Development of Flood Forecasting Model for Chenab River Basin

National Institute of Hydrology
Western Himalayan Regional Centre
Satwari, Jammu Cantt. – 180 003

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ABSTRACT

River Chenab experiences significant floods during the monsoon season. There are some major projects on the river, such as Salal dam, Baglihar, and Dulhasti. On the directions of the Governing Body of NIH, this study was taken up to develop a flood forecasting model for the Chenab Basin. The objectives of the study were to implement snow-melt and rainfall-runoff models for the Chenab basin up to Akhnoor.

Different data layers of the Chenab basin (such as basin boundary, drainage network, DEM, elevation bands, hydro-meteorological network etc.) were generated in GIS. The drainage map of the basin was used to mark various sub-basins at Benzwar, Sirshi, Premnagar, Dhamkund, and Akhnoor. Around 30 years of rainfall data at more than 20 sites and 13 years of discharge data at 10 sites were entered in hydrological data entry system and plots of flood observations at different gauging sites were generated. Using the daily data of rainfall stations, average daily rainfall was worked out in different sub-basins for different flood events. Plots of daily rainfall and discharge data at different stations indicate that most of the flood events in the Chenab basin are generated from rainfall storms mostly concentrated in the middle and lower reaches of the basin below Benzwar/Sirshi.

In view of the status of availability of data and the factors responsible for generation of flood, WINSRM model was applied considering daily rainfall and discharge for sub-basin downstream of Benzwar/Sirshi up to Akhnoor. Model parameters were calibrated and validated to get the best match of observed and simulated flows at Akhnoor.

The travel time of flood wave from Benzwar to Akhnoor is less than one day and hourly hydrological data were crucial for this study. So, availability of short-term (hourly) rainfall, flow, and met data were investigated from different departments. 3-hourly rainfall data and hourly discharge data of Akhnoor and Salal dam site were available for the flood event of year 2006 (September 1 – 6, 2006) and the same were used to simulate flood using unit hydrograph for the sub-basin between Premnagar and Akhnoor (Area – 5043 sq. km). Synthetic unit hydrograph (UH) was developed for this sub-basin. Using the 3-hourly rainfall of Salal station, the daily rainfall data of

various stations (obtained from CWC) for the flood event (September 1 – 6, 2006) were disaggregated and 3-hourly average rainfall in the sub-basin was computed. This rainfall pattern was convoluted with the UH to get the simulated flood at Akhnoor. Simulated flood matches with the expected pattern of flow at Akhnoor to a considerable extent.

If short-term ranfall and flow data of some additional flood events could be gathered, then the unit hydrograph can be fine-tuned so as to better match the observed flow pattern and peak discharge at Akhnoor. Based on the rainfall catch at different stations during various flood storms events, some important rainfall stations have been identified for automatic/ self-recording instrumentation for flood forecasting purpose.

* * *

PREFACE

The Chenab River is one of the five main rivers of the great Indus System. The major part of the Chenab catchment lies in India, spreading over the two states of Himachal Pradesh and Jammu & Kashmir. The Chenab River experiences significant floods during the monsoon season affecting a few important habitations along the river. On the directions of the Governing Body of NIH, the present study was taken up for developing a flood forecasting model for the Chenab Basin up to Akhnoor gauging site so that habitations close to Akhnoor could be timely warned and protected.

For the application of hydrological models for simulating runoff, spatial database was required which has been generated using various techniques of Geographical Information System (GIS). The hydro-meteorological data was collected from CWC, Jammu and the Office of the Chief Engineer, NHPC, Jammu. The plots of daily rainfall and discharge data at different stations for various flood events indicate that most of the flood in the Chenab basin is generated from the rainfall events which mostly remain concentrated in the middle and lower reaches of the basin below Benzwar. Based on the availability of daily hydro-meteorolocal data, WINSRM model has been applied to the sub-basin below Benzwar and reasonable match of observed and simulated flood peaks have been obtained. A synthetic unit hydrograph has been developed for the sub-basin below Premnagar and used to simulate 3-hourly flow pattern at Akhnoor. Limitation of availability of short-term rainfall data (available for only one flood event) is a major constraint in the testing of developed unit hydrograph for other flood events.

I thankfully acknowledge the support and cooperation of the Chief Engineer, NHPC, Jammu and the Executive Engineer, CWC, Jammu in providing all the necessary data required for this study.

The present report has been prepared by Dr. M. K. Goel, Scientist “E2”, Dr. Renoj J. Thayyen, Scientist “C” and Mr. Naresh Kumar, PRA of the Western Himalayan Regional Centre, Jammu.

(R. D. Singh)
Director

Contents

List of Figures

Page No.

Chapter-2

Chapter-3

Chapter-4

List of Tables

Page No.

Chapter-2

Chapter-3

Chapter-4

* * *

Chapter - 1
INTRODUCTION

1.1 General

The Chenab River is one of the five main rivers of the great Indus System. The major part of the Chenab catchment lies in India; its lower reach including the confluence with the Indus River is in Pakistan. In India, the Chenab basin is located in the Western Himalayas between latitudes 30° to 34° N and longitudes 74° to 78° E. It spreads over the two states of Himachal Pradesh and Jammu & Kashmir which comprise the extreme western sector of Himalayas. Upper half of this basin is located between the Zanskar and the Pir-Panjal ranges whereas the lower half is located between the Pir-Panjal and the Dhauladhar ranges. In this way, this basin covers outer, middle and greater Himalayas.

The Chenab River is formed as the result of conflux of the rivers - Chandra and Bhaga. The rivers meet at Tandi in the lap of Upper Himalayas. The Chenab River commences its journey from Himachal Pradesh and is also called as the Chandrabhaga in its initial stages. After leaving the Kulu and Kangra Districts of Himachal behind, the Chenab River enters the state of Jammu and Kashmir at Tandi at an altitude of 9,090 feet. The Chenab River meets several other rivers at different places which include Jhelum, Ravi, Sutlej, and Beas. The Chenab River of Jammu - Kashmir not only has geographical importance but has a great historical value attached to it. It was known as the Ashkini in Vedic Age. It was also known as the Iskamati. The invading Greeks led by Alexander the Great referred it as the River Acesines. The river gains momentum on the way with contributions from numerous branches.

The Chenab River experiences significant floods during the monsoon season. About 60-70% of the area receives snowfall and flood in the basin is a combined manifestation of the snowmelt and rainfall conditions. There are a few important habitations along the river Chenab which get affected by floods. There are some major projects on the river, such as Salal dam, Baglihar, and Dulhasti. Further, there are habitations residing close to the Akhnoor gauging site. It is required to issue timely forecasts so that habitations could be warned and necessary administrative actions could be initiated before the occurrence of the flood.

On the directions of the Governing Body of NIH, the present study was taken up for developing a flood forecasting model for the Chenab Basin up to Akhnoor gauging site. The specific objectives of the study were:

a) To implement a snow-melt model for the snow-covered area of the Chenab basin.
b) To implement a rainfall-runoff model for the snow-free area.
c) To integrate the snow-melt model and the rainfall-runoff model and test the model results with the past events for flow forecasting at selected points on the Chenab river, at Gulabgarh, Doda, Salal dam, and Akhnoor.
d) To review the adequacy of hydro-meteorological network in the basin for the purpose of flood forecasting.

From the plots of daily rainfall and discharge data at different stations for various years (shown in subsequent chapters), it has been inferred that most of the flood in the Chenab basin is generated from the rainfall events which mostly remain concentrated in the middle and lower reaches of the basin below Benzwar. The travel time of flood wave from Benzwar to Akhnoor is less than one day and hourly data is crucial for this study. Based on the availability of short-term rainfall and discharge data, the following strategies was adopted for this study:

a) To apply WINSRM considering daily rainfall, discharge at Akhnoor, and met data and available snow cover area.
b) Develop unit hydrograph for the intermediate catchment (Premnagar to Akhnoor) and use short-duration rainfall and discharge data to simulate the observed flow from the intermediate catchment.

For the application of hydrological model for simulating runoff, detailed database was required which has been generated using various techniques of Geographical Information System (GIS). In addition, the effectiveness of various raingauge stations in recording storm events have been analyzed and presented in the study.

1.2 Scope of the Present Study

The scope of the present study includes the development/application of hydrological models for flood simulation and forecasting in the Chenab basin up to Akhnoor. For this purpose, detailed hydro-meteorological data of the basin were required which has been obtained from Central Water

Commission, Jammu and the Office of the Chief Engineer, NHPC, Jammu. GIS has been extensively used for the development of database for the application of WINSRM model and the Unit Hydrograph approach. Database generation for this study has been discussed in Chapter – 2.

WINDOWS version of the Snowmelt Runoff Model (WINSRM) is a widely used software for simulation of runoff generated from rainfall and snowmelt. This model has been applied to number of flood events in the basin and model parameters have been calibrated. The details of this analysis are presented in Chapter – 3.

WINSRM is a hydrological model that works at daily or higher time step. Since flood simulation and modeling is generally carried out at sub-daily time step (hourly, 3-hourly or so), hydrological modeling has been carried out at 3-hourly time step for the intermediate part of the Chenab basin (Premnagar to Akhnoor). Short-term data availability has been investigated from different departments and very limited data of only one event could be gathered. Synthetic unit hydrograph has been generated for the intermediate catchment and flood event has been simulated. This analysis is presented in Chapter – 4.

* * *

Chapter - 2
STUDY AREA AND DATABASE DEVELOPMENT

2.1 The Chenab River Basin

The river Indus rises from the Tibetan plateau and enters the Himalaya in Ladakh. It enters the Kashmir region near its confluence with the river Gurtang, at an elevation of about 4200 metres. The drainage basin of the Indus river system extends from the Naga Parbat in the extreme North-Western part of the country to the Western slopes of the Shimla ridge in Himachal Pradesh. It includes the whole of Jammu and Kashmir and most of Himachal Pradesh. The extreme Northern tract of the Indus basin comprises of the cold desert of Ladakh, Lahaul-Spiti and Pooh. South of this tract lies the higher Himalayan mountain wall. Lower and middle Himalayas occupy the central part of the Indus basin. The low rolling Shivalik hills occur along its Southern periphery. Climatic conditions in the Indus river system vary from arctic to sub-tropical. The cold desert area remains devoid of rainfall and experiences heavy snowfall. The important rivers of this system are the Satluj, the Beas, the Ravi, the Chenab and the Jhelum.

The Chenab basin in India is spread over the two states, Himachal Pradesh and Jammu and Kashmir, which comprises the extreme western sector of Himalayas. Upper catchment lies in Lahaul area and Pangi Tehsil of Chamba district of Himachal Pradesh. This region is roughly rectangular in shape with main Himalayas on the north, and mid Himalayas on south. These hills rise to a mean elevation of about 5480 m. The total catchment area of the basin up to Akhnoor is about 22,770 km^2. On an average, about 70% of the total drainage area is covered by snow in the month of March/April and about 25% remains under permanent snow cover. The Chenab valley is a structural trough formed by the great Himalayan and Pir Panjal ranges. A view of the Chenab river basin is shown in Figure – 2.1.

The Chenab is formed after the two streams namely the Chandra and Bhaga which merge together near Tandi in Himachal Pradesh. The Chandra and Bhaga originate at about 5412 m and 4891 m from the north and south faces of Baralacha pass respectively in Lahaul Spiti Valley. The Chandra initially flowing south-east for about 88 km sweeps round the base of mid – Himalayas and joins Bhaga.

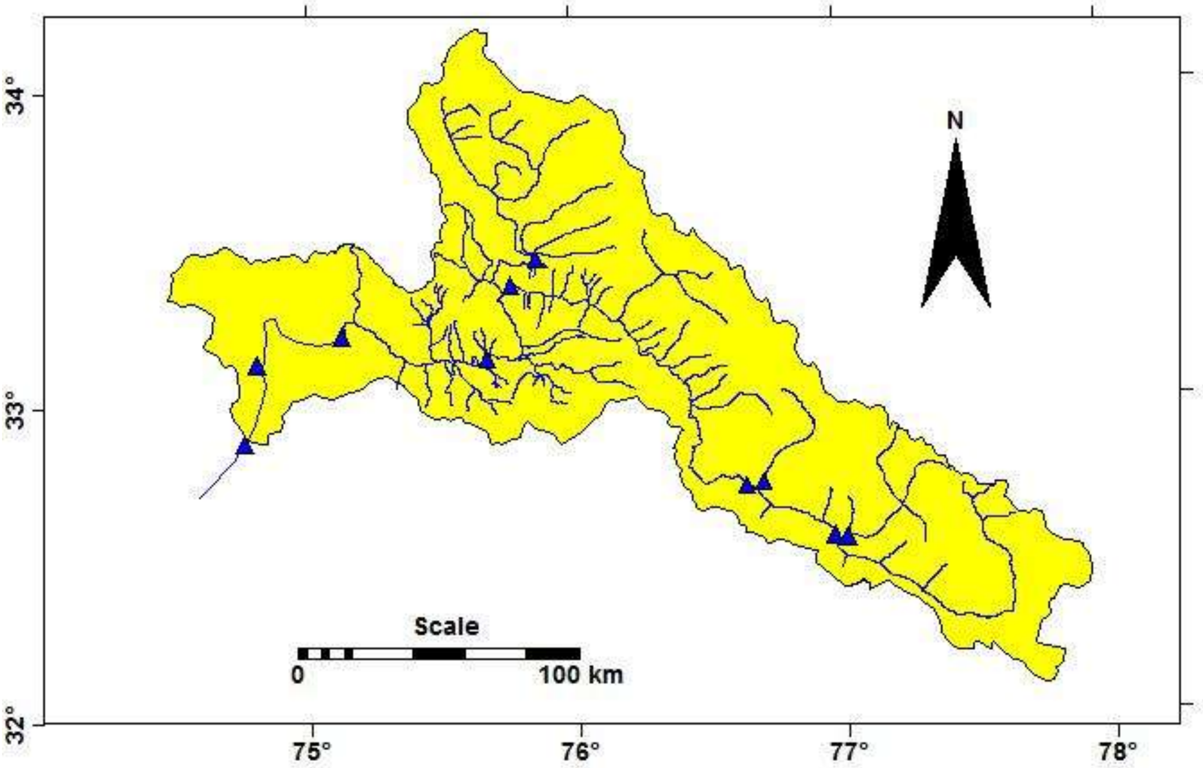

Figure – 2.1: Layout of Chenab River Basin up to Akhnoor

The Bhaga stream originates from the Lahaul valley. A number of snowfed-rivers join it during its course, before it joins the Chandra stream at Tandi. From its origin, the Bhaga river flows in South-South-Westerly direction as a raging torrent before joining the river Chandra. U-shaped valleys, waterfalls, glaciers and moraines characterises the upper catchment of the Bhaga river. The entire tract is devoid of a vegetative cover. The discharge of this river increases during the summer months, when the snow on high mountains begins to melting.

The Chandra river rises in the snows lying at the base of the main Himalayan range in Lahaul-Spiti district. Thereafter, it flows for a considerable distance along the base of thin range in the South-East direction, before making a 180° turn and taking a South-West course in Spiti valley. The entire area is a vast cold desert that receives little or no rain as it lies in the rain shadow of the Pir Panjal range lying towards South. The important human settlement along this river is Koksar.

Total lengths of the Chandra and the Bhaga up to their confluence are about 125 km and 80 km respectively. The combined river, known as the Chenab flows in a north – westerly direction for about 48 km where it is joined by a major tributary, the Miyar Nallah on the right bank. Thereafter, it flows for about 96 km generally in northerly direction in Himachal Pradesh and crosses the Pangi Valley before entering into the Paddar area of Doda district of Jammu and Kashmir. The river flows in a north-west direction for about 61 km where it is joined by its biggest tributary, the Marusudar on right bank near Bhandalkot. Further, downstream the river flow in a southerly direction for about 32 km up to Thathri where it takes a west-ward turn. After about 15 km downstream of Thathri, the Chenab is joined by Niru – Nalla on left bank. Thereafter, it flows in north-west direction for another 41 km till it receives another right bank tributary called Bichleri. Afterwards it flows in westerly direction for about 64 km. In this reach, a number of streams such as Chenani, Talsuen, Yabu, Ans join on the right bank and Panthal Khud on the left bank.

Downstream of Ans confluence, the river takes southerly course and flows for about 55 km up to Akhnoor whereafter it enters Pakistan. The total length of the river between Akhnoor and Chandrabhaga confluence is about 410 km. The entire course of the river in India is through high cliffs except for a small length of about 32 km between Akhnoor and Reasi. The elevation in the Chenab basin up to Akhnoor varies from 308 m to 7042 m. The layout of the basin boundary over the DEM obtained from SRTM data is shown in Figure – 2.2 and the color-shaded relief map of the basin is presented in Figure – 2.3.

