STUDIES ON HYDROMORPHOMETRY AND SNOWMELT RUNOFF USING DATA OF CHENAB CATCHMENT

A THESIS

Submitted in fulfilment of the
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By

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IN THE NAME OF ALLAH, THE
BENEFICIENT, THE MERCIFUL

*****

LO ! IN THE CREATION OF THE HEAVENS AND THE EARTH, AND THE DIFFERENCE OF NIGHT AND DAY, AND THE SHIPS WHICH RUN UPON THE SEA WITH THAT WHICH IS OF USE TO MEN, AND THE WATER WHICH ALLAH SENDETH DOWN FROM THE SKY, THEREBY REVIVING THE EARTH AFTER ITS DEATH, AND DISPERSING ALL KINDS OF BEASTS THEREIN AND (IN) THE ORDINANCE OF THE WINDS, AND THE CLOUDS OBEDIENT BETWEEN HEAVEN AND EARTH : ARE SIGNS (OF ALLAH'S SOVEREIGNTY) FOR PEOPLE WHO HAVE SENSE

(164) SURAH II

THE
GLORIOUS QURAN

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled, 'STUDIES ON HYDRO-MORPHOMETRY AND SNOWMELT RUNOFF USING DATA OF CHENAB CATCHMENT' in fulfilment of the requirement of the award of the Degree of DOCTOR OF PHILOSOPHY, submitted in the Department of Water Resources Development Training Centre, University of Roorkee, Roorkee, is an authentic record of my own work carried out during a period from August, 1980 to April, 1986, under the supervision of Dr. S.M.Seth, Dr. G.N.Yoganarasimhan and Dr. R.P.Gupta.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

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Candidate's Signature

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The planning and development of water resources of a region requires proper understanding of the hydrological behaviour of the river basins. The analysis of available information is necessary to decide about water availability at a site or expected design discharge at a site. The precipitation runoff process of a catchment is very complex phenomenon and an unknown large number of climatic and physiographical parameters, which vary with both space and time, control this phenomenon. The process is still more complicated, when precipitation includes both rain and snow and the basin physiography is mountainous in character, as in the case of the Himalayas. Besides the rugged topography and limited physical accessibility, the Himalayan basins are also faced with problem of limited data availability. As such, there is a need for development of appropriate procedures for estimating snowmelt runoff.

The Himalayan region has the following typical seasons viz (i) snow accumulation season from November to February, (ii) snowmelt season from March to June and (iii) monsoon season from July to October.

In the present study, available data (for 1965-81) of the Chenab basin (area 22850 sq. km) has been used. This includes daily precipitation, daily temperature and daily discharge at some measurement sites, besides other

useful information available from topographical maps and satellite images (for 1975-81). The main thrust of the study is on the following specific objectives using data of different sub-basins in the Chenab basin:

i) Evaluation of hydromorphometric parameters to quantify the physiographic characteristics of the basin.

ii) Development of regression relationships between the flood characteristics and hydromorphometric parameters.

iii) Development of relationship between snowmelt runoff and extent of snow cover at the beginning (i.e. March) and during premonsoon season (i.e. March-June).

iv) Development of a suitable model structure for modelling of daily runoff from snowmelt and rain fall during snowmelt season (March-June) and monsoon season (July-September) for typical conditions of the Chenab basin viz. rugged topography, limited data availability, presence of permanent snow cover etc.

The study has accordingly been carried out to achieve the above mentioned objectives and it involved use of:

i) techniques for interpretation of toposheets and satellite images, (ii) techniques of statistical analysis, (iii) regionalisation of relationship between snowmelt runoff and snow cover characteristics, (iv) model formulation, calibration using optimization, testing with independent data, averaging of parameters and determination of overall parameters for entire basin and (v) studies for effect of change in melt rate, rain fall and daily temperature pattern.

A brief account of salient features of these studies and results obtained is given in following paragraphs.

(a) From the study of hydromorphometric characteristics, it is found that the hydromorphometric relations exhibit deviations from the widely established and accepted laws of drainage compositions.

These variations may not be apparently ascribed to lithological variations. It is interpreted that some of the deviations are related to extra-increase in mean stream length with stream order and could be a result of strong structural influence leading to an elongated basin shape. Further, it is inferred that the phenomenon of recent tectonic uplift, has also played an important role in creating the lack of hydromorphometric maturity and geometric similarity in the Chenab basin.

(b) Using multiple regression analysis approach and judgement criteria of F test and t test, the relationships have been developed for average peak discharge Q_p, maximum peak discharge Q_{mp} and average annual flow Q_{Av} in m^3/sec as dependent variables and drainage area A (km^2), channel slope S_c (%), drainage density D_d (km^{-1}) and length of main stream channel L_c(km) as independent variables. The four relationships have been selected in the study which relate flow/flood parameters Q_p, Q_{mp} and Q_{AV} with A, L_c, $A/S_c\sqrt{D_d}$ (Hickok et al parameter).

(c) The Landsat MSS data mainly for the months of March-June for the years 1975-1981 were used for snow cover area mapping and the corresponding direct runoff (total runoff minus base flow) for premonsoon season (March-June) were computed for different sub-basins in the Chenab basin. Graphical and regression relationships have been developed between this direct runoff assumed as snowmelt runoff and snow cover area at the beginning of melt season. Good fit is indicated in these relationships.

(d) Realising the need for dealing with typical conditions of the Himalayan basins viz. mountainous physiography, limited accessibility, permanent and temporary snow covers, limited data base etc. simple model structure with reasonable physical base, limited data requirements and capability of using remotely sensed data for snow cover area has been adopted.

The snow cover depletion relationship between snow covered area and accumulated generated runoff was established for the sub-basins. For the parameter n of this relationship, relation was established with parameter $(A/S_c \sqrt{D_d})$. Also regional relationships were established between total seasonal snowmelt runoff and snow covered area and between rate of increase of melt rate and weighted mean elevation for sub-basins.

The model structure is based upon split watershed modelling approach sub-dividing it into permanent snow covered area, temporary snow covered area and snow free

area. The snow covered area under temporary snow cover is further divided into melt area and non-melt area using daily data of temperature lapsed to appropriate elevation level, taking base temperature for melting as $0^{o}C$. The melt of snow is computed using simple degree day approach and variable melt rate. The losses are assumed to occur from melt water from permanent and temporary snow covered areas and snow free area, using three coefficients X(1), X(2) and X(3). The excess melt water is routed through a linear reservoir with storage constant X(4) and its output is combined with excess water from snow free area. This is then routed through a second linear reservoir with storage constant X(5) to simulate total daily direct runoff at the catchment outlet.

The Rosenbrook technique of optimization has been used for model calibration using least squares objective criterion and computer program was formulated accordingly for running on DEC-2050, Roorkee University Regional Computer Centre (RURCC).

The results of calibration and prediction gave generally a good performance of daily runoff model as indicated by values of efficiency of model of the order of 70% and above and very good reproduction of total seasonal flows. Snow line and hydrograph shape reproductions are also satisfactory. However, a general over prediction of flows during premonsoon months(March,April,May,June) and under prediction of flows during monsoon months (July, Aug., Sept.) was observed in the model results.

This was examined in the typical prediction runs assuming zero rainfall, % change in rainfall, change in temperature pattern and change in pattern of variation in melt rate. These runs confirmed some effect of these factors on simulation pattern of daily flows. The need for availability of better data base for daily rain fall and temperature and also for specifying the pattern of melt rate variation is indicated for further improving the model performance.

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CHAPTER-I

INTRODUCTION

1.1 PRECIPITATION RUNOFF PROCESS IN HIMALAYAN BASINS

The water is one of the most vital resources for the mankind. The planning and development of water resources has become increasingly important particularly in developing countries with the rapid rise in population, and also due to rise of standard of living, resulting in increased demand of water for various uses such as irrigation, hydropower, domestic and industrial water supply etc. For any water resources development activity, the availability of information of hydrological parameters, to decide about water availability at a site and expected design discharge at the site, is very essential. The precipitation runoff process of a catchment is very complicated phenomenon, which is controlled by an unknown large number of climatic and physiographical factors that vary with both time and space. The process becomes still more complicated when precipitation includes both rain as well as snow. The precipitation runoff process of snow covered areas has been studied in somewhat detail in developed countries (where the snow occurs mostly due to latitudinal considerations rather than altitudinal considerations,) as in countries like India which are located in tropics. The precipitation runoff process of snow covered areas in Himalayas forms an important area of study for planning of water resources development activities in northern parts of the country.

The snowfall and rain in the Himalayas are the main source of supply for the rivers in the Indo-Gangetic plains, both during monsoon season,from rainfall in the lower parts of catchments,and during the premonsoon period from snow-melt. The snow accumulation season in Himalayas is generally from November to February, while the snow melt season is from March to June. The period from June to September constitutes monsoon season,when most of annual rainfall occurs and during October to November, the flow in Himalayan Rivers is mostly from base flow.

The amount of precipitation in the snow covered areas which are high altitude areas, is dependent upon the location, elevation and the meteorological as well as the seasonal factors. The form of precipitation i.e. rainfall or snow is dependent upon the prevailing temperature conditions. Since during March to June the snowmelt runoff is the predominent source of runoff and since during July to September also it forms a significant constituent of runoff, the snowmelt runoff estimate is of vital importance in forecasting water yield for regulating the reservoirs, estimating design floods for hydraulic structures and other water resources development activities. Inspite of its importance, the studies of snowmelt runoff have not progressed in India to desired level so that daily forecasts can be made for runoff from snowmelt. This is mostly due to the fact that very few rain/snow gauging stations are available and which has resulted in very limited hydrologic data availability for Himalayan basins.

Moreover, the available gauging sites for both precipitation as well as runoff are generally located at lower altitudes; and for higher altitudes,where most of snow accumulation and melt occurs, almost no gauging station is located. Because of the possibility of orographic effects, the limited precipitation data available at somewhat lower elevations in the Himalayan region may not be representative of the entire basin. There is a longfelt need for development of suitable methodology for estimation of daily streamflows (consisting of both snowmelt runoff as well as rainfall runoff components) using limited data available from gauging stations at lower elevations.

One very important feature of most of the Himalayan catchments is that some portions of the catchment at higher elevations remain always under permanent snow cover, whereas lower parts of the catchment come under snow cover temporarily during the winter months of November to February. Due to temperature rise, from March onwards, the temporary snow starts melting gradually from lower elevations. In the later parts of the snowmelt season, the effect of rain also comes into play and during monsoon months of July to September rainfall becomes much predominent, with some contributions coming from any remaining temporary snow cover besides meltwater from permanent snow covered areas.

In the study of precipitation runoff process in the snow covered areas where only limited information is available, the only course possible is to consider the main factors affecting the process viz. temperature, areal extent of snow cover and geomorphology of the drainage area. Fortunately, the availability of satellite images provide useful periodic information about extent of snow cover and can thus form a base for such study of precipitation runoff process in snow covered mountainous basin with limited data. Gulati (1972) has discussed the role of snow and ice hydrology in India and has divided the year in four seasons for the purpose of snow and ice hydrological studies. These are snow accumulation season (December to Feb.), snowmelt season (March to May) monsoon season (June to September) and ground water season (Oct. to Nov.). The distributions of seasonal precipitation as percentage of annual precipitation for the Himalayan basins have been given by him for different parts of Himalayas, (Table-1.1):

TABLE-1.1 : PERCENTAGE OF ANNUAL SEASONAL PRECIPITATION

Sl. No.	Name of Himalayan Section	Snow accumulation Season (Dec. to Feb.)	Snow Melt Season (Mar. to May)	Monsoon Season (June to Sept.)	Ground water Season (Oct.to Nov.)
1.	Kashmir Himalaya	22.1	22.0	53.6	2.3
2.	Punjab Himalaya	11.0	8.1	78.4	1.6
3.	Garhwal Himalaya	6.0	3.6	87.8	2.6
4.	Nepal Himalaya (Western and Central)	3.9	2.9	88.0	5.2
5.	Nepal Himalaya(Eastern)	2.9	6.8	85.0	5.3
6.	Sikkim Himalaya	2.0	16.5	74.6	6.9
7.	Assam Himalaya	2.4	25.7	65.8	6.1

Bagchi (1981) has referred to Seasonal Flow of the rivers in Indus basin as percentage of annual flow on a 3 monthly basis (in Table-1.2)

TABLE-1.2 : PERCENTAGE OF ANNUAL SEASONAL FLOW OF THE INDUS CATCHMENT RIVERS

Sl. No.	Name of the Rivers	April to June	July to Sept.	October to Dec.	Jan. to March
1.	Indus	31	54	8	7
2.	Jhelum	44	36	8	12
3.	Chenab	28	56	7	9
4.	Ravi	30	51	8	11
5.	Beas	15	67	10	8
6.	Satluj	23	62	9	6
7.	All rivers together	30	54	8	8

The study and review of available information and literature clearly shows that the snowmelt season from March to May forms an important contribution to the annual runoff, and the snowmelt runoff studies in the Himalayan basins are very useful and necessary.

1.2 IMPORTANCE OF GEOMORPHOLOGY

Snowmelt runoff process in the Himalayan basins takes place in high altitude areas. The location as well as the lie of the Himalayas from the view of latitude is unfavourable

The study of geomorphology of Himalayas is also necessary, in order to understand the differences in the morphological characteristics of Himalayan basins and basins in Europe and U.S.A., where the snow is mostly located in high latitude areas and where altitude is not comparatively of much significance. Such comparisons would also be very helpful in deciding about appropriateness and applicability of the techniques for modelling of snowmelt runoff developed elsewhere for typical conditions in Himalayan basins. For the present study, the data of Chenab river basin in Himalayas have been used.

1.3 THE CHENAB RIVER

The Chenab river is one of the big tributories of Indus (Sanskrit:Sindu) river, which is the western most of the Himalayan rivers, Krishnan (1968). The river catchment (Fig. 1.1) is located between 32°-35°N latitude and 74°-78°E longitude. In Sanskrit, the name of Chenab river is Asikni or Chandra Bhaga, consisting of two branches viz. Chandra and Bhaga rivers. Chandra river originates from south and south east of the Great Himalayas at an elevation of 6517 m and Baralacha pass (elev. = 4880 m) in Lahaul, flowing through snow clad barren uninhabited country. It makes a knee near Barashigri tributary 96 km from its source, whereas Bhaga river is a precipitous stream originating from the south of Great Himalayas (Elevation of 6319 m), from the other side of Baralacha pass. The two rivers join at Tandi and flow through Chamba state in a north westerly direction for a

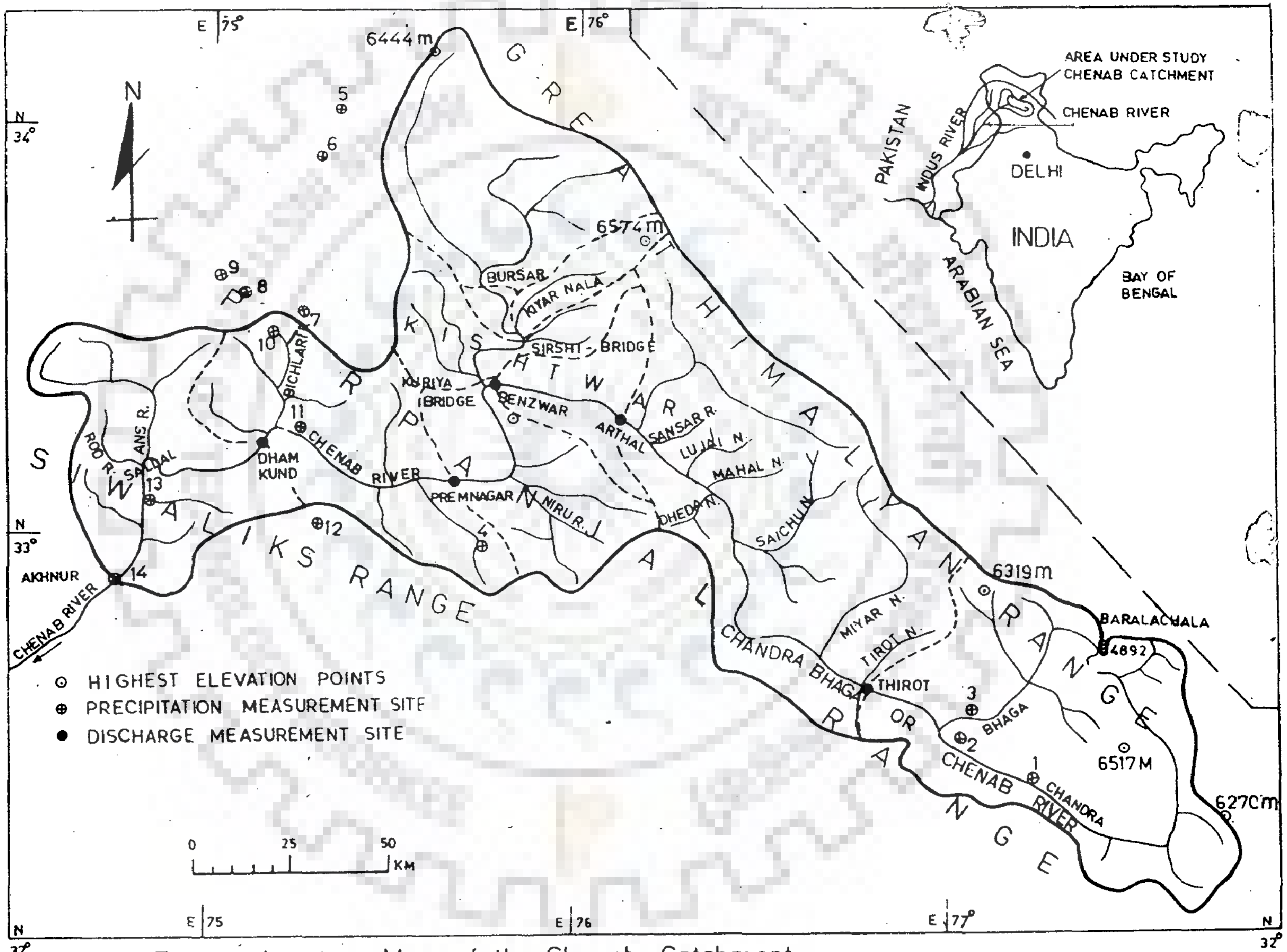


Fig. 1.1 Location Map of the Chenab Catchment

distance of about 160.0 km between the Great Himalayas and the Pirpanjal mountains on the same alignment as the river Jhelum in Kashmir valley. De-Terra (in Krishnan, 1968) states that 'there is evidence about the Jhelum originally flowing in a south-eastern direction (i.e. to the reverse of the present direction) into the Chenab valley. This may be true because, at present, there are several tributaries of the Jhelum, joining it in a direction opposite to the present course. On the other hand, the Chenab basin indicates greater maturity on its course than the Jhelum valley and evidently is older in age than the latest uplift of the Himalayas. The Chenab river also makes two sharp knee-bands in Kishtwar region at Benswar and Premnagar and also a very sharp knee at Sirshi-bridge along Marusudar river, near Benswar and flows across the Pirpanjal and Siwalik to Akhnur, 543.0 km from source. The average gradient is (10.22 m/km) as measured from the Survey of India topographic map of scale 1:50,000. Its gradient is very steep at its source and gradually reduces down-stream. After Akhnur, it flows in the Indo-Gangetic plains and enters Pakistan near the Marala weir, below the junction of the Tawi. In Pakistan, the Chenab flows for more than 644. km (Report of the Irrigation Commission, 1972) to Panjnad where it joins Sutluj , and finally flows into the Indus river.

1.3.1 Topography

The Chenab river basin is one of the major river basins of the Himalayas, covering around 22850 sq. km area upto

Akhnur as measured from the topographic maps published by the Survey of India topographical section. Study of the above maps show large variation in elevations and lithology in the basin which is located inside the mountains and consists of seperate valleys which act as sub-basins, contributing considerable amount of runoff as the tributaries of the Chenab river. The most important tributaries of this river, initiating from the great Himalayas and joining the river are: Bhaga river, Thirot Nala, Miyar Nala, Saichu Nala, Mahal Nala, Lujai Nala, Sansari Nala, Bhut river, which are located between Thirot and Arthal discharge measurement stations and also Marusudar river which joins the main river at Benswar discharge station.

The tributaries that are originating from Pirpanjal mountains are Dheda Nala, near Arthal, Kal Nala and Niru river from the left near Prem Nagar, Bichlari river and Ans river simultaneously joining the main river near Dhamkund discharge measurement site and at Sallal, from the right (looking d/s). It is thus obvious that a number of smaller tributaries join the Chenab river along its course.

1.3.2 Climate

There is no specific detail readily available for the climatic conditions of the Chenab basin, but as this basin is inside the Himalayan ranges the climate condition can be studied from the general information available for the Himalayan Catchments.

Climatically the year in this region can be divided into three major seasons(Report of the Irrigation Commission 1972)

i) The hot weather season (April to June)
ii) The rainy season (July to September)
iii) The cold weather season (October to March)

The climate of the region is perpetually snow clad peaks in part of (Himachal Pradesh) Chenab basin. In summer due to increase in temperature the atmospheric pressure falls over the heated land and humidity also drops. The day temperature increases considerably in association with the heat waves which generally develops during this period over North India, the temperature rises as high as 27 °C as observed at Banihal station (elevation = 1630 m a.sl) located inside the Chenab basin. Occasionally dust storms bring about a sudden fall in temperature and sometimes these storms are followed by light rain which result in slight lowering of the temperature.

The rainy season commences in the month of July and lasts till September. The major part of the precipitation occurs in this period. The monsoon showers bring relief after the prolonged heat of summer season.

The cold weather [illegible] starts in the month of October. November is slightly cooler; December and January are markedly cold and the temperature sometimes falls to, -5 °C, as indicated by the available data at Banihal station. There is some winter precipitationsduring these months, which experience snow in the hills. The temperature starts to increase in the month of March and as such the snow starts melting from the lower elevation zones of the basin.

1.4 THE DATA

The available data for the Chenab basin, which is the area under study, are as below:

(i) Topographic Maps:

The topographic maps published by the Survey of India topographical section are in two different scales i.e. 1:50,000 or large scale and 1:250,000 or small scale. These maps provide useful information for investigation of the morphology to understand the morphological characteristics and determination of morphologic parameters of the basin. These quantitative estimates are used for developing the relationship between hydrological and morphological characteristics of the basin and also to quantify some of the hydrometerological parameters of each of the sub-basins as required for the daily Snowmelt and Rainfall - Runoff model proposed to be developed in this study.

(ii) Satellite Images:-

The available LANDSAT images (45 nos. covering period from March 75 to June 81) for the area of study, were obtained from the EROS Data Centre, Geological Survey, U.S.A. and the National Remote Sensing Agency, Hyderabad, India, for snow cover mapping (Appendix, IV-1).

iii) Hydrometeorological Data:

a) Precipitation Data:- Available daily rainfall data of stations (listed in Appendix I.1) whose locations are indicated in Fig. (1.1),have been used in the analyses. Rainfall data were collected from India Meteorological Department (I.M.D.), New Delhi for the period from 1965-1980.

b) Temperature Data:- Daily maximum and minimum temperature data at Banihal (EL=1630M. ASL) were collected from Meteorological Centre, Rambagh, Srinagar and I.M.D., New Delhi for the months of March to May for 16 years and for the months of June to September for 9 years covering the period during 1965-80. The average daily temperature has been used in this study.

c) Discharge Data:- The available daily discharge data for 1965-1981 from sub-basins at the ten discharge sites (listed in Appendix I.2, locations are shown in Fig. 1.1) were collected from the Statistical Section, Ministry of Irrigation, New Delhi.

1.5 THE PROBLEMS

As stated earlier, the snowmelt runoff estimation is of vital importance in forecasting seasonal water yield for regulating the storage reservoirs, estimating design flood and planning of water resources development in Himalayan basins, where the increased demand for water, strategic importance and need for power have led to considerable construction activities in recent years. The data availability in the Himalayan region is rather limited with only precipitation and temperature data being available at lower elevations and runoff data are available only for few sites. The Chenab basin, as described earlier, is a typical case for such limited data availability. Besides this information, the other useful information available is that from topographical maps and satellite images. The main thrust of the present study is on the following specific problems:

1) To study hydromorphometric characteristics of the Chenab basin.

2) To develop suitable relationships between flood characteristics and hydromorphometric characteristics

3) To analyse available satellite images and runoff data, in order to understand and develop the relationship between snowmelt runoff and extent of snow cover.

4) To study and review important modelling studies of snow melt runoff done elsewhere, and to develop a suitable model of daily runoff from snowmelt and rainfall during snowmelt season and monsoon season, which can be applied for typical conditions of the Chenab basin.

1.6 SCOPE OF THE STUDY

In order to study the four specific problems listed in the previous section, using the available data of Chenab basin, the scope of the study is limited to the following specific tasks:

(i) Statistical Study of Temperature and Discharge Data:

(a) Temperature data:

This will involve the use of computer program to find out the mean, standard deviation and skewness of the daily temperature for each day of record during March to September. The computed mean daily temperature ± specified % of standard deviation would be used as alternative temperature data in place of the recorded temperature, for estimation of snowmelt runoff under varying temperature conditions.

(b) Discharge data:

Statistical analysis of the discharge data to obtain average flow, standard deviation of daily flow alongwith the mean monthly flow and mean annual flow from the available data at each of the sites will be carried out using computer program. These will be used for development of relationships with morphometric parameters.

(ii) Study of Hydromorphometric Characteristics:

This involves the study and analysis of available topographic sheets for the Chenab basin for obtaining hydromorphometric data. Since hydromorphological characteristics have an important role in snow melt runoff hydrological process in high altitude mountainous areas, the various linear, areal and gradient aspects of drainage system viz. bifurcation ratio, length ratio, area ratio, slope ratio and basin shape etc. will be studied and various hydromorphometric relations will be established. The data, interpreted in the light of the well-known empirical relations and deviations from the normal rule in the Chenab basin, will be systematically examined and explained. The main idea is to seek and establish hydromorphometric relations in this basin and quantify the hydromorphometric characteristics for relating the same to hydrological data:

(iii) Establishment of Relationships Between Hydrological and Hydromorphometric Characteristics:

Though the data base is somewhat limited, particularly number of years for which runoff data are available range from 10 to 16 years only, a scientific study for the development of suitable regression relationship between flood/flow characteristics and morphological characteristics for the Chenab basin would provide useful information for planning and design of structures.

