainfall) and field losses that vary from 10–20% in the different canal commands of IBIS.

5.5 Estimation of Effective Rainfall for the Canal Commands in the Indus Plains

A comparison of four of the aforementioned methods for estimation of effective rainfall will be presented in this section. The methods are: USBR method; ET_P–Precipitation Ratio method; Renfro equation; and the IBM(R) method. The criteria for short listing of these four methods has been smaller data requirements (number of variables) and simplified computational procedures. The comparison has been made for four canal commands in the Upper Indus Plain (Punjab) for rainfall during the year 1993-94. In addition to monthly rainfall totals, data on canal deliveries and crop water requirements on 10-daily/monthly basis has been used. The crop water requirements have been taken from an undergoing study on this issue for the Indus Basin canal commands (Kalleemullah and Habib, IWMI-Pakistan). As mentioned earlier in chapter 1, the estimation of rainfall (and consequently, the effective rainfall) in the Indus Basin canal commands in case of all the major studies was either based on rainfall data for one particular year or long term averages. In most cases point rainfall data from different rain-gauging stations was assumed to be representative of areal rainfall over the canal commands. In this analysis, areal rainfall for the different canal commands of the Indus Plains has been used for estimation of effective rainfall.

The four canal commands in this comparison of effective rainfall estimation methods are: Lower Jhelum Canal (LJC), Upper Dipalpur Canal (U. Dpr), Lower Bari Doab Canal (LBDC), and Fordwah Canal (Ford). The first two fall in the moderate rainfall zone (annual rainfall 350–600 mm) of the Upper Indus Plain. The third and the fourth, respectively, fall within



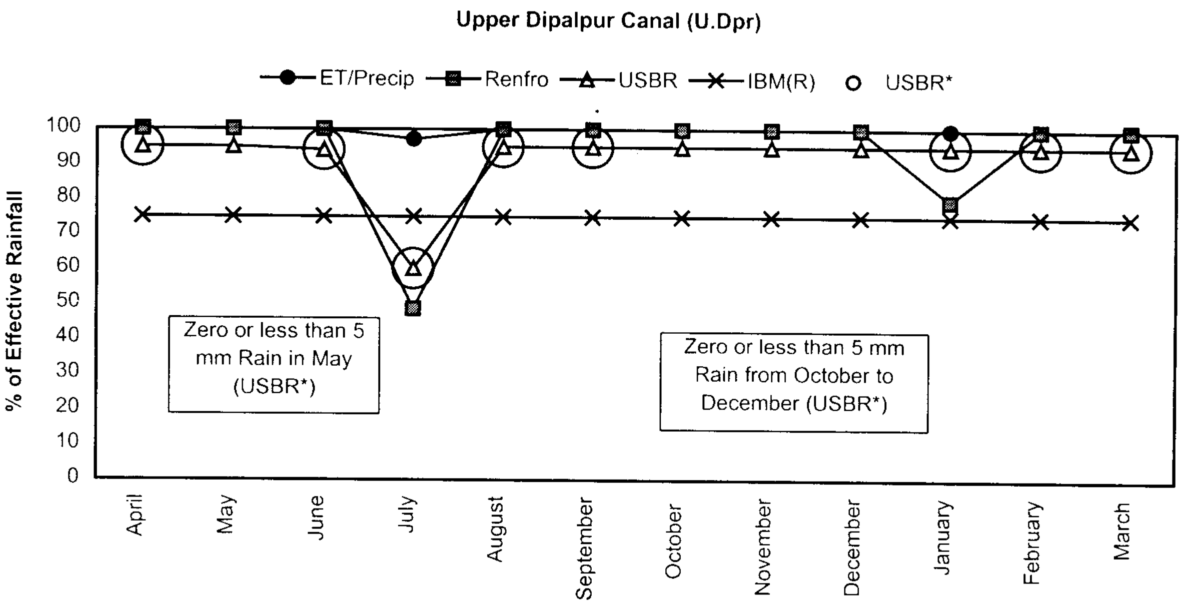


Figure 5.2. Comparison of Four Different Methods of Effective Rainfall Estimation for UJC and Upper Dipalpur Canal.