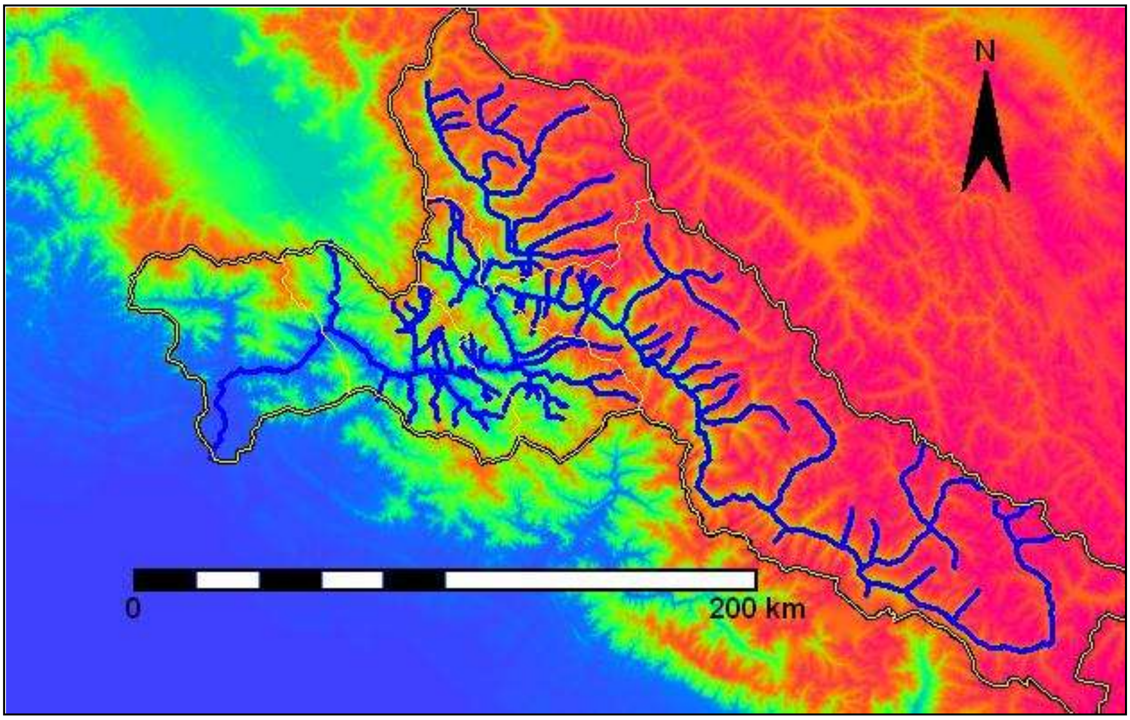

Figure – 2.2: Layout of Chenab basin boundary over the DEM

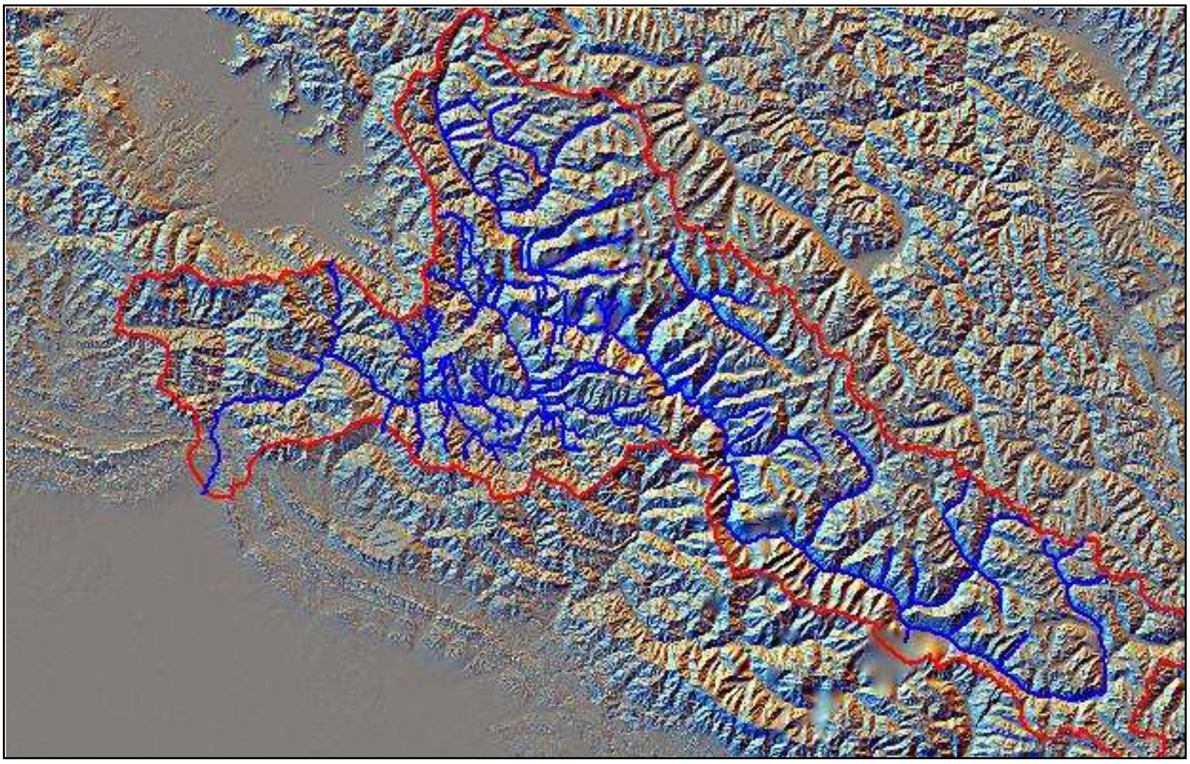

Figure – 2.3: Color-shaded relief map of Chenab basin up to Akhnoor

A view of the Chenab River emerging from the steep mountains and upstream of the Akhnoor gauging site is shown in Figure – 2.4.

Figure – 2.4: A view of the Chenab River in April upstream of Akhnoor

2.1.1 Climate in the Chenab Basin

The climate in the upper Chenab is arid and extreme cold especially in the Lahaul area. Rainfall is scanty and snowfall is very heavy due to which the area remains almost cutoff from rest of the country during winter season. Average maximum temperature at Keylong area ranges from 0.7°C in February to 23.1°C in August and average minimum from -10°C in February to 10°C in July. Average rainfall in Lahul area is about 45 cm. In Pangi the rainfall is further less and seldom it exceeds 30 cm annually.

Lower down in Jammu and Kashmir, the elevation of the catchment varies widely from about 7000 m high mountain peaks to 300 m at Akhnoor, thus giving rise to extraordinary variety of climatic conditions. The local variations of temperature mainly depend upon the location, elevation and amount of winter snowfall, its period and depth. The average annual rainfall in the basin is about 121.7 cms.

2.1.2 Hydropower Potential in the Chenab Basin

The river Chenab and its tributaries flow through deep gorges having steep bed slope and a number of bends in its course. The elevation of the catchment varies widely from 305 m to 7000 m. The bed slope is about 10 m/km in the higher reaches and 3 to 4 m/km in the lower reaches. These characteristics provide excellent prospects of hydro power generation. The total power potential as estimated is of the order of 11400 MW (CWC, 1996).

2.2 Hydrological Network in Chenab River Basin

There are nine river gauging sites of Central Water Commission (CWC) in the Chenab basin up to Akhnoor. Long-term data at these sites are available at daily time step. The Irrigation and Flood Control Department, Govt. of J & K also has one river gauging station at Akhnoor. Further, there are 24 rainfall measuring stations of CWC located in various parts of the basin. The layout of river gauging stations is shown in Figure – 2.5 while the rainfall stations are shown in Figure – 2.6. There are two CWC meteorological stations at Akhnoor and Sirshi. The Sirshi station has been closed since 1995. In addition, there are two meteorological stations of IMD in the basin at Batote and Bhaderwah. The data at these stations are available up to 2001.

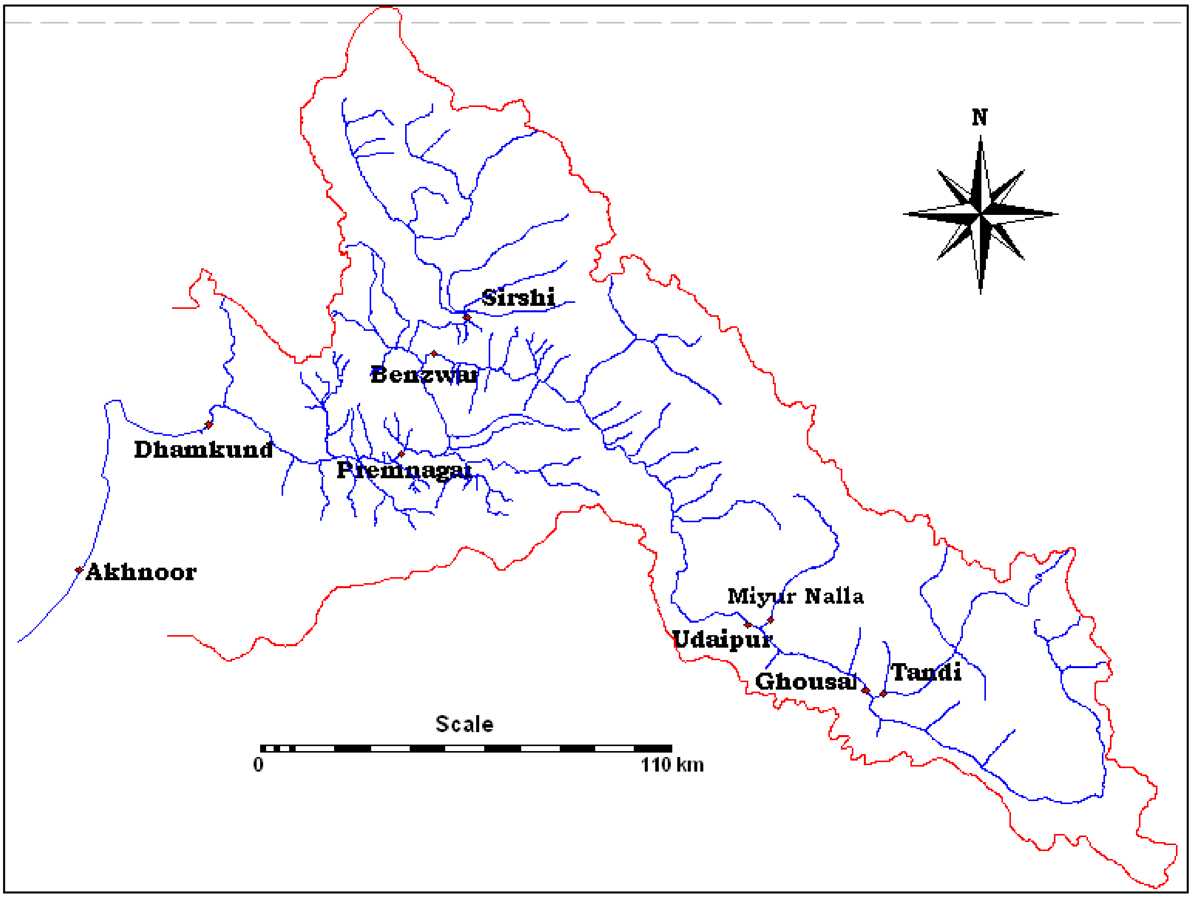

Figure – 2.5: Network of river gauging stations in Chenab basin up to Akhnoor

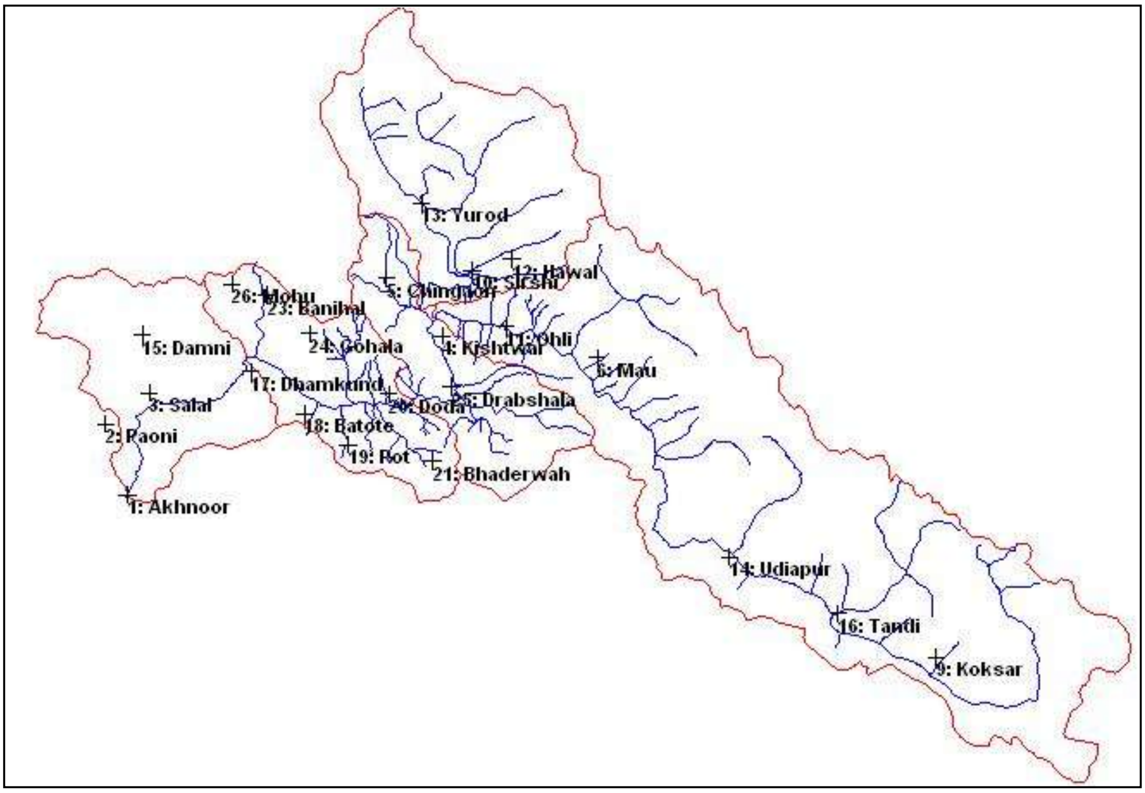

Figure – 2.6: Raingauge stations in the Chenab basin up to Akhnoor

From the hydrological network, it is observed that very few rainfall and snow gauging stations have been provided in snow-dominated areas in upper part of the basin. Most of the stations are concentrated in the middle and lower parts of the basin. In addition, the meteorological observations are continuously being observed at Akhnoor and the data of this site can be used for snow-melt modeling.

2.3 Availability & Plots of Hydrological Data

The rainfall and discharge data of different CWC stations have been available from 1967 to 2007. Since the present study concentrates on the flood generation aspect of the basin, daily plots of discharge data at different gauging stations has been carried out for those years that have experienced flood events of varying magnitude. The rainfall and discharge data of CWC has been entered in computer in the SWDES (Surface Water Data Entry System) system and plots have been generated. To take into account the recent hydrological conditions in the catchment, the years having significant flood events since 1990 have been considered. The years that have observed significant flood events include 1992, 1993, 1996, and 1997. The plots of discharge data for these years (from November to subsequent October) are shown in Figure 2.7, 2.8, 2.9, and 2.10 respectively.