(iv) Snow cover Area Study from Satellite-Images:

The LANDSAT images have been procured for different dates (spread over a period of 3-5 years). These provide a limited but useful information for the estimation of areal extent of snow cover. The images have been studied to develop a relationship between snow cover area on a particular day and subsequent snowmelt runoff during remaining period upto June. This could be a useful technique for application purpose during planning and operation stages, when only limited information from satellite images are available. Such studies have been conducted elsewhere also and the results obtained in present study have been compared with these studies.

(v) Development of Model for Snowmelt Runoff Process:

The data availability in Himalayan basins in general and the Chenab basin in particular being a constraint, the development of the model has to be primarily based on limited data availability. This consists of daily rainfall and daily temperature at lower elevations and daily runoff at catchment outlet besides topographic maps and satellite images. The model has also to take into consideration typical conditions of Chenab basin; the presence of permanent snow covered areas and the effect of rain on the temporary snow covered areas. The daily snowmelt runoff model to deal with limited data availability situation, developed in this study, is simple but still representative enough to enable prediction of daily snowmelt runoff and is consistent with established physical laws of the snowmelt runoff process. The data of 5 out of the total 6 catchments (subbasins of the Chenab basin)have been used for the caliberation studies to develop appropriate relationships between model parameters and catchments characteristics. The model has been tested with independent data of sixth catchment. The study also involves extensive use of digital computer and optimisation techniques for estimation of parameters. The model structure makes use of the information of area elevation characteristics obtained from toposheets through hydromorphometric analysis and extent of snow cover information obtained from available satellite (MSS) images. The prediction of extent of snow cover on each date and the corresponding elevation of the snow line is an important aspect of the model studies so that the model is capable of being used in real time operation. The Model has also been used for some prediction runs for studying the variation in the snowmelt runoff due to possible change in daily rainfall and temperature conditions and also for different assumptions regarding melt rate variations during the season.

CHAPTER - II

HYDROMORPHOMETRIC ANALYSIS

2.1 GENERAL

2.1.1 Scope

Systematic analysis of morphometry of any drainage basin and its stream system is of great importance in understanding hydrological behaviour of the basin. The hydromorphometric characteristics should directly affect rainfall-runoff as well as snowmelt runoff patterns. With this view in mind, hydromorphometric analysis of the Chenab basin was carried out with the aim to:

i) Seek and understand mutual relations between various hydromorphometric parameters and

ii) generate data on hydromorphometric parameters which could be related to hydrological data and also used in snowmelt runoff studies.

In this chapter attention would be focussed on the first point i.e. to seek and understand mutual relations between various hydromorphometric parameters. The data generated during the course of this analysis have been used as inputs in subsequent chapters, which aim at relating hydromorphometric data with hydrologic data (Chapter-III), and their role in snowmelt runoff (Chapter IV). Further, the morphometric data have also been used in computations for developing the model for daily snowmelt runoff(Chapter-V).

2.1.2 Morphometric Studies and Previous Work

The major factors which affect the basin configuration can be considered either in terms of geometrical factors or physical factors. Geometrical factors consist of shape, slope, elevation, orientation, circularity, elongation, perimeter, stream density and, frequency etc. Physical factors are those which deal with the lithology-formation of the area. However, the physical factors are again manifested in terms of geometric factors. For geometric analysis, the study can be systematically arranged into three aspects : linear aspects of the drainage basin, areal aspects of the basin and gradient aspect of channel network (Strahler 1964) and from these three, all of the various geometric factors can be derived.

To understand the inter-relations between different geometric characteristics of the basin,they have to be expressed in quantitative form, for the simple reason that fairly complex relations exist between these parameters. In this way the idea of quantitative morphometric analysis has grown. In the early 20th century, stream ordering system was conceived and new measures and approaches for description of the drainage basin characteristics were prepared (Horton, 1932, 1945; Longbein 1947). Stream ordering method earlier stated by Horton (o.cit) was modified by Strahler (1957). A number of drainage basin characteristics have been proposed by different workers (e.g., Horton, 1932; Longbein, 1942; Johnston and Cross, 1949; Strahler, 1964; Gray, 1965;, Chorby, 1967 and Murphey et al.,1977). The hydromorphometric parameters used in this study have been mentioned in 2.3.4.

There have been numerous geomorphological and related investigations in the Himalayas, like geomorphic evolution and neotectonics (e.g. Pal and Merh, 1975, Singh and Saklani, 1980; Verma, 1982) , landslides (e.g. Mithal, et al. 1972; Kalvoda, 1972); flash floods (e.g. Prasad and Rawat, 1982), silt yield and stream erosion (e.g. Subramanian and Dalavi 1980; Rawat, 1985). However, hydromorphometric studies on quantitative lines have been only a few. Shukla and Verma (1973) studied the basin morphometry and related it to slope development in the Eastern part of the Dehradun valley, lying in the Siwalik (Sub-Himalayan) ranges Parasad and Verma (1975) carried out similar morphometric studies in the Western part of the Dehradun valley.

Mithal et al. (1982) and Rawat, (1982) carried out hydromorphometric studies in the Ramganga catchment, Garhwal Himalayas and related the variations in morphometric parameters like stream length, stream number, length ratio, area, basin relief and basin length etc. to rock types like limestone, plyllites, quartzite etc.

Joshi and Rawat (1983) studied the development of morphometric parameters in a river basin in Kumayun Himalayas and related these to the degree of metamorphism and tectonics. They found that drainage parameters like drainage density, stream frequency and ruggedness number can be considerably controlled by metamorphism and tectonics and also concluded that the Horton's laws of drainage composition may be adversely affected to a good degree by such inhomogeneities.

Further, quantitative morphometric studies of some catchments lying in Peninsular India have also been reported (e.g., Subramanyan, 1975, James and Padmini 1983) and their data have been used to derive comparison between catchments of mature stage (Peninsular, India) and young stage (Himalayas).

2.2 GEOLOGICAL SETTING

An appraisal of the geological setting of the Chenab catchment area is important, as that would affect the hydro-morphometric characteristics. The geological structure of the area is very complex consisting of a number of highly deformed tectonic units (Gansser, 1964). Broadly, there are three major physiographic ranges, viz. the Great Himalayan range, the Pir-Panjal range and the Siwalik range (Fig. 2.1). All the three trending nearly NW-SE and correspond, more or less, to the three major geotectonic units (Fig. 2.2). The Precambrian metamorphic rocks (granites, gneisses and crystallines) constitute the northern most range of the Great Himalayas; the Pir-Panjal range in the middle consists of low-grade metamorphics and sedimentary rocks of mostly Palaeozoic age (though it also includes the Precambrain metamorphic crystallines at places) and the southern-most range is the Siwalik range comprising of Plio-Pleistocenesedimentary deposits. Based on other investigations, it has been

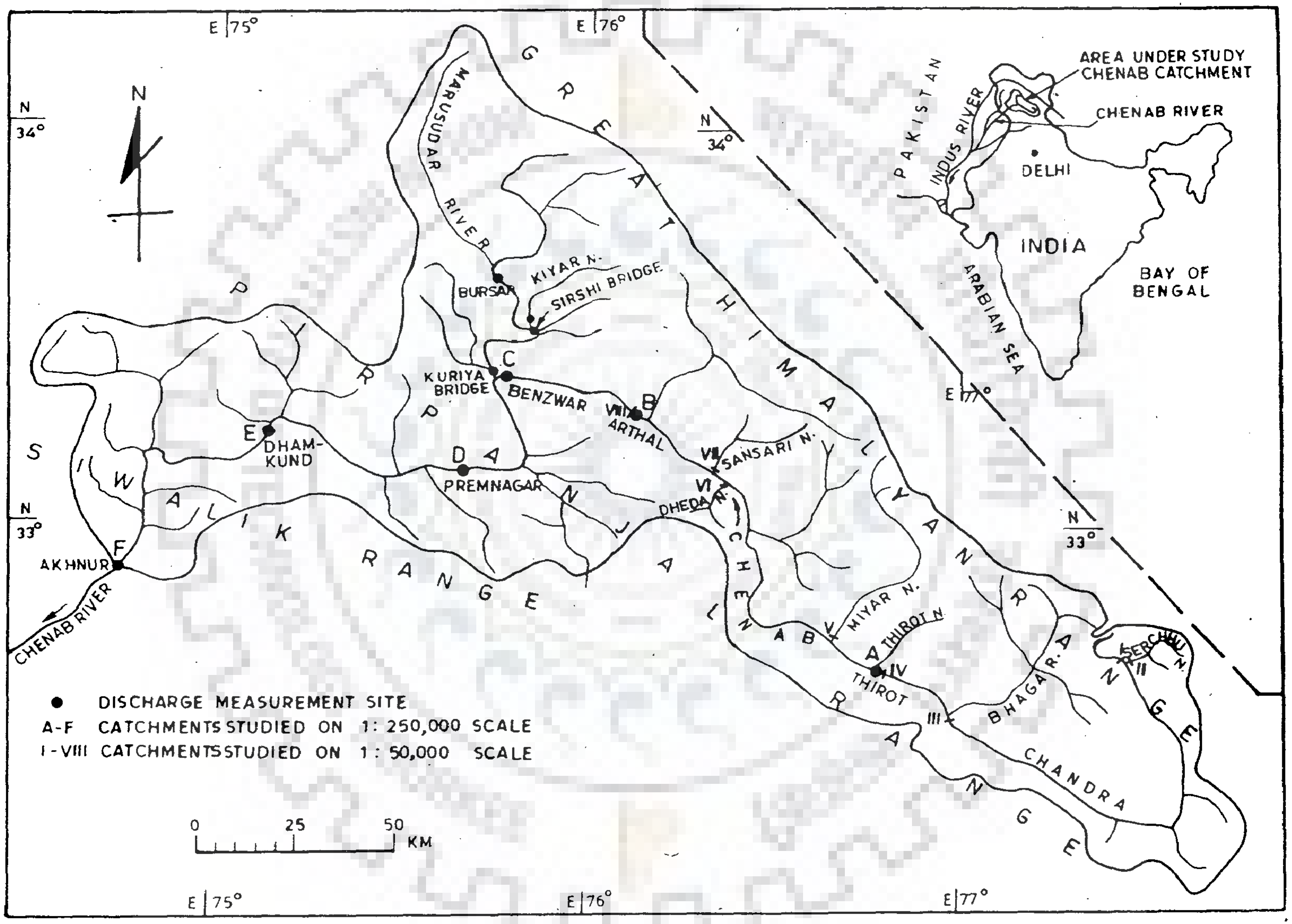


Fig. 2.1 Location map of the Chenab Catchment and Subcatchments Studied for Hydromorphometric Parameters

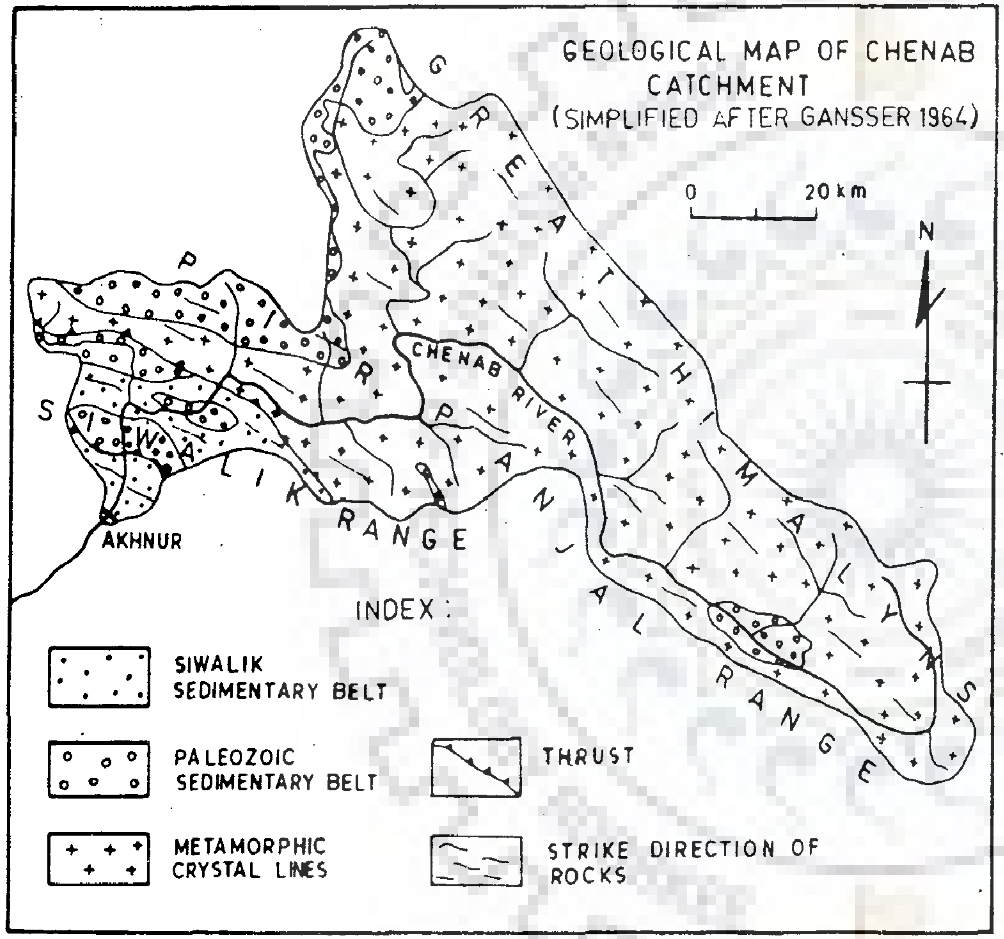


Fig. 2.2 Geological Map

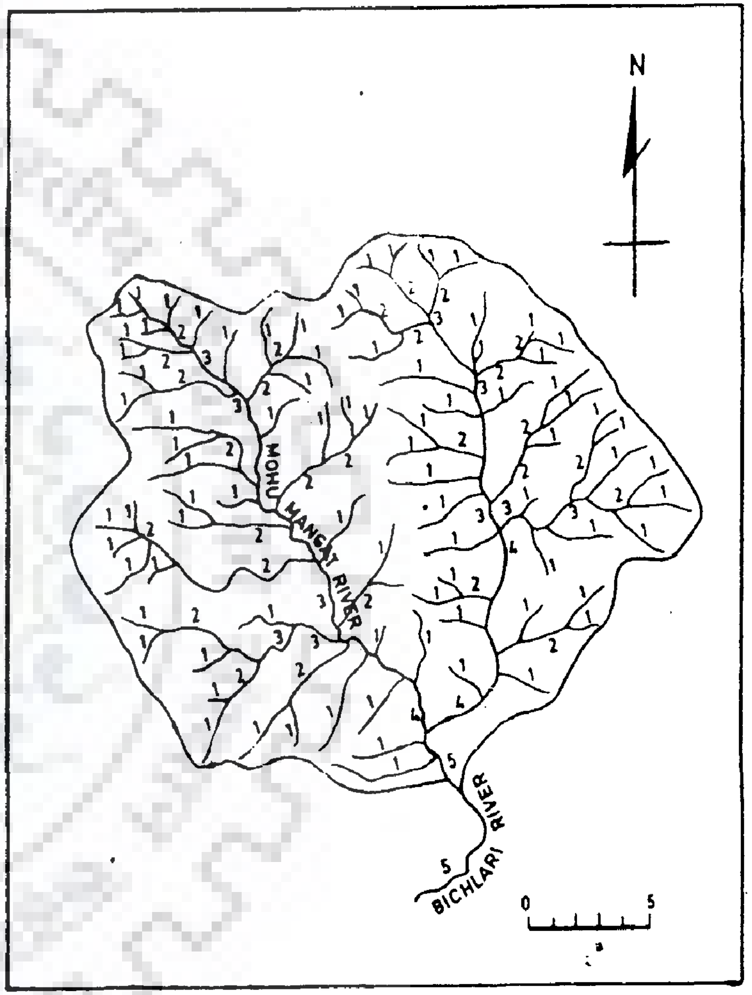


Fig. 2.3 Stream Ordering System

inferred by various workers that there have been tectonic movements in this area as late as in Quaternary times (Gansser, 1964; Bhatt, 1978; Bhatt and Chatterji, 1979). De Terra (in Krishnan, 1968) opines that in earlier times the Jhelum river followed a south-easterly course (i.e. reverse to the present direction) and flowed into the Chenab valley as many tributaries of the Jhelum join it in a direction opposite to its present course. These points also indicate that neotectonic movements have taken place in this part of the Himalayas in the recent past. The role of the above geotectonic features in controlling the hydromorphometric character is discussed later.

2.3 METHODOLOGY OF HYDROMORPHOMETRIC ANALYSIS

2.3.1 Data Source

Scale is an important factor in the Hydromorphometric study as details visible depend on the scale of investigation. The hydromorphometric studies have been reported on different scales ranging from 1:1000,000 to about almost 1:10,000, the most commonly used being 1:250,000 to 1:25,000. However, the hydromorphometric laws enunciated have been found to be valid independent of the scale of investigation. In the Chenab catchment, the hydromorphometric parameters have been measured and computed on two scales viz. 1:250,000 (small scale, hereafter called S-scale) and 1:50,000 (Large scale, hereafter called L-Scale) to bring out the regional and detailed picture of the morphometric characteristics of the area.

The entire catchment of the Chenab river was drawn from the topographic sheets published by the Survey of India. On those overlays, all the wet and dry streams, water divides of the catchment and main stream basins and contour lines were traced. The location of discharge sites, temperature stations and the rainfall stations as obtained from hydrometeorological reports were identified for use in the analysis of the hydrologic data (in Chapter III,IV,V).

2.3.2 Subdivision of the Basin

To facilitate relative comparison of one part of the basin with another, the Chenab basin under study has been subdivided into several smaller sub-basins, as follows:

(a)S-Scale: In this investigation, the study was confined to the main stream (Chandra and Bhaga i.e. Chenab).* The catchment from source to Akhnur was divided into six sub-regions A,B,C, D,E and F. The curves plotted for the above areas are respectively designated as curves No.A,B,C.....F. The subdivisions of the area into smaller subareas has been made as follows(Fig.2.1):

i) The drainage area upto Thirot discharge site is called area A.

iii) The area upto Arthal discharge site (including area A) is called area B.

iii) The area upto Benswar discharge site (including area B) is called area C.

iv) The area upto Premnagar discharge site (including area C) and also Marusudar branch) is called area D.

v) Similarly the area upto Dhamkund discharge site(including area D) is called area E and

---

* Though Marusudar is an important stream, it is a 5th order stream as compared to the 6th order stream of the river Chenab. As the catchment is already very big no sub-divisions in the Marusudar branch were considered in this morphometric study. However, as Marusudar River has three discharge locations sites at Bursar, Sirshi-Bridge and Kuriya Bridge specific morphometric data required for use in Chapter-III,IV and V, was computed.

vi) The entire drainage area of the Chenab River upto Akhnur is called area F.

(b) L-Scale:- To understand the morphometric characteristics in greater detail, a portion of the drainage area extending from the source upto Arthal discharge site was studied on 1:50,000 scale (L-scale). Initially on this scale, twenty five sub-regions were studied for linear, areal and gradient aspects. However, it was found that there is much repetition in the type of inferences drawn and therefore, only eight representative sub-regions numbered I-VIII have been selected for presentation and discussions here. The details of the sub-catchments I-VIII are as follows(Fig.2.1):

I - The first-tip of the Chandra River upto just before its junction with the Serchu Nala,

II - The Serchu Nala, before its junction with the Chandra River,

III - The Chandra River just before its junction with the Bhaga River,

IV - From source upto Thirot discharge site,

V - Miyar Nala, before its junction with the Chenab river,

VI - Dheda Nala, before its junction with the Chenab river,

VII - Sansar Nala, before its junction with the Chenab river,

VIII - From the source upto Arthal discharge site.

2.3.3 Parameters Used

The boundary of the drainage catchment, all dry and wet streams, has been mapped from the topographic sheets (1:50,000). The lengths of stream have been measured using a rotometer and areas of basin by planimeter. The gradient aspects have been deduced from contours.

The following parameters were measured and computed (for data please see Appendices II.1 - II.6).

(a) Measured Parameters:

i) Stream order

ii) Number of streams in each order

iii) Average length of each stream order

iv) Average area of each stream order

v) Average slope (gradient) of each stream order and relief.

vi) Perimeter, elongation, length of trunk channel in each sub-catchment.

(b) Computed Parameters: (Stream order wise)

i) Bifurcation ratio and its mean;

ii) Length ratio and its mean.

iii) Area ratio and its mean.

iv) Slope ratio, and its mean.

v) All the factors expressing the drainage basin shape, such as circularity ratio, elongation ratio, form factor and other factors such as drainage density, stream frequency, length of overland flow, relief ratio, ruggedness number and hypsometric relation.

It may be mentioned that on the L-scale, linear, areal and gradient aspects have been studied, whereas only linear, areal and some gradient aspects have been investigated on the S-scale. The interpretation of the above data is quite interesting as many deviations from the normally accepted hydromorphometric relations have been observed. The salient points of the results are discussed in the following sections:

2.4 LINEAR ASPECTS

2.4.1 Stream Order

For assigning orders to streams, different methods as given by Horton (1945), Strahler (1957) and Scheidegger (1970) are available. However, the various relations between hydromorphometric parameters as given by Horton (1945), would be applicable only if his method of stream ordering is followed. Therefore, the Strahler's system, which is in fact slightly modified Horton's method, has been followed here. According to this, every finger tip channel from its point of origin is designated as a Channel segment of the first order; the combination of any two first order channel segments produces a segment of the second order; the combination of any two second order produces a segment of third order and so on. (Fig. 2.3). The junction of any lower order segment with higher order channel does not however produce any change in the order of the main segment it joins.

When this ordering system is applied over the entire drainage network of the Chenab river, it is found that at Thirot station (region A), the order (on S-scale) is the 5th order channel, having been formed by meeting of two 4th order streams, namely Chandra and Bhaga rivers. The same order continues upto the junction with the Saichu Nala, which is also a 5th order stream. Thereafter the river becomes a 6th order stream and this continues upto Akhnur discharge station. When the ordering system of the same catchment is done on L-scale, it is found that at Thirot, the stream order is 7th order. This difference is evidently due to more details seen on the L-scale. The scale of mapping thus has a direct influence on the degree of order.

2.4.2 Stream Number

The number of stream channels presented in each order in different regions of the catchment have been counted. The ratio of the number of stream segments of a given order(N_u) to the number of segments of the high order (N_{u+1}) is called the bifurcation ratio (R_b). It has been calculated for different stretches of the catchment (Appendix III.2 and III.3).

2.4.3 Stream Number v/s, Stream Order

Horton's (1945) law of stream number states that the number of stream segments of each order is in inverse geometric sequence with order number i.e.

$$N_u = R_b^{k-u} \qquad \ldots(2.1)$$

where k is the order of the trunk segment, u is the stream order, N_u is the number of streams of the u^{th} order and R_b is the bifurcation ratio (N_u/N_{u+1}). This law, called the law of stream number has received verification by the accumulated data from various parts of the world. In the present area of the Chenab catchment, the bifurcation ratio is found to vary from nearly 2 to 7 on the S-scale and from 2 to 8 on the L-scale. The data of number of streams have been plotted orderwise (Fig. 2.4). The curves on S-scale (Fig. 2.4a) are nearly rectilinear, almost parallel to each other indicating that the bifurcation ratio is generally same throughout the catchment. Some of the curves are bent in the lower portion (near to X-axis) which is due to incomplete regime of the highest stream order. On detailed examination, it is observed that the curves A to F exhibit minor decrease in slopes. This is also corroborated by the data (Appendix II.2) that the bifurcation ratio decreases from the higher reaches to the lower reaches. It implies that for a particular stream order N_u there are much more number of streams of N_{u-1} order in the higher reaches, than for the same stream order in the lower reaches of the catchment.