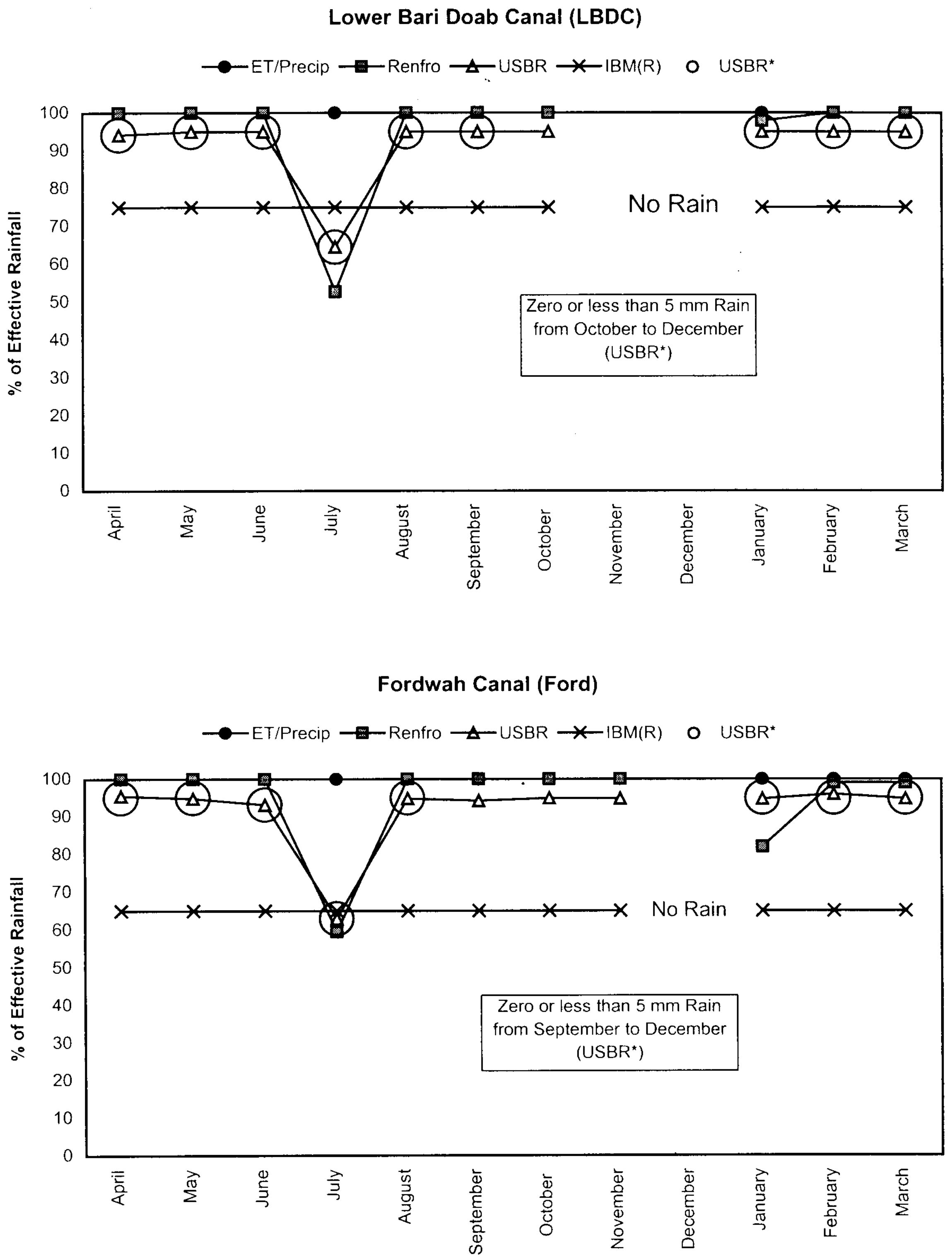


Figure 5.3. Comparison of Four Different Methods of Effective Rainfall Estimation for LBDC and Fordwah Canal.

Chapter 6

6 DISCUSSION

1. The areal rainfall gives a more representative picture of rainfall rather than point rainfall assumed to be representative of rainfall over the entire canal command area. Furthermore, instead of using long term averages, it is suggested that rainfall figures for the canal commands may be expressed with a certain level of probability depending upon the nature of work for which the value of rainfall is going to be used. The annual rainfall for Upper Dipalpur Canal (U. Dpr) and Central Bari Doab Canal (CBDC), using the Massland Method (WSIPS, 1990) was estimated to be 730 mm for each of the canal commands. This was estimated from precipitation records from the Lahore climatic station. If we look at the probability tables (Annex III) this corresponds to the rainfall figures at the 10% probability level of exceedence. The purpose, for which the figures for canal command-wise rainfall were used in that study (WSIPS), it would have been more appropriate to use rainfall values corresponding to a more conservative level of probability.