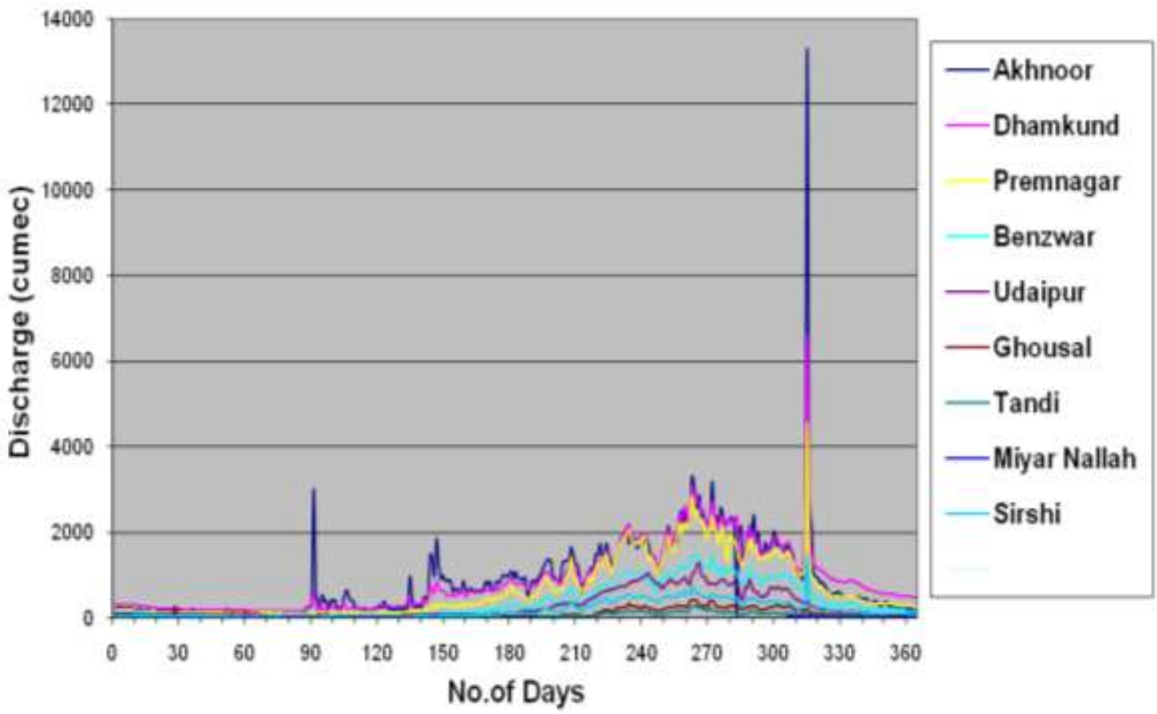

Figure- 2.7: Plot of discharge at different stations during Nov 1991 to Oct 1992

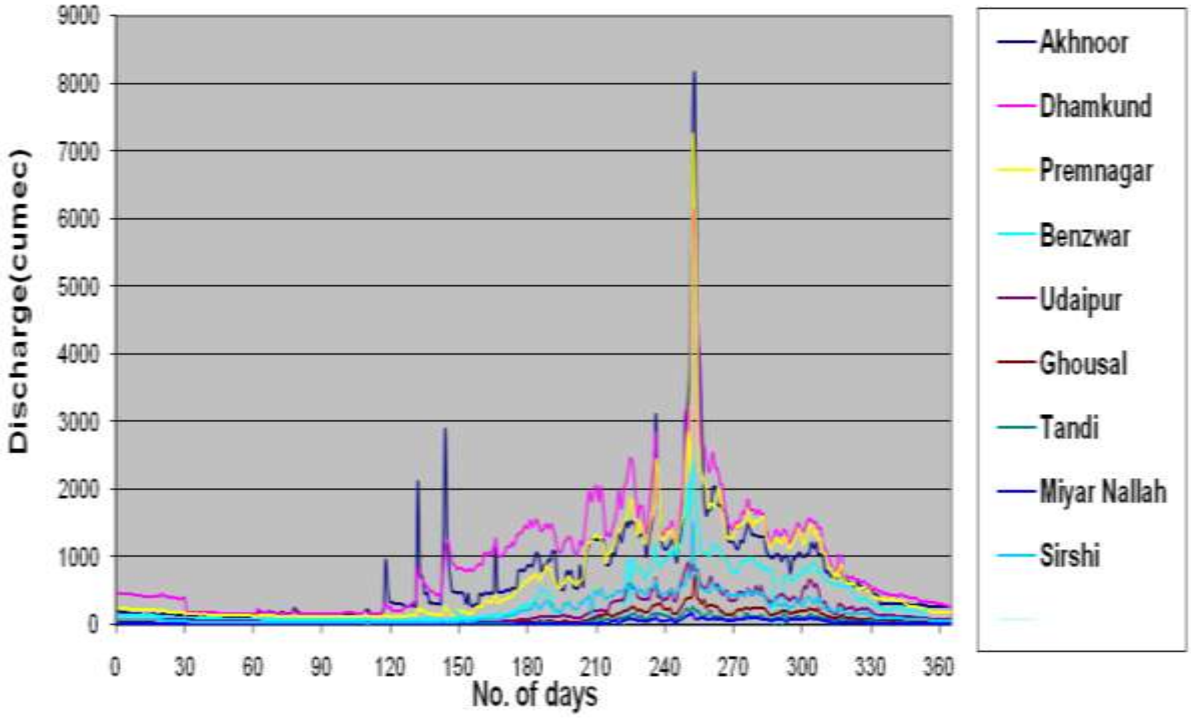

Figure- 2.8: Plot of discharge at different stations during Nov 1992 to Oct 1993

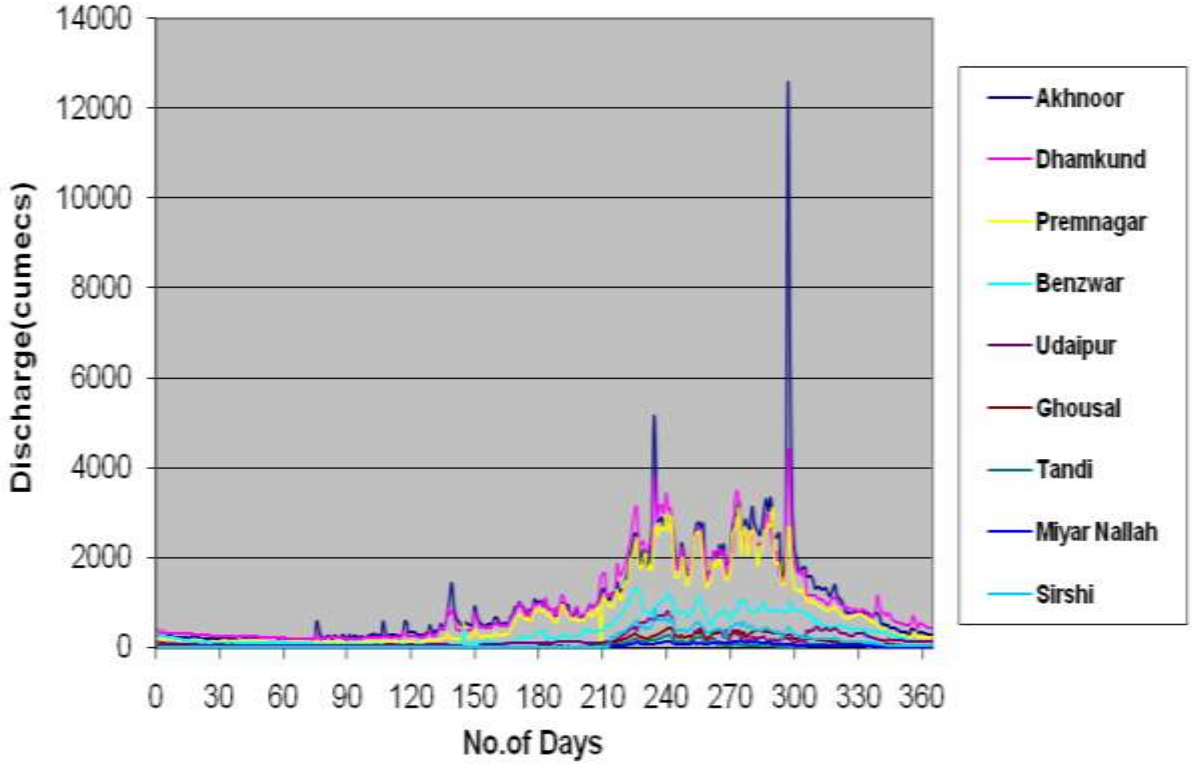

Figure- 2.9: Plot of discharge at different stations during Nov 1995 to Oct 1996

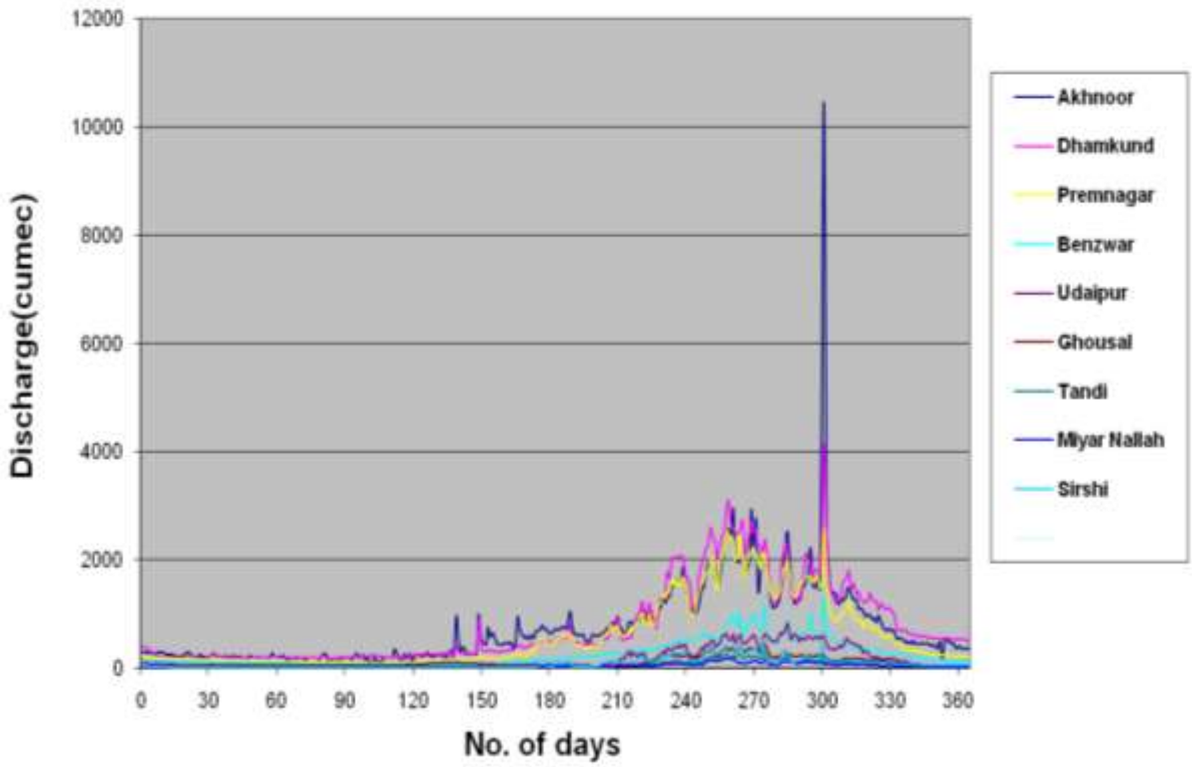

Figure- 2.10: Plot of discharge at different stations during Nov 1996 to Oct 1997

Since the flood simulation in the Chenab basin requires short-term (hourly or so) discharge and rainfall data at different gauging stations, the availability of the same was investigated from different departments. Hourly discharge data of CWC were available at Akhnoor gauging site only for the flood event of year 2006 (during September 01 – 06, 2006). However, hourly rainfall data at any station of CWC or State Irrigation Department were not available. Then, availability of such data from other departments was investigated and 3-hourly rainfall data of Salal rainfall station of NHPC (National Hydro Power Corporation), Jammu could be obtained for this flood event. A plot of the hourly discharge data of Salal and Akhnoor and the corresponding average rainfall for the flood event of September 01 – 06, 2006 is shown in Figure – 2.11.

2.4 Derivation of Spatial Basin Information Using GIS

Various types of spatial data have been used for the modeling study. Spatial database includes maps related to basin boundary, river network, elevation, slope, sub-basins corresponding to different gauging sites, elevation bands for different range of elevations, and Thiessen polygons of rainfall stations.

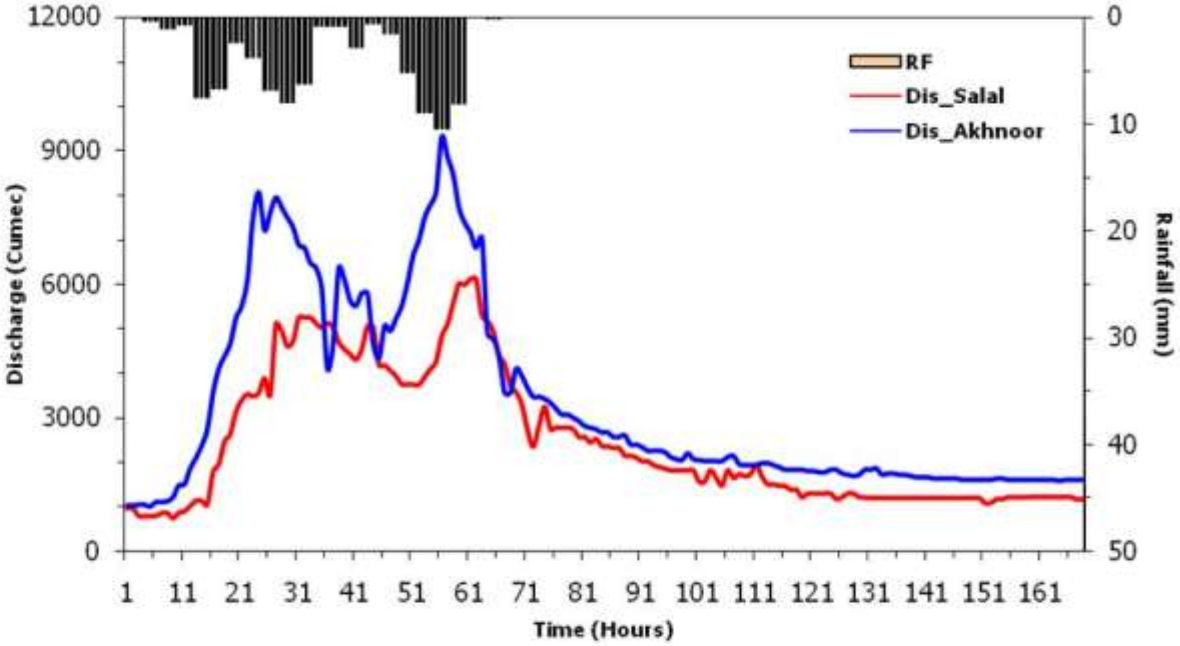

Figure – 2.11: Observed flow at Salal & Akhnoor and average basin rainfall pattern (3-hourly) during September 1 – 6, 2006

All the spatial data have been developed in GIS. ILWIS GIS system, a system in public domain, has been used. Because of the availability of the 90 m resolution digital elevation map of the area from SRTM data, grid size of analysis has been kept as 90 m. All the data layers have been generated with "Polyconic" projection, ellipsoid "Everest 1956", datum "Indian (India, Nepal) and origin coordinates as 74˚ E longitude and 32˚ N latitude.

Maps related to basin boundary, slope, drainage network, and sub-basin have been derived from the GIS analysis of digital elevation map of a river basin. In the present study, these maps for the Chenab River basin have been generated by using the "DEM Hydro-processing" module of ILWIS. The SRTM data for the Chenab basin at 90 m resolution has been downloaded from the internet and it is geo-referenced to the topographical maps of the area (from the Survey of India) by using the major drainage network. Using the digital elevation map, DEM Hydro-processing module generates maps of slope, flow direction, drainage network, flow accumulation and sub-basins at specified gauging stations.

In the present study, the Chenab basin up to Akhnoor gauging site has been considered. So, the basin area corresponding to the outlet (coordinates of the Akhnoor gauging site) has been obtained. The total area of the Chenab River basin up to Akhnoor gauging site comes out to be 22769.613 sq. km. The drainage map of the basin is already presented in Figure – 2.1 and the basin boundary map of Chenab basin superimposed on the DEM of the area is presented in Figure – 2.2. The drainage map obtained from the DEM analysis had a close match with the digitized drainage map from the SOI toposheets. The sub-basin map corresponding to different gauging stations is depicted in Figure – 2.12.

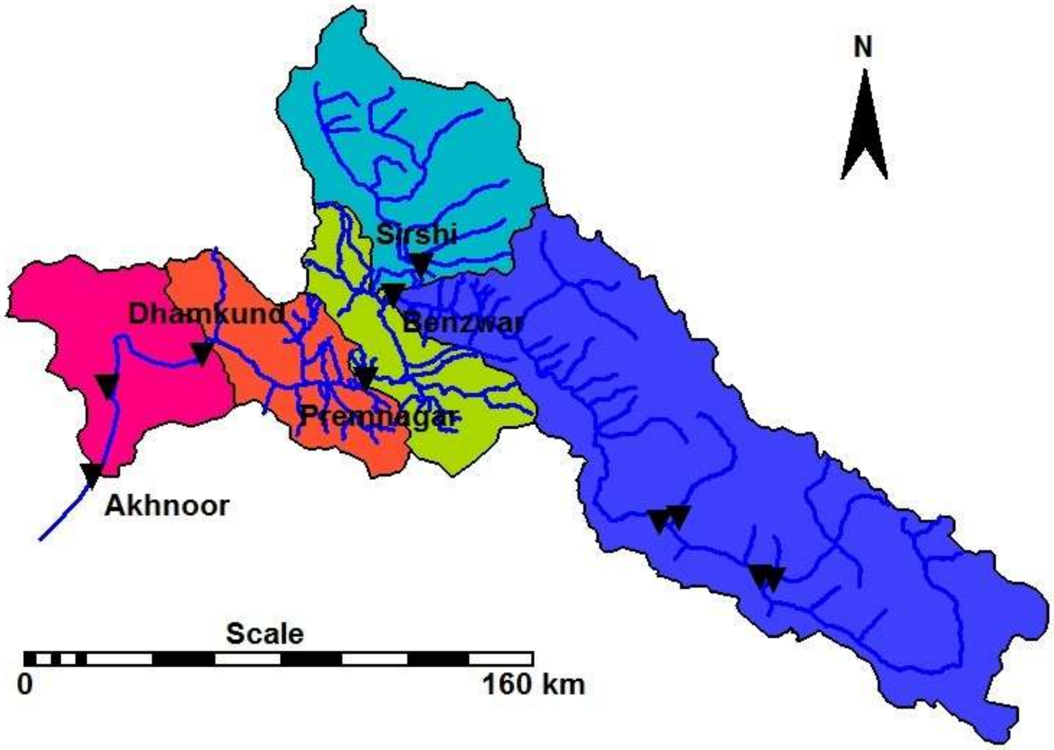

Figure – 2.12: Five major sub-basins in the Chenab River basin

In the demarcation of various sub-basins, five sub-basins have been drawn corresponding to Benzwar, Sirshi, Premnagar, Dhamkund, and Akhnoor gauging sites. Upstream of Benzwar, the sub-basin mostly remains snow-covered and is considered as one sub-basin. Further, though the Sirshi gauging site is located on the distributary of the Chenab River, the corresponding sub-basin is marked at its confluence with the Chenab River. The areas of different sub-basins are shown in Table - 2.1.

Table – 2.1
Areas of different sub-basins of Chenab River basin

Gauging site Description	Area (Sq. km)
Up to Benjwar	11278.16
Up to Sirshi	4221.364
Below Sirshi up to Premnagar	2226.421
Premnagar to Dhamkund	2381.451
Dhamkund to Akhnoor	2662.22

The elevation range in the Chenab River basin up to Akhnoor ranges between 328 to 7042 m. For the application of a snow-melt model for the basin, the basin has been divided into seven different elevation ranges as: Zone-1 (up to 1000 m), Zone-2 (1001 to 2000 m), Zone-3 (2001 to 3000 m), Zone-4 (3001 to 4000 m), Zone-5 (4001 to 5000 m), Zone-6 (5001 to 6000 m), and Zone-7 (greater than 6000 m). The map showing the elevation bands is depicted in Figure – 2.13 and the areas of Chenab basin falling within different elevation bands are presented in Table - 2.2.

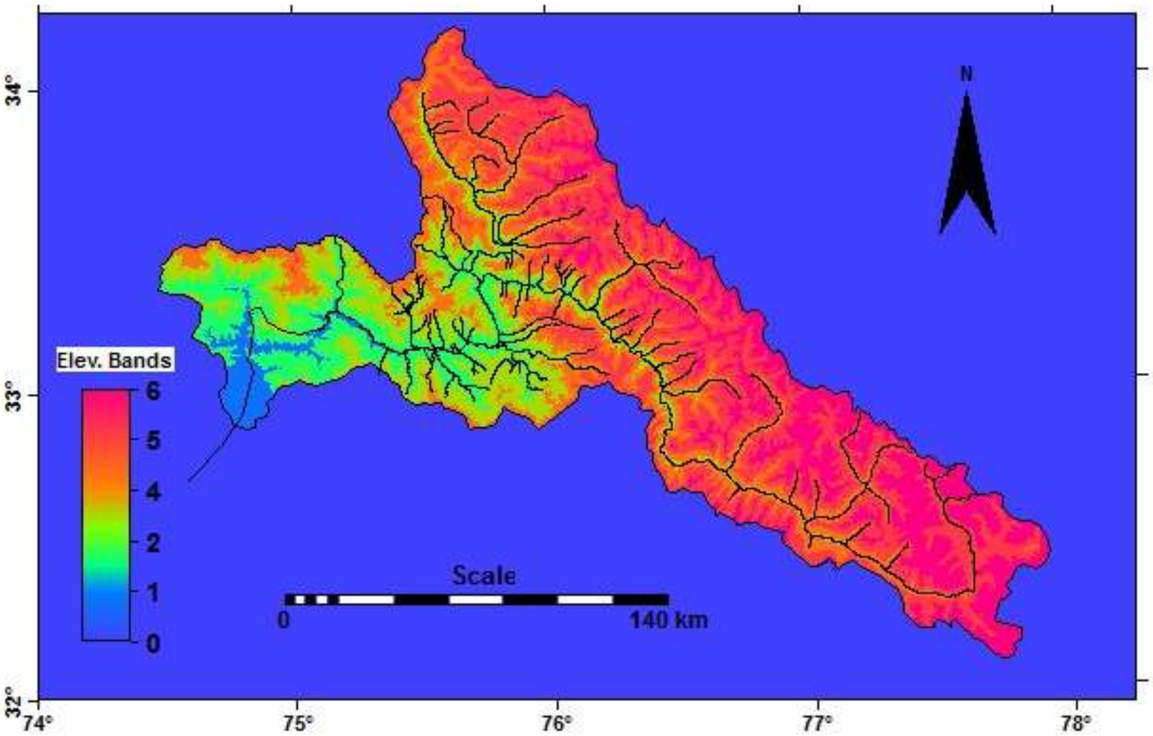

Figure – 2.13: Different elevation bands in Chenab River Basin

Table – 2.2
Areas of different elevation bands in Chenab basin

Elevation Range (m)	Elevation Band	Area (Sq. km)
Up to 1000	1	21.23
1001 – 2000	2	3516.53
2001 – 3000	3	6691.27
3001 – 4000	4	4760.01
4001 – 5000	5	3713.45
5001 – 6000	6	2455.95
Greater than 6000	7	866.18

Since the present study is concerned with the flood simulation which is mostly generated in the middle and lower parts of the Chenab basin, the snowmelt runoff model has been applied to the middle and lower parts of the basin (below Sirshi and Benjwar gauging sites). The elevation bands below the Sirshi and Benjwar sub-basins are shown in Figure – 2.14 and their areas are shown in Table – 2.3.