The relation between stream order and number of streams on the L-scale, also exhibits a general parallelism of the curves (Fig. 2.4b) implying the over-all maintenance of the bifurcation ratio. However, the difference in slopes of the curves pertaining to subcatchments of the higher reaches vis-a-vis those of the lower reaches is more clearly brought out here . The curve No. I and II are more steep than the

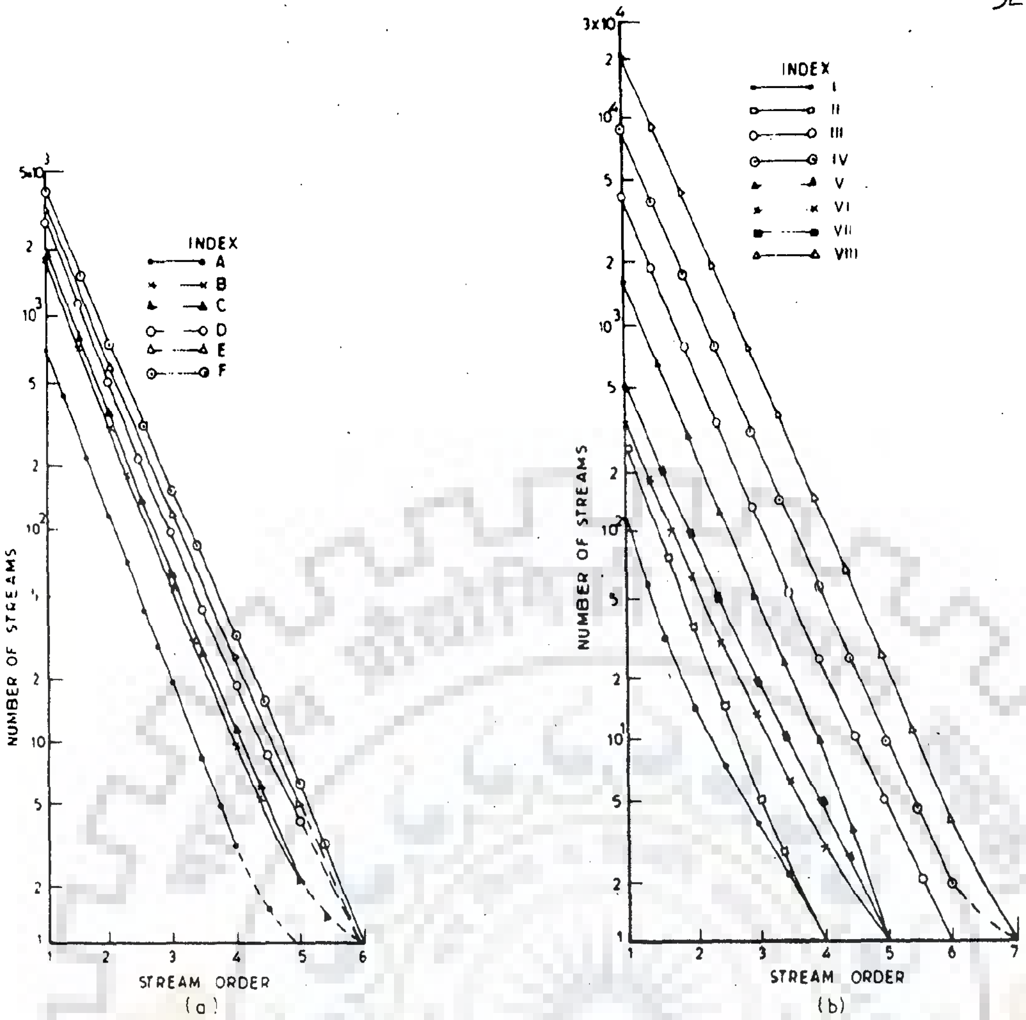


Fig. 2.4 Relationship Between Number of Streams and Stream Order

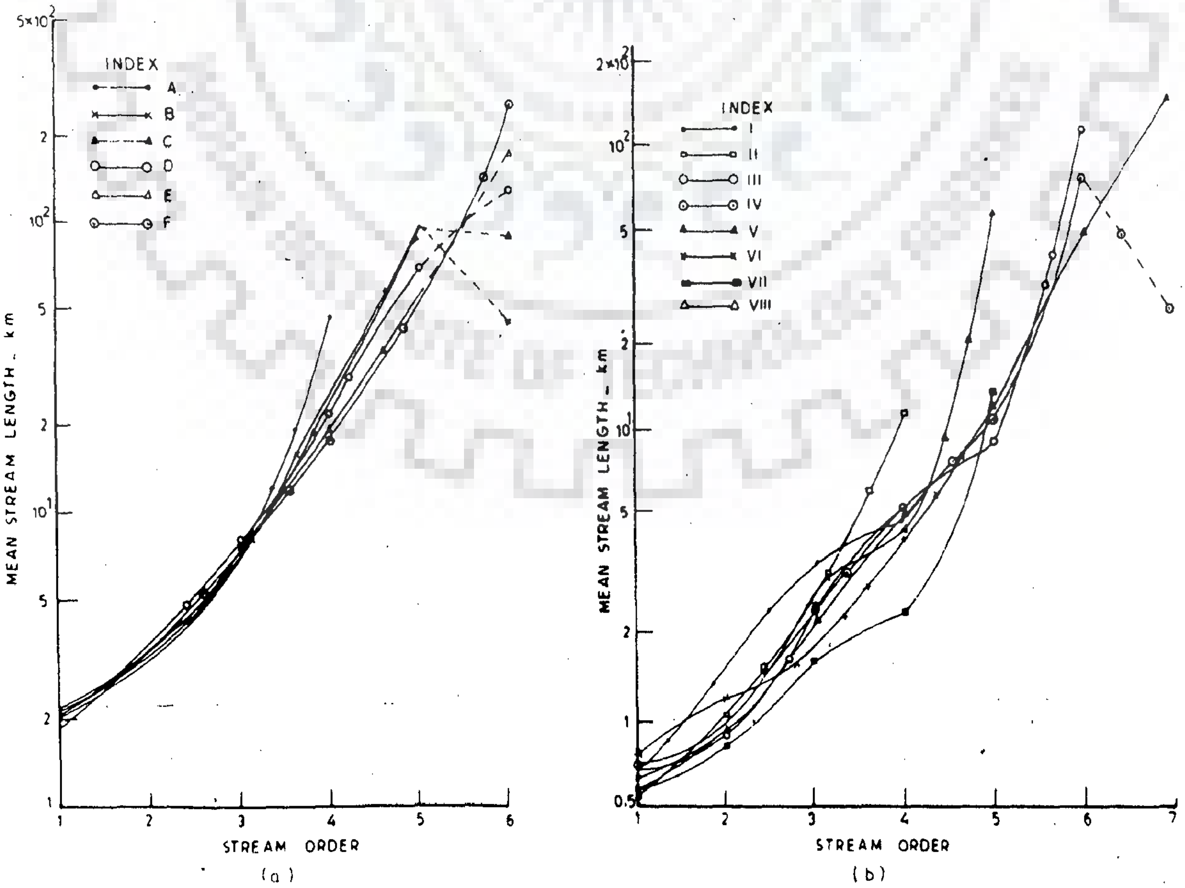


Fig. 2.5 Relationship Between Mean Stream Length and Stream Order

other curves (Fig. 2.4b). The bifurcation ratio in the case of I and II subcatchments reaches a very high value of 8.4 (for 1st and 2nd order streams (Appendix II.3). These variations may be related to particularly steep topography in the higher reaches of the catchment.

2.4.4 Stream Length

Stream channel lengths have been measured by rotometer (Chartometer). The topographical stream lengths which are somewhat shortened by projection upon a horizontal plane as represented on maps, have been measured. Larger the scale of the map, more accurate are the measurements of the length. In practice, all segments of a given order within the specified drainage network are measured successively at a time and the cumulative streams length divided by the number of stream segments (N_u) of that order, gives mean stream length i.e. '$\bar{L}_u$'.

$$\bar{L}_u = \frac{\Sigma L_u}{N_u} \qquad \text{...(2.2)}$$

2.4.5 Stream Order v/s, Mean Stream Length

The mean length of channel segment of a given order is greater than that of the next lower order, but less than that of the next higher order. Horton (1945) postulated that the ratio R_L (which is the ratio of the mean length $\bar{L}_u$ of segment of order u, to the mean length of segment $\bar{L}_{u-1}$ of the next lower order L_{u-1}) tends to be constant throughout the successive order of a watershed. His law of stream lengths states that 'the mean length of stream segments of each of successive order of a basin tends to approximate a direct geometric sequence', in which the first term is the average length of the segments of the first order:

$$\bar{L}_u = \bar{L}_1 R_L^{u-1} \qquad ...(2.3)$$

where $\bar{L}_1$ is the mean stream length of the first order. If the law of stream lengths is valid, the logarithm of stream length as a function of order should yield a set of points lying essentially along a straight line.

Fig. 2.5a shows the above relationship on S-scale where the overall linear relationship between the stream order and logarithm of mean stream length is observed. However, the following points deserve special mention : (i) there is a gradual steepening of curves from lower stream order to higher stream order, implying that the mean lengths of the higher order streams are longer than what should be normally expected. This phenomenon is well indicated in all the subcatchments A to F. and specially so in the subcatchment : A; (ii) the points of initiation of the curves have a systematic pattern,the 'A' curve starting lower-most and the 'F' upper-most. Thus the mean length of first order stream increases as one moves from higher reaches to lower reaches within the catchment. This general character is also true for higher order stream segments (Appendid-II.2).

The same relation (i.e. between log of mean length and stream order) on the L-scale is shown in Fig. 2.5b). It also shows a general increase in mean stream length with higher order. However, here the curves are more zig-zag which appears to be due to non-uniform terrain and geological conditions. One point clearly observed is that in general, the higher order streams are longer than expected in comparison to the lower order streams. This was also observed on the S-scales. The abnormally longer mean length of higher order streams may be due to the following reasons: (i) the topography is very steep at higher reaches making geological control minor and topographic slope a major factor, (ii) the higher order stream segments are channelized along geological discontinuity planes at places, as is indicated by the fact that the Chenab River follows a general SE-NW course, parallel to the strike of the rocks here (Fig. 2.2). This would lead to longer mean stream length at higher order. It seems that both these factors collectively have played a role to bring about non-uniform length ratios resulting in the above picture of curves.

2.4.6 Mean Steam Length v/s, Number of Stream

Figs. 2.6a and 2.6b exhibit the relation between mean stream length and number of streams. On the S-scale(Fig.2.6a) the curves are quite smooth and show a uniform pattern and the curves for larger sub-catchments are quite straight. On the L-scale the curves show somewhat non-uniform pattern, especially for smaller subcatchments i.e. for those located at higher reaches (I, II, V and VI in Fig. 2.6b). A general inference made from the Fig. 2.6 is that the curves steepen

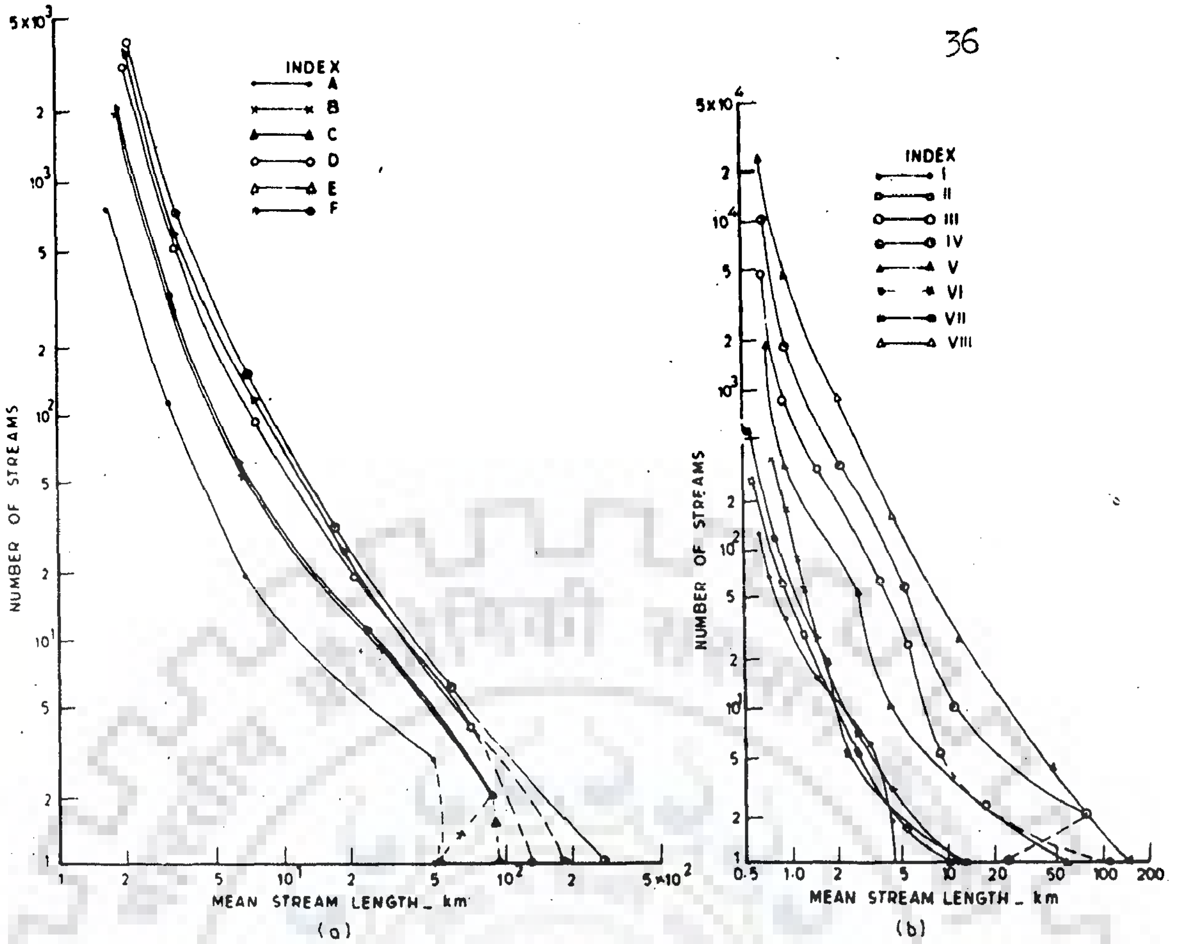


Fig. 2·6 Relationship Between Number of Streams and Mean Stream Length

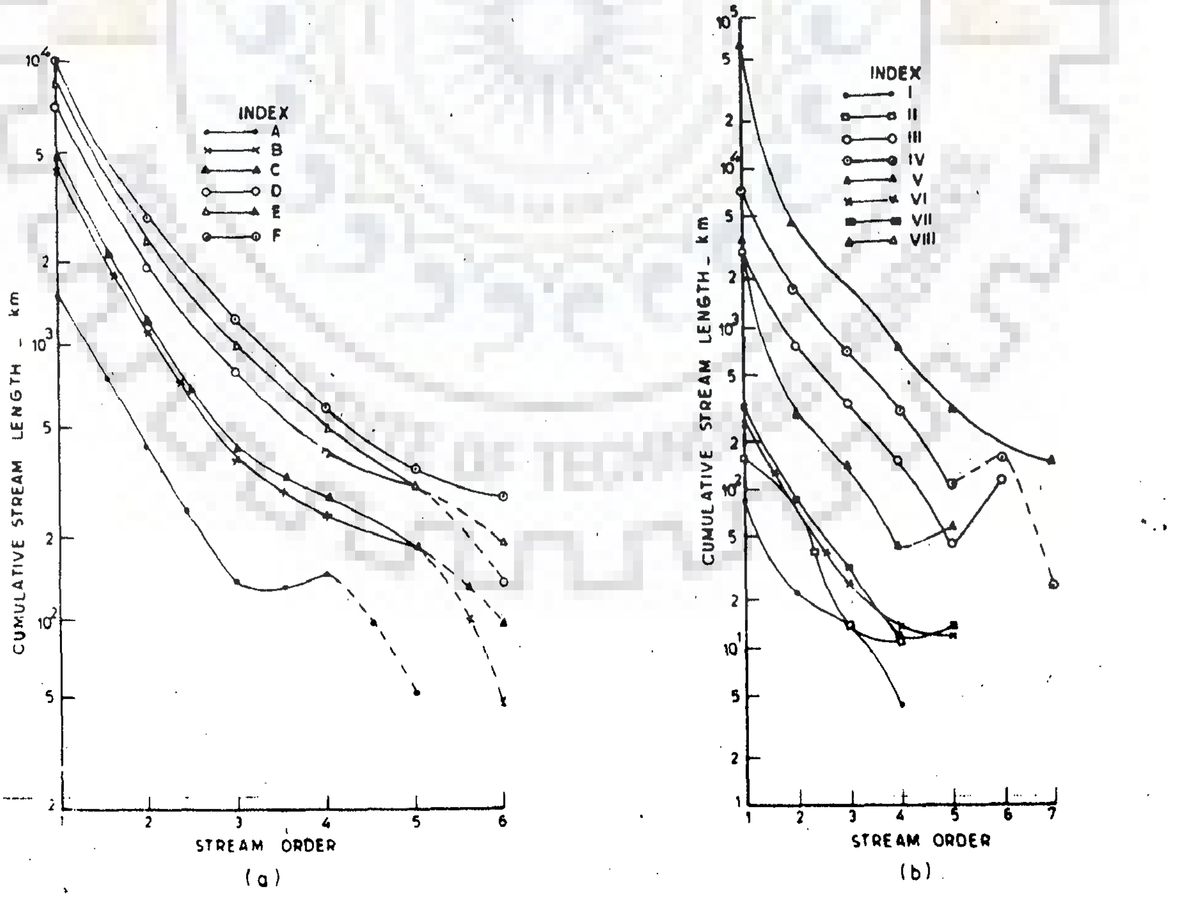


Fig. 2·7 Relationship Between CumulativeStream Length and Stream Order in the regimes of lower order streams, which would mean that the number of lower order streams is relatively very high in the areas.

2.4.7 Cumulative Stream Length v/s Stream Order

The law of stream number and law of stream length have been combined as a product to yield an equation for the total length of channel for a given order u, as:

$$\sum_{i=1}^{N} \bar{L}_u = \bar{L}_1 R_b^{k-u} \ R_L^{u-1} \qquad \ldots(2.4)$$

Thus, logarithm of cumulative stream length and stream order should have linear relationship. This relation as observed in the Chenab catchment is shown in Fig. 2.7a and 2.7b . Since cumulative stream length is a function of number of stream and mean length of the stream, Fig. 2.7 can be taken as supplementary to Figs. 2.4 and 2.5.

In general, there is a decrease in cumulative stream length with increasing order (Fig. 2.7) which is logical. However, some anomalous situations occur, where higher order streams are cumulatively longer than the immediately next lower order streams (Curve A in Fig. 2.7a and III, IV, V and VI in Fig. 2.7b). There seems to be an abrupt break in the nature of curves between the 3rd and the 4th order on S-scale or 4^{th}-6^{th} orders on L-scale (actual stream segments being same). This implies that, the basin geometry is not perfectly uniform or coherent throughout the catchment. Therefore, the concept of estimating total length of Channels from parameters like mean length, bifurcation ratio and length ratio as used in other basins (c.f. Strahler, 1964, p.47) may not be applicable here. The cause of this anomaly, i.e. higher value of cumulative stream length in some cases than normally expected, should be related to geological phenomena in the area, like presence of weak planes locally which channelize stream and tectonic uplift, and affect the stream network geometry.

2.5 AREAL ASPECTS

2.5.1 Stream Area

The area of a drainage basin is another important parameter just like length of the stream draining it. The areas of various drainage basins of different orders have been measured. From this data, mean area of the sub-basin of each order and the area ratios have been computed orderwise (Appendices II.2, II.3).

2.5.2 Mean Drainage Area v/s Stream Order

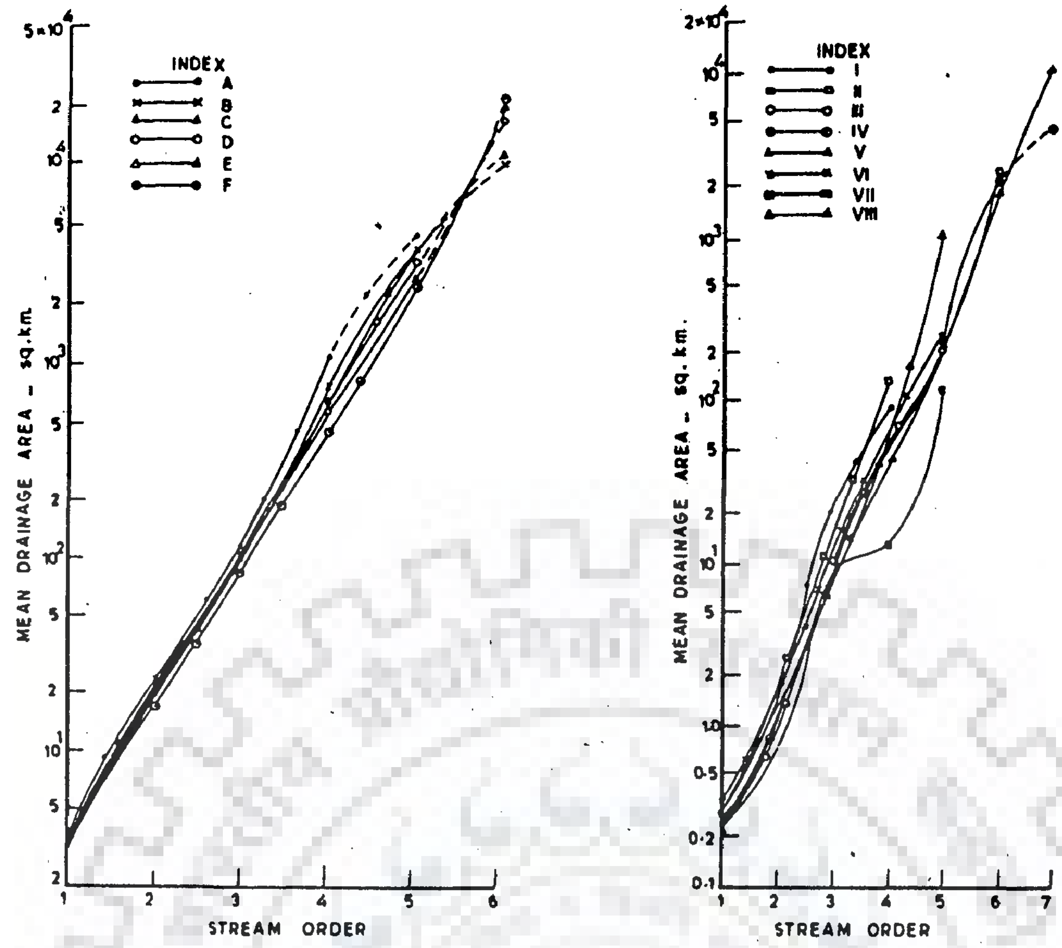
The law of stream areas states that, the mean basin area of streams of each order tends closely to approximate a direct geometric sequence in which the first term is the mean area of first order basin. This law may be written as:

$$\bar{A}_u = \bar{A}_1 R_a^{u-1} \qquad \ldots(2.5)$$

where $\bar{A}_u$ is the mean area of basin of order u, $\bar{A}_1$ is the mean area of the first order basin, and R_a is the area ratio (analogous to the length ratio). Fig. 2.8 gives the relation between log of the mean basin area and stream order in the present area of study. Near linear relations are observed on the two scales for nearly all the sub-catchments, which means that the mean drainage area systematically increases with the order of the streams. The area ratio is found to have a general value of about 5.8 and varies from 2.2 to 15.8 (Appendices II.2 and II.3).

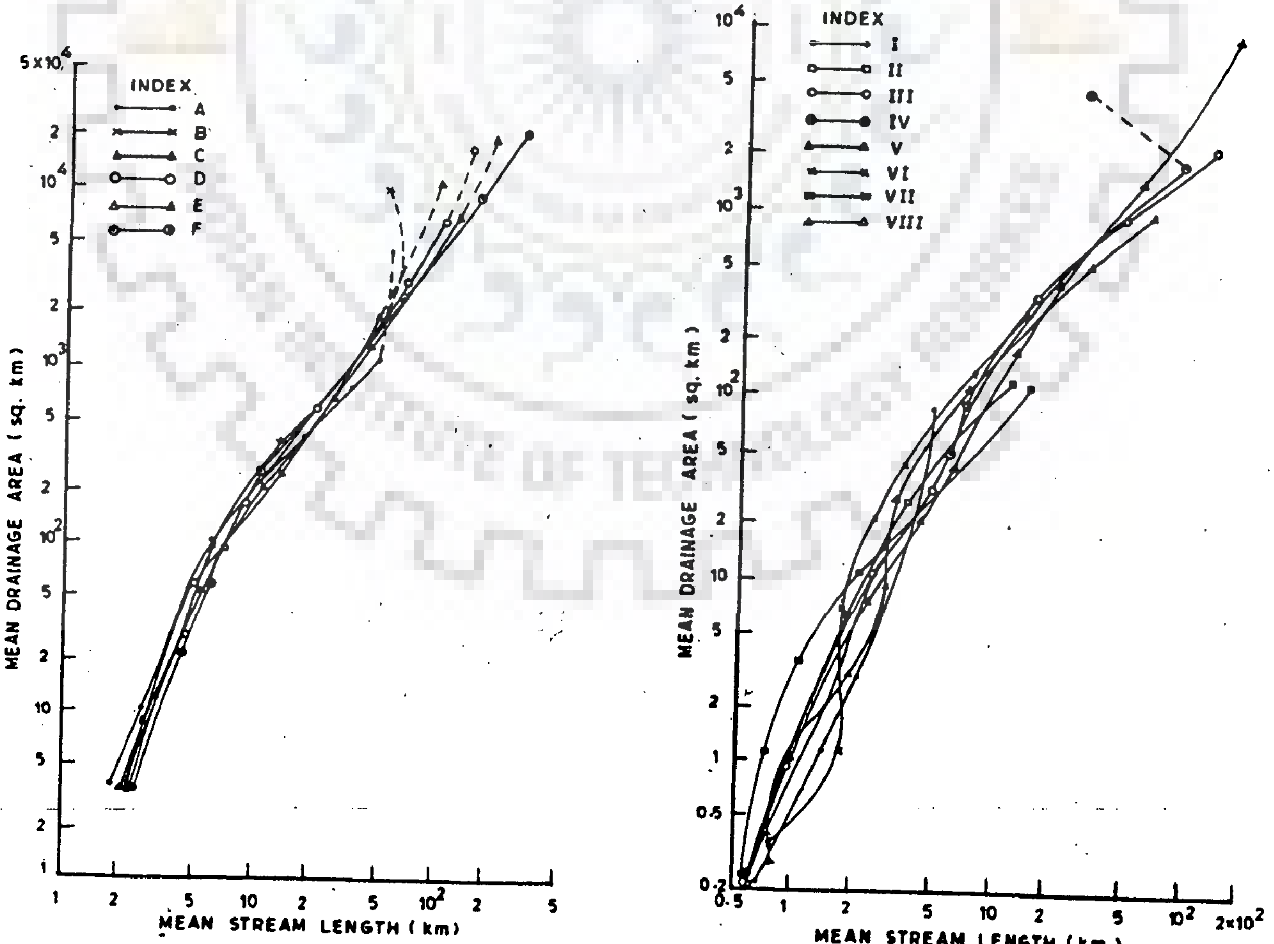
2.5.3 Mean Drainage Area v/s, Mean Stream Length

Logarithm of mean stream length and logarithm of mean stream area have linear relations in many basins (e.g. see Strahler, 1964). The relation between the orderwise mean stream length and the corresponding mean basin area for the Chenab basin is shown in Fig. 2.9. On the S-Scale, a pattern almost uniform over the entire area is observed (Fig. 2.9a). On the other hand, on the L-scale the picture is somewhat irregular. However, it can be seen that the mean drainage area does not increase with the mean stream length at the same rate throughout. First it increases at a faster rate and when the mean stream length reaches about 10 km (at which point the mean area has a value of about 2 x 10^2 sq.km) there occurs a sharp break in the geometry of the catchment (Fig. 2.9a). After this, the area increases with stream length at a rate lower than the earlier one the decrease in slope of the curves is inferred to be related to elongated basin shape formed by the higher order streams (also refluxion points in Fig. 2.5a, 2.6a, 2.7a at the same level



(a) (b)

Fig. 2·8 Relationship Between Mean Drainage Area and Stream Order



(a) (b)

Fig. 2·9 Relationship Between Mean Drainage Area and Mean Stream Length of 10 km mean stream length). These observations are in conformity with the earlier inferences of basin geometry from higher reaches to lower reaches and also imply that the sub-basins do not perfectly match each other in geometry through.

2.5.4 Length of Overland Flow:

It is a measure of length of non-channel flow and is inversely proportional to the degree of drainage development (or drainage density).

$$L_o = \frac{1}{2\,D_d} \qquad \ldots(2.6)$$

where L_o is length of overland flow and D_d is the drainage density. The length of overland flow (computed from data on both L and S-scales) is high in lower order stream subcatchments and decreases as subcatchment size increases (Fig. 2.10a, Appendix II.4). It is clear that, at higher reaches fewer stream channels are developed and more water runs off overland in comparison to lower reaches, where development of drainage is better and flow is more channelized.