2. For the Upper Indus Plains (Zones I and II) rainfall is higher. There are only 7 Canal Commands, out of a total of 42 in the whole of the Indus Plains, that fall within these two zones of moderate to high rainfall. The Canal Commands of Zone-IV (Punjab) and Zones VI to VIII (Sindh) fall within an area of low rainfall and high variability. Therefore, these Canal Commands need protection not only from droughts but also from potential damages that may result from excessive rains.

3. As mentioned earlier, rainfall in the entire canal command areas of the Indus Plains is concentrated in the months of July–September and December–March for the *Kharif* and *Rabi* seasons respectively. These temporal imbalances vis-a-vis rainfall must be kept in mind especially while working out the water stress in the Canal Commands. These temporal imbalances also have an impact on the effectiveness of rainfall. As we have seen in the previous chapter (Section 5.5) that rainfall during July which is the month with maximum amount of rainfall was reduced to the lowest degree of effectiveness. In such cases, it would be more appropriate to use the monthly time-step and estimate the areal rainfall using the procedure described earlier (Section 3.4).

4. The comparison of the four methods suggests that the USBR method would provide good enough estimates of effective rainfall at the Canal Command level. It requires only rainfall data and involves very simple computational procedure. The IBM (R) method is also simple but assumes a constant percentage of rainfall for every month without taking into account the effects the amount and intensity of rainfall have on the effectiveness of rainfall. ET_P–Precipitation Ratio method and the Renfro Equation require data regarding crop water requirements. The Renfro Equation uses, in addition, data on average monthly irrigation application to the crops from other sources. Thus, data requirements for estimation of effective rainfall are more in case of these two methods. Furthermore, in case of some Canal Commands, ET_P calculations are bound to be influenced by low reported cropping intensities resulting in incorrect estimates of effective rainfall.

5. The time series analysis of rainfall data for Mianwali and Faisalabad in Zone-II (Punjab) and Bahawalnagar (Zone-IV) suggests that hydrometeorological time series from different climate stations within the Indus Plains be studied in detail in a climate change perspective. It would require studying the frequency of Monsoon storm tracks and the Westerlies (Western Disturbances) over the years. Furthermore, rain-gauging techniques and condition of equipment, urbanization of areas where these gauges are located etc are important factors that must be taken into consideration.

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ANNEXURES

ANNEX I. RAINFALL GAUGING STATIONS IN THE INDUS PLAINS.

No.	RG Station	Longitude	Latitude	Province	Department	Length of Data Available
1.	Islamabad	73.10	33.72	Capital	PMD	1960_95
2.	Kotli	73.53	33.80	AJK	PMD	1960_95
3.	Bannu	70.45	32.97	NWFP	PMD	_
4.	D. I. Khan	70.92	31.82	NWFP	PMD	1960_95
5.	Kohat	71.43	33.57	NWFP	PMD	1960_95
6.	Peshawar	71.58	34.02	NWFP	PMD	1960_95
7.	Saidu	72.35	34.73	NWFP	PMD	1974_95
8.	Bahawalnagar	73.25	29.97	Punjab	PMD	1963_95
9.	Bahawalpur	71.68	29.38	Punjab	PMD	1960_95
10.	Fort Abbas	72.85	29.20	Punjab	PMD	_
11.	Fort Munro	69.95	29.92	Punjab	PMD	_
12.	Faisalabad	73.10	31.43	Punjab	PMD	1960_95
13.	Hafizabad	73.68	32.07	Punjab	Not Known	_
14.	Jhelum	73.73	32.93	Punjab	PMD	1960_95
15.	Kasur	74.45	31.12	Punjab	PMD	_
16.	Khanpur	70.63	28.65	Punjab	PMD	1960_95
17.	Lahore	74.33	31.55	Punjab	PMD	1960_95
18.	Mianwali	71.52	32.55	Punjab	PMD	1960_95
19.	Multan	71.43	30.20	Punjab	PMD	1960_95
20.	Rahim Yar Khan	70.28	28.38	Punjab	PMD	_
21.	Rajanpur	70.32	29.10	Punjab	PMD	_
22.	Sahiwal	73.03	30.68	Punjab	PMD	_
23.	Sargodha	72.66	32.08	Punjab	PMD	1960_95
24.	Shorkot	72.20	30.78	Punjab	PMD	1972_95
25.	Sialkot	74.53	32.52	Punjab	PMD	1960_95
26.	Talagang	72.42	32.92	Punjab	Forest (Punj)	_
27.	Taunsa	70.65	30.70	Punjab	PMD	_
28.	Badin	68.83	24.63	Sindh	PMD	1961_96
29.	Chhorr	69.75	25.53	Sindh	PMD	1961_96
30.	Dadu	67.78	26.73	Sindh	PMD	_
31.	Diplo	69.55	24.47	Sindh	PMD	_
32.	Hyderabad	68.41	25.53	Sindh	PMD	1961_96
33.	Jacobabad	68.46	28.28	Sindh	PMD	1961_96
34.	Karachi	66.98	24.80	Sindh	PMD	1961_96
35.	Keti Bander	67.93	24.15	Sindh	PMD	_
36.	Larkana	68.20	27.55	Sindh	PMD	1987_96
37.	Mirpur Khas	69.03	25.53	Sindh	PMD	_
38.	Nagar Parkar	70.83	24.35	Sindh	PMD	_
39.	Nawabshah	68.36	26.25	Sindh	PMD	1961_96
40.	Padidan	68.83	26.82	Sindh	PMD	1961_96
41.	Reti	69.86	28.08	Sindh	PMD	_
42.	Rohri/Sukkur	68.90	27.66	Sindh	PMD	1961_96
43.	Thano Bula Khan	67.85	25.37	Sindh	PMD	_
44.	Thatta	67.93	24.75	Sindh	PMD	_
45.	Kalat	66.58	29.03	Balochistan	PMD	1961_96
46.	Khuzdar	66.60	27.80	Balochistan	PMD	1966_86
47.	Kohlu	69.25	29.92	Balochistan	PMD	_
48.	Lasbela	66.32	26.23	Balochistan	PMD	1982_96
49.	Musakhel Bazar	69.82	30.85	Balochistan	PMD	_
50.	Sibbi	67.88	29.55	Balochistan	PMD	1961_96