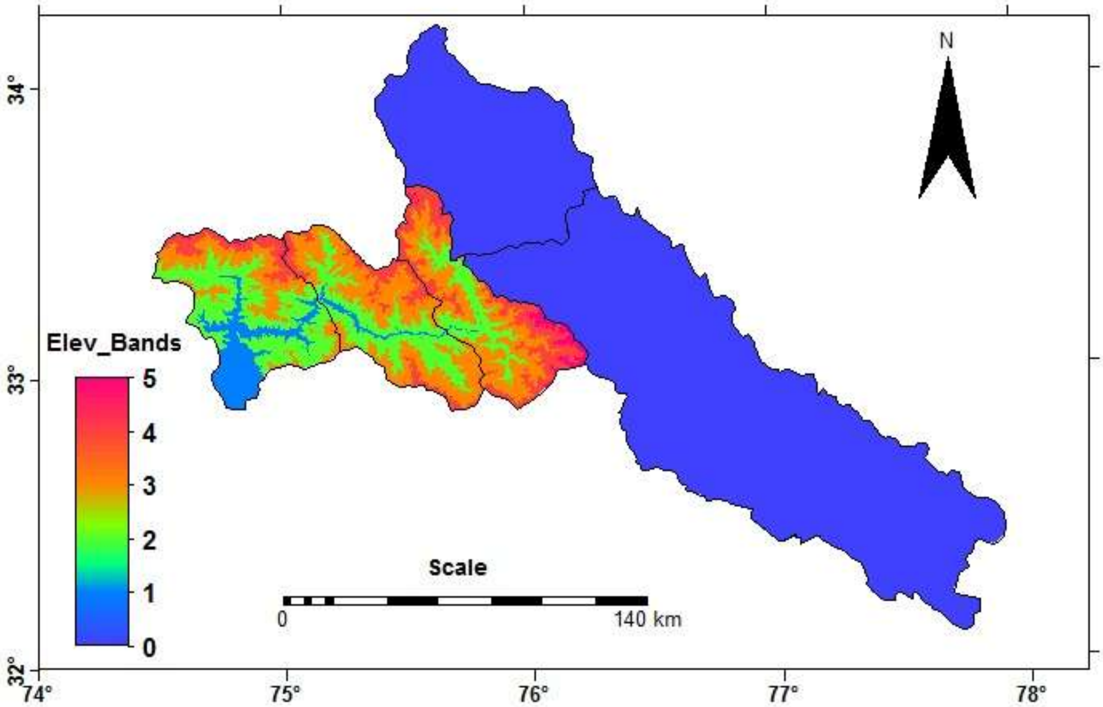

Figure – 2.14: Elevation bands below Sirshi and Benjwar sub-basins

Table – 2.3
Areas of elevation bands below Sirshi/Benjwar sub-basins

Elevation Range (m)	Elevation Band	Area (Sq. km)
Up to 1000	1	706.05
1001 – 2000	2	2386.37
2001 – 3000	3	2740.36
3001 – 4000	4	1254.06
Greater than 4000	5	182.74

In addition to the spatial data as specified above, thiessen polygon of various rainfall stations available for a flood event have also been derived from the GIS analysis. The thiessen polygone map of various rainfall stations is shown in Figure – 2.15 and the weights of different stations are presented in Table – 2.4.

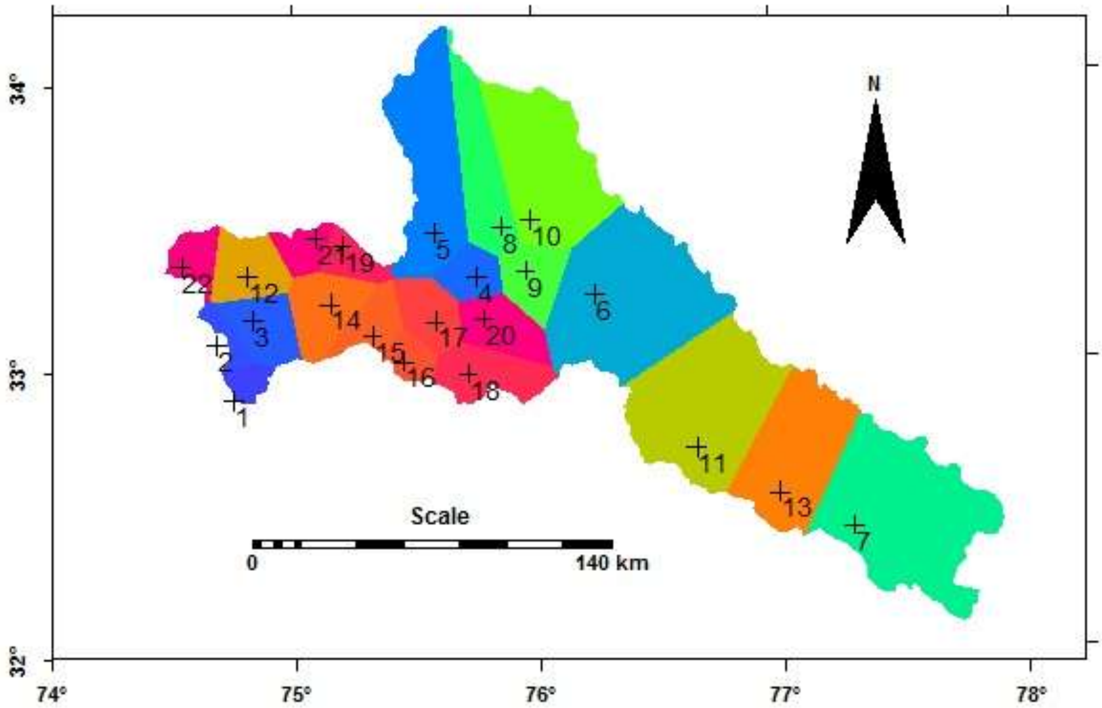

Figure – 2.15: Thiessen polygon of different rainfall stations

Table – 2.4
Weights of different rainfall stations in Chenab basin

Station Name	Numeric Identity	Weight
Akhnoor	1	0.008845
Paoni	2	0.00855
Salal	3	0.026658
Kishtwar	4	0.017748
Chingaon	5	0.084605
Mau	6	0.134958
Koksar	7	0.13755
Sirshi	8	0.048234
Ohli	9	0.025556
Hawal	10	0.091958
Udaipur	11	0.115213
Damni	12	0.028564
Tandi	13	0.080208
Dhamkund	14	0.031978
Batote	15	0.019294
Rot	16	0.011898
Doda	17	0.024329
Bhaderwah	18	0.031869
Banihal	19	0.014737
Drabshala	20	0.02786
Mohu	21	0.013916
Nandan	22	0.015472

It needs to be mentioned here that for different storm events in different years, data of some rainfall stations were not available. So, based on the availability of data, stations have been selected for various flood events and respective thiessen polygons have been prepared and weights have been worked out for computing the average rainfall.

For application of the snowmelt model at daily time step, thiessen polygon map has been convoluted with the elevation band map to work out the weights of different stations in different elevation bands so that average rainfall in each band could be worked out. For the unit hydrograph based model application at sub-daily scale, the average rainfall in the sub-basin between Premnagar and Akhnoor has been worked out by estimating the weights of different stations in this part of the basin. GIS has been frequently used for this purpose.

* * *

Chapter - 3
APPLICATION OF SNOWMELT RUNOFF MODEL

3.1 Characteristics of Chenab River Basin

Chenab basin forms the boundary of Monsoon-arid transition zone in the Himalaya (Mayewski and Jeschek, 1979, Wagnon et al., 2007). The Chenab basin up to Akhnoor covers an area exceeding 22,000 km^2 and has an altitudinal extent from 300 to 7200 m a.s.l. This is one of the major glacier bearing basins of the Indus River. There are 1278 glaciers in the basin covering an area of 2300 km^2 (Raina & Srivastava, 2008). In winter, snow covers major part of the basin ranging from 67.6 to 74.9% of the basin area and by the end of the summer season snow cover area reduces to 18.1 to 31.6% (Singh et al., 1997). While hydrology of the higher altitude region is dominated by snow and glaciers, monsoon plays the dominant role in the lower part of the basin. The outer Himalayan region with an altitude range of 300 to 1000 m a.s.l. experiences highest rainfall. Along the outer Himalayan range, annual average precipitation is around 1728 mm. On the other hand, average annual rainfall in the middle Himalayan range of the basin is 938 mm (Manohar et al., 2006). The rainfall stations operating between 2000- 3100 m a.s.l. show that average annual rainfall in this altitude band is around 356 mm.

3.2 Floods in the Chenab Basin

During past four decades (1967 – 2007), Chenab basin experienced 9 floods with peak discharge of 7000 cumec (m^3/sec) and above. During 1970's, there were two floods while in the 1980's only one flood occurred. 1990's witnessed five floods in regular intervals in 1992, 1993, 1995, 1996 and 1997. Three of them were severe floods with maximum discharge exceeding 10000 cumec. Among them, most severe flood was in 1992 and occurred on 10 September, 1992. This flood was so severe and forced Pakistan to initiate the Flood Protection Sector Project (FPSP-1) in 1994. Pakistan experienced another major flood in 1998, though data available for the Akhnoor gauging site did not show any high discharge in 1998. This suggests that the 1998 flood was generated from catchment areas in the Pakistan itself. The flood in 1998 affected 460,000 persons over an area of 2,555 km^2 in 1243 villages of Wazirabad, Gujrat and Sialkot tehsils of Pakistan (Awan, 2003). At Akhnoor, most severe flood occurred on 10

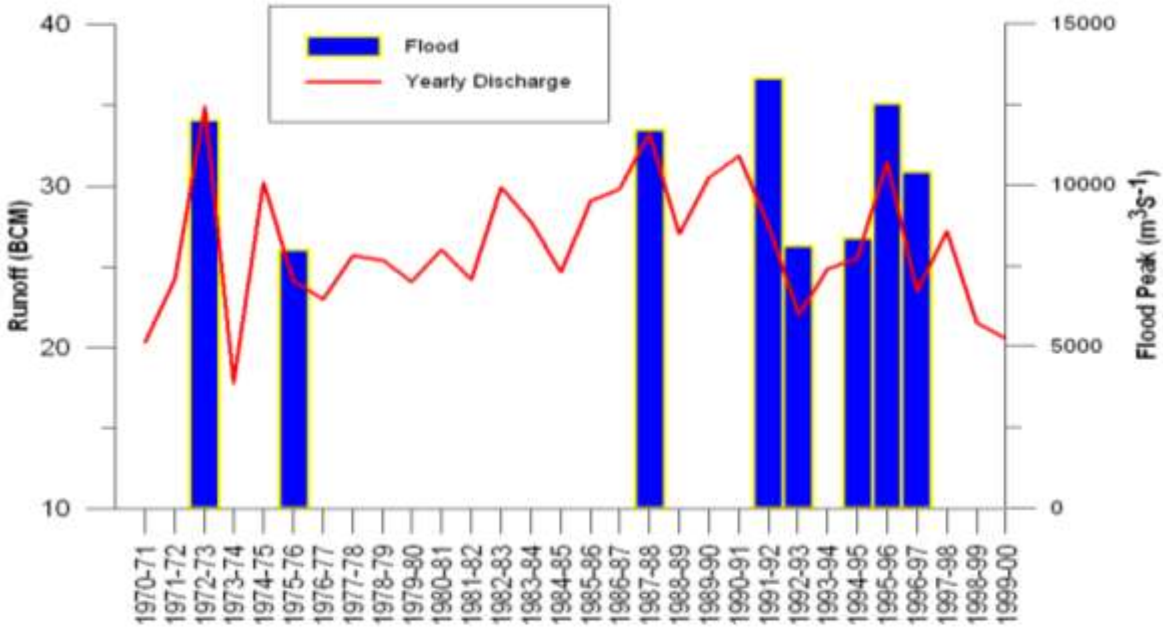

Figure-3.1: Occurrence of major floods at Akhnoor from 1970 to 2000

September, 1992 with a peak discharge of 13300 cumec. The second severe flood was on 23 August, 1996 with discharge of 12523 cumec as shown in Figure – 2.9.

Study of flood characteristics in the Chenab basin shows that most of the floods in the basin have occurred in months of August and September, which clearly indicates that snowmelt is not influencing the formation of floods at Akhnoor as the peak snowmelt usually occurs in the month of May and June. Out of nine major flood occurrences in the past 40 years (1967 – 2007), only two floods have occurred in the month of July. Both these floods were comparatively less severe with peak flood discharge reaching only 8365 cumec (as shown in Figure-3.2).

Further, analysis of daily flood hydrographs at different gauging stations along the stream continuum from high altitude snow and glacier zones to lower precipitation dominant areas has been studied. Discharge station at Benzwar covers most of the snow and glacier areas of the catchment. Between Benzwar and Premnagar stations, only Marusudar river brings in snow and glacier melt water to the River Chenab. From the plots of discharge data at various gauging sites for various flood events, it is clear that major flood in Chenab basin is generated below the Benjwar/Sirshi gauging sites. The difference is most prominent along the crest of the annual hydrograph, when monsoon is active. It is clear from Figure – 3.2 that formation of floods generally take shape along the stream continuum below

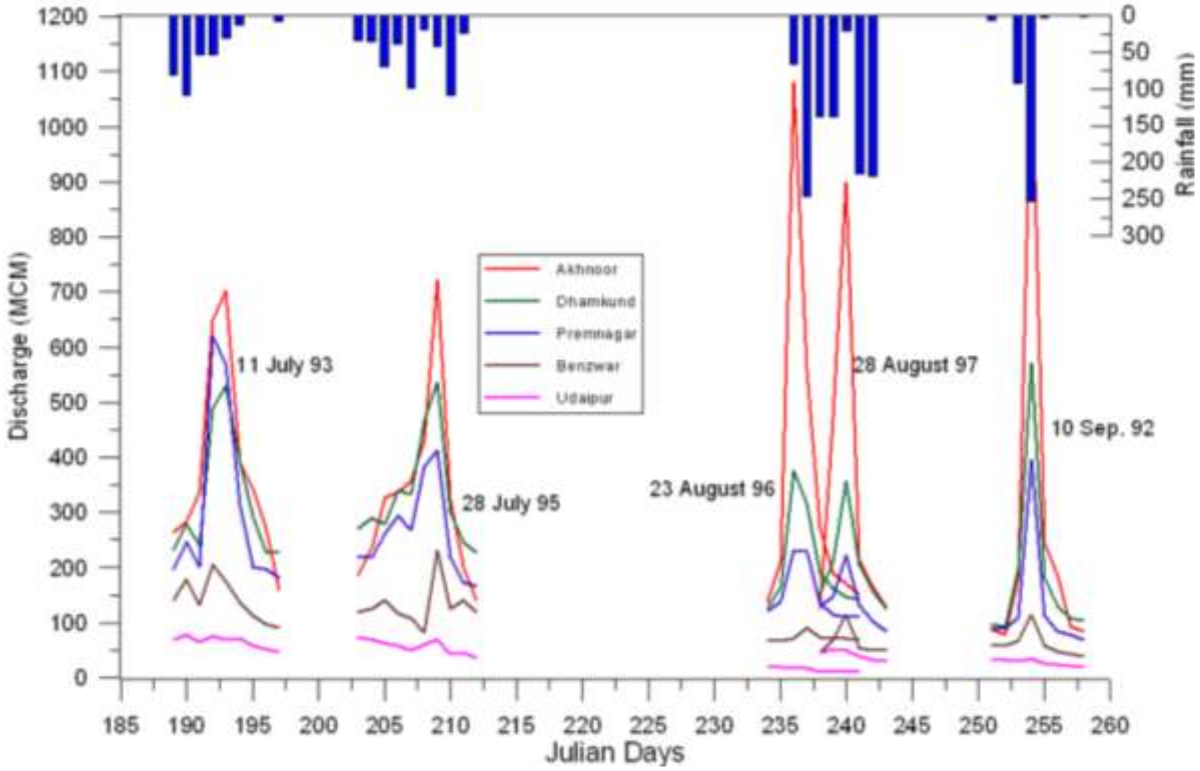

Figure – 3.2: Illustration of different flood events along stream continuum

Sirshi/Benjwar up to Akhnoor. This area falls in the outer and middle Himalayas, where highest monsoon rainfall occurs. This clearly shows that in most of the major flood events at Akhnoor, snow and glacier melt have no role to play. After these observations, flood simulation analysis has been carried out for the part of the basin below Benjwar/Sirshi up to Akhnoor.