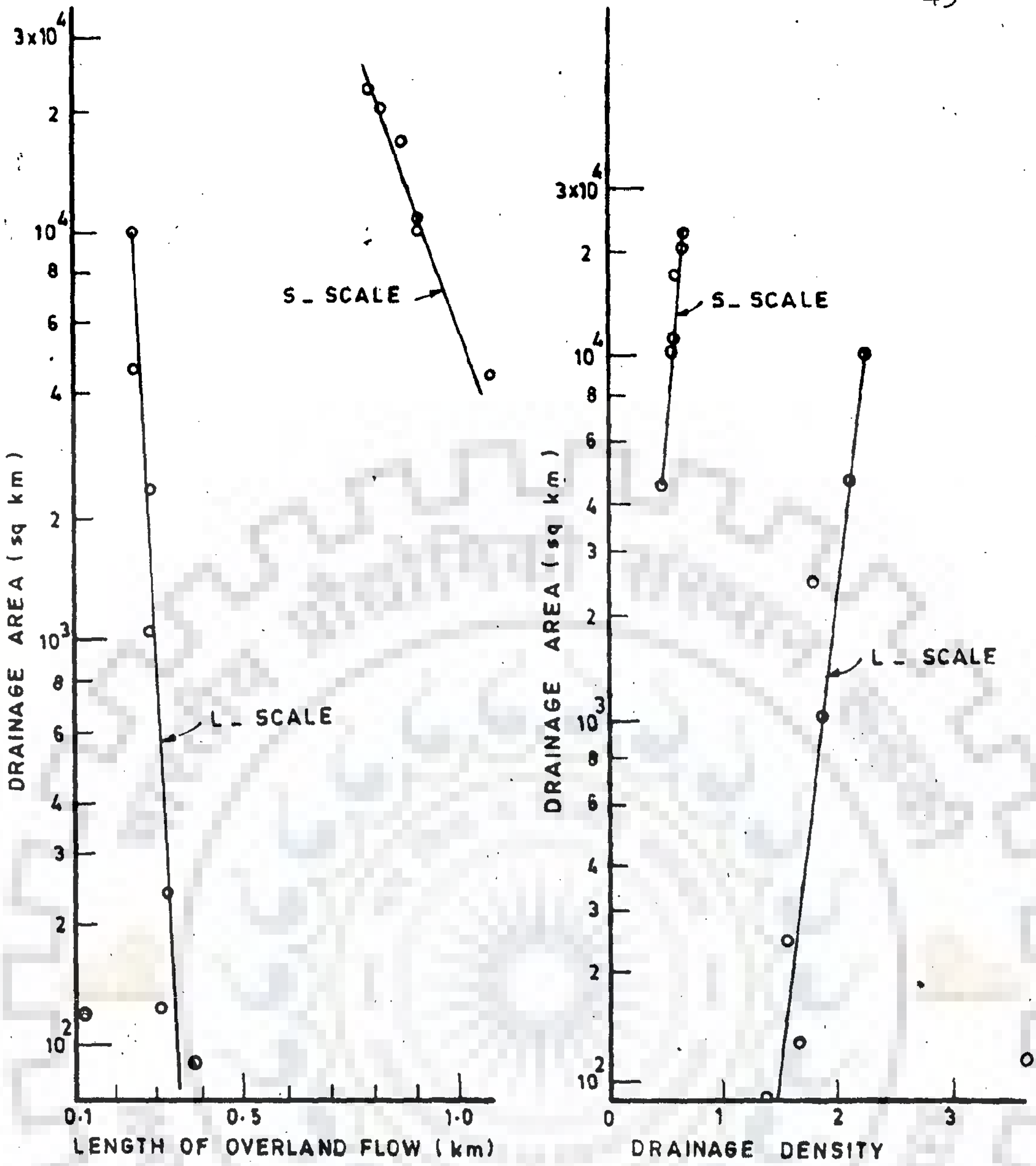
2.5.5 Drainage Density

Drainage density (D_d) is the length of drainage network per unit area. It can be expressed as L_t/A.

The drainage density has been computed on both S-scale and L-scale. In general it is found to be of the same order (= 2.1/km) as obtained by Mithal et al. (1972) for a sub-catchment in the Ramganga River catchment. On detailed examination in the Chenab catchment, it is found to vary systematically from higher reaches to lower reaches, being low in higher reaches and higher in lower reaches (Appendix II.4 and Fig. 2.10b). This regular variation could be due to two reasons. Firstly, the rocks forming higher reaches are granites and crystallines (see Fig. 2.2) and as they are very hard, the drainage development here is rather poor. This is in comparison to areas of softer rocks present at lower reaches which permit better drainage development, Secondly, as the slopes become steep, the chance of drainage development is less and the overland flow is more at higher reaches. Further, the drainage density on S-scale has much lower value than at L-scale. This is because of the lack of visibility of lower order streams on the smaller scale (Appendix II.4, Fig. 2.10b).

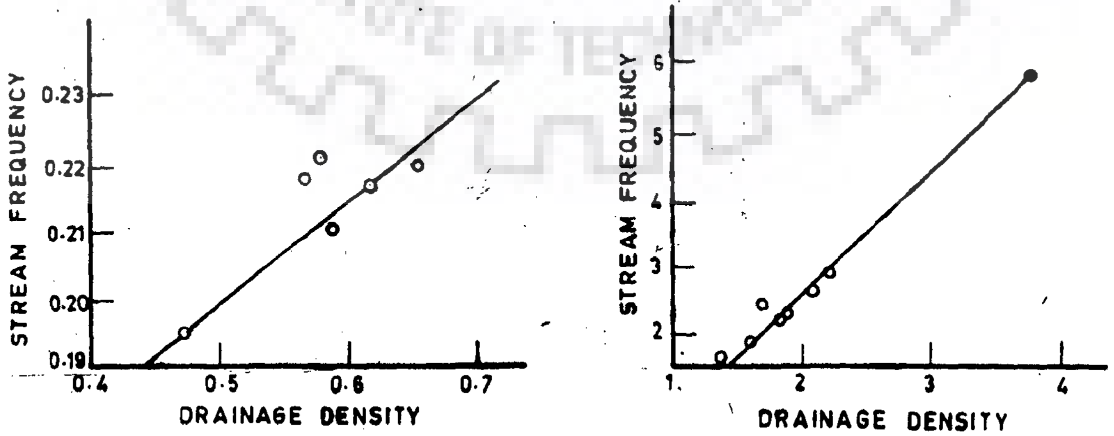
3.5.6 Stream Frequency

The stream frequency is computed by dividing number of streams by area. It is also of the same order (= 2.9) as obtained by Mithal et al. (1972) for a sub-catchment in the Ganga catchment Himalayas. In the Chenab catchment, the stream frequency varies in the same fashion as the drainage density, it is lower for the lower order sub-catchments situated at higher reaches and higher for the higher order subcatchments encompassing also lower reaches (Appendix II.4). The stream frequency and drainage density are well correlated (Fig. 2.11a and 2.11b). The causes leading to variation in



(a) (b)

Fig. 2.10 Relationship Between Drainage Area and : (a) Length of Overland Flow (b) Drainage Density



(a) (b)

Fig. 2.11 Relationship Between Stream Frequency and Drainage Density the stream frequency should be the same as those in case of drainage density.

2.5.7 Basin Configuration

To evaluate basin configuration, three factors viz. circularity ratio, basin elongation and form factor have been computed.

(a) Circularity Ratio:- Miller's circularity ratio is the ratio of the area of the basin to the area of a circle having the same circumference as the perimeter of the basin. The circularity ratio in the area for different subcatchments on S-scale varies from 0.36 to 0.18 (Appendix II.5). As the basin size increases, it is found that the circularity ratio decreases.

(b) Basin elongation:- Basin elongation is the ratio between the diameter of a circle of the same area as the drainage basin and the maximum length of the basin. Elongated basins have low values of basin elongation factor. This parameter is found to have higher values in upper reaches (small sub-basin of lower stream order), and lower values when larger subcatchments are considered (Appendix II.5).

(c) Form factor: - It is given by the ratio of area of the basin to square of the maximum basin length (A/L_b^2). Elongated basins have smaller value of form factor. In the Chenab catchment, the form factor has higher values for small sub-basins of lower stream order and lower values when larger sub-catchments are considered (Appendix II.5).

Inverse of form factor is called basin shape factor (L_b^2/A).

The above measures of basin configuration indicate that the catchment as a whole is elongated as is seen in Fig. 1.1. The elongated shape of the basin may be related to the fact that the course of the main stream Chenab is E-W or SE-NW and is greatly influenced by the general strike of the rocks in the area.

2.5.8 Drainage Patterns

Drainage patterns are the aggregate arrangement of drainage ways in a basin. Stream pattern is the path followed by a single drainage way, permanent flow or otherwise. Drainage patterns may reflect the structural or lithological control of underlying rocks or may be related to other factors.

Two types of drainage patterns are generally distinguished : (a) Basic and (b) Modified basic patterns. A basic pattern is one whose gross characteristics easily distinguish it from the other basic patterns. The basic patterns are identified as dendritic, parallel, trellis, rectangular, radial and angular. Modified basic patterns , variations of the basic pattern such as dendritic patterns,may be modified to subdendritic pinnate, anostomatic or distributary. The parallel patterns are modified as subparallel or colinear. Trellis patterns may be modified to sub-trellis directional trellis, recurved trellis, fault trellis or joint trellis and so on (Howard 1967).

Important factors on which drainage patterns depend are : (i) drainage texture, which is influenced by the rock characteristics, infiltration capacity, topography, climate and stage of erosion and (ii) drainage anomalies, which are the local deviations from regional drainage, and may suggest structural or topographic deviations. The anomalies appearing along individual streams may be rectilinear, abrupt and localized appearance of meanders or their disappearance, compressed meanders, abrupt and localized braiding, anomalous pinching or flaring of valleys, anomalous pond, marshes or alluvial fills, anomalous breadth of levees and anomalous curves and turns etc.

Drainage patterns, as such, do not form strictly a part of hydromorphometric study. However, a mention of these is relevant as the drainage patterns reflect basin inhomogenieties. Drainage patterns in the Chenab basin are of many types and are briefly described below:

(i) Parallel pattern:- It shows parallel or near parallel streams and tributaries. These patterns develop on steep slopes and are commonly found in the higher reaches of the basin (Fig. 2.12a).

(ii) Trellis pattern:- This pattern shows development of main stream along a single major trend with smaller tributaries lying at near-right angles to the main trend. This type of drainage is generally found in folded and layered sequences, such as in the middle reaches of the Chenab catchment, (Fig. 2.12b).

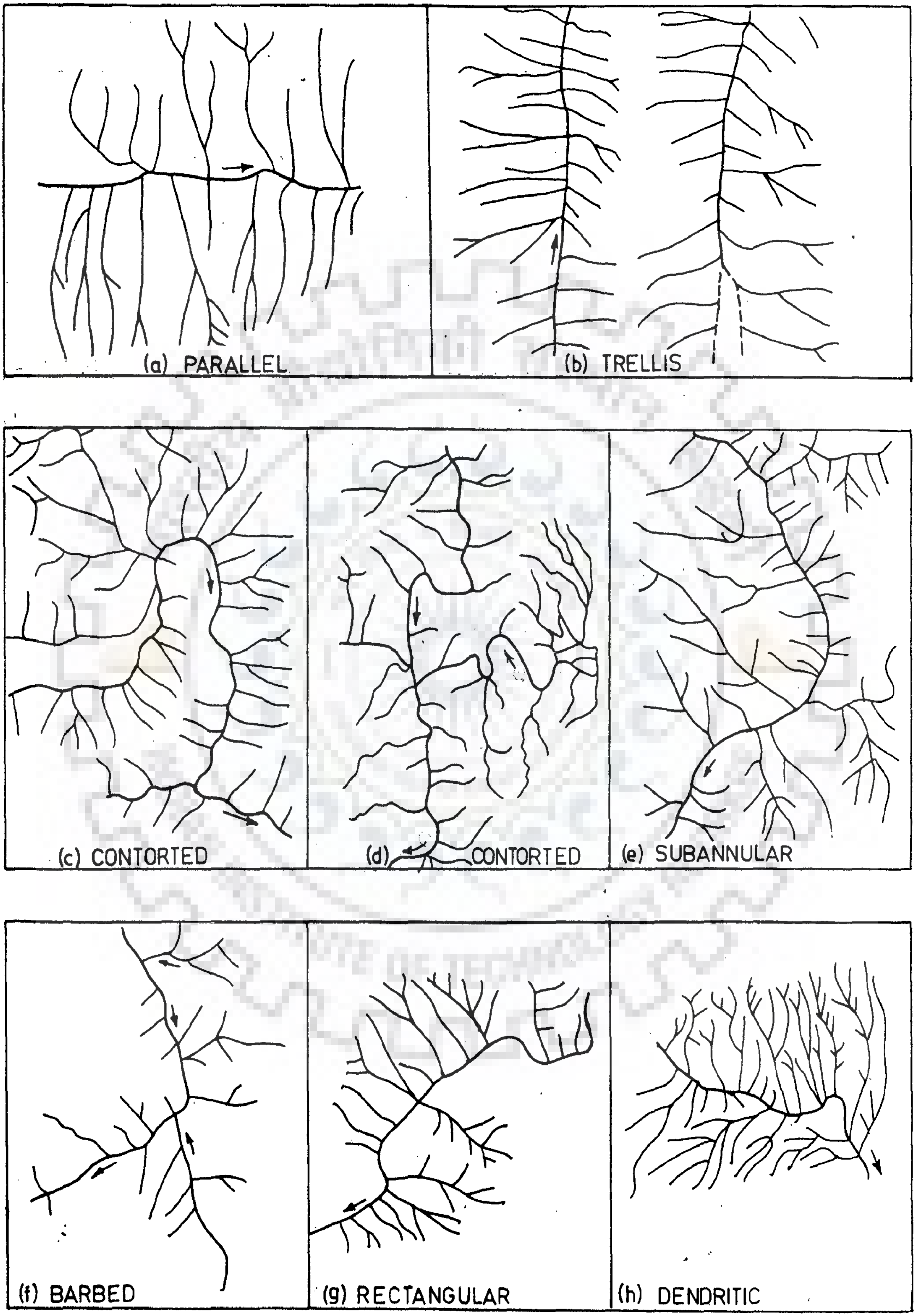


Fig. 2.12 Typical Drainage Patterns in Chenab Basin

(iii) Contorted pattern:- In this type of pattern, the streams show reversed flow directions. Thus, drainage is largely controlled by geological (structural or lithologic) features. This type of pattern is shown by the Chenab River at several places, e.g., near Salal and by Marusudar river near Benswar (Fig. 2.12c,d).

(iv) Sub-annular pattern:- When the drainage lines are concentric or curvilinear, it can be called annular or sub-annular drainage. This type of drainage is found at places in the middle and upper reaches of the catchment area (Fig. 2.12e).

(v) Rectangular pattern:- Where the streams join each other at right-angles or take rectangular turns ,it is called rectangular pattern (Fig. 2.12.g).

(vi) Barbed pattern:- Where the tributaries join the main stream at obtuse angles, it is called barbed pattern. This type of pattern indicates reversal in flow direction and therefore strong geotectonic control. (Fig. 2.12f).

(vii) Dendritic pattern:- It is a common pattern developing on homogeneous isotropic rocks. It is also called tree-like or arborescent pattern and lacks any structural control. This type of pattern is more commonly found on the rocks of the Siwalik ranges, (Fig. 2.12h).

2.6 RELIEF ASPECTS

2.6.1 Channel Gradient (Longitudinal Profile)

The longitudinal profile or channel gradient is a plot of altitude gradients as a function of horizontal distance (abscissa), marked along the channel at several places. The longitudinal profile of the Chenab River upto Akhnur is shown in Fig. 2.13. The longitudinal profile shows that the channel gradient is very high at higher reaches (= 0.0843) and gradually reduces (0.0034) near Akhnur.

2.6.2 Composite Profile

A composite profile is drawn to show the average slope of stream segments order-wise. Thus, a triangle for each order of stream is drawn in sequence, with the average vertical height for that stream order on the ordinate and the corresponding mean length on the abscissa. The plot(Fig.2.14) shows the result of study on the L-scale for the sub-catchment from source upto Arthal. The data pertaining to channel slope is also given order-wise. It is found that the average slope of the first-order stream is as high as 668.18 m/km and this reduces to 3.84 m/km for the seventh order stream at Arthal.

2.6.3 Channel Slope as a Function of Stream Order

The Horton's law of stream slopes says that the channel slope and the stream order are in inverse geometric sequence i.e.:

$$\bar{S}_u = \bar{S}_1 R_s^{k-u} \qquad \ldots(2.7)$$

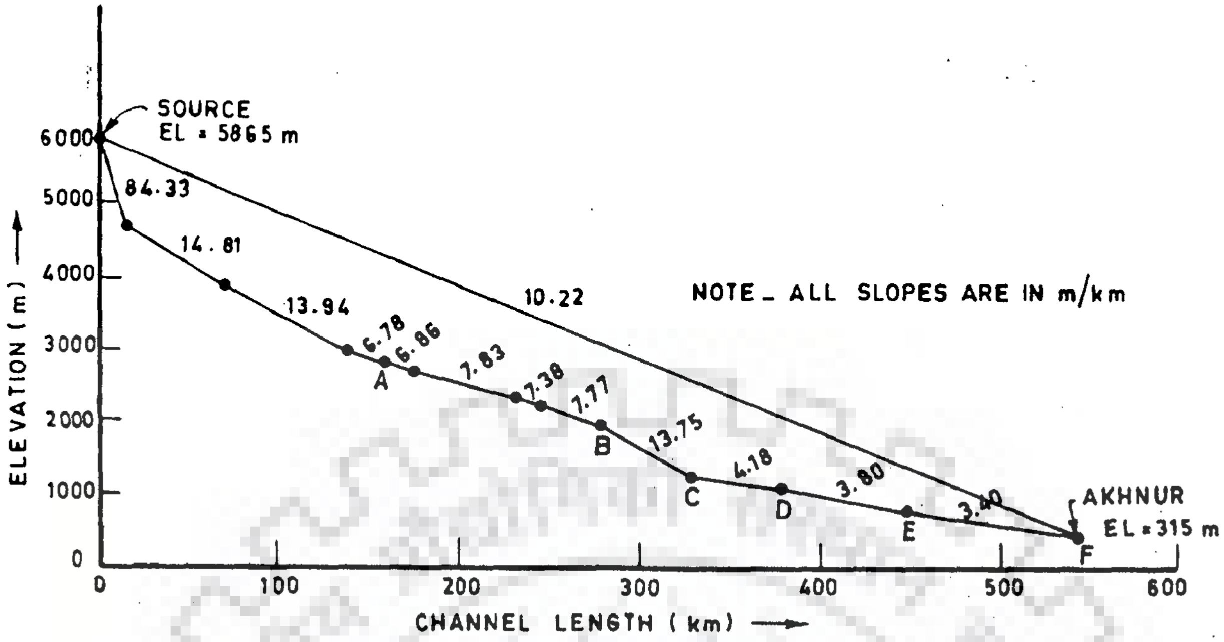


Fig. 2·13 Channel Gradient-Longitudinal Profile

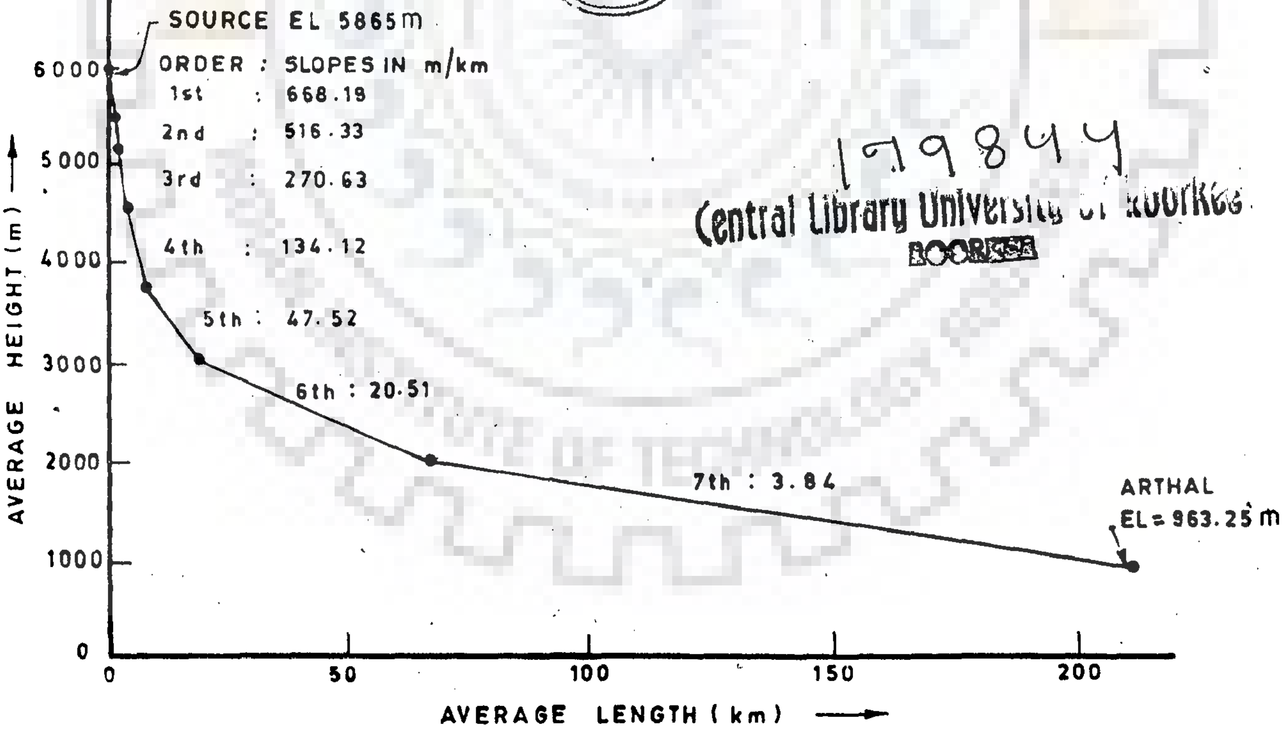


Fig. 2·14 Composite Profile

where $\bar{S}_u$ is the average slope of segment of order u, $\bar{S}_1$ is the average slope of the first order segment, R_s is a constant (= slope ratio) and k is the order of the highest order segment. This means that a plot of stream order v/s logarithm of channel slope would appear as a straight line. This has been verified in many catchments (Strahler, 1964). The relation between logarithm of channel slope and stream order was studied on the L-scale in the Chenab catchment (Fig. 2.15).

As mentioned above, the channel slope for lower order streams has a very high value (500-700 m/km), whereas for higher order streams it is gradually reduced to about 4 m/km. The slope ratio is found to vary between 0.52 to 5.86 in different regions, being low in the lower order subcatchments and high in the higher order ones. The curves for various subcatchments (Fig. 2.15) do not show a simple straight-line relation as is expected from the Horton's law. Generally speaking, the curves can be said to be composed of two straight-line segments - one from 1st to nearly 4th order and the other from 4th order to 7th order. A noteworthy feature is that in some cases, a higher order stream has a higher channel slope than the immediately next lower order stream, (e.g. I and VII in Fig. 2.15). This type of anomaly can be caused by strong geologic influence such as recent tectonic movements and uplift. The above is in conformity with earlier inferences and also indicates that perfect hydromorphometric maturity and geometric similarity has yet to be established within the basin.