ANNEX II. **STATISTICAL PROPERTIES OF POINT RAINFALL DATA AND THE CANAL COMMANDS FALLING IN THE DIFFERENT RAINFALL ZONES WITHIN THE INDUS PLAINS.**

THE UPPER INDUS PLAIN

Zone-I	Zone-II	Zone-III	Zone-IV
1. RAIN-GAUGE STATIONS			
Islamabad, Jhelum, Sialkot, (Kotli).	Lahore, Sargodha, Faisalabad, (Mianwali).	DI Khan, Shorkot, (Faisalabad), (Bahawalnagar).	Multan, Bahawalpur, Bahawalnagar, Khanpur.
2. Canal Commands			
UJC, UCC, MRI, BRBDI.	Thal, LJC, LCC, CBDC.	Thal, CRBC, LJC, LCC, LBDC, L.Dpr, U.Dpr, U.Pakpn, Haveli, Rangpur.	Thal, Sidhnai, Mailsi, L.Pakpn, U.Bah/Qaim, Fordwah, E.Sadq, DGK, MGH, Punj, Abbs.
3. Rainfall Distribution			
75–80% in Kharif	75–80% in Kharif	70–80% in Kharif	75% in Kharif
4. Annual Normal Rainfall (1960-95)			
High Rain >600 mm	Moderate Rain 350–600 mm	Low Rain 250–350	Very Low Rain <250 mm
5. Variability (C_V)			
22–25%	35%	35–45%	45–75%
6. Lag-Zero Cross Corr. Among RG Stations			
Khairf			
0.48–0.55	0.50–0.60	0.60	0.60–0.64
Rabi			
0.60–0.85	0.60–0.77	0.70	0.48–0.60
7. Rainy Days in an year			
30–45	≈ 25	10–20	≈ 10

NAMES (AND ABBREVIATIONS) OF MAIN CANAL COMMANDS IN THE UPPER INDUS PLAIN:

Upper Jhelum Canal (UJC), Upper Chenab Canal (UCC), Maral-Ravi Internal (MRI), Raya Branch (BRBDI), Thal Canal, Lower Jhelum Canal (LJC), Lower Chenab Canal (LCC), Central Bari Doab Canal (CBDC), Chashma Right Bank Canal (CRBC), Lower Bari Doab Canal (LBDC), Upper Dipalpur Canal (U. Dpr), Lower Dipalpur Canal (L. Dpr), Upper Pakpattan Canal (U. Pakpn), Lower Pakpattan Canal (L. Pakpn), Haveli Internal, Sidhnai Canal, Mailsi Canal, Upper Bahawal Canal (U. Bah), Qaimpur Canal (Qaim), Fordwah Canal, Eastern Sadiqia Canal (E. Sadq), Dera Ghazi Khan Canal (DGK), Muzaffergarh Canal (MGH), Punjnad Canal (Punj), and Abbassia Canal (Abbs).