3.3 Storm Distribution in the Chenab Catchment

In the present study, focus is on the floods occurred in the 1990's, which include two major floods of 1992 and 1996. A comparative study of each flood generating storm in various raingauge stations in the basin has also been carried out. A plot of storm distribution in the stations belonging to different river segments is shown in Figure - 3.3. This plot shows that the lowest segment of Chenab basin in India (Dhamkund to Akhnoor) experiences highest precipitation during all the storms which highlights the important role of this area in generating flood at Akhnoor. Among five storms analysed, the Poani raingauge station recorded the highest precipitation at all times. However, measurement of rainfall at this station has been discontinued since 2000. Storm distribution studies show that of the various rainfall stations in the Chenab basin, only seven stations

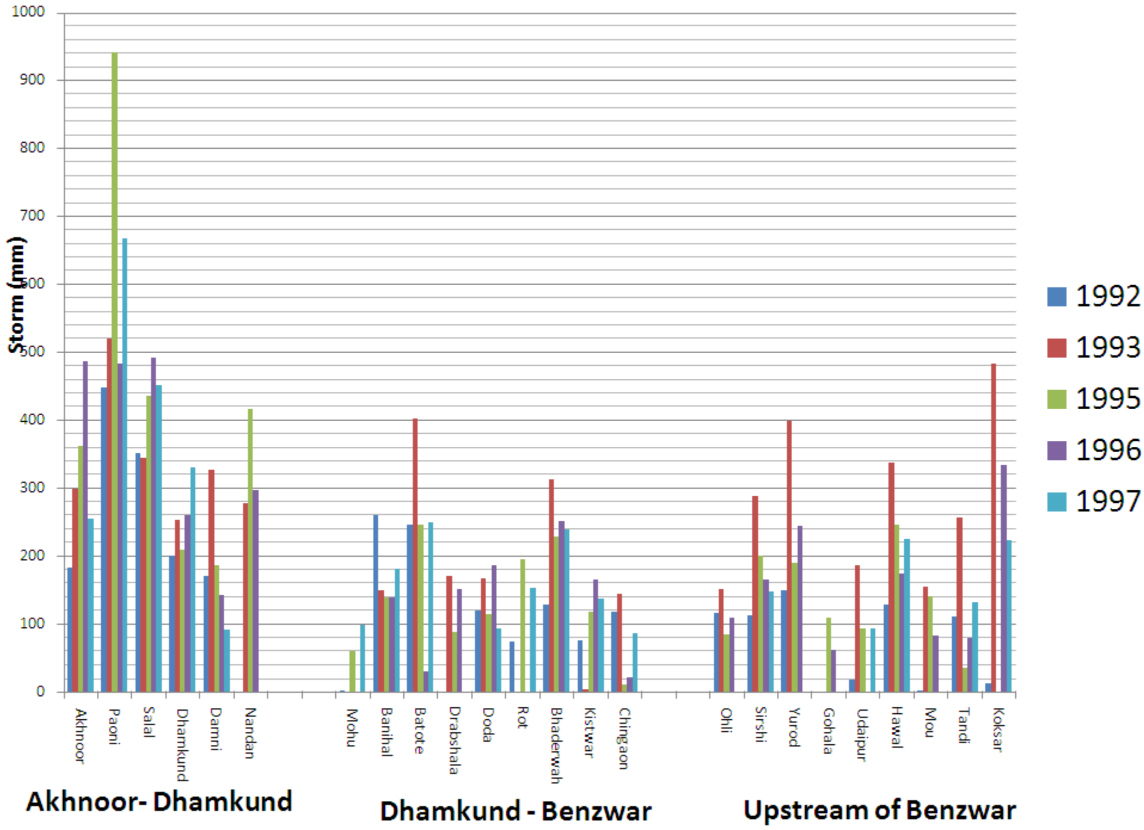

Figure – 3.3: Distribution of flood generating storm along different river segments

experienced storms during all the five instances. These stations are Akhnoor, Banihal, Bhaderwah, Dhamkund, Hawal, Paoni and Salal. Hence it is realized that for any flood forecasting mechanism to be established in the Chenab basin, real-time monitoring of rainfall at these seven stations may be imperative. Among them, Paoni raingauge station seems to be the most important. Capturing of rainfall distribution in mountainous region is a challenging task, especially during a storm event. However, we could develop index stations for the flood warning purpose and Poani station is the most important one. The storm distribution recorded at various raingauge stations for various storm events is presented in Table – 3.1.

3.4 Application of Snowmelt Runoff (SRM) Model for Chenab Basin

The WINDOWS version of Snowmelt Runoff Model (Win SRM) (USDA, 2006) computes the runoff from snowmelt and rainfall that is produced each day and superimposed on the calculated recession flow and transformed into daily discharge at the basin outlet according to equation (3.1):

$$Q_{n+1} = [c_{sn}.a_n(T_n+\Delta T_n)S_n+C_{Rn.}\ P_n].A.10000/86400(1-K_{n+1}) + Q_nK_{n+1} \quad ...(3.1)$$

Table – 3.1
Storm distribution (mm) at various raingauge stations in Chenab basin

Raingauge Stations	Recorded Rainfall for Storm Events (mm)				
	7-14 Sept. 1992	7-15 July 1993	22-31 July 1995	21-28 Aug. 1996	26-31 Aug. 1997
Akhnoor	**184**	**298**	**363**	**487**	**255**
Banihal	**260**	**150**	**139**	**139**	**180**
Batote	246	402	246	31	250
Bhaderwah	**128**	**313**	**229**	**252**	**239**
Chingaon	117	145	12	22	86
Damni	171	327	186	143	92
Dhamkund	**201**	**254**	**210**	**261**	**331**
Doda	119	168	115	187	94
Drabshala	0	170	88	151	
Gohala			110	62	
Hawal	**129**	**337**	**246**	**174**	**226**
Kistwar	76	4	117	165	137
Koksar	12	483	0	334	224
Mohu	2		60	0	99
Mov	2	155	141	84	
Nandan	0	277	416	298	0
Ohli	116	151	84	109	0
Paoni	**447**	**521**	**942**	**484**	**668**
Rot	74		195	0	152
Salal	**352**	**345**	**436**	**492**	**452**
Sirshi	112	288	200	165	147
Tandi	112	256	36	79	132
Udaipur	19	186	94	0	94
Yurod	150	399	190	245	

where Q is the average daily discharge [m^3s^{-1}], C is runoff coefficient expressing the losses as a ratio (runoff/precipitation) with C_s referring to snowmelt and C_R to rain, a is degree-day factor [$cm.^0C^{-1}.d^{-1}$] indicating the snowmelt depth resulting from 1 degree-day, T is the number of degree-days [$^0C.d$], ΔT is the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone[$^0c.d$], S is the ratio of the snow covered area to the total area, P is the precipitation contributing to runoff [cm], A is the area of the basin or zone [km^2], K is the recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall, and n is the sequence of days during the discharge computation period. K is computed as Q_{m+1}/Q_m where m and m+1 are the sequence of days during a true recession flow period.

A pre-selected threshold temperature, T_{CRIT}, determines whether this contribution is rainfall and immediate. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur. Equation 3.1 is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n+1 day. Factor (10000/86400) is used to convert discharge from $cm.km^2.d^{-1}$ to m^3s^{-1}. T, S and P are variables to be measured and specified for each day. c_R and c_S are the lapse rate parameters, and ΔT, T_{CRIT}, K and lag time are other parameters which are characteristic for a given basin or, more generally, for a given climate.

If the elevation range of the basin exceeds 500 m, it is recommended that the basin be subdivided into elevation zones of about 500 m each. For an elevation range of 1500 m and three elevation zones A, B and C, the model equation becomes

$$Q_{n+1}= \{[cs_{An}.a_{An} (T_n+\Delta T_{An})S_{An}+C_{RAn}.P_{An}]\ A_A.10000/86400+$$

$$[c_{SBn}.a_{Bn}(T_n+\Delta T_{Bn})S_{Bn}+c_{RBn}.P_{Bn}]\ A_B.10000/86400+$$

$$[c_{Scn}.a_{cn}(T_n+\Delta T_{cn})S_{cn}+c_{Rcn}.P_{cn}]A_C.10000/86400\}(1-K_{n+1})+Q_n.K_{n+1} \quad ...(3.2)$$

The indices A, B and C refer to the respective elevation zones and a time lag of 18 hours is assumed. Other time lags can be selected and automatically taken into account. In the simulation mode, SRM can function without updating. The discharge data serve only to evaluate the accuracy of simulation. In the forecasting mode, the model provides an option for updating by the actual discharge every 1-9 days.

3.4.1 Model parameters

As it is seen that flood at Akhnoor is always produced by the storm events in the lower reaches of Chenab basin, irrespective of the background flow produced by the snow and glacier melt, only the rainfall module of the SRM model is being used in the present study. The discharge generated by the rainfall below Benzwar and Shirshi stations has been calculated by subtracting the daily flow at Benzwar and Shirshi stations from the daily flow at Akhnoor. This discharge data has been used as input data in the model for calibrating the model. The total area contributing to the flood at Akhnoor below Benzwar/Sirshi is 7268 km^2.

For modeling purpose, this area has been divided into five 1000 m elevation bands as shown in Figure – 2.14 and Table – 2.3 ranging from 300 to 5000 m. Major part of the area is in the 1000 to 3000 m zone, which covers an area of 5126 km^2. Lower elevations, which experience highest rainfall in the 300-1000 m zone cover an area of 706 km^2.

Recession coefficient

The Recession coefficient (k) is an important parameter in the model. K has been determined by using the historical data. Using the values of Q_n and Q_{n+1} from the recession limb of flood hydrograph, k is determined as Q_{n+1}/Q_n. However, while considering the annual hydrograph the recession coefficient is not constant. Period of high flow and low flow can have different recession coefficients. The procedure adopted in the SRM manual has been adopted for determining k. Two parameters, k_1 and k_2 are related to the discharge as:

$$k_1 = X \,.\, Q_1^{-y}$$

$$k_2 = X \,.\, Q_2^{-y}$$

By solving these equations for two observed discharge values along the recession limb, we get X and Y values for a given basin. For discharge below Benzwar in the Chenab basin, values of X and Y have been estimated as 0.83 and 0.055 respectively. These values have been used in the model for flow simulation.

However, for heavy rainfall events, recession coefficient needs further adjustment. In the present study, this adjustment is very important as we are concerned with accurately simulating the flood peaks which is produced by heavy rainfall. In such situations, input is concentrated in a short time interval creating a sudden rise and fall in the hydrograph. The model has an inbuilt capacity to alter the recession coefficient for a rainfall above a defined threshold rainfall which is defined as 2 cm in the present study.

Runoff coefficient

Runoff coefficient of rainfall is another important parameter determining the runoff volume in the stream associated with a storm. In a mountain basin, precipitation distribution is hard to establish accurately, especially during a storm event. Present distribution of rain gauge stations is insufficient to capture the rainfall distribution during storms. In the present study, it is found that to simulate the flood peak, a runoff coefficient on 2.4 is required and this value is used consistently for all the years of simulation. This obviously affected the simulation of runoff during the non-strom periods, but keeping our objective of flood simulation in mind, this high value is considered appropriate. Some other studies in the Himalayan basins suggest that the rainfall could be as high as 4 - 5 times along the mountain ridges and peaks as compared to valley bottoms (Yasunari and Inoue, 1978). The present study is hugely constraint by the single value of discharge measured in a day. In the absence of hourly discharge during the flood it is difficult to find the runoff delay. So the delay period has been adjusted to match flood peak of each year, which varied between 3-6 hours.

Storm distribution

Average precipitation in different elevation bands has been computed by using the rainfall at different raingauge stations and the corresponding weights of those stations in various elevation bands (determined from GIS analysis). Analysis of the storm rainfall in various elevation bands show that the elevation band 300-1000 m a.s.l. experienced highest precipitation. Rainfall observed in the various elevation bands (absolute value and as percent of rainfall in lowest band (300 – 1000 m)) is shown in Table - 3.3.

Table – 3.2
Storm distribution in various elevation bands

		B-1	**B-2**	**B-3**	**B-4**	**B-5**
1992	**Total(mm)**	**280.1**	**174.6**	**103.4**	**75.3**	**46.6**
	% of B-1		62.4	36.9	26.9	16.6
1995	**Total(mm)**	**423.6**	**210.5**	**148.9**	**114.4**	**117.6**
	% of B-1		49.7	35.2	27.0	27.8
1996	**Total(mm)**	**409.8**	**213.4**	**143.3**	**109.3**	**90.6**
	% of B-1		52.1	35.0	26.7	22.1
1997	**Total(mm)**	**382.6**	**223.8**	**133.6**	**86.1**	**74.7**
	% of B-1		58.5	34.9	22.5	19.5

3.5 Simulation flood in the Chenab River

Simulation of daily flows in the Chenab basin, generated below Sirshi/ Benjwar gauging sites up to Akhnoor has been carried out for full years having significant flood events. Same values of model parameters have been used for different years and they have been fine-tuned so as to closely match the observed flows. The comparison of simulated flows obtained from WINSRM application and the observed flows for different flood events is presented below.

3.5.1 Simulation of 1992 flood

Flood in the Chenab river in 1992 occurred on 10 September and peak discharge observed at Akhnoor was 13300 cumec. This was the biggest flood recorded in the Chenab river during the past four decades. Flood peak at Premnagar and Bezwar was much lower at 4569 m^3/sec and 1315 m^3/sec respectively. Flood peak after subtracting the Benzwar and Shirshi station was 10513 m^3/sec. Figure - 3.4 shows the zone-wise precipitation distribution deduced by the Theissen polygon method and Figure – 3.5 shows the simulated flood. The simulated flood peak is 8801 m^3/sec, which is lower than the observed flood peak for Premnagar- Akhnoor section. This clearly shows the difficulty in capturing the storm distribution in the mountain catchments.

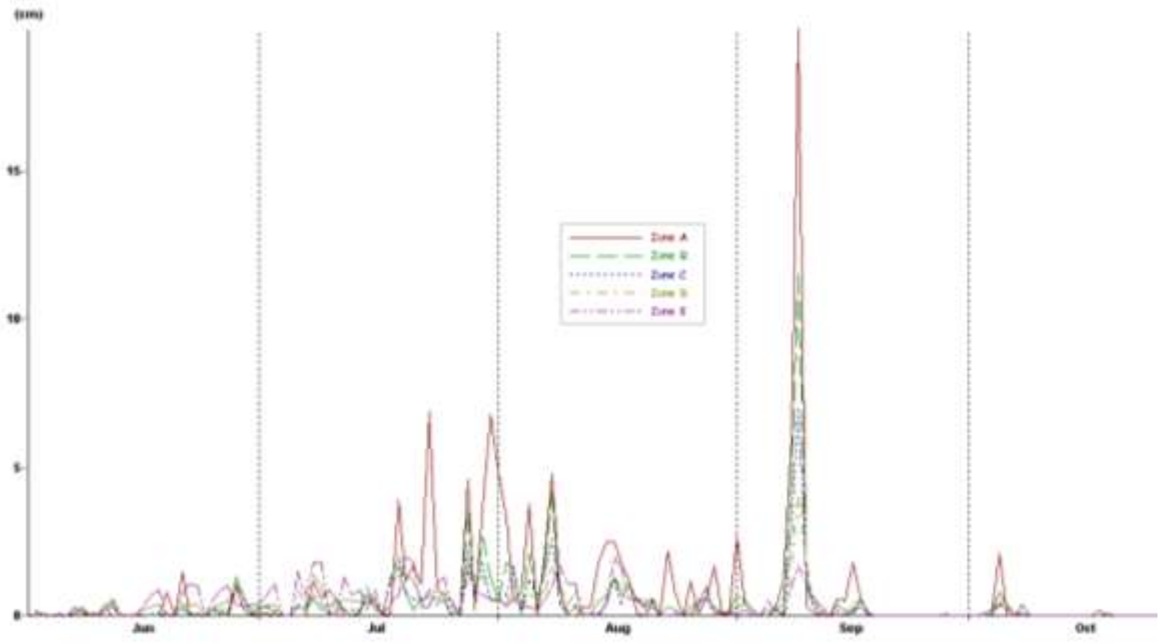

Figure – 3.4: Precipitation distribution in each zone to simulate 1992 flood

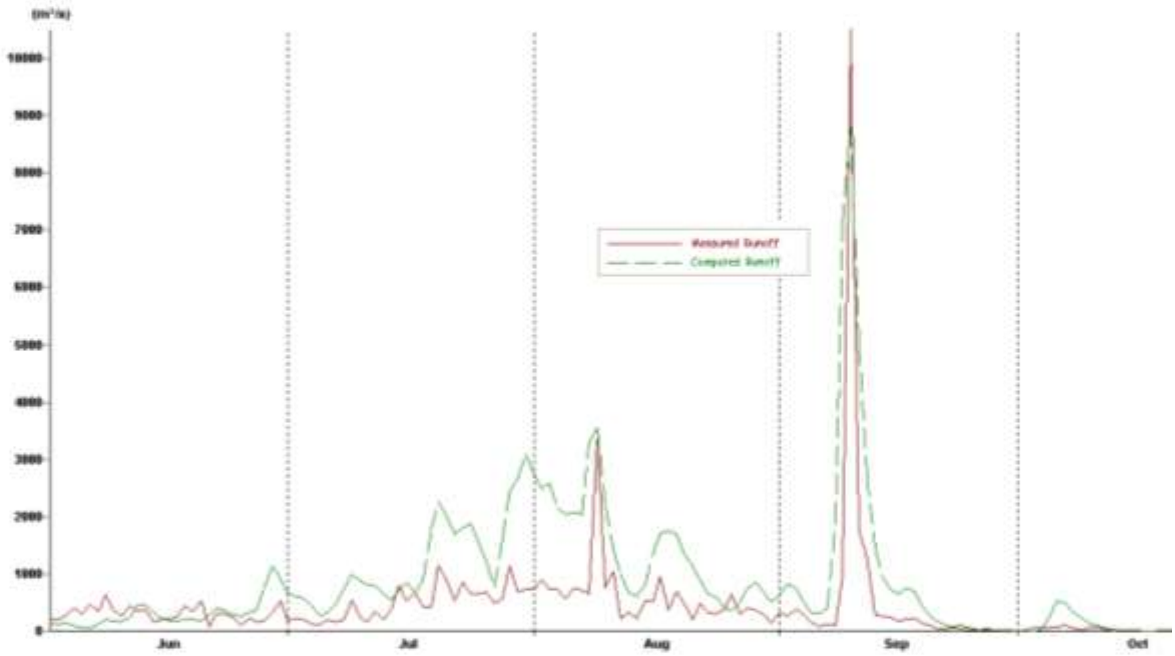

Figure – 3.5: Simulated and observed flood at Akhnoor in year 1992

3.5.2 Simulation of 1995 flood

In 1995, flood in the Chenab river occurred on 28 July. Flood peak recorded at Akhnoor was 8365 m^3/sec. Figure - 3.6 shows the zone-wise precipitation distribution during this flood event and Figure – 3.7 shows the simulated and observed floods. Corresponding flood peak generated from the benjwar/Sirshi to Akhnoor section was 5688 m^3/sec. Simulation results show flood peak at Akhnoor as 7497 m^3/sec though second smaller peak has been simulated correctly.