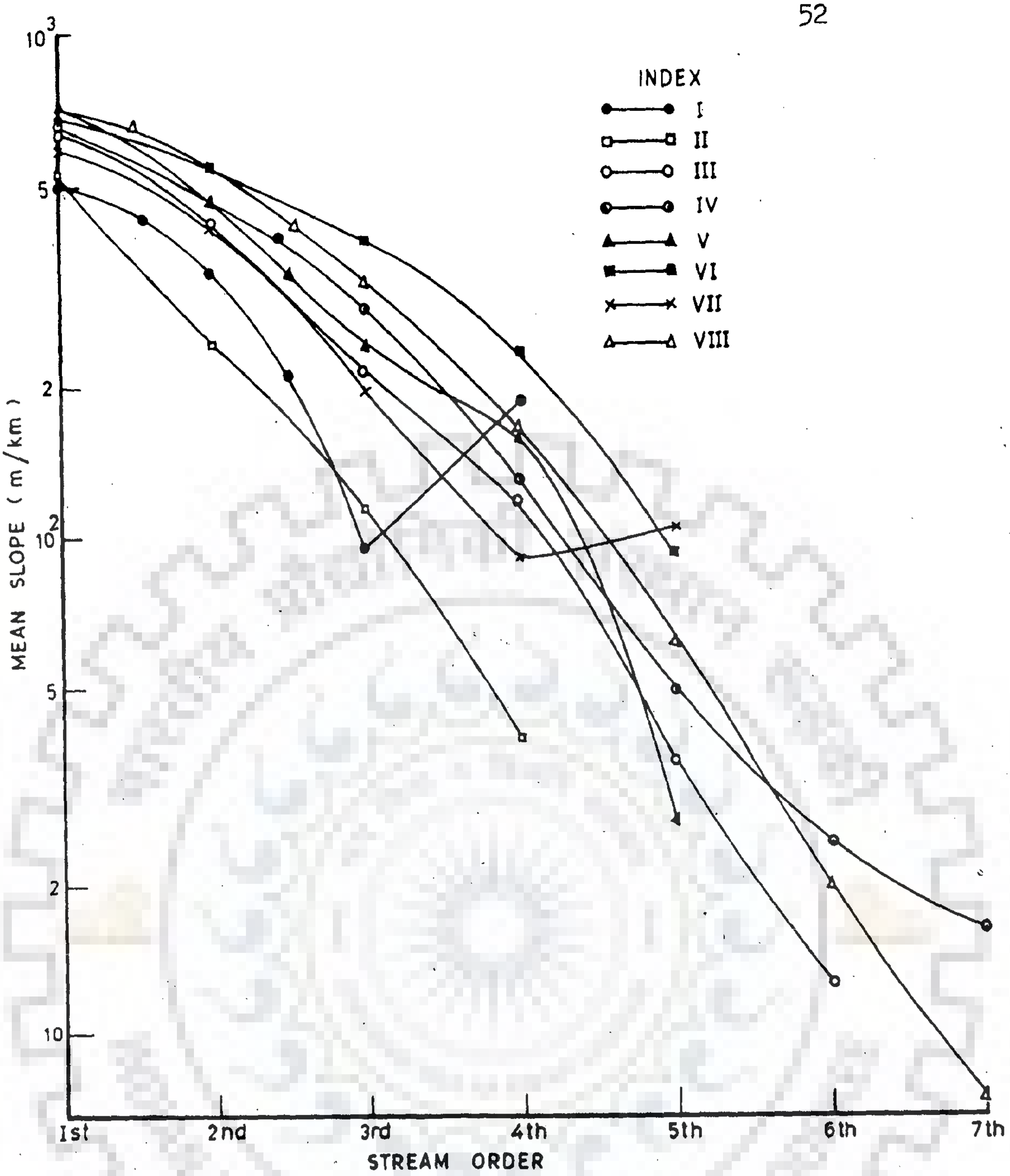


Fig. 2.15 Relationship Between Mean Slope and Stream Order

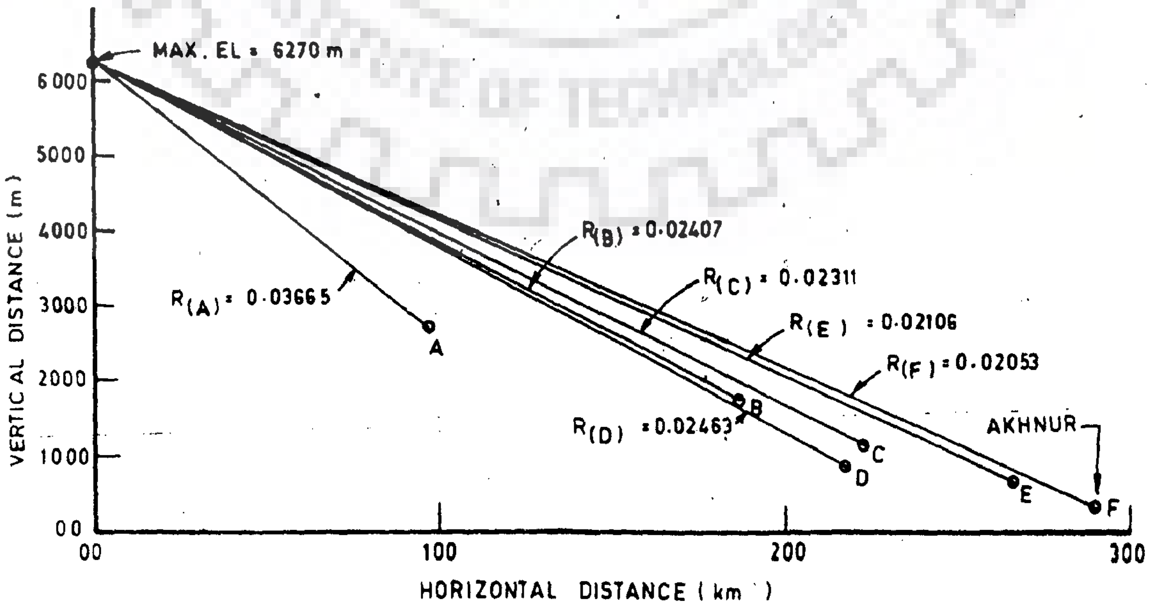


Fig. 2.16 Relief Ratio

2.6.4 Relief Ratio

Relief ratio has been computed to give a measure of relief in the catchment. It is given as the maximum basin relief (i.e. the elevation difference between highest point on the basin perimeter and mouth) divided by maximum measured length of the drainage basin (Schumm 1956). The relief ratio is a dimensionless number. It is a measure of the overall steepness in drainage basin and is also a parameter indicating the intensity of erosional processes acting on the basin slopes. The relief ratio was computed for all the sub-catchments (Fig. 2.16). The ratio is obtained as 0.02053, for the region upto Akhnur, which is a fairly high value. This compares with average values of 0.005 reported for mature areas (Subramanayan, 1975). It indicates high relief and points towards the intense erosional processes operating on hill slopes.

2.6.5 Ruggedness Number

Strahler (1964) suggested the use of another parameter called ruggedness number to estimate the relief aspect. The ruggedness number is given by the product of relief of basin and drainage density and is a dimensionless number. The value of ruggedness number for the present catchment upto Akhnur is 3.87. As this is a very high number as compared to the values of about 0.4 to 0.5 reported for mature terrains (e.g. Subramanyan 1975), it also indicates that the present terrain is highly rugged.

2.6.6 Hypsometric (Area-Altitude) Analysis

The hypsometric analysis can be used to find the relationship between horizontal cross-sectional area and vertical height of a drainage basin (e.g. Langbein, 1947 ; Miller, 1953; Coates, 1958). The two important factors i.e. drainage area and the corresponding heights can be computed from the topographic maps. From this data, relative ratios used in this analysis are computed as follows:

(a) Relative area ratio a/A, where 'a' is the basin area laying above a given contour and 'A' is the total basin area.

(b) Relative height ratio h/H, where 'h' is the height between the given contour and the base and H is the maximum height (relief) in the drainage basin above the base.

In the present study, the various contours at every 1000 m interval from the base elevation were traced. This was used to give the areas lying above different contour lines. The area ratios 'a/A' and likewise the corresponding elevation ratios 'h/H' were computed for different contour levels (Appendix II.6). A graphical representation of these ratios is plotted (Fig. 2.17). The resulting curve obtained in this manner is called 'percentage hypsometric curve'. It starts at the top left hand corner at 1.0 and ends at the bottom right hand corner at 1.0, changing its shape in between anywhere inside the square. The shape of the curve depends on geological stage of development of the basin. The area lying below the curve was also planimetrically measured, and

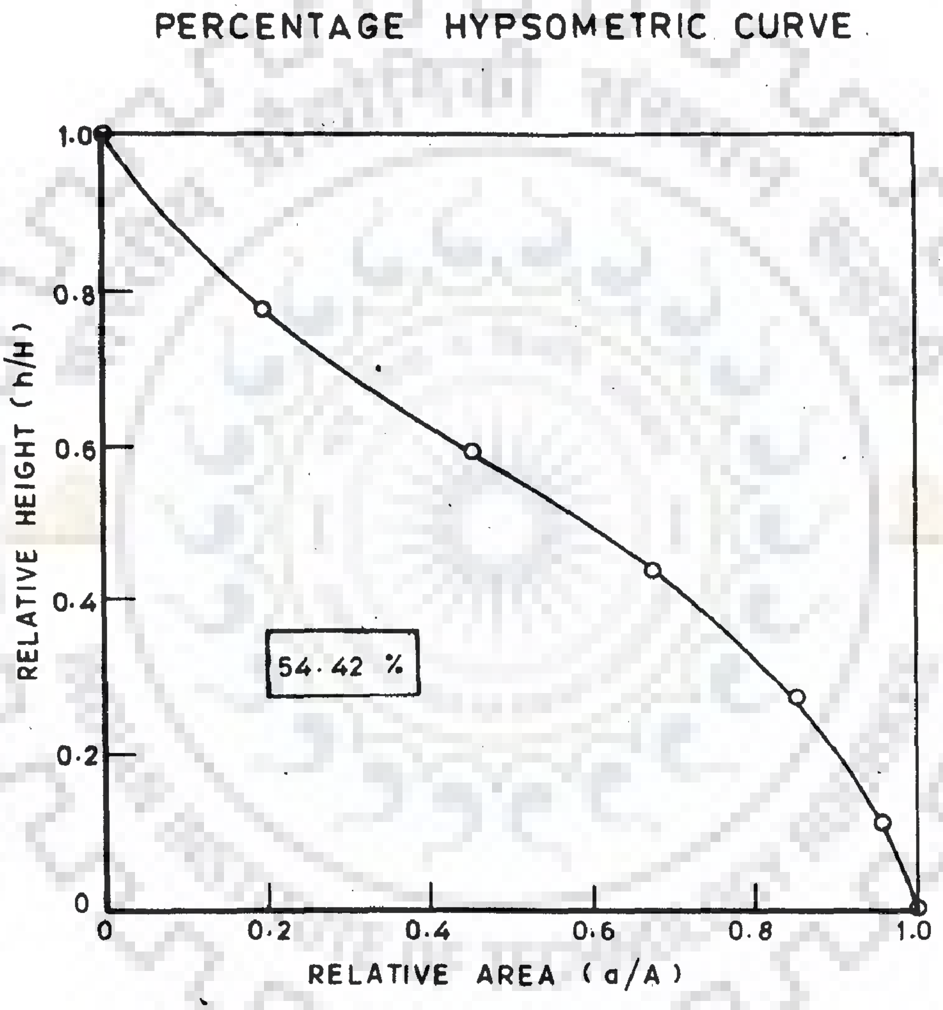


Fig. 2.17 Hypsometric Curve for Chenab Basin

related to the total area of the square enclosing the curve. This gives hypsometric percent integral (= 55%). It is found to have a very high value as compared to the values of about 30-35 % reported for mature basins. It also indicates that the basin is in a youthful stage of development.

2.7 GEOMORPHIC PARAMETERS COMPUTED FOR CORRELATION WITH HYDROLOGIC DATA

As mentioned earlier one of the aims of carrying out morphometric analysis was to relate the basin parameters with hydrological characteristics. For this purpose, several morphological parameters, computed above, were considered viz. drainage area (A), basin length (L_b), basin shape factor (L_b^2/A). Length of the main stream channel (L_c), drainage density (D_d), relief ratio (R_h), main channel slope (S_c), stream frequency (F_s), and ruggedness number (S_g). Besides, some parameterswhich have been shown to have good correlation with hydrological characteristics by other workers, were specially computed for this purpose. These parameters are (i) modified Hickok Keppel Rafferty parameter ($A_s/S_c\sqrt{D_d}$) (ii) Gray parameter ($L_c/\sqrt{S_c}$) and (iii) Murphey Wallance-Lane parameter (L_b^2/A^2) correlation. Results of the analysis are given in Chapter-III.

2.8 SUMMARY AND CONCLUSIONS

In the foregoing pages salient hydromorphometric features of the Chenab basin have been discussed. In brief, the catchment lies in the young Himalayan Mountain ranges. The values of relief ratio and ruggedness number are high, indicating general steepness of slopes and ruggedness of the terrain. The rocks in the area have an overall trend of NW-SE to W-E and the main Chenab also follows this trend for a long distance, evidently controlled by the trend of the rocks in this area. This has led to the development of elongated basin as is also evidenced by the values of basin configuration factors (circularity ratio, basin elongation and form factor) computed for the catchment.

The upper reaches of the catchment have very high relief. They are marked by parallel drainage pattern, high bifurcation ratio, shorter mean stream length, low drainage density and high overland flow. The relatively middle and lower reaches of the catchment exhibit rectangular, rectilinear, contorted and barbed drainage patterns pointing towards geological control (viz., localization of streams along geological weak planes and reversal of flow due to change in gradient and tectonic uplift). In these reaches, the bifurcation ratio is relatively low and mean stream length abnormally high (larger than expected if geometric similarity from the upper reaches is extended).

Cumulatively stream length generally decreases with stream order but in some instances, the higher order streams have larger cumulative stream length. The area ratio is generally high, particularly in upper reaches, implying that the area of the basin rapidly increases with stream order. This could be related to high bifurcation ratio, high length ratio and low drainage density in the upper reaches. The mean drainage area does not increase with mean stream length at the same rate throughout: first it increases rapidly and then the rate decreases. The channel slope ratio also exhibits pattern which can be correlated with the above. it is low for lower order segments and higher for higher order streams. In some instances, the channel slope of the higher order stream is anomalously higher than that for the immediately next lower order stream segment.

Thus, the investigation brings to light that the various established relations of hydromorphometry can be said to be only broadly valid here on regional scale. Though the morphometric laws are known to hold good irrespective of the scale of investigation, when the Chenab catchment is examined on large scale, numerous deviations are found for example, the basin characteristics like bifurcation ratio, length ratio, area ratio, and slope ratio, which are supposed to be constant for a particular basin, are quite variable here and vary from upper reaches to lower reaches of the basin.

These variations have not been ascribed to lithologic variations in the first instance, as several subcatchments showing the above relative variations are underlain by the same group of rocks (viz. crystallines and metamorphic rocks see Fig. 2.1 and 2.2). Though some lateral variations may occur within one group of rocks, it is considered that they may not be sufficient to cause such systematic and wide-spread variations in hydromorphometric characteristics. It is inferred that some of deviation related to extra-increase in mean stream length with stream order could be a result of strong structural influence leading to elongated basin shape. Besides, the phenomenon of recent tectonic uplift, has been reported by several workers, on the basis of other evidences in this area (Gansser, 1964; Bhatt, 1978,1980; De Terra in Krishnan, 1968). On the basis of the observations the topography is particularly steep in higher reaches (high overland flow, low drainage density high bifurcation ratio, high area ratio), barbed and contorted drainage patterns occur in the area and in some subcatchments higher order streams have anomalously larger cumulative stream length and higher average channel slope than the immediately next lower order stream. It is inferred that phenomenon of recent tectonic uplift has also played a key-role in creating the lack of geometric similarity in the Chenab basin. In this way, the above systematic investigations bring to light an example from the Himalayas, where strong structural influence have lead to the lack of geometric, similarity within the catchment. As mentioned earlier, one of the aims of this investigation was to generate data on hydromorphometric parameters which could be related to hydrological data and used in snowmelt runoff studies. These aspects have been discussed in Chapters-III, IV, and V).

CHAPTER - III

RELATIONSHIP BETWEEN HYDROLOGICAL AND HYDROMORPHOMETRIC PARAMETERS

3.1 INTRODUCTION AND PREVIOUS WORK

Hydrological characteristics of a watershed are intimately related to geomorphic parameters ,the latter can be used for predicting some of the former like Maximum Peak Flow, Average Annual Peak Flow and the Average Annual Flow.

Many workers have related the morphometric and hydrological parameters : A regression relation of peak stream discharge and factors of topography, basin area, and rainfall was determined empirically by Potter (1953) for 51 basins in the Appalachain Plateau.

Morisawa (1959) established significant regressions for average discharge and peak discharge on stream length, relief ratio, and slope ratio for subdivisions of a small watershed.

Maxwell (1960) used digital computer program to relate stream-discharge to several elements of drainage basin geometry in the San Dimas Experimental Forest of Southern California. He computed multiple correlations between peak discharge and storm rainfall, snowcover density, antecedent rainfall and nine geomorphic properties taken five at a time. The geomorphic-variables considered were fifth-order area and diameter, means of second order area and diameter, relief, drainage density, channel frequency and relief ratio; and watershed bifurcation, length, perimeter and area ratios. It was concluded that fifth and second order areas or perimeter together with second order drainage density and relief ratio provide a good estimate of the variability in peak discharge which can be explained by geomorphic variation inside watershed. According to Sokolov et al (1976), for steady uniform flow, channel velocity (V) is expressed by the equation $V = CR^m . S_{ch}^n$, where, C=channel roughness coefficient, R = Hydraulic radius, S_{ch} channel slope, m and n are constants. In the Mananing's equation, $m = 2/3$ and $n = 1/2$. Murphey et al (1977) related gross hydrograph characteristics such as rise time, mean peak discharge, peak volume-ratios and duration of flow related to basin characteristics and as Hickok et al parameter $(A/S_c\sqrt{D_d})$, Gray parameter $(L_c/\sqrt{S_c})$, drainage area (A), main channel length (L) channel slope (S_c) drainage density (D_d), stream frequency (F_s) basin shape factor (S_b) relief ratio (R_h), using the data of Walnut Gulch experimental watershed in Mexican Range province. They concluded that; the average rise time and duration of flow decreased as drainage density increased and as the slope of the main channel increased as predicted by Hickok et al (1959) and Gray (1961) respectively. Mean peak discharge volume ratios decreased as drainage area increased, reflecting the influence of transmission losses as predicted by Renard and Keppel (1966). Betson (1979) derived regression equation for predicting stream flow from geomorphic parameters. Gupta et al (1980) employed a kinetic theoretical framework for obtaining an explicit mathematical representation for the instantaneous unit hydrograph at the basin outlet. Bras (1982) also developed analytical model using rainfall characteristics and basin morphometric parameters to predict instantaneous unit hydrograph. Some other workers like Osborn and Keppel (1966), Osborn, et al (1972) have indicated that rainfall records may not be good enough to use for predictive purposes and Murphey et al (1977) have stated that the success for predicting average volume (V) was almost nonexistent. Rawat (1985) used the hydromorphometric parameters like total stream length and relief ratio of the lower Ramganga catchment in Himalayas, to define allometric change of hydrometric parameters i.e. stream discharge and silt delivery. The regression equations derived for the above are significant at 95 % confidence level for stream discharge and at 99 % for silt delivery.

3.2 PARAMETER SELECTION FOR REGRESSION ANALYSIS

3.2.1 Hydrological Parameters

Following hydrological parameters have been computed from the available daily discharge data of the period 1965-1980 for the regression analysis (Table 3.1):

i) Average annual peak flow (Q_p in m^3/sec): The total annual peaks divided by the period of record.

ii) Maximum peak flow (Q_{mp} in m^3/sec) : The highest value of the annual peak discharge during entire period of record.

iii) Average annual flow (Q_{av} in m^3/sec) : The average annual discharge obtained from the summation of the daily flows averaged for calender days during the record period.

TABLE-3.1 : HYDROLOGICAL PARAMETERS

Name of stations	No. of observation in years	Av. annual peak flow Q_p.(m^3/sec)	Maximum peak flow Q_{mp}(m^3/sec)	Av. annual flow Q_{av}.(Cumec-days)
Thirot	6	875.83	1048.00	72666.00
Arthal	5	1807.80	2308.00	129175.00
Benswar	16	2128.06	3147.00	145029.00
Bursar	14	502.14	788.00	41989.80
Kiyar Nala	12	153.08	291.00	11396.28
Sirshi-bridge	15	717.67	918.00	56648.94
Kuriya-bridge	15	827.87	1412.00	71523.06
Premnagar	17	2822.18	4710.00	228969.00
Dham kund	17	3499.06	6614.00	279585.00
Akhnur	16	4813.75	12001.00	296131.00

The maximum peak discharge has been found for Thirot in 1967; Arthal in 1980; (there was no observation available in 1967 on Arthal site); Benswar, Kuriya-Bridge, Premnagar and Dhamkund in 1975; Sirshi Bridge and Akhnur in 1973; Kiyar Nala in 1969 and in Bursar in 1965.

3.2.2 Morphological Parameters

In the initial phase of the study, the task was to select the morphometric parameters on S-scale which have a direct relation with hydrologic parameters. Initially plotting of all the morphometric parameters like drainage area (A), basin shape factor (S_b), main channel slope (S_c), drainage density (D_d) relief ratio (R_h), length of main stream channel (L_c), stream frequency (F_s), modified Hickok-Keppel Rafferty parameters ($A/S_c\sqrt{D_d}$), Gray parameter ($L_c/\sqrt{S_c}$), Murphey-Wallace-Lane parameter(L_b^2/A^2) and ruggedness number (R_n) (Table 3.2) was carried out one at a time against one of the hydrologic parameters (3.2.1). The selected morphometric parameters for the regression analysis are those which have indicated some pattern of possible relation in the plot with the hydrological parameters. The parameters which have not been selected are those which show a nonuniform relationship in the plot. It is found that all those parameters possessing basin length (L_b) factor in their calculation, like basin shape factor, relief ratio and the simplified parameter given by Murphey et al, have to be discarded . These parameters give a zigzag shaped curve against all the hydrological parameters, which may be due to the fact that the main channel flows along a highly zigzag path round between Benswar and Premnagar stations. In fact the Chenab river flows in geographically reverse direction in this region for substantial distance so that the basin length (L_b) at Benswar (223.5 km) is more than that at downstream station

TABLE-3.2 : HYDROMORPHOMETRIC PARAMETERS

Name of gauging sites	Drainage area (km^2)	Basin length (km)	Basin shape factor (No unit)	Length of main stream channel	Drainage Density (km^{-1})	Relief ratio	Channel slope	Stream frequency	Modified Hickok Keppel Rafferty parameter	Gray parameter $L_c/\sqrt{S_c}$	Rugged ness number $Rg=H.D_d$ No.unit	Murphey et al parameter S_b/A (km^{-2}) $x10^{-4}$
	A	L_b	$(S_b)=L_b^2/A$	L_c (km)	D_d	$R_h=\frac{H}{L_b}$	(S_c%)	F_s	$A/S_c\sqrt{D_d}$ 10^2 $km^{2/5}$	km(10)		
Thirot (A)	4537.98	97.40	2.09	160.50	0.471	0.03665	1.972	0.200	3353.09	114.29	1.681	4.62
Arthal (B)	10330.51	186.60	3.37	280.99	0.569	0.02407	1.459	0.220	9418.92	233.03	2.555	3.26
Benswar (C)	11162.19	223.50	4.46	330.00	0.581	0.02311	1.442	0.220	10155.38	274.81	3.001	3.99
Prem-nagar(D)	17622.46	218.00	2.69	379.00	0.594	0.02463	1.310	0.210	17454.28	331.13	3.190	1.52
Dham-kund(E)	20172.64	267.50	3.53	448.15	0.634	0.02106	1.167	0.220	21709.82	414.85	3.571	1.74
Akhnur (F)	22846.96	290.06	3.68	542.80	0.675	0.02053	1.022	0.220	27209.82	563.93	4.02	1.61
Bursur D_1	2896.34	62.40	1.28	87.30	0.568	0.0637	2.777	0.180	1383.88	52.387	2.324	3.969
Diyur D_2	554.99	51.50	5.16	60.0	0.355	0.0927	5.040	0.158	186.27	26.833	1.695	100.303
Sirshi-Bridge D_3	3588.12	85.00	1.88	109.80	0.540	0.0552	2.740	0.183	1782.05	66.333	2.533	4.878
Kuriya-Bridge D_4	4812.62	96.2	1.87	142.80	0.569	0.0549	2.514	0.192	2537.82	90.068	3.005	3.783

of Premnagar (L_b = 218.00 km). Further, as the stream frequency parameter is found to be almost same as Dd, also not selected in the regression analysis. The selected morphological parameters in this study are the following:

i) Drainage Area (A):- It is the total area contributing runoff from the water divide to the outlet. As the drainage area increases, the discharge quantity and duration increase, the peak decreases and the specific peak discharge (discharge per square kilometer) decreases.

ii) Channel Length (L_c):- It is the length along the stream bed between the extreme initial source upto the outlet of the drainage area. According to Zhelezniak (1965), the greater the length of main channel for a given basin size, the greater is the flood duration.

iii) Drainage Density (D_d):- It is the total channel length per unit area. Higher drainage density is representative of well developed drainage network and provides a faster flow path for water because channel flow is faster than overland flow, the higher the drainage density, the shorter the basin lag and time to the peak.

iv) Channel Slope (S_c):- Channel slope is the difference of elevation between the initial source and the out-let(h) of the stream divided by the length of the channel (L_c). The travel time is a function of the channel slope which is directly proportional to the channel velocity, Consequently, the basin lag decreases with increase in channel slope.

v) Modified Hickok, Keppel and Rafferty Parameter 1977, $(A/S_c\sqrt{D_d})$:- Total drainage area (A) divided by product of main channel slope (S_c) and square root of drainage density. In this expression area is in sq km, and drainage density in (km^{-1}) and slope in percent as such the unit for this parameter is $km^{5/2}$.

vi) Gray's Parameter $(L_c/\sqrt{S_c})$:- Length of main stream (L_c) divided by square root of main channel slope (S_c). Its unit is km.

vii) Ruggedness Number (S_g):- It is the product of the basin relief and the drainage density and thus combines slope steepness with its length.

3.3 REGRESSION OF FLOOD AND FLOW STATISTICS ON MORPHOLOGICAL CHARACTERISTICS

3.3.1 Methodology

As stated in earlier section, 3 parameters have been identified for flood statistics, viz. average peak discharge (Q_p), maximum peak discharge (Q_{mp}), average annual flow (Q_{av}), while 7 parameters have been selected to represent morphological characteristics, viz. drainage area (A), main channel slope (S_c), drainage density (D_d) and main channel length (L_c), modified Hickok et al parameter $[A/(S_c\sqrt{D_d})$, Gray parameter $(Lc/\sqrt{Sc})$ and Ruggedness number (Sg). These have been finally selected for use in deriving the relationship between flood parameters and morphological parameters using multiple regression analysis.

approach. This approach consists of developing a relationship between dependent variables and independent variables of the form given below:

$$Y_i = A X_i + B \qquad \ldots(3.1)$$

$$Y_i = A X_i^B \qquad \ldots(3.2)$$

The equation (3.1) represents a simple linear regression relationship while, the Eqs. 3.2 is a non-linear relationship between one dependent and one independent variable. The non-linear relationship of Eq. 3.2 could be transformed by taking logarithm of both sides of the equation as given in Eq. 3.3. In these eqs., Y_i represents the flood and flow statistics as dependent variable and X_i represents independent variable, while A and B are the coefficient of the relationship. The corresponding multiple linear relationship in more than one independent variables are as given in Eqs. 3.4, 3.5, 3.6, where X_1, X_2, X_3 etc. are the independent variables and B_1, B_2 B_3 etc. are coefficients of the relationship:

$$1\text{-}2\ Y_i = \log A + B \log X_i \qquad \ldots(3.3)$$

$$Y = B_o+B_1X_1+B_2X_2+B_3X_3 \qquad \ldots(3.4)$$

$$Y = B_o\ X_1^{B_1}\ X_2^{B_2}\ X_3^{B_3} \qquad \ldots(3.5)$$

$$\log Y = \log B_o+B_1\log X_1+B_2\log X_2+B_3\log X_3 \qquad \ldots(3.6)$$

In the present analysis, the data of 10 basins were available and as such the number of independent variables used at a time were limited to 4. The selection of one or two or three or four morphological parameters as independent variables was made after studying their interdependence using correlation analysis.

The criterion for selection of suitable relationships out of various alternative combinations of independent and dependent variables studied was on the basis of goodness of fit of the relationships as judged by correlation coefficient, standard error of estimation, and 'F' and 't' tests. A value of correlation coefficient nearer to one or a value of standard error of estimation nearer to 0 indicates a good relationship.