THE LOWER INDUS PLAIN

Zone-V	Zone-VI	Zone-VII	Zone-VIII
1. RAIN-GAUGE STATIONS			
Jacobabad, Sukkur	Nawabshah, Padidan, (Sukkur), (Hyderabad)	Hyderabad, Chhorr, (Badin), (Karachi)	Karachi, Badin, (Hyderabad), (Chorr)
2. Canal Commands			
Pat/Desert, Begari, Ghotki	North West, Rice, Dadu, K. East, K.West, Rohri	Rohri, Nara	Kalri, Pinyari, Fuleli, Lined C.
3. Rainfall Distribution			
80–100% in Kharif	80–90% in Kharif	80–90% in Kharif	80–90% in Kharif
4. Annual Normal Rainfall (1961-96)			
Very Low Rain 100 mm	Very Low Rain 100–150 mm	Very Low Rain 150–225	Very Low Rain 210–235 mm
5. Variability (C_V)			
110–130%	100%	70–85%	90%
6. Lag-Zero Cross Corr. Among RG Stations			
Khairf			
0.77	0.74–0.85	0.73–0.75	0.73–0.75
Rabi			
0.64	0.71–0.78	0.44	0.43–0.71
7. Rainy Days in an year			
10	10	10	10–15

NAMES (AND ABBREVIATIONS) OF MAIN CANAL COMMANDS IN THE LOWER INDUS PLAIN:

Pat Feeder Canal (Pat), Desert Feeder Canal (Desert), Begari Feeder Canal, Ghotki Canal, North West Canal, Rice Canal, Dau Canal, Kairpur West Canal (K. West), Kharipur East Canal (K. East), Rohri Canal, Nara Canal, Kalri Canal, Pinyari Canal, Fuleli Canal, and Lined Canal (Lined C.).

RABI SEASON

No.	Canal Command	Probability of Exceedence				
		90% (mm)	75% (mm)	50% (mm)	25% (mm)	10% (mm)
1	Upper Jhelum Internal	78	101	137	183	240
2	Upper Chenab Internal	62	81	110	150	194
3	Marala-Ravi Internal	86	110	147	194	247
4	BRBD Internal	69	90	122	164	213
5	Lower Jhelum	48	64	90	125	167
6	Jhang (LCC West)	36	50	70	100	134
7	Gugera (LCC East)	31	42	62	88	120
8	CBDC	48	65	90	124	165
9	Thal	38	52	75	105	142
10	CRBC/Paharpur	48	64	89	122	161
11	LBDC	23	31	46	66	90
12	Upper Dipalpur	40	54	75	104	139
13	Lower Dipalpur	28	37	54	76	103
14	U. Pakpattan	19	25	37	53	73
15	Haveli Internal	21	30	46	69	99
16	Rangpur	20	29	44	66	95
17	Sidhnai	16	23	37	57	85
18	Fordwah	21	28	40	56	75
19	E. Sadqia	16	23	33	47	64
20	L. Mailsi/L. Pakpattan	12	19	30	47	71
21	U. Bahawal/Qaimpur	14	20	30	46	66
22	L. Bahawal	11	16	27	43	64
23	DG Khan	15	21	32	48	67
24	Muzaffergarh	16	23	36	56	83
25	Panjand	11	16	24	35	50
26	Abbassia	12	18	26	37	55
27	Pat Feeder	15	21	31	45	63
28	Desert Feeder	12	17	25	37	52
29	Beagri Feeder	13	18	26	39	54
30	Ghotki Feeder	10	14	22	33	48
31	North West	14	20	30	43	60
32	Rice	12	18	27	40	57
33	Dadu	11	16	25	38	56
34	Khairpur West	11	15	24	36	52
35	Khairpur East	10	15	22	34	50
36	Rohri	10	14	21	31	44
37	Nara	10	13	19	28	39
38	Kalri	10	15	25	40	63
39	Pinyari	10	14	22	36	53
40	Fuleli	10	14	21	30	41
41	Lined C. (Tando Bago)	7	11	18	28	43
42	Gaja Branch	10	14	21	31	44