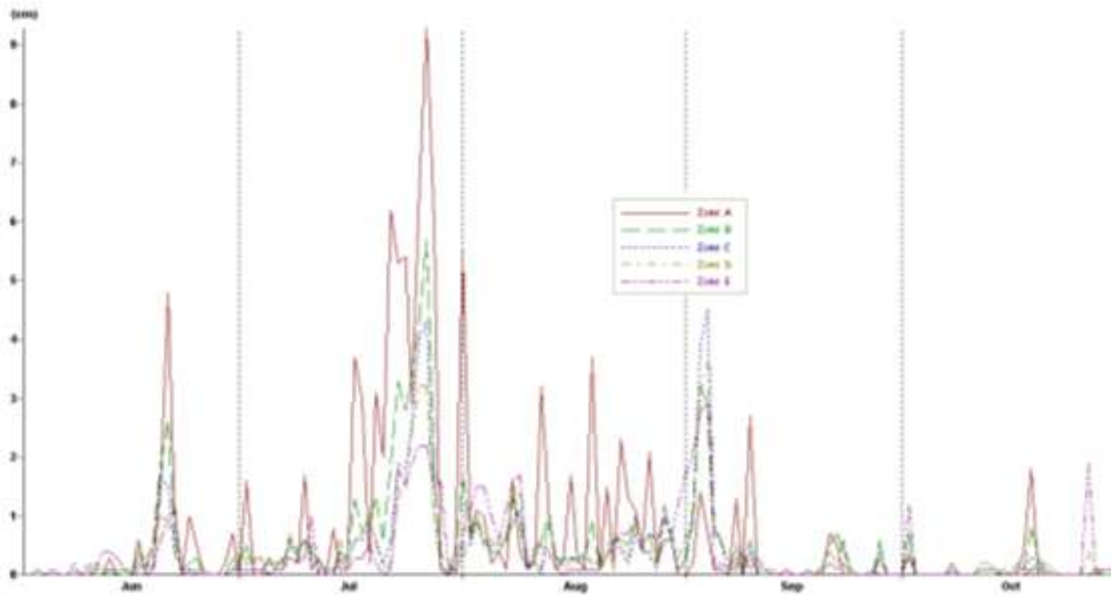

Figure – 3.6: Precipitation distribution in each zone to simulate 1995 flood

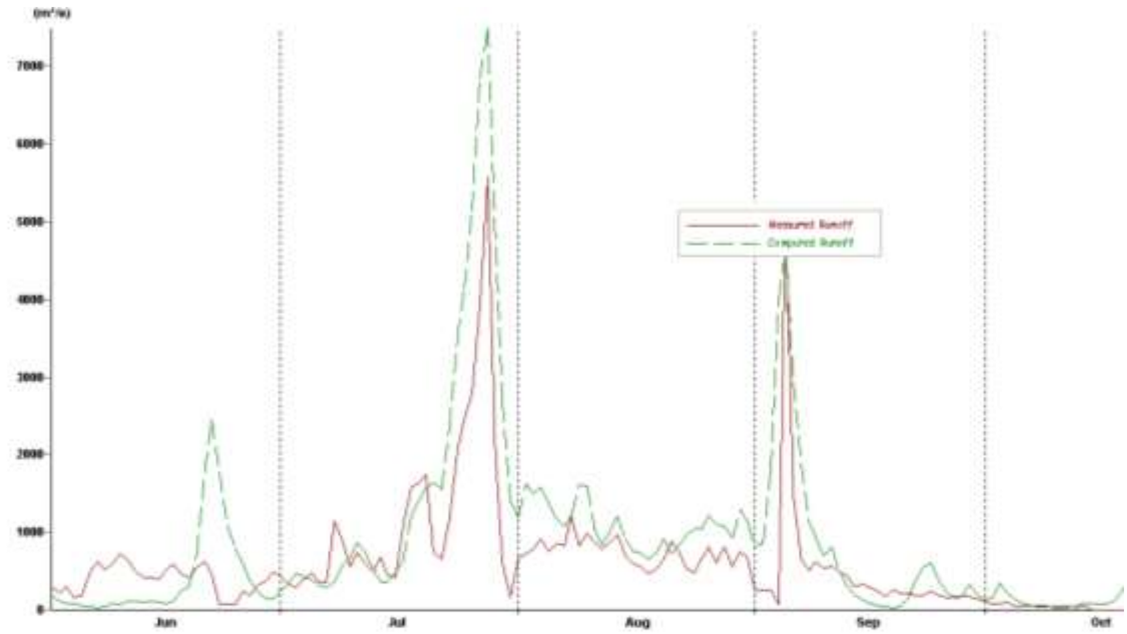

Figure – 3.7: Simulated and observed flood at Akhnoor in year 1995

3.5.3 Simulation of 1996 flood

Flood in the Chenab river on 23 August 1996 was second biggest flood since 1970's. Flood peaks at Akhnoor, Premnagar, and Benjwar were 12523, 2668, and 824 cumec respectively, which shows that major part of the flood has generated from the middle/lower part of basin. Net peak discharge from the catchment between Benjwar/Sirshi and Akhnoor has been observed to be 11238 cumec while the simulated peak is of the order of 10202 cumec. Figure - 3.8 shows the zone-wise precipitation distribution during this flood event and Figure – 3.9 shows the simulated and observed floods.

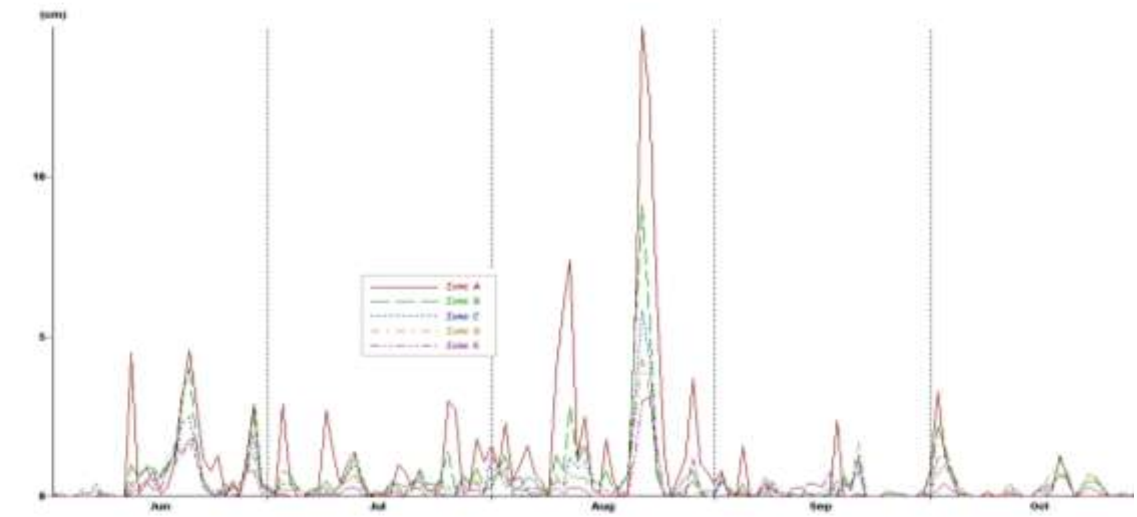

Figure – 3.8: Precipitation distribution in each zone to simulate 1996 flood

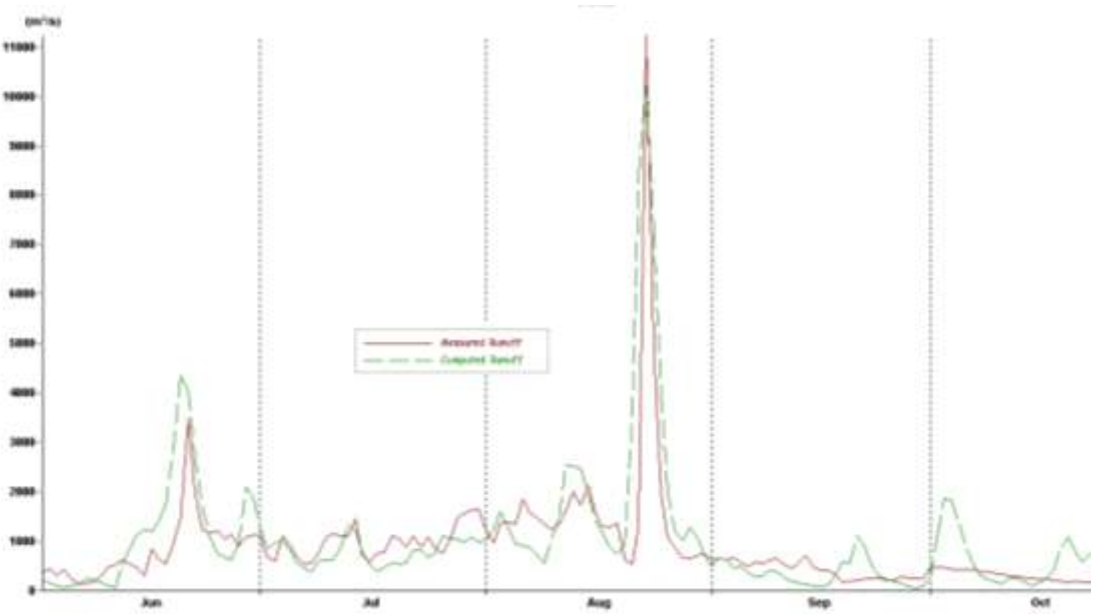

Figure – 3.9: Simulated and observed flood at Akhnoor in year 1995

3.5.4 Simulation of 1997 flood

In 1997, flood in the Chenab river was recorded on 28 August. Flood peak recorded at Akhnoor was 10422 cumec while corresponding flood peak generated at Benjwar and Premnagar were 1327 and 2574 cumec. Simulation results show flood peak at Akhnoor as 8651 m^3/sec, which closely matches with the observed flood peak at Akhnoor generated from the catchment beween Benjwar and Akhnoor. Figure - 3.10 shows the zone-wise precipitation distribution during this flood event and Figure – 3.11 shows the simulated and observed floods.

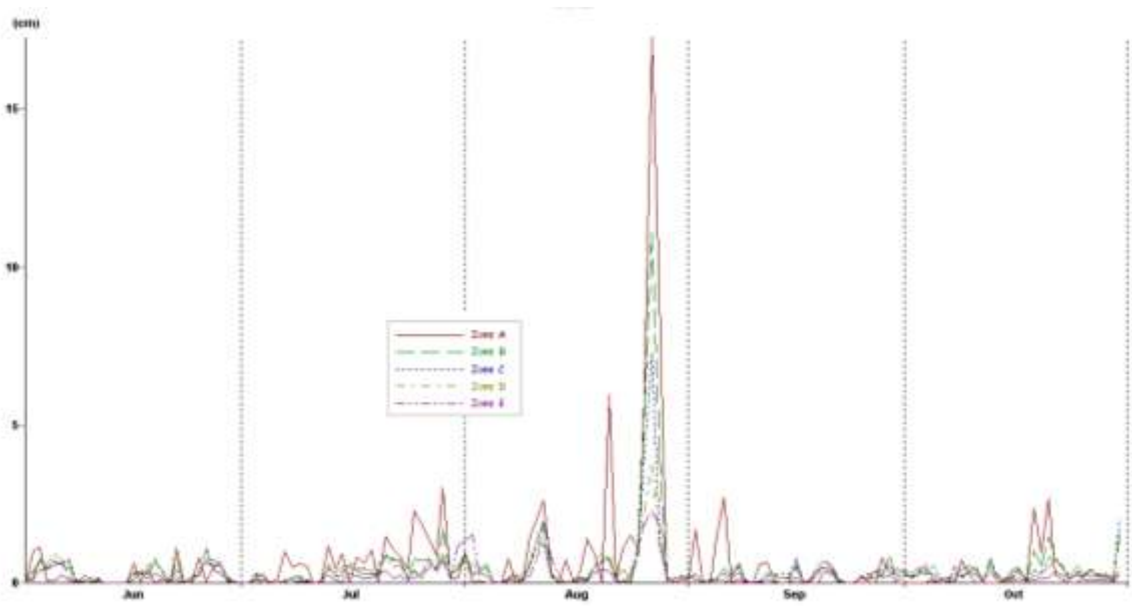

Figure – 3.10: Precipitation distribution in each zone to simulate 1997 flood

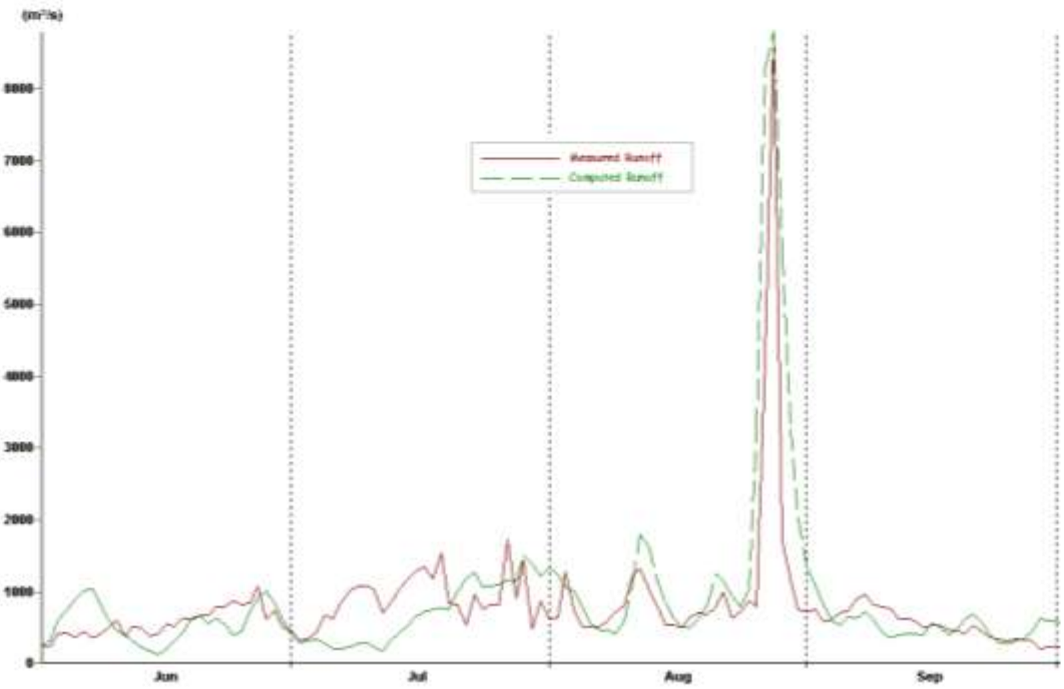

Figure – 3.11: Simulated and observed flood at Akhnoor in year 1997

3.5.5 Simulation of 2006 flood

After almost a decade to the 1997 flood, the Chenab river experienced another flood on 3 September, 2006. Flood peak at Akhnoor was 9445 cumec. In the observed data, flood peak generated in-between Benzwar/ Shirshi and Akhnoor was 7545 cumec while the simulated peak discharge has been found to be 5987 cumec. Figure - 3.12 shows the zone-wise precipitation distribution during this flood event and Figure – 3.13 shows the simulated and observed floods.

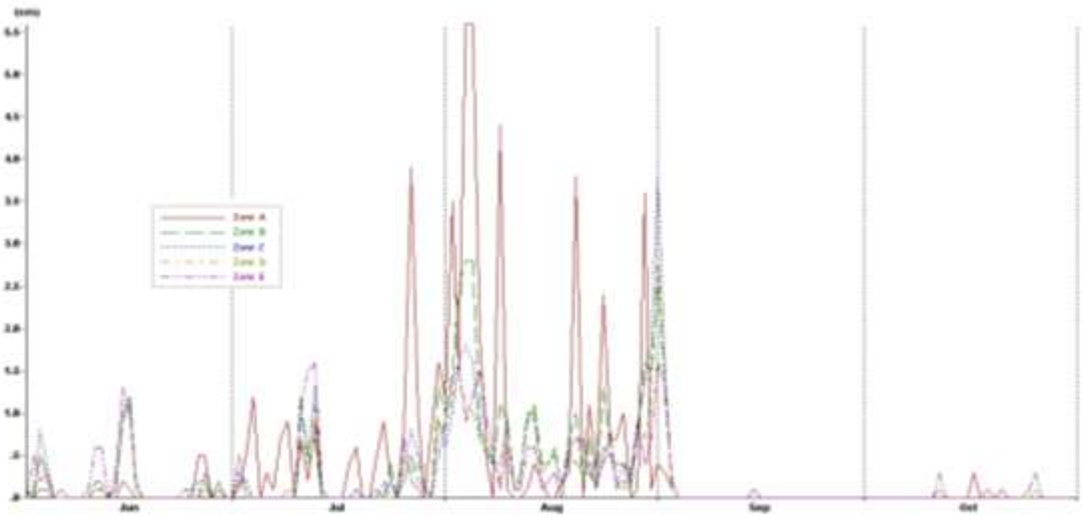

Figure – 3.12: Precipitation distribution in each zone to simulate 2006 flood

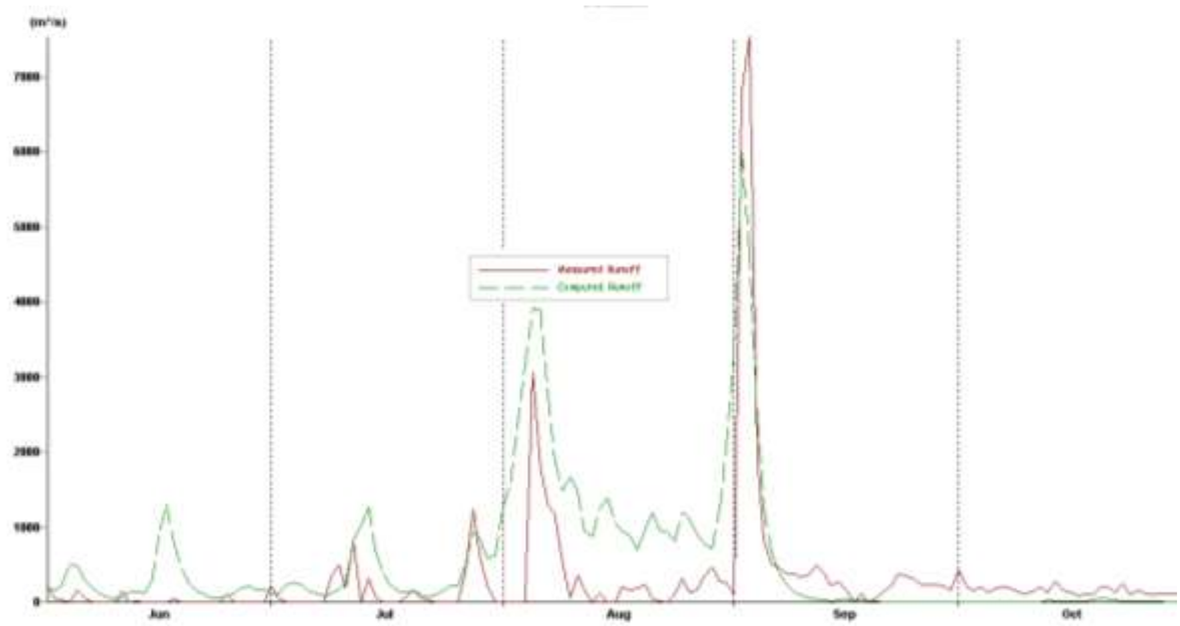

Figure – 3.13: Simulated and observed flood at Akhnoor in year 2006

The flood of year 2006 has also been simulated using hourly analysis. Some discrepancy in the observed rainfall data has been found from the records of different departments which could be one of the reasons for some mismatch between the observed and the simulated flows. Further, it is also difficult to catch the true nature of precipitation distribution in mountainous catchments which could be another major couse of mismatch. However, it needs to be mentioned that same values of parameters of WinSRM model have been used in the simulation of various flood events and reasonable simulation of peak discharge has been obtained in most of the cases. So, if the average precipitation can be forecasted in different elevation bands of the Chenab basin, a reasonable value of peak discharge and its time of occurrence can be predicted using WinSRM model and the derived parameters. Next chapter explains the estimation of flood hydrograph at Akhnoor at hourly time step using the unit hydrograph approach.