The 't' test is a test of hypothesis that the particular independent variable is not contributing significantly to explain the variation in dependent variable. The hypothesis is rejected if 't' value execeeds the tabulated value at the required probability level. In other words, a particular dependent variable is said to be significant at a particular probability level if computed 't' value is greater than tabulated 't' value.

The 'F' test is a test of the hypothesis that the regression equation is not explaining a significant amount of variation in the dependent variable. The hypothesis is rejected if 'F' value for the regression equation exceeds the tabulated value at the required confidence level.

In other words, regression equation explains significant amount of variation in dependent variable, if computed 'F' value is greater than tabulated 'F' value at required confidence level.

The details of the judgement criteria for the relationships are given in Appendix-III.1. A standard computer program in FORTRAN language was used for the multiple regression analysis and the computer runs were made using the available data for flood and morphological parameters on the DEC-2050 computer of Roorkee University Regional Computer Centre.

3.3.2 Analysis and Results

As stated above, for all the three flood parameters alongwith different combinations of morphological parameters, computer runs were made. The number of morphological parameters used in the analysis as independent variablesvaried from one or two or three or four at a time. The preliminary analysis of the results thus obtained indicated that the relationships obtained by using one independent variable at a time with Eqn.3.2 are comparatively better and addition of more than one independent variables does not lead to any significant improvement in the relationship, as was judged through the values of correlation coefficient and standard error of estimation . The values of parameter 't' also indicated similar trend and helped in identification of the significant independent variables for use in development of the relationships.

The relationships of the non-linear form of Eq.(3.2)for all the 3 flood/flow parameters are given in Table-3.3 for alternative independent variables taken one at a time alongwith values of correlation coefficient, standard error of estimate , computed 't' and computed 'F'.

From the standard tables Pearson and Hartley (1976) for 't' theoretical tabulated value for $\alpha = 5\%$, total number of values of $N = 10$ and total number of parameters $M = 2$ was found as t, $1-\alpha/2$, $N-M$ = t, 0.975, 8. The value of tabulated theoretical value of 't' was found as 3.355. The corresponding values for $\alpha = 1\%$ were found as 4.501 respectively. Similarly, the theoretical tabulated value of 'F' for $\alpha = 5\%$ and 1% were found (against the $F_{1-\alpha}$, M-1, N-M) as 5.32 and 11.26 respectively.

The comparison of computed values of parameters of 't' and 'F' with these theoretical values clearly indicated that all the relationships listed in the table are able to explain significant amount of variation of the dependent variable and goodness of the relationships could be judged by the value of correlation coefficient since the higher the value of correlation coefficient, the lesser is the standard error of estimation.

From the results given in Table-3.3 best possible relationship for each of the flood flow parameters could be selected and they are given at S.No. 1,2 and 3 in each of the 3 cases. It could be seen that the independent variables which are involved in this relationships are; drainage area

TABLE-3.3 : SUITABLE RELATIONS BETWEEN HYDROLOGIC AND MORPHOLOGIC PARAMETERS

Sl. No.	Y_i	X_i	Υ	Log_eSEE	Comp. 't'	Comp. 'F'	Mathematical Relationship
1.	Y_1	X_5	0.9939	0.1226	25.48	649.3	$Y_1=4.1829\ X_5^{0.6726}$
2.	Y_1	X_1	0.9930	0.1314	25.76	564.8	$Y_1=0.39701\ X_1^{0.9148}$
3.	Y_1	X_6	0.9856	0.1880	16.48	271.5	$Y_1=6.841452X_6^{1.037}$
4.	Y_1	X_4	0.9810	0.2159	14.28	204.0	$Y_1=0.8468X_4^{1.368}$
5.	Y_1	X_2	0.9584	0.1891	-16.38	265.80	$Y_1=4619.3071X_2^{-2.084}$
6.	Y_1	X_3	0.9760	0.5361	5.14	26.40	$Y_1=26108.077X_3^{5.11}$
1.	Y_2	X_4	0.9754	0.2625	12.51	156.4	$Y_2=0.862X_4^{1.456}$
2.	Y_2	X_6	0.9753	0.2629	12.48	155.8	$Y_2=8.18252X_6^{1.099}$
3.	Y_2	X_5	0.9658	0.3087	10.53	110.9	$Y_2=5.414064X_5^{0.6996}$
4.	Y_2	X_1	0.9636	0.3180	10.20	104.0	$Y_2=0.472414X_o^{0.9504}$
5.	Y_2	X_2	0.9609	0.3294	-9.82	96.4	$Y_2=7958.533X_2^{-2.176}$
6.	Y_2	X_7	0.8831	0.5583	5.32	28.3	$Y_2=69.2692X_7^{3.419}$
1.	Y_3	X_1	0.9980	0.0671	44.83	2010.0	$Y_3=41.09X_o^{0.8816}$
2.	Y_3	X_5	0.9963	0.0910	33.01	1090.0	$Y_3=\ 402.89X_5^{0.6464}$
3.	Y_3	X_2	0.9824	0.1989	-14.89	221.6	$Y_3=336298.8X_2^{-1.992}$
4.	Y_3	X_6	0.9756	0.2340	12.56	157.9	$Y_3=688.4X_6^{0.9846}$
5.	Y_3	X_4	0.9687	0.2645	11.04	121.8	$Y_3\ \ 96.33X_4^{1.295}$
6.	Y_3	X_3	0.8808	0.5046	5.26	27.68	$Y_3=1802.626X_3^{4.927}$

where,

Y_1 = Q_p = Average peak discharge (m^3/sec)

Y_2 = Q_{mp} = Maximum peak discharge (m^3/sec)

Y_3 = Q_{AV} = Average annual flow (m^3/sec)

Table-3.3 Contd.

X_1 = A = Drainage area (km^2)

X_2 = S_c = Main channel slope (%)

X_3 = D_d = Drainage density (km^{-1})

X_4 = L_c = Main channel length(km)

X_5 = $A/S_c\sqrt{D_A}$ = Modified Hickok, Kepple, Raffterty parameter

X_6 = $Lc/\sqrt{Sc}$ = Gray's parameter

X_7 = Sg = Ruggedness number

r = Correlation coefficient

SEE = Standard error of estimate

't' = t-student test. Its theoretical value at 99% confidence level = 4.501

'F' = F-test. Its theoretical value at 99% confidence level = 25.42

(A'), main channel length (L_c), main channel slope (S_c) and drainage density (D_d).

In order to have an idea of performance of the relationships in case of the 3 flood flow characteristics with drainage area 'A', the corresponding relationships are tabulated below:

$$Q_p = 0.39701 \ (A)^{0.9148}$$

$$Q_{mp} = 0.47241 \ (A)^{0.9504}$$

$$Q_{AV} = 41.09 \ (A)^{0.8816}$$

It can be seen from the values of the statistical parameters used for judging the performance that the drainage area as independent parameter gives a good relationship for average peak discharge as well as average annual flow, while for maximum peak discharge it gives reasonable good relationship.

On the basis of best possible performance satisfying all the 4 statistical parameters performance criteria, the following 4 relationships could be selected:

1) $Q_p = 4.1829\ [A/(S_c \sqrt{D_d})]^{0.6726}$ ...(3.7)

2) $Q_{p'} = 0.39701(A)^{0.9148}$ ...(3.8)

3) $Q_{mp} = 0.862\ (L_c)^{1.456}$ ...(3.9)

4) $Q_{AV} = 41.09\ (A)^{0.8816}$ ...(3.10)

These relationships provide 2 alternative relationships for average peak discharge.

3.4 CONCLUSIONS AND REMARKS

Analysis of the detailed runoff characteristics of a watershed is greatly dependent on hydromorphological factors and is rather a difficult task which has been attempted in later Chapters (Chapter-IV and V) of this thesis.

Gross hydrograph characteristics such as average annual peak flow, maximum peak flow and average annual runoff have been related to morphologic parameters using data from 10 subbasins of the Chenab catchment.

It has been found that the morphologic parameter viz. Drainage area, channel slope, main channel length, drainage density and computed morphologic parameters as given by

Hickok et al ($A/S_c\sqrt{D_d}$) and Gray ($L_c/\sqrt{S_c}$) have very good relationship with the hydrological parameters. The relationships derived are significant at 99% confidence limit. These parameters are obtainable from field as well as from the topographic maps. However, the Hickok et al and Gray's parameters are slightly tedious for calculating the hydrologic parameters. Watershed area is the most reliable simple parameter for use in the prediction of average annual peak flow and average annual flow. The channel length is also a simple parameter which can be used to predict the maximum peak flow.

CHAPTER - IV

SNOWCOVER AREA AND ITS RELATION WITH PREMONSOON SNOWMELT RUNOFF

4.1 INTRODUCTION

Snowmelt is an important source of stream flow in many areas and in some instances, it may form the major share of the annual discharge e.g. Goodell (1966) has indicated that about 90% of the yearly water supply in the higher elevations of the Colorado Rockys, U.S.A., is derived from snowmelt. In the Himalayas, during the period March - June, snowmelt forms the major part of the total streamflow. It is important for hydrologists to understand the nature and distribution of snowfall and snowmelt processes, if reliable estimates of the streamflow are to be made. Early prediction of the likely subsequent snowmelt runoff could facilitate more efficient utilization of the limited water supply for power generation, irrigation and industrial requirements etc. However, snow is one of the most difficult parameters to measure. Snow cover area, water equivalent, age, thickness and density - all these factors, beside the meterological conditions during the melt season, affect the contribution of snowpack to runoff.

In the Chenab catchment under study, snowmelt is a very important hydrologic parameter as a large part of the precipitation in the period November - February, occurs as snow which gets stored in the catchment and undergoes melting later when the temperature rises. Therefore, there is a great need to take into account the snowmelt for effective hydrological forecasting.

4.1.1 Snow Surveys

Snow surveys for hydrological investigations are conducted for determining the characteristics of the snowpack, such as water equivalent, density, depth and areal extent and their temporal variation. The conventional method of snow surveying has been mostly the field method, giving point data on snow thickness and snow density. These surveys involve use of snow boards and snow stakes for measurement of snow thickness in the field (Rodda, 1976). For evaluation of water equivalent core samples of snow from different depths of the snow packs are taken and analysed for snow density.

Though snow survey field methods have greatly improved during the last few decades, in regard to the accuracy, reliability and frequency of observations over snow-covered areas, it is practically impossible to determine the water reserves stored in the snow pack of a rugged mountain basin using conventional data, because direct point measurement of the snow-water equivalent are widely separated and are limited. New techniques of non-conventional procedures are under development in this field of investigation. Nuclear snow gauging devices give directly water equivalent of snow-pack without any need for coring (Smith et al, 1970). To help these objectives isotope snow gauges have been developed. The observation by gamma radiation helps one to determine the water equivalent of a given snow pack

Based on this principle several types of instruments have been developed during the last three decades. This technique is useful for managing the snow pack reservoirs (Bahadur,1983). However, aerial surveys utilizing low-altitude platforms for measurement of natural (Gamma) radiations, are not suited for rugged terrains with highly variable and deep snow pack. Echo-sounding method using back-scatter of radiowaves is a promising method but is still in exploratory and developmental stage. Satellite remote sensing in the visible and near infrared region can be used to give repetitive coverages which permit fairly accurate monitoring of extent of snow-covered areas and this can be well used in snowmelt runoff studies. (for details refer article 4.2.2). However, evaluation of snow-pack properties from remote sensing data is still under research and development.

4.2 SNOW COVER AREA AND SNOWMELT RUNOFF

4.2.1 Importance

Areal extent of snow is a prominent observable variable in regions which have seasonal snow cover. It is natural that the snowmelt would be related to the snow cover area in the preceeding accumulation season. As the snowmelt commences, snow starts disappearing from the lower elevations of the watershed and the snowcovered area decreases and the hydrograph begins to rise. In an ideal case, it would continue to do so until the snow pack area would reach a critical limit. Then, the hydrograph would begin to recede until the remaining annual snow pack would disappear. Thus, the snow-cover area becomes an important aspect and can be used as an indicator of the snowmelt runoff in a particular catchment. The characteristic of the snow cover depletion can be related to the pattern of the area/elevation curve, as well as to frequency distribution of the snow depth. It can be approximated by the equation (Leaf, 1967):

$$A = 100/(1+e^{-bt}) \qquad \ldots(4.1)$$

where, A , is the percent snow-free area in the catchment,
t , is the time measured from an arbitrary origin,
b , is a coefficient, and
e , is the base of natural logarithm.

A number of land observations and meteorological satellites have been launched till date (for example, the NOAA series, SMS/GOES, NIMBUS Series, TIROS, ATS, and Landsat series), which can be used for snow cover area mapping. The snow cover area obtained from these orbital platforms can be empirically related to observed discharge to yield models. These models can be used for predicting discharge or subsequent runoff.

4.2.2 Relation Between Satellite Snow Cover Area and Snowmelt Runoff - Previous Work

Several workers have used Landsat and other meteorological satellite data for mapping snow cover area for modelling of snowmelt runoff. Odegaard and Ostrem (1977) used

Landsat data to map snow cover area in a number of Norwegian catchments. They found that the relationship resulting from the combination of snow cover area and subsequent runoff in several catchments can be generalized by fitting a new curve through these points with relatively small deviations. They expressed the result as:

$$Q = 128\ (e^{0.0018A} - 1) \qquad \ldots(4.2)$$

where,

Q = Subsequent runoff (10^6 m^3)

A = Snow cover area (km^2)

Rango, Salomonson and Foster (1977) studied the snow cover area of Indus and Kabul River catchments using meteorological satellite data and established a relation giving decrease in snow cover area with increase in the mean monthly runoff in the snowmelt season. Martinec (1975) developed a model to simulate daily stream flow for basins which remain snow-covered for a considerable period of the year. In this model snowmelt in Landsat snow cover area forms an important input parameter and snowmelt is estimated by temperature index method dividing the basin in several elevation zones. Rango and Martinec (1979) found that this model can be applied to give daily runoff values upto ± 1 to ± 5 percent accuracy. Martinec and Rango (1981) discussed a method to determine areal distribution of the maximum seasonal water equivalent of snow in mountainous basin. This utilizes monitoring of disappearance of snow in grid units from satellite data and the number of degree-day required to melt the snow from meteorological data. From these data, snowwater equivalent is calculated which can improve the evaluation of water reserves in snow for seasonal discharge. Hawley et al (1980) have compared different models for forecasting snowmelt runoff volumes. The models compared by them include the Tank model, Martinec model and the Regression model. They have concluded that Martinec model is relatively more effective if forecasting period is one or two days, while regression model was the best for forecasting of 60 days or longer. They also found that the Martinec model would be probably more accurate on small watersheds. Gupta et al (1982) have studied the Beas catchment which lies to the east of the Chenab catchment. They have correlated the snow cover area with subsequent cummulative runoff and have found that the slope of the regression line depends on morphologic factors of the catchment.

In the Himalaya region, snowmelt runoff investigation using satellite data have been reported by only a few workers (Rango et al , 1975, 1977, Bagchi, 1979; Ramamorthi and Subba Rao 1981, Duggal et al 1982; Gupta et al 1982; Ramamorthi, 1983; Dey et al ,1983; Dey and Subba Rao,1984) focussing attention on selected catchments viz., Indus, Kabul, Beas and Sutlej.

4.3 METHODOLOGY

The purpose of this part of investigation was to establish a relationship between snow cover area and subsequent snow melt runoff and to seek the role of geomorphic factors, if any, which may affect this relationship. For this investigation the following data were used: (i) snow cover area as mapped from the satellite images (ii) hydrologic data computed to give subsequent snowmelt runoff, (iii) morphologic data as computed earlier in Chapter-III.

4.3.1 The Landsat Images and Their Selection

(i) The Landsat MSS Image:

The Landsat System:- The Landsat (originally called ERTS) has clearly demonstrated the feasibility of mapping and monitoring the earth surface from space, its main advantages being synoptic view, multispectral approach temporal repetitivity and good geometric fidelity (see e.g. Williams and Carter, 1976). Till date, five Landsats have been placed into orbit-Landsat, 1,2,3,4 and 5. They have carried different earth observation sensors on board viz. MSS, RBV and TM. This study has used the MSS data from landsat 1,2 and 3 only. (As data from Landsat 4 and 5 have not been used, these will not be discussed further). The Landsats, 1,2 and 3 have identical orbital parameter (App. IV-1) and almost similar space-craft characteristics,

MSS:- The MSS data have been used in this study. This sensor is briefly discussed here. The MSS system of the landsat 1,2 and 3 operates in the solar reflection region (The Landsat 3 carried a channel in thermal infrared region as well, but this failed and could not supply data). The solar energy falling on the earth's surface is scattered, absorbed and transmitted by the objects. The relative amounts of these depend on the spectral characteristics of the ground object. The MSS system subdivides the back-scattered electromagnetic radiation into spectral bands viz:

MSS channel 4 = 0.5-0.6 μ , MSS channel 5 = 0.6-0.7 μ ;
MSS channel 6 = 0.7-0.8 μ , MSS channel 7 = 0.8-1.1 μ

The operation of details of the MSS are given below:

The satellites of this class-Landsat 1, Landsat-2, and Landsat 3 are in orbit. Sensors of the above Landsats are no longer active. The data for the present study were collected from Landsat 2 and 3. These satellites are on near polar Sun-Synchronous, altitude 900 km (nominal). The orbital plan is inclined to the equator at an angle of 99°, measured anti-clockwise from West. Data are acquired when the Satellite is on its South bound course. A full revolution round the earth takes 103 minutes.

In the MSS, a front coated flat mirror oscillates about an axis parallel to the direction of motion of the spacecraft and this gives an across track coverage of 185 km, on ground. The long track coverage is provided by the motion of this Satellite. The light reflected by the mirror is split up in 4 bands and is collected by appropriate sensor. The rate of oscillation, 13.62 Hz, of the mirror is decided by the motion of the Sub-Satellite Point which is 6.47 km/sec. Spatial resolution of Landsat MSS images is about 80 m which is the size of smallest element of a picture called pixel.

The intensity of back-scattered reflected electromagnetic radiation, received by the MSS sensor, is detected, digitized, and recorded. This information is relayed to the ground receiving station on the earth where it is converted into black and white images for visual display using suitable grey-scale. These images are found to be very useful in monitoring of the earths' surface phenomena, including snow cover area, and these form the basic material used in this study here.

(ii) Selection of the Landsat Images of the Area

The Chenab catchment is covered under the path and row numbers (numbers applicable to Landsat 1,2 and 3 orbits) : 158-037, 159-036, 159-037, 160-036 and 160-037 (for path and row number, see e.g. Williams and Carter, 1976).

As March - September is the period of snowmelt, suitable Landsat scenes were selected for this period, for the years 1975-81. The selection of the scenes was based on the considerations of date of coverage, cloud cover and radiometric quality of scenes. Unfortunately, no good data was available.

of snow cover area (c.f. O'Brien and Munis, 1975; Gupta et al 1982) and they would lead to smaller estimates of the snow-cover area. Therefore, MSS-5 images have been used for snow mapping in the present study.

(ii) Melting Snow:- As the snow would start melting, a thin film of moisture would develop on the top surface of snow in lower reaches of the catchment. This film of moisture would absorb infrared radiation and therefore, would lead to a dark tone in the infrared bands (MSS 6 and MSS 7). However, in the visible range (MSS-4 and MSS-5), the area would continue to have a bright tone as it is still covered with snow which has high albedo in this area. Therefore, the melting snow can be identified. As the melt season advances, the region of melting snow shifts to higher topographic levels.

(iii) Snow-Free Area:- The snow-free area has relatively much darker tone in both visible and infrared ranges and a clear boundary can be placed between the snow-free and snow-covered regions. The snow free regions occur at lower elevations in comparison to the snow covered areas. The exception could be steep slopes which even at higher elevation could be snow-free. However, their areal extent is limited and such features are not mappable on the Landsat images.

(iv) Shadows:- The Himalayan mountains are rugged and have high relief. As the landsat coverage is obtained in early forenoon, the prevailing low-angle of illumination leads to shadows. The sun-azimuth in the images used ranges from N 100° to N 152° and the sun-angle from 33° to 60° (see

Appendix-IV-1). Figure (4.1) illustrates the presence of shadows in low-sun-angle Landsat images. In such cases snow covered shadowed regions appear similar to snow-free areas in tone. It is obvious that if a density-slicing type of feature categorization is carried out (classifying all bright areas to be snow and non-bright areas to be snow-free in such areas), the measured snow-cover area will be less than the actual snow cover area present. Therefore, it is necessary to discriminate between snow-free area and the shadows. It is done by considering the elevations, sun-angle, sun-azimuth and interpolating the boundary through shadowed regions. This gives actual snow cover area on images.

(v) Cloud Cover:- Clouds appear bright white on visible as well as on infrared images and these are likely to be mixed up with snow during interpretation. However, as they do not rest on the ground, a shadow is cast by them. This helps in differentiating clouds from the snow. Besides, the form and pattern of clouds is also frequently distinctive.

(vi) Method of Snow Cover Mapping:- Due to rugged terrain and oblique solar illumination resulting in shadows, and occasional cloud-cover in the area, it is necessary to take help of topographic maps for snow-mapping. The following procedure was adopted:

i) Study of the enlarged Landsat MSS images.

ii) Study of the topographic maps to get an idea of the terrain, relative elevation and orientation of valleys and hills.

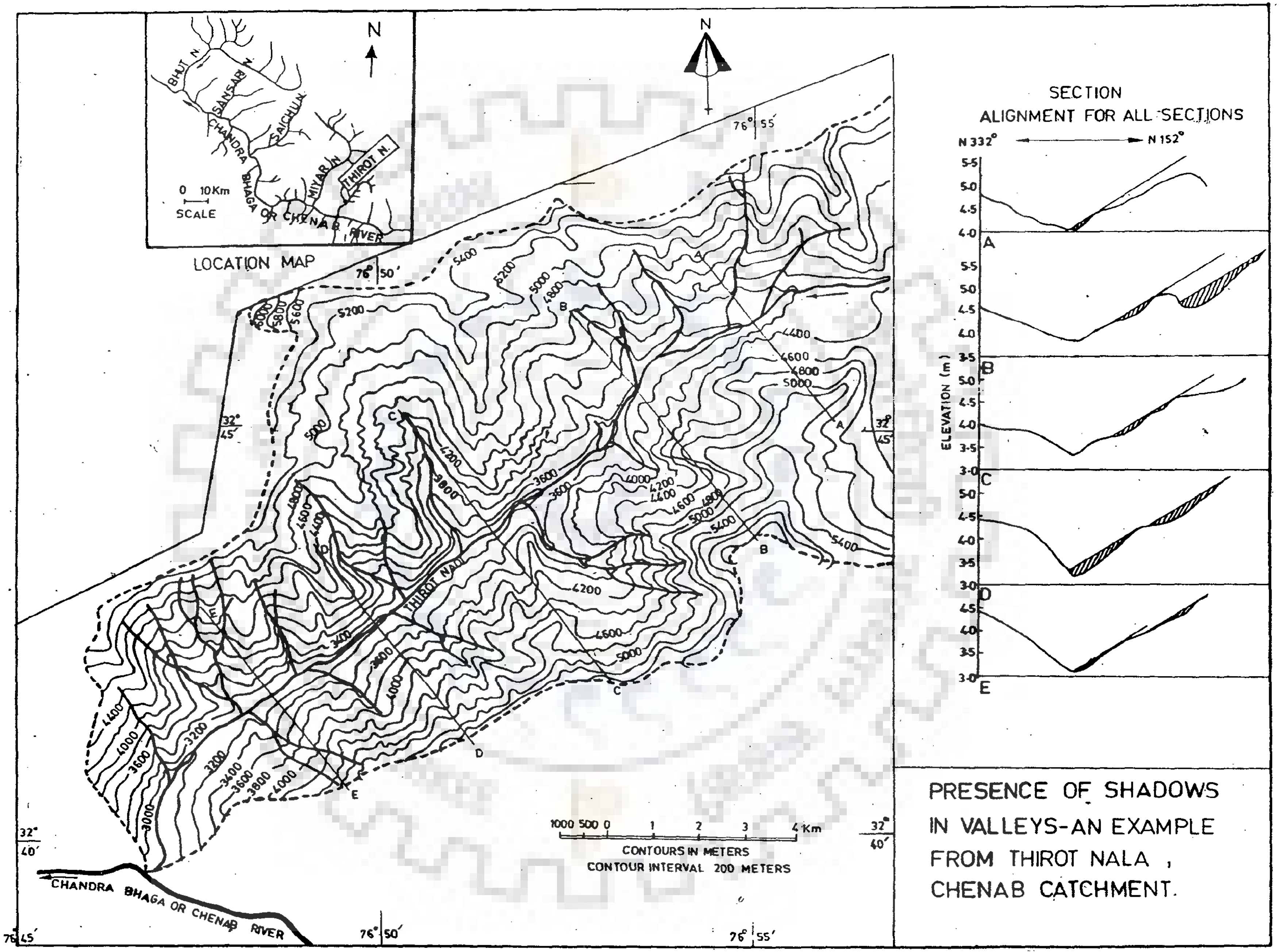
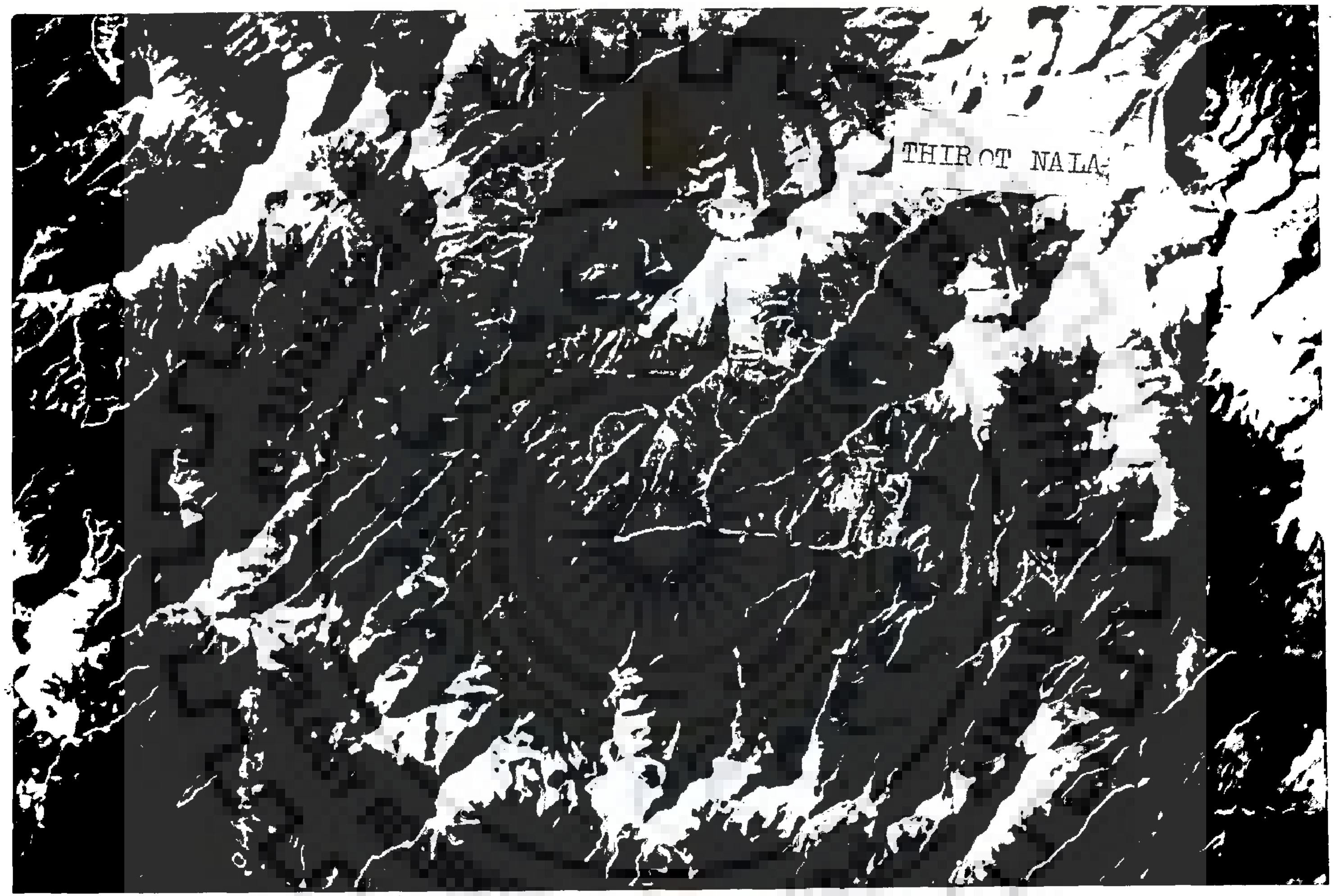


Fig. 4.1 (a) Typical Example of Presence of Shadows in Valleys



DATE 16 NOV.1972. SUN ELEVATION 33°, SUN AZIMUTH 152°.