* * *

Chapter - 4
DEVELOPMENT & APPLICATION OF UNIT HYDROGRAPH MODEL FOR CHENAB BASIN

4.1 Rainfall-Runoff Process

Rainfall-runoff modeling is an important aspect of hydrologic analysis and design. Choice of an appropriate approach to modeling of rainfall to runoff transformation process in a basin is influenced by various factors which include (i) typical features of the system; (ii) objectives of the study; (iii) degree of realism; and (iv) availability of data and resources; and (v) time scale of analysis.

A study of a river basin's hydrology and consequently, the design of suitable study approach is quite extensive. While the design of suitable hydrologic methodologies is an important consideration, equally critical is the manner of application of these methodologies. It is impossible to build exact scale models of the hydro-climatological systems on which one could perform experiments to understand the nature of its operations on rainfall and its eventual transformation into runoff. The mathematical modeling approach is an alternative path.

A streamflow hydrograph is a graph of the time distribution of water discharge at a location. The graph is plotted with discharge on the ordinate and time on the abscissa. A hydrograph for a given storm reflects the influence of all physical characteristics of the drainage basin and, to some extent, also reflects the characteristics of the storm causing the hydrograph. A hydrograph can be considered a thumbprint of the drainage basin. The actual shape of a hydrograph is determined by the rate at which water is transmitted from the various parts of the drainage basin to the gauging site. Most of this water is carried by the channels, but some water flows overland directly to the observation station. No two drainage basins produce identical hydrographs for the same storm. Similarly, no two storms produce identical hydrographs from the same basin.

4.1.1 Components of Streamflow

The two main components of runoff are: (a) direct runoff and (b) baseflow. Total runoff corresponds to a given storm event and its volume is determined by including in the streamflow hydrograph all runoff between the baseflow discharge occurring prior to the storm up to the same baseflow discharge after the storm. The direct runoff is divided into surface runoff and quick interflow, whereas the baseflow is divided into delayed interflow and groundwater runoff.

Surface Runoff

Surface runoff or overland flow is that water which travels over the ground surface to a drainage channel. Most surface runoff flows to the first-order channels because they collectively drain the greatest area of the drainage basin. Surface runoff also includes the precipitation that falls directly on water flowing in the channel. Sheet flow usually occurs from an impervious surface such as a paved parking lot, but can only occur on a natural drainage basin when rainfall intensity uniformly exceeds the infiltration capacity. This condition does not frequently happen. Variations in the distribution of soil type and rainfall over a drainage basin usually result in limited sheet flow. Surface runoff is believed to be the principal contributor to the peak discharge from a storm event. Because this water runs off over the surface to the channel, it is the first to reach the channel and, hence, forms the rising limb and peak of the hydrograph.

Interflow

Interflow, also called subsurface storm flow, is that part of surface water that infiltrates into the surface layer and moves laterally beneath the surface to a channel. Interflow can occur on forest floors, where the leaves and other debris cover the ground. Interflow might occur in shallow soils filled and loosened by tree roots, rock debris covering the ground surface, or surface soils. During interflow, the movement of water is subject to greater flow resistance than surface runoff. As a result, interflow does not move as rapidly as surface runoff. Accordingly, interflow does not add to the peak discharge, but reaches the outlet after the peak discharge has passed.

Direct Runoff

Direct runoff is usually considered to be the sum of surface runoff and interflow. Direct runoff is frequently equated with surface runoff. These two flow components move more rapidly than groundwater flow and are often lumped together for hydrologic purposes. Such lumping is reasonable because it is logical to believe that some interflow near the outlet will arrive before surface runoff from farther up the basin.

Baseflow

Baseflow, or groundwater flow, is the flow component contributed to the channel by groundwater. Groundwater occurs from surface-water infiltration to groundwater table and then moving laterally to the channel through aquifer. Such water moves much more slowly than direct runoff and does not contribute to the peak discharge for a given storm. Flow in a perennial stream prior to a storm event is from baseflow. During a storm event, the baseflow is augmented by infiltration. Drainage basins with highly permeable, thick soils usually have a high groundwater-flow and relatively small direct-flow component, whereas basins with heavy-clay, low-infiltration soils have a small or negligible groundwater and high direct-runoff component.

4.1.2 Delineation of Runoff Components

A streamflow hydrograph is shown in Figure – 4.1, with points illustrating the major flow components. By common definition, point A marks the beginning of surface runoff, which is believed to end at the change in slope shown as B; point B is considered to be the beginning of interflow, which ends at point C; point C marks the beginning of groundwater flow, which continues beyond the end of the hydrograph. Of course, this division of hydrograph components is subjective and has no quantitative basis. It is There is difficult to verify the source of water during most the hydrograph and separation boundaries cannot be verified.

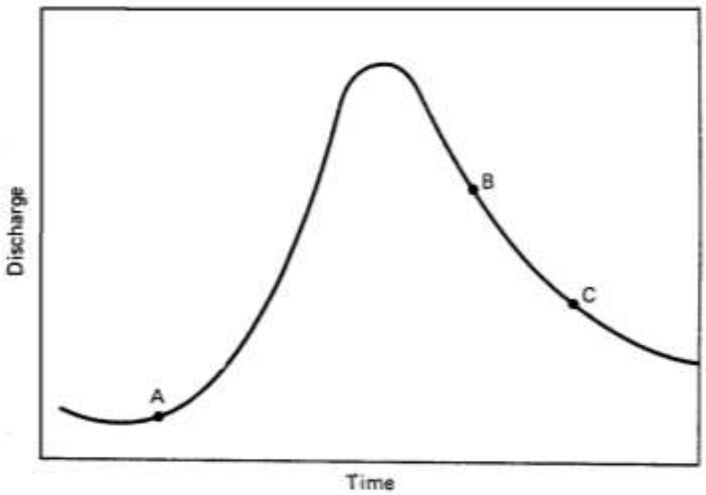

Figure – 4.1: A discharge hydrograph

Several factors affect a streamflow hydrograph during a runoff event on a drainage basin. Some of the major factors include drainage characteristics, rainfall characteristics, and soil and land use.

4.1.3 Elements of a Hydrograph

Typical elements of a hydrograph are shown in Figure – 4.2. These are briefly described below.

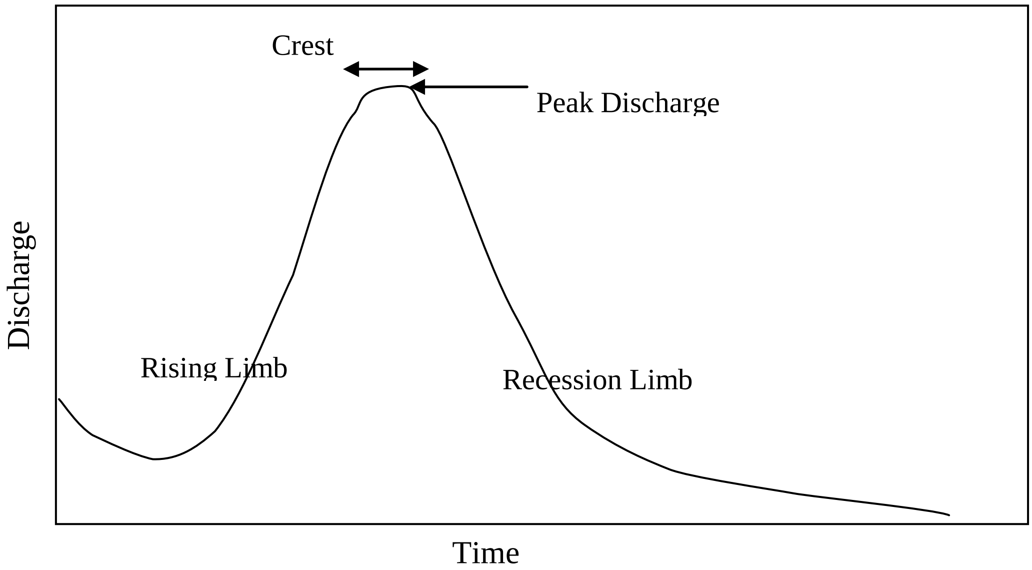

Figure – 4.2: Typical elements of a hydrograph

Rising Limb

As surface runoff reaches the basin outlet, the water begins to rise in the channel. With continuing elapse of time, more and more surface runoff reaches the gauge and the water in the channel continues to rise until it reaches a maximum discharge and after this stage, water begins to recede. The rising portion of the hydrograph is called the rising limb.

Crest

The time interval of highest discharge at the peak of the hydrograph is called the crest. The crest might be of a short time interval represented by a sharp peak or of a fairly long interval represented by a flat peak. The crest is not necessarily composed of equal discharges, but represents a subjective zone of nearly equal highest discharges. The greatest discharge within the crest is peak discharge, which is of primary interest in hydrologic design.

Recession Limb

The portion of the hydrograph after the peak is known as the receding limb, falling limb, or recession curve. The receding limb represents decreasing discharge as water is withdrawn from the drainage basin storage after rainfall ceases. The slope of the receding limb indicates the rate at which water is drained from the basin. The lower part of the recession, which has a much lower slope, is believed to represent groundwater contribution because the water is withdrawn much more slowly than the other components. Streamflow recession can be expressed as

$$Q_t = Q_0 K_r^t \qquad \text{...(4.1)}$$

where Q_0 is the initial discharge at any time, Q_t is the discharge after t time interval later, and K_r is the recession or depletion constant dependent upon the units of time and is less than unity.

4.1.4 Hydrograph Time Characteristics

The shape, and therefore, the characteristics of a hydrograph can be measured in terms of time as described below.

Time to Peak: The time to peak is the time elapsed from the beginning of the rising limb to the peak discharge. It depends upon the drainage-basin characteristics such as travel distance, drainage density, channel slope, channel roughness, and soil infiltration characteristics. It is somewhat altered by the distribution of rainfall over the basin. For a given amount of runoff, longer time to peak has lower peak discharge than shorter peak time.

Time of Concentration: The time of concentration is the time required for a drop of water falling on the most remote part of the drainage basin to reach the basin outlet. It includes the time required for all portions of the drainage basin to contribute runoff to the hydrograph. This time represents the maximum discharge that can occur from a given storm intensity over the drainage basin. By assuming a uniform rainfall over the entire drainage basin, the discharge increases as water from progressively farther distances arrives at the outlet. The hydrograph continues to rise as time elapses and rainfall continues until drainage from the most remote point on the basin arrives at the outlet. At this time, the discharge becomes a constant because all areas within the basin are contributing to the discharge. If the rainfall continues at the same uniform rate, the hydrograph peak would become flat at its maximum discharge and would continue so until rainfall intensity changes. It is important to distinguish between the time to peak and the time of concentration. In practice, the hydrograph peak is sharply defined and the storm duration is less than the time of concentration. The time of concentration is determined by many formulae. One of the most commonly used formulae is by Kirpich (1940):

$$t_c = 0.0078\ (L/S^{0.5})^{0.77} \qquad \ldots(4.2)$$

where t_c is the time of concentration in minutes, L is the length of travel in feet from the most remote point on the drainage basin along the drainage channel to the basin outlet, and S is the slope determined by the difference in elevation of the most remote point and that of the outlet divided by length. The equation assumes uniform rainfall over the drainage basin.

4.2 Rainfall-Runoff Models

A model is a simplified representation of a complex system. It aids in making decisions, particularly where data or information are scarce or there are large-number of options to choose from. Hydrological models represent the physical/chemical/biological characteristics of the catchment and simulate the natural hydrological processes. Hydrological models are essentially mathematical models where the physical processes of hydrologic cycle are described by a set of mathematical equations, logical statements, boundary conditions and initial conditions, expressing relationships between inputs, variables and parameters. Hydrological models may be broadly classified in two groups:

(i) Deterministic Hydrological Models,

(ii) Stochastic Hydrological Models.

A deterministic hydrological model is one in which the processes are modelled based on definite physical laws and no uncertainties in prediction are admitted. Deterministic models permit only one outcome from a simulation with one set of inputs and parameter values. It has no component with stochastic behaviour, i.e. the variables are free from random variation and have no distribution in probability. Deterministic models can be further classified according to whether the model gives a spatially lumped or distributed description of the catchment area, and whether the description of the hydrological processes is empirical, conceptual or fully physically based.

Stochastic models allow for some randomness or uncertainty in the possible outcomes due to uncertainty in input variables, boundary conditions or model parameters. The vast majority of models used in rainfall-runoff modelling are used in a deterministic way, although again the distinction is not clear-cut since there are examples of models which add a stochastic error model to the deterministic predictions of the hydrological model and there are models that use a probability distribution function of state variables but make predictions in a deterministic way. A working rule is that if the model output variables are associated with some variance or other measure of predictive dispersion the model can be considered stochastic; if the output values are single valued at any time step the model can be considered deterministic, regardless of the nature of the underlying calculations.

Empirical or black box models contain no physically based transfer function to relate input to output. In other words no consideration of the physical processes is involved in such models. These models are basically input-output based models. Within the range of calibration, such models may be highly successful. However, in extrapolating beyond the range of calibration, the physical link is lost and the prediction relies on mathematical technique alone.

Lumped conceptual models occupy an intermediate position between the fully distributed physically based approach and empirical black box analysis. Lumped models treat the catchment as a single unit, with state variables that represent averages over the catchment area, such as average storage in the saturated zone. Such models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of the process element in the system being modelled. Parameters of such type of models are calibrated using trial and error method or automatic optimisation technique or combination of both.

Fully distributed physically based models are based on our understanding of the physics of the hydrological processes which control catchment response and use physically based equation to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss) while black box models can offer only one output. Unlike lumped conceptual models, physically based distributed models do not consider the transfer of water in a catchment to take place between a few defined storages. Instead the transfers of mass, momentum and energy are calculated directly from the governing partial differential equations.

4.2.1 Unit Hydrograph Approach

As stream flow records are somewhat limited for most locations, it is necessary to relate runoff to rainfall. Knowing rainfall rates, a function to convert rainfall to runoff is required. Unit hydrograph (UH) is such a tool. The unit hydrograph (UH) theory proposed by Sherman (1932) is primarily based on the principle of linearity and time and space invariance. A UH is a hydrograph of surface runoff resulting at a given location on a stream from a unit rainfall excess amount occurring in unit time uniformly over the catchment area up to that location. The rainfall excess excludes losses (abstractions) from total rainfall and unit rainfall excess normally equals 1 mm. The selection of unit time depends on the duration of storm and size of the catchment area. For small catchments, periods of 1 or 2 hours can be assumed and for larger catchments, 3, 4, 6, or even 12 hours can be adopted. Thus

(i) A UH is a flow hydrograph;

(ii) A UH is a hydrograph of direct surface runoff (DSRO), not total runoff;

(iii) The hydrograph of surface runoff results from the rainfall excess;

(iv) The rainfall excess represents total rainfall minus losses (abstractions);

(v) During the unit time period, the rainfall excess is assumed to occur uniformly over the catchment;

(vi) Typical unit times used in UH analyses are 1, 2, 3, 6, 8, and 12 hours. Beyond this, time period is generally taken as an integer multiple of 24 hours.

A unit hydrograph can be interpreted as a multiplier that converts rainfall excess to direct surface runoff. The direct surface runoff (DSRO) is the streamflow hydrograph excluding baseflow contribution. Since, a unit hydrograph depicts the time distribution of flows, its multiplying effect varies with time. In real-world application, the unit hydrograph is applied to each block of rainfall excess and the resulting hydrographs from each block are added for computing direct surface runoff hydrographs, to which baseflows are further added to obtain total hydrographs.

Factors affecting UH shape

The factors affecting the shape of the unit hydrograph are the rainfall distribution over the catchment and physiography of the catchment, viz., shape, slope, vegetation, soil type etc. Variations in areal pattern of rainfall, rainfall duration, and time intensity pattern greatly affect the shape of the hydrograph. A hydrograph resulting from rainfall concentrated in the lower part of a basin will exhibit a rapid rise, sharp peak, and rapid recession. On the other hand, rainfall concentrated in the upper part of the same basin will yield a slow rising and receding hydrograph having broad peak. Thus, UHs developed from rainfall of different areal distributions will exhibit differing shapes. Given the amount of runoff, the time base of the unit hydrograph increases and peak lowers as the duration of rainfall increases.

Natural physical characteristics of a watershed are affected by man's influence. For example, follow-up of watershed management practices significantly change the land cover, and consequently, the shape of the derived UH also changes. Steep catchment slopes produce runoff peak earlier than flatter slopes. Consequently, UHs of steep catchments exhibit peaks occurring earlier than those of flatter slopes. Urbanization of a catchment causes drastic changes in the shape of hydrograph and, in turn, the UH. Urbanisation reduces the natural storage of the basin as well as the average loss rate. As a result, the derived UH exhibits higher peak and shorter time of concentration. Seasonal and long-term changes in vegetation or other causes such as fire, also change the physical characteristics of the watershed. It resorts to developing a regional relationship between UH parameters and existing basin characteristics, for deriving the unit hydrograph in the changed environment.

Derivation of Unit Hydrograph for Gauged Catchments

Conventionally, unit hydrographs can be derived from analysis of rainfall and runoff records in those catchments where such data are available. The procedures used to derive a unit hydrograph are dependent upon whether the storm from which a unit hydrograph is to be calculated is:

- a simple or single-period storm, or
- a multi-period storm

Thunder-storms are usually intense and of short duration, and more likely to be treated as single period storms. Frontal storms are usually of longer duration and therefore, are generally not suitable for single period analysis. A multiperiod approach should be followed for these. Generally, the unit hydrographs derived from various events are not the same and a representative unit hydrograph for a catchment is derived.

As mentioned above, the unit hydrograph is a conversion factor which converts the rainfall (excess rainfall) to runoff (direct surface runoff). For this conversion, the duration of unit hydrograph should be the same as the duration of each of the excess rainfall blocks. If the duration of unit hydrograph and excess rainfall blocks differ, then the duration of unit hydrograph should be changed to the duration of excess rainfall, and the unit hydrograph with changed duration should be used for converting the excess rainfall to the direct surface runoff.