Fig.4.1(b) Presence of Shadows in Valleys: Landsat Imagery.

iii) Mapping of snow cover area, first, on illuminated slopes only.

iv) Marking of shadow zones and cloud cover zones.

v) Estimating elevation of snow line by superimposing the above prepared snow-line map over topographic maps in different parts of the catchment.

vi) Interpolating snow line in the shadow zones and cloud cover areas, based on the above snow-line map and elevation data from topographic maps.

Thus, in this manner, the snow cover maps corresponding to various Landsat images have been prepared.

It has been found that the permanent snow line in the area lies at the elevation of around 4530 m which forms nearly 30% of the area. At the close of winter season and just before the snowmelt starts, the snow line descends to an elevation of nearly 1950 m and approx. (86%) of the area is under snow at that time. It is further seen that as the snow melt season sets-in, the dirty snow (or melting snow) appears on the lower fringes of the snow cover and the zone of melting snow gradually advances towards higher elevations. An important point is that the local melting process is greatly affected by topography i.e. the orientation of the valleys and hill slopes. Those hill slopes, which are northerly-facing, receive less direct sunlight in comparison to the southerly-facing slopes. Therefore, in several instances where the valleys are approximate (East-West Trending, e.g. Chenab valley from Thirot to Benswar), it happens that the snow line on the southerly-facing hill slopes is quite high whereas that on the northerly-facing slopes is still at lower elevations. The snow area has been planimetered to give the snow-cover area in different sub-catchments corresponding to the different discharge measurement sites.

4.3.3 Computation of Cumulative Snowmelt Runoff(Premonsoon)

The study of hydrographs at various discharge sites and of the meteorological data in the Chenab catchment reveals that the arrival time of the monsoon in this region is around 30th June. During the month of December to February, the river discharges reach minimum values and are quite steady. This discharge can be taken as the 'base flow.' From March onwards the river discharge at all the discharge measurement sites rise. The daily discharge excess over the base flow (at the time when there is no significant concurrent rainfall), can be only due to snowmelt. As the situation is found to be quite complicated after the arrival of the monsoon rains, that is, after 30th June or so the rain contribution significantly increases, in this chapter of the study, snowmelt runoff only upto the 30th June of each year, has been considered. It has been found that during the period March - June the direct rain contribution is of the order of only 3 - 11% of the total surface runoff (see Chapter V). Therefore, the direct rain contribution has not been considered in this period (March - June).

The cumulative runoff excess over the base flow has

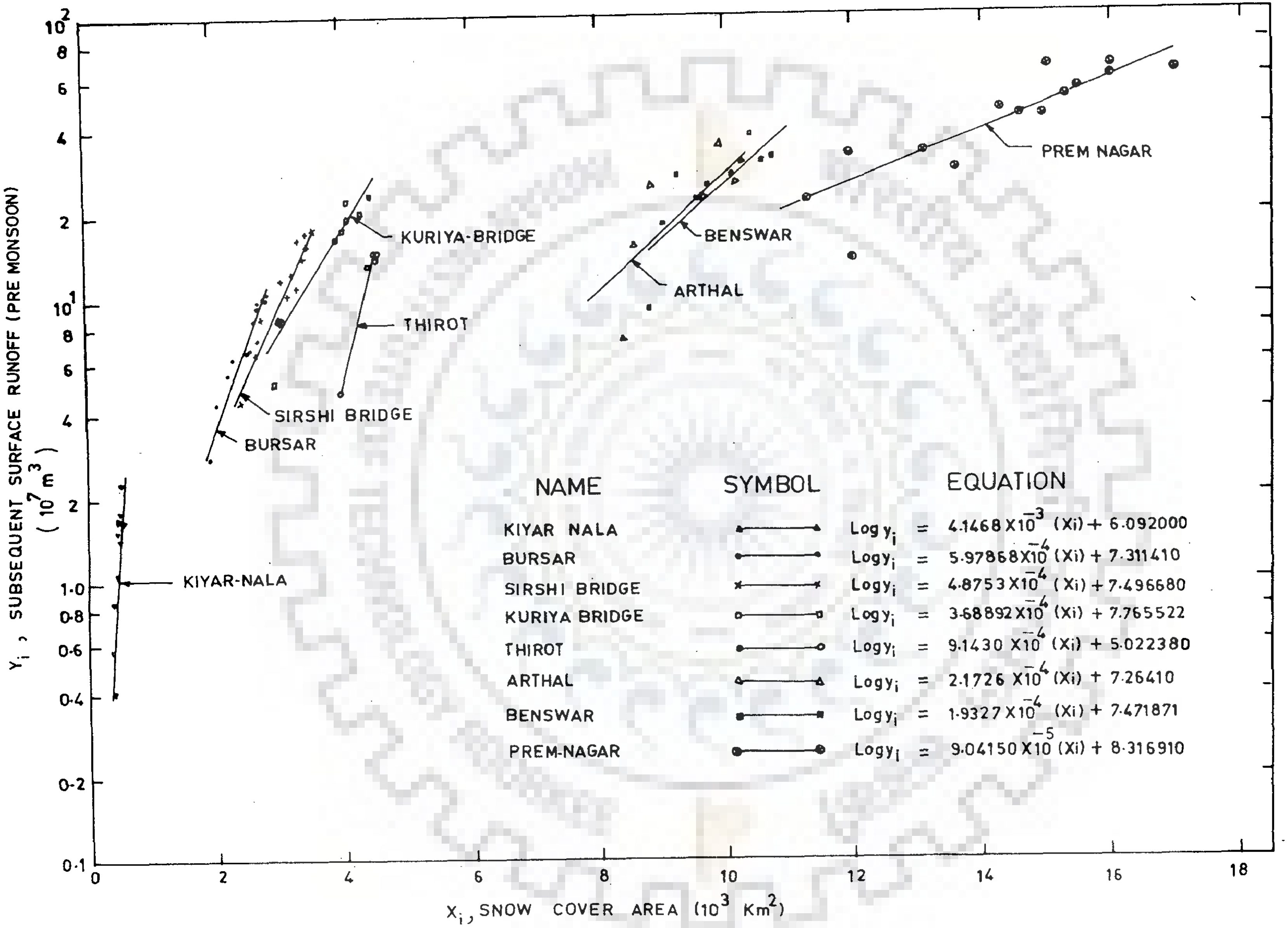


Fig. 4.2 Relation Between Snowcover area and Subsequent Surface Runoff (Pre-monsoon)

subcatchments. The variation in the nature of the regression curves is interpreted to be related to hydromorphologic features (Table 4.1) as has also been shown in the Beas catchment by Gupta et al (1982).

4.5.1 Geographic and Meteorologic Variation:

It is interpreted that the above systematic variation in the regression lines from subcatchment to subcatchment is not caused by relative geographic or meteorological factors. To elucidate this point consider five sub-catchments of Kiyar, Bursar, Sirshi, Kuriya and Thirot (Fig. 4.2):

i) Subcatchment Kiyar Nala and Bursar are very close to each-other but still the regression lines corresponding to the two sub-catchments, show differences in location and slope.

ii) Subcatchments Bursar, Sirshi, and Kuriya are located in the North-Western part of the Chenab catchment and Thirot is situated in the Eastern part of the catchment but even then regression curves of the four sub-catchments are quite similar.

iii) Kiyar sub-catchment as also Bursar, Sirshi and Kuriya-subcatchment have North-East to South-West elongation, however, their regression curves differ from each other. On the other hand Bursar, Sirshi and Kuriya sub_catchments have North-South extension whereas Thirot has North-South and East-West extension where as the regression curves of all the above subcatchments are of the similar type. Therefore, it can be said that relative geographic location and orientation

TABLE- 4.1 : CATCHMENT CHARACTERISTICS OF THE SUB-BASINS

Sub-catchments	Area (km^2)	Permanent snowcover area including glacial terrain (%)	Mean elevation of the sub-catchments (m)	Generalised geographic elongation of the sub-catchment	Stream order (toposheet scale-1:250,000 used)	Slope of the regression curve Fig.(4.3) (10^{-4})	Y-intercept made by the regression curve (Fig.4.3)	Major rock types
Kiyar-Nala	554.99	40.22	4380.30	SW-NE	3	41.46800	6.09200	Metamorphic crystalline
Bursar	2896.34	28.65	4105.60	N-S	5	5.97868	7.31141	
Sirshi-Bridge	3588.12	29.35	4076.20	N-S	5	4.87530	7.49668	Palaeozoic sedimentary belt and Metamorphic crystalline
Kuriya-Bridge	4812.62	24.11	3848.30	N-S	5	3.68892	7.76552	
Thirot	4537.98	63.46	4889.30	NW-SE	5	9.14300	5.02238	
Arthal	10330.51	53.49	4640.00	NW-SE	6	2.17260	7.26410	
Benswar	11162.19	51.85	4564.70	NW-SE	6	1.93270	7.47187	

of the sub-catchments is not important in causing variation in these regression curve from sub-catchment to sub-catchment.

iv) Meteorological factors like snowfall, wind velocity, cloud cover etc. may differ within the Chenab catchment from one part to another, For example, there could be more snow in one part of the catchment in one hydrologic year and in another part of the catchment in another hydrologic year. This is illustrated by comparing Landsat images of the year 1975 and 1976 (Fig. 4.3.a,b). These local variations in meteorological phenomena would cause corresponding variation in snowmelt runoff. However, the above systematic differences in the regression curves from sub-basin to sub-basin may not be caused by random meteorological variations. It is considered that this pattern is determined by more fundamental basin characteristics like permanent snow cover, average altitude of the sub-catchment, relief, area of the sub-catchment,channel slope and all collectively put in terms of possibly stream order.

4.5.2 Results and Discussion

From Fig. (4.2) the following main observations can be made:

a) There is a general logarithmic relationship between the snow-cover area and the subsequent pre-monsoon cumulative runoff. The actual relationship is different for different sub-catchments.

Landsat Images Showing Lateral Variation in snowcover in different years. In Nov.1975 (Fig.4.3a) there is more snow in the NW Part of the catchment then in the SE part and in Sept.1976 (Fig.4.3b) reverse happens.

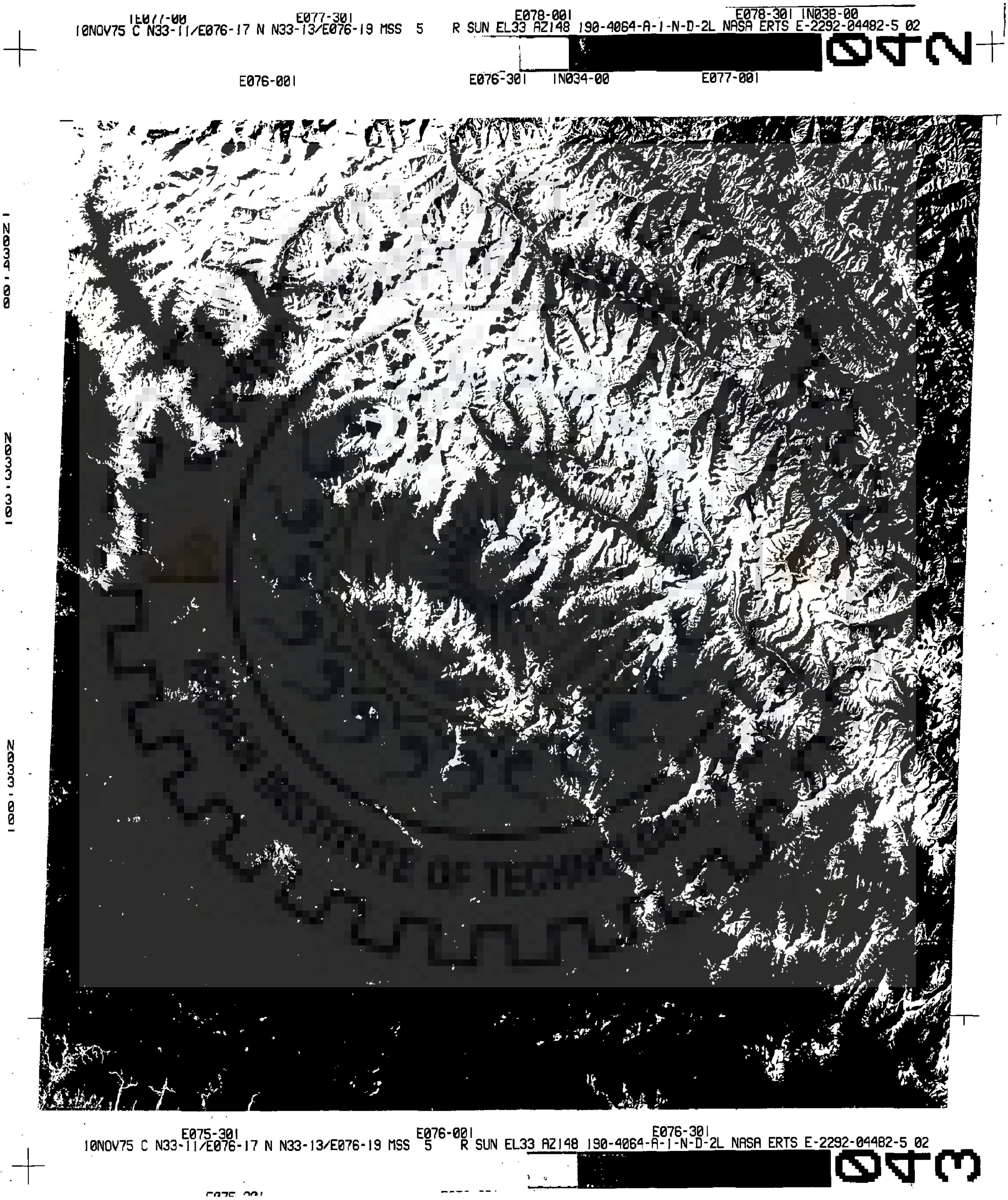


Fig.4.3a

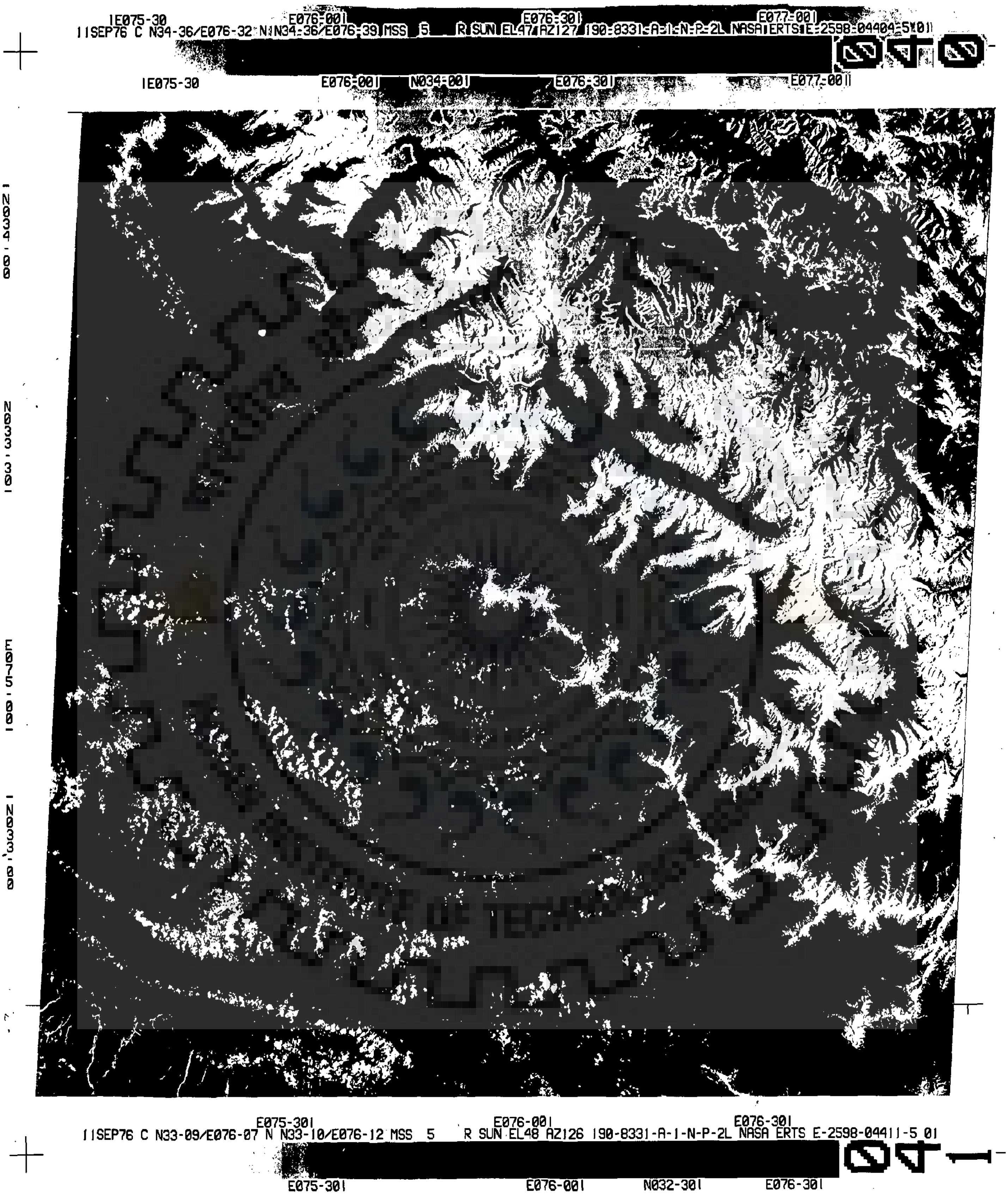

E075-30
E076-001
E076-301
E077-001
11SEP76 C N34-36/E076-32 N N34-36/E076-39 MSS 5 R SUN EL47 AZ127 190-8331-A-1-N-P-2L NASA ERTS E-2598-04404-5 01
E075-30
E076-001
N034-001
E076-301
E077-001
N034-00
N033-30
E075-00
N033-00
E075-301
E076-001
E076-301
11SEP76 C N33-09/E076-07 N N33-10/E076-12 MSS 5 R SUN EL48 AZ126 190-8331-A-1-N-P-2L NASA ERTS E-2598-04411-5 01
E075-301
E076-001
N032-301
E076-301

Fig.4.3b

b) The regression lines are successively right shifted along the X-axis as the catchment size increases.

c) There is a systematic variation in the slope of the regression lines.

These are in conformity with observations made by Gupta et al (1982) for the Beas catchment and each of these observations are discussed below:

(a) Logarithmic Relationship Between Snow-cover Area and Subsequent Cumulative Snowmelt Runoff:

The logarithmic relationship between the snow cover area and the cumulative snowmelt runoff is clearly seen from Fig. (4.2). It means that, initial increments in snow-cover area yield smaller increments in snowmelt runoff than later increments in snow-cover area of the same magnitude. This is quite logical, as in the initial stage with the setting of snowfall season, the regions on the periphery of the permanent snow line are thinly snow covered. As the temporary snow line descends to lower elevations snow cover area increases but it is also accompanied by ever increasing snow pack in the already snow covered areas in the higher reaches. Therefore, at closing stage, in the snow accumulation season, only a marginal increase in the snow cover area implies a large volume of seasonal snow. This leads to a logarithmic relationship between snow cover area and snowmelt runoff (c.f. Gupta et al 1982, Ferguson,1984).

(b) Right-Shifting of the Regression Line Along the X-Axis:

The regression curve for the different sub-catchments are successively shifted to the right. along the X-axis in Fig. (4.2). This systematic variation is interpreted to be related to size of the sub-catchments, mean elevation and permanent snow-cover area. As the sub-catchments become larger, the permanent snow-cover area generally increases and therefore, the starting points of the curves for the particular sub-catchment would be right shifted .

(c) Slope of the Regression Line:

The slope of regression curve for different sub-catchments show substantial but systematic variation. This is interpreted to be related to an interplay of several factors, like catchment area, permanent snow-cover area , average altitude of the sub-catchment,relief and channel slope, all of which can be possibly put together in terms of stream order (in a relatively, uniform terrain and on the same scale).

The regression curve for Kiyar Nala is steepest and belongs to stream order 3 (Table 4.1). Subcatchment Bursar, Sirshi, Kuriya Bridge and Thirot have regression curves of similar slopes and all of them belong to the same stream order 5. Regression curve of Arthal and Benswar have similar slopes and belong to stream order 6. The regression curve for Premnagar sub-catchment is more gentle than the curve for Arthal and Benswar, though it also belongs to the same stream order 6. This latter anomaly can be explained by the consideration that Marusudar is a big tributary which meets the main Chenab River between Benswar and Premnagar. Though it increases the total catchment area and the permanent snow area significantly, as it is a 5th order stream, the order of the main Chenab river does not change. Therefore, though on one hand Some parameters, like total catchment area, permanent snow cover area, and mean elevation etc, which are all related to stream order, undergo substantial change, the stream order remains unchanged, because of peculiar or exceptional conditions. Therefore, stream order seems to be a representative number generally, however, exceptions may occur.

The systematic variation in the slope of the above regression curves would mean that a particular snow cover area would give a higher amount of snowmelt discharge in a lower stream order sub-catchment than in a cognate higher stream order sub-catchment (c.f. Gupta et al 1982). This is logical because of the following arguments:

i) If a particular value of maximum snow-cover is mapped in a lower stream order and also in a higher stream order than the higher stream order catchment, being larger, will have more permanent snow-cover area and relatively less temporarily snow-cover area. On the other hand, a sub-catchment of lower stream order, with the same Landsat snow cover area will have less permanent snow cover and more temporary snow-cover. Therefore, the later will yield more snowmelt runoff than the former.

ii) If a particular value of maximum snow-cover is taken to occur in lower order stream catchment and also in a higher stream order catchment, not only the area of temporary snow will be larger in the lower order stream catchment but also its thickness will be greater in the lower stream order sub-catchment than in the higher stream order sub-catchment. This is because of the fact that in the case of a lower stream order basin, the snowline would descend to lower elevations and fill up depressions and valley slopes to yield a particular value of snow-cover area. However, the same area of Landsat snow-cover would be obtained in a higher stream order catchment (which has greater permanent snow-cover area) when only higher peaks and steeper slopes are snow-covered, where snow accumulation may not be so thick. Therefore, in the lower stream order basin there is more thickness of snow column than in the higher stream order basin, for the same value of Landsat snow cover area. This results in greater amount of snowmelt from a lower order basin than for the higher order basin, even if the two have the same value of Landsat snow-cover area.

iii) The mean elevation of a lower order catchment is greater than that of a cognate higher stream order catchment. Therefore, if the Landsat snow-cover area is the same in the two cases, the temporary snow pack will be greater in the case of a lower stream order basin than in the case of a higher stream order basin, for the simple reason that the former, situated at general higher elevation would possess generally greater snow thickness. This could be another reason as to why for the same value of Landsat snow-cover area, there will be more snowmelt from a lower stream order sub-catchment.

iv) The lower stream order sub-catchments have higher averaged channel slope and ground slope than the higher stream order sub-catchments. This would allow less infiltration to sub-surface water in a lower stream order basin and relatively more infiltration in a higher stream order case. This could also be another reason for more surface runoff from meltwater in a lower stream order sub-catchment than in the case of a higher stream order sub-catchment.

Therefore, the various factors like permanent snow-cover, average altitude, total area of the sub-catchment, channel slope and ground slope, could explain well the above variation in the regression curves between Landsat snow cover area and cumulative snowmelt runoff (pre-monsoon).

On the other hand, considering it the other way round, it seems quite logical that the slope of the regression curves between snow-cover area and the subsequent snowmelt runoff should be related to stream order. The reason is that, a particular order catchment has a typical catchment morphology and the rate at which snow volume increases with snow cover area should be a function of catchment morphology. Therefore, in a generalized way, slope of the relation between snow cover area and snowmelt runoff (i.e. volume of temporary snow) should be controlled by catchment morphology (like permanent snow-cover area, average altitude of the basin, channel slope, ground slope and basin area all of which can generally be put together in terms of a single parameter, i.e. stream order).