Areal uniformity is a principle of the unit hydrograph theory and it is difficult to obtain for larger catchments. The upper limit for the application of this principle is usually adopted as 5000 sq. km. If the catchment is greater than 5000 sq. km., one unit hydrograph should not be used, but the catchment should be divided into sub-areas and different unit hydrographs and corresponding flood hydrographs should be developed for different sub-basins.

UH Derivation for Ungauged Catchments Using Snyder's Method

Snyder gave some empirical relationships for synthetic UH based on his studies carried out in USA for several catchments in the Appalachian Highlands. Those relationships were originally developed in FPS system. The relationships in metric unit to be used to derive 't_r' hour unit hydrograph characteristics using this approach are given below :

Time Lag or Basin Lag (hrs)

$$t_p = C_t \, (L \,.\, L_{ca})^{0.30} \qquad \text{....(4.1)}$$

where t_p is the basin lag (or time lag) in hours, L is the length of main stream in km, L_{ca} is the distance from outlet to centre of area of catchment along the stream in km, and C_t is a coefficient varying from 0.3 to 6.0 for different regions.

Peak of UH (cumec)

$$Q_p = (\, 2.78\, C_p\, CA\,) \,/\, t_p \qquad \text{....(4.2)}$$

where Q_p is the peak of UH in cumec, CA is the catchment area in sq km, and C_p is a coefficient varying from 0.31 to 0.93.

Unit Hydrograph Duration (hrs)

$$t_r = t_p \,/\, 5.5 \qquad \text{....(4.3)}$$

where t_r is the unit hydrograph duration.

Modified time lag or basin lag (hrs) for non-standard rainfall duration t_r'

Basin lag may be modified for the desired duration of UH (t_r') using the relationship:

$$t_p' = t_p + 0.25\, (t_r' - t_r) \qquad \text{....(4.4)}$$

Peak of UH for desired duration, t_r'

$$Q_p' = (\, 2.78 * C_p * CA\,) \,/\, t_p' \qquad \text{....(4.5)}$$

Width of UH in hour at 50% peak discharge (W_{50})

$$W_{50} = a \,/\, q^{1.08} \qquad \text{....(4.6)}$$

where $q = Q_p' \,/\, CA$ & a is a coefficient for the region.

Width of UH in hour at 75% peak discharge (W_{75})

$$W_{75} = W_{50} / b \qquad ....(4.7)$$

where b is a coefficient for the region.

Base width of UH (t_b)

For large catchments:

$$t_b = 3 + 3 (t_p'/24) \quad \text{(in days)} \qquad ....(4.8)$$

For small catchments:

$$t_b = 5 (t_p' + t_r' / 2) \quad \text{(in hours)} \qquad ....(4.9)$$

The UH peak, basin lag time, W_{50}, W_{75} and t_b are used to define the shape of UH preserving the unit volume equal to one cm. In India, CWC has recommended some relationships after study of large number of catchments varying from 25 to 500 km^2. These are:

The peak discharge of a D-h unit hydrograph Q_{pd} in cumec is given by:

$$Q_{pd} = 4.44 \,.\, A^{3/4} \qquad \text{for } S_m > 0.0028$$

and $$Q_{pd} = 222 \,.\, A^{3/4} \,.\, S_m^{2/3} \qquad \text{for } S_m < 0.0028 \qquad ....(4.10)$$

where A is catchment area in sq. km and S_m is weighted mean slope. The lag time in hours (time interval from mid-point of rainfall excess to the peak) of a 1-h unit hydrograph t_{p1} is given by:

$$t_{p1} = 3.95 / (Q_{pd}/A)^{0.9} \qquad ....(4.11)$$

The duration of rainfall excess for design purpose is taken as:

$$D = 1.1 \,.\, t_{p1} \,.\, h \qquad ....(4.12)$$

4.3 Unit Hydrograph derivation for part of Chenab Basin

Using the Snyder's method as mentioned above and the Indian practices as specified CWC, the synthetic unit hydrograph has been developed for a part of the Chenab basin between Premnagar and Akhnoor gauging sites. The catchment area of this sub-basin is 5043 sq. km which is appropriate for the development and application of a unit hydrograph. The length of the main river in this sub-basin is 141 km while the length of outlet from the centroid of the basin is 83 km. The duration of unit hydrograph was obtained as 3 hour and fortunately the rainfall data at this frequency was available for the flood event that occurred in the basin during September 01 – 06, 2006. The values of different parameters of the unit hydrograph, as obtained, are mentioned in Table – 4.1.

Table – 4.1

Different parameters of Synthetic UH for part of Chenab basin

Unit hydrograph parameters	Values
UH duration	3 hours
Peak discharge	600 cumec
Time to peak	16.6 hours
Time base	100 hours

The unit hydrograph developed from the various parameters was plotted in MS-EXCEL and it was fine tuned so that the area under the unit hydrograph represents unit depth of water. A number of trial and errors were carried out and the final unit hydrgraph obtained for the sub-basin between Premnagar and Akhnoor is shown in Figure – 4.3.

4.4 Derivation of Flood Hydrograph for Premnagar-Akhnoor Sub-basin

The unit hydrograph, developed above, was convoluted with the average rainfall in the sub-basin between Premnagar and Akhnoor to find out the flood hydrograph at Akhnoor. The only flood event that was available in the basin with sub-daily rainfall and discharge data was during September 01 – 06, 2006. From the records of National Hydroelectric Power Corporation, Jammu (NHPC), 3-hourly rainfall data for this flood event was

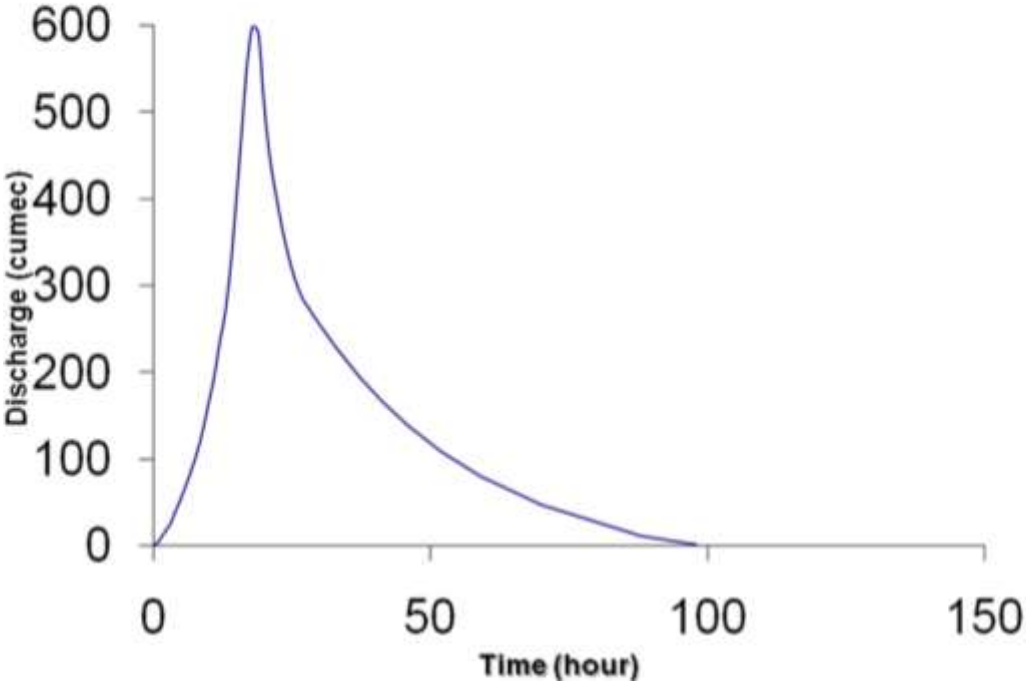

Figure – 4.3: Unit hydrograph for sub-basin between Premnagar & Akhnoor

obtained for the Salal rainfall station. First, the average daily rainfall for the sub-basin between Premnagar and Akhnoor was worked out by the Thiessen polygon method. The rainfall stations considered to work out the average rainfall in the sub-basin included Akhnoor, Salal, Kishtwar, Dhamkund, Batote, Rot, Doda, Bhaderwah, Banihal, Drabshala, Mohu, and Nandan. Then using the time distribution of 3-hourly rainfall at Salal rainfall station, the average daily rainfall data of the sub-basin were disaggregated and the 3-hourly average rainfall in the sub-basin was calculated. The hourly flow data at Salal were obtained from NHPC, Jammu and hourly flow data at Akhnoor were obtained from the CWC, Jammu. A plot of the discharge data and 3-hourly average rainfall pattern during the flood event of September 01 – 06, 2006 is shown in Figure – 2.11.

Next, the 3-hourly average sub-basin rainfall was convoluted with the unit hydrograph and the added to the flow data of Premnagar to compute the flood hydrograph at Akhnoor corresponding to the observed storm rainfall in the sub-basin. The computed flood hydrograph for the storm event is shown in Figure – 4.4. Salal dam lies on the upstream of Akhnoor gauging site. It is seen from the derived flood hydrograph that as expected, the peak of simulated flood at Akhnoor lies in the downstream of the observed flood hydrograph at Salal. The same is not seen in case of observed discharge at Akhnoor.

It needs to be mentioned here that the sub-daily rainfall data of only one event was available in the present case. Therefore, the developed unit hydrograph could not be validated for other flood events. If further sub-daily

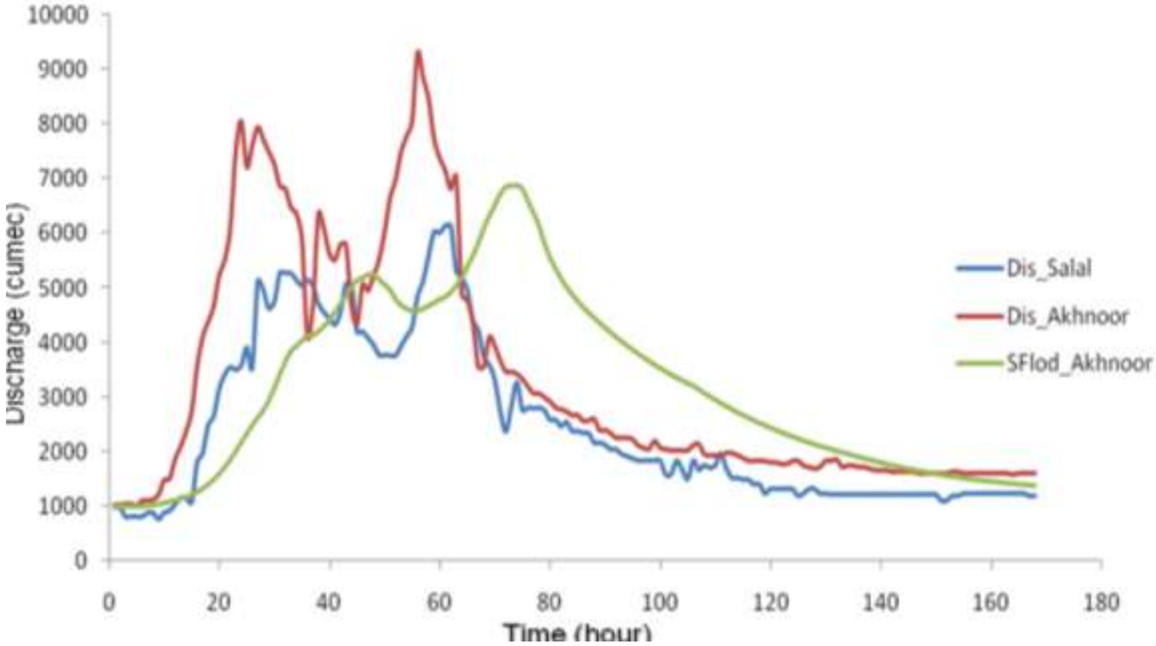

Figure – 4.4: Observed and simulated flood hydrographs at Salal & Akhnoor

rainfall and discharge data becomes available in the sub-basin, the flood hydrographs can be generated from the rainfall records and compared with the actual observations. The unit hydrograph can also be fine-tuned in this way to match the observed and simulated flows in most of the cases.

4.5 Prominent Rainfall Stations During Flood Events

Though rainfall stations are well distributed in the middle and lower reaches of the Chenab basin, there are a few rainfall stations that have captured the signatures of a significant storm during various flood events. To identify such rainfall stations, the rainfall data of various stations during different flood events were accumulated for the period of flood events and the same is already presented in Table – 3.1. The table clearly shows that Paoni, Salal, Akhnoor, Dhamkund, Halwal, Banihal, and Bhaderwah are some important rainfall stations that have obtained and recorded significant rainfall amounts during all flood events in the Chenab basin. Therefore, it is important that these stations are properly maintained and if automated stations that record short-interval (say, hourly) rainfall data are installed at these stations, then storm pattern can be captured and the flood forecasting with better accuracy can be achieved.

* * *

Chapter - 5
CONCLUSIONS

The Chenab River is one of the five main rivers of the great Indus System. Upper half of this basin is located between the Zanskar and the Pir-Panjal ranges whereas the lower half is located between the Pir-Panjal and the Dhauladhar ranges, thus covering outer, middle and greater Himalayas. The Chenab River experiences significant floods during the monsoon season and there are a few important habitations along the river Chenab which get affected by floods. It is required to issue timely forecasts so that habitations could be warned and necessary administrative actions could be initiated before the occurrence of the flood. This study is taken up to simulate the flood events in the Chenab basin using hydrological models so that knowing the forecast rainfall in the basin, the flood hydrographs could be developed.

From the plots of daily rainfall and discharge data at different stations for various years, it is inferred that floods in the Chenab basin are generated from the rainfall events which mostly remain concentrated in the middle and lower reaches of the basin below Benzwar. The travel time of flood wave from Benzwar to Akhnoor is less than one day and hourly data was crucial for this study. Based on the availability of short-term rainfall and discharge data, it was envisaged to apply WINSRM (at daily time step) considering daily rainfall, met data, and discharge at Akhnoor and develop unit hydrograph (at 3-hourly time step) for intermediate catchment (Premnagar to Akhnoor) and use short-duration rainfall and discharge data to simulate the observed flow from the intermediate catchment. Hydro-meteorological data of the basin was obtained from Central Water Commission, Jammu and the Office of the Chief Engineer, NHPC, Jammu. GIS was used for database development for WINSRM model and unit hydrograph analysis.

All the spatial data was developed in GIS using ILWIS GIS system. 90 m spatial resolution digital elevation map of the area from SRTM data was used and map layers corresponding to basin boundary, slope, drainage network, and sub-basin at specified gauging stations were derived from the GIS analysis of digital elevation map by using the “DEM Hydro-processing” module of ILWIS. Five sub-basins have been drawn corresponding to Benzwar, Sirshi, Premnagar, Dhamkund, and Akhnoor gauging sites. Upstream of Benzwar, the sub-basin mostly remains snow-covered and is considered as one sub-basin.

In addition, elevation zones for different elevation ranges were prepared using GIS for use in the WINSRM model. Thiessen polygons of various rainfall stations available for a flood event were derived from the GIS analysis. Thiessen polygon maps were convoluted with the elevation zones map to work out the weights of different stations in different elevation bands so that average rainfall in each band could be worked out. For the unit hydrograph analysis at sub-daily time scale, average rainfall in the sub-basin between Premnagar and Akhnoor was worked out by estimating the weights of different stations in this part of the basin.

WINDOWS version of the Snowmelt Runoff Model (WINSRM) is widely used software for simulation of runoff generated from rainfall and snowmelt. The model computes the runoff from snowmelt and rainfall that is produced each day and superimposed on the calculated recession flow and transformed into daily discharge at the basin outlet. This model was applied to number of flood events in the basin and model parameters were calibrated. Same values of parameters of WINSRM model were used in the simulation of various flood events and reasonable simulation of peak discharge was obtained in most of the cases. So, if the average precipitation can be forecasted in different elevation bands of the Chenab basin, a reasonable value of peak discharge and its time of occurrence can be predicted using this model and the derived parameters.

WINSRM model works at daily or higher time steps. Since flood simulation and modeling is generally carried out at sub-daily time step (hourly, 3-hourly or so), hydrological modeling was carried out at 3-hourly time step for the intermediate part of the Chenab basin (Premnagar to Akhnoor). Short-term data availability was investigated from different departments and very limited short-interval data of only one event could be gathered. Synthetic unit hydrograph was generated for the intermediate catchment using Snyder’s method. Using the 3-hourly rainfall data of Salal rainfall station, the average daily rainfall in the intermediate catchment was disaggregated. Next, 3-hourly rainfall was convoluted with the unit hydrograph and the observed flood event at Akhnoor was simulated. If some additional hourly/3-hourly rainfall data is made available, then the unit hydrograph can be fine tuned so as to better match the observed short-term flow and peak discharge at Akhnoor. Based on the rainfall catch at different stations during various flood storms, some important rainfall stations are also identified for automatic/self-recording instrumentation.

REFERENCES

Arora, M., Singh, P., Goel, N. K., and Singh, R. D. (2006). "Spatial distribution and seasonal variability of rainfall in a mountainous basin in the Himalayan region", Journal of Water Resources Management, 20, pp. 489-508.

Awan, S. A. (2003). "Pakistan: Flood management-River Chenab from Marala to Khanki", WMO/GWP Associated programme on Flood management, 1-4.

Mayewski, P. A. and Jeschke, P. A. (1979). "Himalayan and Trans-Himalayan glacier fluctuations since AD 1812", Arctic Alpine Res., 11 (3), 267-287.

Raina, V. K., Srivastava, D., Singh, R. K., and Sangewar, C. V. (2008). "Glacier regimen, fluctuation, hydrometry and mass transfer studies in the Himalayas", In: *Glacier Atlas of India*, edited by: Raina, V. K., and Srivastava, D., Geol.Soc. India, Bangalore, 206-216.

Singh, P., Jain, S. K. and Kumar, N. (1997). "Estimation of snow and glacier contribution to the Chenab River, Western Himalaya", Mountain Res. Dev., 17 (1), pp. 49-55.

Subramanya, K. (1991). "Engineering Hydrology", Tata McGraw-Hill Publishing Company Limited, New Delhi.

USDA (2006). "Snowmelt Runoff Model", United States Department of Agriculture.

Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakkal, J. G., Berthier, E., Ramanathan, A., Hasnain, S. I. & Chevallier, P. (2007). "Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya", Journal of Glaciology, 53 (183), pp. 603-61.

Yasunari, T. and Inoue, J. (1978). "Characteristics of Monsoonal precipitation around peaks and ridges in Shorong and Kumbu Himalaya", Journal of Japan Society of Snow and Ice, 40, pp. 26-32.