It is considered that the regression curves, as obtained above, should be useful in predicting subsequent snowmelt run-off cumulative upto June 30, if the snow-cover area is shown at any stage after the end of snow accumulation season. Moreover, this methodology can be applied to other basins as well.

CHAPER - V

MODELLING OF DAILY RUNOFF

5.1 GENERAL

The snow on high mountains and rainfall in lower elevations are the important sources of water in many parts of the world. This is especially so in the Himalayan basins, which are the biggest reservoirs of stored water in the form of permanent and temporary snow accumulation during the winter season, contributing to river flows during the snowmelt season . A methodology for determination of runoff contributions from the mountainous catchments would be dependent upon the availability of information required for snowmelt runoff modelling.

In the Himalayan catchments, reliable data, other than daily rainfall and daily temperature at low altitude stations and daily streamflow records at some gauging sites on rivers, are almost non-existent. Therefore, reliable and reasonably accurate methods of predicting daily, monthly and seasonal melt water yield from the snow, using available (somewhat limited) data are needed for water resources planning and management.

5.1.1 Some Important Studies Including Studies for Himalayan Basins

(1) Snow Hydrology (1956) gives a very detailed report of the snow investigations by U.S.Army Corps of Engineers. In a

detailed discussion on temperature indices, the variation of degree day factors from basin to basin and from month to month has been indicated. A general decrease in melt rates with increasing forest cover and also the increase in the melt rates as the melt season progresses, are reflected. The various causes listed for the normal increase in the degree day factors with time are : (i) increasing ripeness of the snow pack, (ii) decrease of snow surface albedo, (iii) depletion of snow cover, (iv) increase in incoming solar radiation, (v) increase in percentage of sheltered snow cover area, and (vi) the increase in mean elevation of the snow covered area.

An empirical scheme has been suggested to approximate the observed increase in degree day factors with time as the melt season progresses, which involves considering the degree day factor as a nonlinear function of difference of daily temperature and base temperature. It is, however, mentioned that this method has not been extensively tested and as such it is only an empirical device to simulate increase in the value of degree day factor.

(2) Martinec (1960) used a new method for measuring the snow water content with radio-active cobalt for obtaining more accurate data for calculation of snowmelt with the use of the degree day factor. The snow water content measurements were made without disturbing the snowcover and simultaneously continuous measurements of the air temperature were carried out in experimental mountain stations. It was found that the values of the degree day factor increase in the course of

summer in accordance with the rising density of snow. A similar effect caused by the wind was also observed in several cases.

It was shown that degree day factor varied between 2.6 to 8.7 mm/1°C corresponding to density of snow varying between 20.5% to 75.6%. The relation between the snow density (D) in % and the degree day factor (T) in cm/$^{\circ}$C was expressed by a simple linear relationship of the form $T = C.D$ and value of $C = 0.011$ was indicated.

(3) Gulati (1972) presented a collection of information regarding role of snow and ice in hydrology in India. The year was split into four seasons - snow accumulation (Dec. to Feb.), snowmelt (March to May), monsoon (June to Sept.) and groundwater (Oct. to Nov.). For the Kashmir Himalayas, percentage of annual seasonal precipitation for four seasons were given as follows:

i)	Snow accumulation season	22.1 %
ii)	Snowmelt season	22.0 %
iii)	Monsoon season	53.6 %
iv)	Groundwater season	2.3 %

The lowest position of the winter snowline over the Himalayas was also mentioned to occur in the Kashmir mountains, where it is about 2133.6 m (7000 ft).

(4) Chatterji and Chopra (1976) have studied snowmelt contribution in the Sutlej catchment for the purpose of flood and low flow forecasting for Bhakra reservoir. For Kotgarh

station the seasonal distribution of precipitation was estimated for total annual value of 1102.9 mm, as given below:

	% of Annual Value
1) Snow accumulation season (Dec - Feb)	17
2) Snowmelt season (March - June)	29
3) Monsoon season (July - Sept.)	50
4) Groundwater season (Oct. - Nov)	4
	100

The average value of degree day factor was assumed as 0.05 inch per °C per day, 60% of rainfall was considered as contributing to runoff, while 90% of snowmelt was considered as contributing to runoff.

(5) Bahadur et al (1977) have highlighted the use of isotope techniques in the study of hydrological problems including those related to combinations of snow and glaciers to river flow. In [illegible] review of isotopic techniques for snow and glacier hydrology of mountain watersheds, Bahadur (1983) has discussed in detail typical applications such as determination of water equivalent of snowpacks, regional surveys for assessment of water supply from snowmelt, determination of rates of snow accumulation, differentiation between contributions from snow and glacier melt to river flows etc. He has also mentioned about sparsely explored Himalayan region and justified introduction of isotopic studies for various aspects of snow and glacier hydrology.

(6) Rango et al (1977) used low resolution meteorological satellite data and simple photo-interpretation techniques to map snow covered areas during early April over the Indus river and Kabul river basins in Pakistan using data of 1969 - 1973 . The early spring snow covered area was significantly related to April through July 31, streamflow in regression analysis for each watershed. Predictions of 1974 seasonal stream flow using the regression equations were within 7 % of actual 1974 flow.

(7) Martinec and Rango (1981) proposed a method to determine the areal distribution of the maximum seasonal water equivalent of snow in mountain basins. The disappearance of the seasonal snow cover is monitored during the melting period by Landsat and the maximum accumulation of snow and its distribution over a mountain basin in terms of water equivalent is approximated. In order to achieve this, air temperatures are extrapolated to a detailed system of grid points in a basin, melting degree days are calculated and the amount of snowmelt upto the point of snow disappearance is determined. The lapse rate of 0.65°C per 100 m was assumed in the study. The value of degree day factor was determined according to Martinec (1960) as a function of measured snow density and was used to compute the total snowmelt in each basin grid point, rather than using an average value of 0.45 cm $^{o}C^{-1}$ d^{-1}.

(8) Seth (1981) presented a study dealing with development of a snowmelt runoff model using information about the areal

extent of permanent and temporary snow covers obtained from satellite images and observed data of daily precipitation (rain and snow) and daily temperature. for premonsoon months. Three years (1977, 1978, 1979) data from Beas river catchment upto Manali gauge site (1829 m above m.s.l) were utilised in the study for verification of the model. The catchment was divided into four elevation zones at 610 m intervals for temporary snow covered area upto permanent snowline position (4269 m above m.s.l), and the area above this elevation was considered as permanent snow covered area. The altitudinal effect on temperature was considered by lapse rate and the orographic effect on precipitation was also considered by adding an incremental value of 5% to precipitation at Manali for each 305 m rise in elevation. The model employed simple degree day approach and simple assumptions for abstractions and routing. The degree day factor was assumed to vary during melting season and seperate parameter values varying between 1.53 to 2.0 mm/deg.day for March and April, and 2.46 to 3.0 mm/deg. day for May were obtained in calibration runs using pattern search optimisation technique.

Though only limited data were used, this model study provides encouraging results of application of simple model structure with limited data and also indicates need for:

i) Consideration of permanent snow covered area separately, and

ii) Variation of melt rate, involving a gradual increase as melting season progresses, for the daily snowmelt runoff studies for Himalayan basins.

(9) Bagchi (1981) carried out a detailed study of snowmelt runoff in Beas basin using satellite images for his Ph.D. thesis. He expressed the stream flow on any day as the ordinate of the normal recession curve together with additional discharge due to snowmelt or rain in the basin on that day, as follows:

$$Q_{n+1} = Q_n \cdot K_n + [(I_s)_n + (I_R)_n] (1-K_n)$$

where Q_{n+1} = discharge on $(n+1)^{th}$ day

Q_n = discharge on n^{th} day

$(I_s)_n$ = snowmelt input

$(I_R)_n$ = rainwater input

K_n = $(1.00 - 0.0008\ Q_n)$, is the recession constant .

For the determination of snowmelt input I_s, Bagchi (1981) adopted a temperature index method, which gives:

$$\sum_{i=1}^{n} (I_s)_i = a \sum_{i=1}^{n} \sum_{j=j'}^{j''} (T_{max})_{ij} \ \Delta A_j$$

where a = degree day factor

$(T_{max})_{ij}$ = maximum temperature on i^{th} day in the j^{th} zone

ΔA_j = area of j^{th} zone (the basin area divided into 200m elevation zones, j=1 to 20)

In the above equation, j' refers to the lowest zone in the snow covered area, the extent of which is obtained from Landsat images and j'' is the highest zone, For T_{max} above 0^oC. The value of $(T_{max})_{ij}$ was determined using the temperature data at the base station and assuming a lapse rate of $0.65^{\circ}C/100$ m. The value of degree day factor was taken as 2.1 mm per degree day.

For finding effective precipitation at different altitudes in the Beas catchment, Bagchi (1981) used a coefficient β as an orographic increase factor and showed that β increases from unity to 3.25 with change of altitude from 1900 to 4000 m and then decreases to 0.9 at 5900 m. The percentage of snow in the total precipitation (X) has been assumed as a function of the minimum daily temperature of the place as follows:

$$X = 9(3.5 - T_{min})$$

The study is a good attempt in snowmelt runoff modelling However, it lacks in some significant aspects, viz. (i) permanent snow cover area has not been considered appropriately, (ii) the orographic factor and percentage of snow factor involve gross assumptions in the absence of reliable data base, (iii) the effect of increase of snowfree area with gradual decrease in snowcover area has not been considered and (iv) abstractions from snowmelt and rainfall have not been considered directly.

(10) Upadhyay and Bahadur (1982) have dealt with hydrometerological aspects of precipitation in Western Himalayas and brought out salient features of orographic precipitation such as windward/ leeward effects and altitudinal variations. For the Western Himalayas, for elevation range of 400-3200 m, range of increase in precipitation has been indicated as 3 to 200 mm/100 m.

(11) Dhar et al. (1982) have presented study of the effect of Pir Panjal range of Himalayas over monsoon rainfall distribution in Kashmir valley. It is mentioned that in other seasons of the year (excepting the south west monsoon months of July to Sept.) the area south of the Pir Panjal range (which includes the Chenab basin) receives less rainfall than the area north of it.

(12) Jeyaram and Bagchi (1982) reported the investigations carried out to estimate snowline altitude of Tos basin in Himachal Pradesh using Landsat images. Linear relationships have been established for the snowline altitudes of neighbouring basins (Beas, Ravi and Manali) with corresponding altitudes for Tos basin.

(13) Upadhyay et al (1983) have analysed various components of energy input to a snow cover including short wave and long wave radiation, convective transfer, latent heat of condensation, conduction from ground underneath and heat of rainfall over snow surface and worked out monthly budget for net energy available for snowmelt for a number of stations in Himalayas using meteorological data on temperature, vapour pressure, wind and cloudiness.For Srinagar (elev. 1586 m above m.s.l) and Leh (elev. 3514 m above m.s.l.) stations in Kashmir Himalayas,their results indicate the following:

(a) For Srinagar, the net energy budget is maximum in July (700 langleys/day) and minimum in January (-81 langleys/day) where, 1 langley = 1 calori/cm^2. It remains negative from December to February.

(b) For Leh, the net energy budget is negative from November to March. The snow cover receives maximum energy in July (488 langleys/day) and loses maximum energy in January (-189 langleys/day).

Based on the energy budget, the theoretical quantities of snowmelt were also worked out which were as follows for Srinagar and Leh stations (read from plots), during premonsoon and monsoon months.

TABLE-5.1 : MONTHLY MEAN TEMPERATURES AND MELT RATE

Month	Monthly Melt Rate (cm/day)		Monthly Mean Temperature (°C)	
	Leh	Srinagar	Leh	Srinagar
March	-	1.5	-0.1	8.3
April	0.7	3.7	5.4	13.1
May	2.6	5.9	9.7	17.7
June	4.5	7.8	13.7	21.5
July	6.1	8.7	17.3	24.4
August	5.3	7.6	16.7	23.7
September	4.3	6.7	12.9	20.3
October	2.1	3.6	13.1	14.0

These results clearly indicate the rate of variation in melt rate as melt season progresses due to availability of increased net energy, as also indicated by pattern of variation of temperature.

(14) Abbi et al (1983) have presented an estimate of maximum snow cover water equivalent and computed monthly snowmelt by using degree day method for river Beas upto Pong Dam site (catchment area 12500 km^2). From Nov. to March/April, regions above 2000 m receive precipitation mainly in the form of snow. During May to September, the higher reaches above 5000 m receive solid precipitation. On the basis of 3 years (1971-1973) data recorded at Kothi station, they have reported following properties of seasonal snow cover in February:

i) Standing snow (cm) - 134
ii) Mean max. standing snow(cm) - 227
iii) Density of snow surface - 0.11

(15) Dey et al (1983) have presented results of studies involving utilization of satellite snow cover observations for seasonal streamflow estimates in the Western Himalayas. A regression model relating seasonal flow from April through July, 1974 to early April snow cover explains 73% and 82% of the variance, respectively, of the measured flow in the Indus and the Kabul rivers. It has been shown that remotely sensed snow cover area data provides the best available input in empirical snowmelt prediction techniques for the remote Himalayan basins, which are characterised by rugged physiography, limited physical accessibility and inadequate hydrometeorological data base. The study has also indicated high correlation of concurrent flows in adjoining Himalayan basins like the Indus and Kabul.

(16) Dey and Goswami (1984) evaluated a model of snow cover area versus runoff against a concurrent flow correlation model in the Western Himalayas, using data of Sutlej, Indus, Kabul and Chenab rivers. It was found that the concurrent flow correlation model explains more than 90% of the variability of flows in these rivers, while the snow cover model explains somewhat less of the variability in flows. It is mentioned in the study that these rivers carry significant amounts of snowmelt runoff, which on the average, account for more than 55% of the mean annual flows. The mean seasonal snowmelt runoff (April - June) in the Indus, Kabul, Sutlej and Chenab rivers are given as 4027, 851, 735 and 1508 m^3/sec respectively for catchment areas of 162100, 88600, 38000 and 26155 km^2. The snow cover area versus runoff relationships mentioned by these authors are as follows for three rivers, for which such relationships have been established:

i) $Y = 0.06493\,X - 0.363325$, for Sutlej river

ii) $Y = 0.472\,X + 4.73895$, for Indus river

iii) $Y = 0.54337\,X - 5.24243$, for Kabul river

above Y = seasonal runoff, April - July in $10^9\ m^3$

X = Average percent of snowcover of the basin.

These relationships have the potential for use in operational forecasting and water resources studies.

(17) Ferguson (1985) presented a study of runoff from glacierized mountains (upper Indus in Pakistan) and a model for annual variation of runoff and its forecasting. His approach is based on identification of a number of glacio-

logical and climatological factors other than snow covered area, keeping in view the results of previous studies giving differing values of the regression coefficients of runoff on snowcover with change in basin size. Neglecting the rainfall runoff and groundwater discharge, and also losses, the total melt water runoff has been assumed to be sum of three components : (i) complete melting of a[illegible] glacier snowpack, (ii) complete melting of glacier ablation zone snow cover, and (iii) glacier ice melt from a contributing fraction of area. He has provided useful information about characteristics of high mountain basins in northern Pakistan based upon 1975-78 data as given below and clearly brought out the importance of permanent snow covered areas in any study of snowmelt runoff in Himalayan basins.

TABLE-5.2 : SNOW COVER AND RUNOFF CHARACTERISTICS

River Basin	Area (km^2)	April to August runoff (mm) (mean)	Snow cover(%) mean	Icecover estimate (%)
Hunza	13000	763	88	38
Gilgit	26000	578	86	27
Indus	160000	303	83	11
Shyok	33000	292	93	9
Jhelum	25000	644	74	2

The review of important studies of snowmelt process and also studies for Himalayan basin clearly indicates the following:

a) The melt rate changes as the melt season progresses due to various processes including increase in density of snow.

b) The snowmelt runoff is predominant component of river flows for rivers originating in Himalayas and it is contributed by both permanent snow cover as well as temporary snow cover.

c) The melt season commences around March in Himalayas and the contributions from snowmelt continue upto September.

d) Simple degree day approach is well suited for typical conditions of data availability and physical processes in Himalayan basins.

e) There is good correlation between snowmelt runoff and snowcover area for Himalayan basins.

f) **Satellite images** provide very useful information for difficult terrain situations of Himalayan basins.

5.1.2 Simple Snowmelt Runoff Models

(1) Anderson (1978) has highlighted a set of principles that govern the use of conceptual models in snow covered areas which are concerned with model structure, data input, model calibration and the operational use of models. A number of elements have been mentioned, which are needed in the structures of a model to simulate adequately snowmelt runoff process. These include the following:

i) Model structure should be physically based.

ii) Model should require only readily obtainable data.

iii) Data used in model study should be as unbiased as possible, since biased data can distort parameter values.

iv) Mathematical representation of unit process should be expressed in terms of single valued parameters rather than in the form of multi valued tables, whenever possible. This also facilitates automatic optimisation and development of relationships of individual parameters with physical characteristics of the basin.

v) Parameters should have unique effect on outputs

vi) Other available real time information should be used to up-date the model.

Anderson (1978) has also dealt in detail various aspects of model structure including snow accumulation, surface energy exchange, water retention and movement, snow cover properties, snow cover distribution, snow soil interaction etc. A seasonal variation in the melt factor has been considered essential primarily because of the variation in net available solar energy and the air temperature in general has been found as adequate index of snow cover energy exchange where the meteorological factors (dew point, wind etc.) do not deviate significantly from normal. He has also mentioned about the effect of transmission of melt water through the snow, resulting in both lag and attenuation.

(2) The SSARR (Stream flow Synthesis and Reservoir Regulation) model was developed progressively since 1956 to provide a generalized computer simulation technique for analyzing and forecasting various types of hydrologic systems.

The program description and user manual for SSARR (1972) has been brought out by U.S. Army Engineer Division, North Pacific, Portland, Oregon. Rockwood (1981) has discussed the theory and practice of this model as related to analyzing and forecasting the response of hydrologic systems. The calculation of snowmelt by the SSARR model is a major element of the model and it includes application of both (i) the temperature index method for daily forecasting application and (ii) energy budget approach for design flood derivations. The model has two options for evaluating snowmelt runoff from a watershed viz. (i) In the first option, the snow cover depletion is described by use of a function which relates the snow covered area to the accumulation of runoff in proportion to the total seasonal runoff volume, (ii) the second option provides for the capability to subdivide the watershed area into 'bands' of equal elevation, as determined from area elevation relationships.

The differentiation between snow covered and snow free area is represented by a snowline which usually follows an elevation contour. In the split watershed program option, the snowcovered and snow free areas are treated as two separate watersheds,each with its own characteristics and parameters. This enables, the effect of gradual drying out of snow free area to be taken into account by maintaining separate account of the soil moisture index. The model also has provisions for melt rate variability during the snowmelt season which can be specified for each day of the run or for critical intermediate, beginning or end periods (depending upon availability of data) and for the other days, it is interpolated linearly.

The model, however, has no separate provision for consideration of permanent snow cover and also new snow during melt season is not automatically compensated.

(3) Martinec (1975) developed a snowmelt runoff model, which uses air temperature, snow coverage, and precipitation during the snowmelt period as essential data. The model structure was tested using data of well equipped representative catchment. The general form of the model is as follows:

$$R_n = C_n[a_n T_n S_n + P_n] (1-k_n) + R_{n-1} k_n$$

where, R_n = daily runoff depth [cm]
C_n = runoff coefficient
a_n = degree day factor [$\text{cm} \times {}^{\circ}\text{C}^{-1}\ \text{d}^{-1}$]
T_n = number of degree days [${}^{\circ}\text{C} \times \text{d}$]
S_n = snow coverage (100 % = 1.0)
P_n = precipitation contributing to runoff (cm)
k_n = recession coefficient
n = index referring to the sequence of days.

The area of catchment was divided in different elevation zones and the air temperature values at base station were extrapolated to the average hypsometric elevations of the zones in order to determine the number of degree days, using a variable lapse rate.

(4) Rango and Martinec (1981) presented results of runoff simulation from various basins using Martinec's snowmelt runoff model, in order to predict the accuracy of simulations in future application of the model. It was found that the model can be applied to nearly any mountainous basin where snowmelt runoff is an important factor, if input data on temperature, precipitation and snowcover are available. It was also shown that simulation accuracy would depend on the quality of input data and most accurate simulations will result when (i) temperature and precipitation are recorded at the basin mean elevation, (ii) snow cover observations are available once per week, (iii) several climatic stations are available for large basins and (iv) a few years of runoff records exist for determination of the recession coefficient. The availability of satellite observations of snowcover extent was shown to be a very important information for application of model to large basins.

(5) Quick and Pipes (1977) have presented the design requirements for a watershed model in mountainous catchments. Orographic temperature and precipitation gradients have been used to distribute point meteorological data to all parts of the watershed. There are four main subdivisions of this model, which is designated as UBC (University of British Columbia) watershed model, viz. (a) meteorological data processing, (b) snowmelt calculation, (c) soil moisture budget and (d) routing of slow components to channel out flow point. The soil moisture budget section of the model

subdivided the total rain and snowmelt inputs into fast, medium, slow and very slow components of runoff and thus acts as a non-linear mechanism. These components of runoff are then routed to the basin outflow point using linear routing techniques. It was concluded that for representative input data, preferably at mid-elevation of the watershed, the modelling assumptions were quite realistic for flow forecasting purposes, as indicated by model tests with field data.

This review of some simple snowmelt runoff models clearly shows that significant developments have taken place in the area of development of conceptual models for use in snow covered areas. The models involving application of simple degree day approach have given reasonably good performance. Keeping in view rugged physiography, limited physical accessibility and inadequate hydrometeorological data base of Himalayan basins, only simple model structures with reasonable physical base, limited data requirements and capability of using remotely sensed data for snow cover area seem to be appropriate for such conditions.

5.2 AVAILABLE DATA

5.2.1 Morphological Data

As discussed in Chapter III, detailed studies have been made involving measured and computed values of the various morphological parameters viz. drainage area, channel length, slope, area between each 1000 m contour intervals and Hickok et al parameter etc. Various characteristics like area elevation relationships, weighted mean elevation and variation of parameter - channel length/square root of main channel slope ratio ($L|\sqrt{S}$), have been studied for different sub-basins. The hydrological/hydrometeorological characteristics have been related with the values of these morphological parameters for the sub-basins.

5.2.2 Hydrometeorological Data

(a) Precipitation:

Average daily precipitation data from precipitation stations (Fig. 1.1) as listed in Appendix (1-1) has been used in the analysis of daily runoff. This precipitation data was collected from India Meteorological Department (I.M.D.), New Delhi, as available for the period 1965-1980. The total precipitation depth for each sub-basin for pre-monsoon and monsoon season alongwith the computation period is given in Table 5.3.

(b) Temperature Data:

Available daily maximum and minimum temperature data at Banihal (elev.-1630 m above m.s.l) were collected from

Meteorological Centre, Rambagh, Srinagar and I.M.D., New Delhi for the months of March to May for 16 years, and for the months of June to September for 9 years, for the period from 1965 to 1981.

TABLE-5.3 : PRECIPITATION DEPTH DURING THE RUNOFF PERIOD

Basin name	Runoff Period	Precipitation(mm)	Basin Name	Season of year	Precipitation (mm)
Prem Nagar	3 Mar-11 Sept. 1975	1052.70	Sirshi-Bridge	3 Mar-11 Sept 1975	1162.35
	2 Apr-11 Sept. 1976	824.67		2 Apr-11 Sept 1976	615.83
	10 Mar-11 Sept. 1977	615.88		10 Mar-11 Sept 1977	684.77
	18 Mar-11 Sept. 1979	502.68			
Benswar	3 Mar-11 Sept. 1975	1216.25	Bursar	3 Mar-11 Sept 1975	1040.40
	2 Apr-31 July 1976	379.80		1 Mar-11 Sept 1976	416.20
	10 Mar-11 Sept. 1977	705.15		10 Mar-11 Sept 1977	670.98
Kuriya Bridge	3 Mar-11 Sept. 1975	1319.64	Kiyar-Nala	2 Apr-31 July 1976	327.00
	2 Apr-31 July 1976	347.48		10 Mar-11 Sept 1977	1124.10
	10 Mar-11 Sept. 1977	678.96			

5.2.3 (a) Hydrological Data

Available daily flow data for 1965-81 from 10 sub-basins at the discharge sites (locations shown in Fig. 2.1) was collected from the Statistical Section, Ministry of Irrigation, New Delhi, Daily flow data of the following sites has been used in the model study.

1. Premnagar
2. Benswar
3. Kuriya Bridge
4. Sirshi Bridge
5. Bursar
6. Kiyar Nala

(b) Base Flow Separation:

The average daily minimum flows during January or February of each year have been assumed to represent the constant rate of the base flow contributions from the drainage area of the corresponding rivers. The percentage of base flow in the total runoff computed for the season under study for each sub_basin is given in Table 5.4 . This shows that baseflow contribution varies from 6.59% to 18.09% and thus represent only a small component of total runoff. In modelling study,direct runoff after subtracting base flow has been used and has been termed as runoff.

5.2.4 Satellite Data

Snow covered area was mapped and measured from the Landsat images MSS-5 for different sub-catchments, the permanent

TABLE-5.4 : BASE FLOW DURING THE COMPUTATION PERIOD

Basin	Season of Year	Constant Base flow m^3/sec	No. of days	Vol. of Base flow Cumec-days	Total Run-off (Cumec - days)	Base Flow % of Total Runoff
Prem-nagar	1975	80	193	15440	203382	7.59
	76	80	163	13040	178224	7.32
	77	80	186	14880	171159	8.69
	79	90	178	14240	208448	6.83
Benswar	1975	50	193	9650	137649	7.01
	76	50	121	6171	86787	7.11
	77	51	186	9300	133660	6.96
Kuriya-Bridge	1975	31	193	5983	69247	8.64
	76	27	121	3267	45271	7.22
	77	33	186	6138	55961	10.97
Sirshi-Bridge	1975	20	193	3860	50812	7.60
	76	24	163	3912	46552	8.40
	77	32	186	5952	41054	14.50
Bursar	1975	14.57	193	2812	29860	9.42
	76	21	122	2562	14220	18.02
	77	18	186	3348	23151	14.46
Kiyar-Nala	1976	4	121	484	4762	10.16
	77	3	186	558	8466	6.59

snow covered, temporary snow covered and the remaining area of each sub-catchment have been measured. The position of permanent snow-line elevation and the temporary snow-line elevation on different dates were specified. In this study, the available 45 images for different dates during 1975-81 have been analysed.

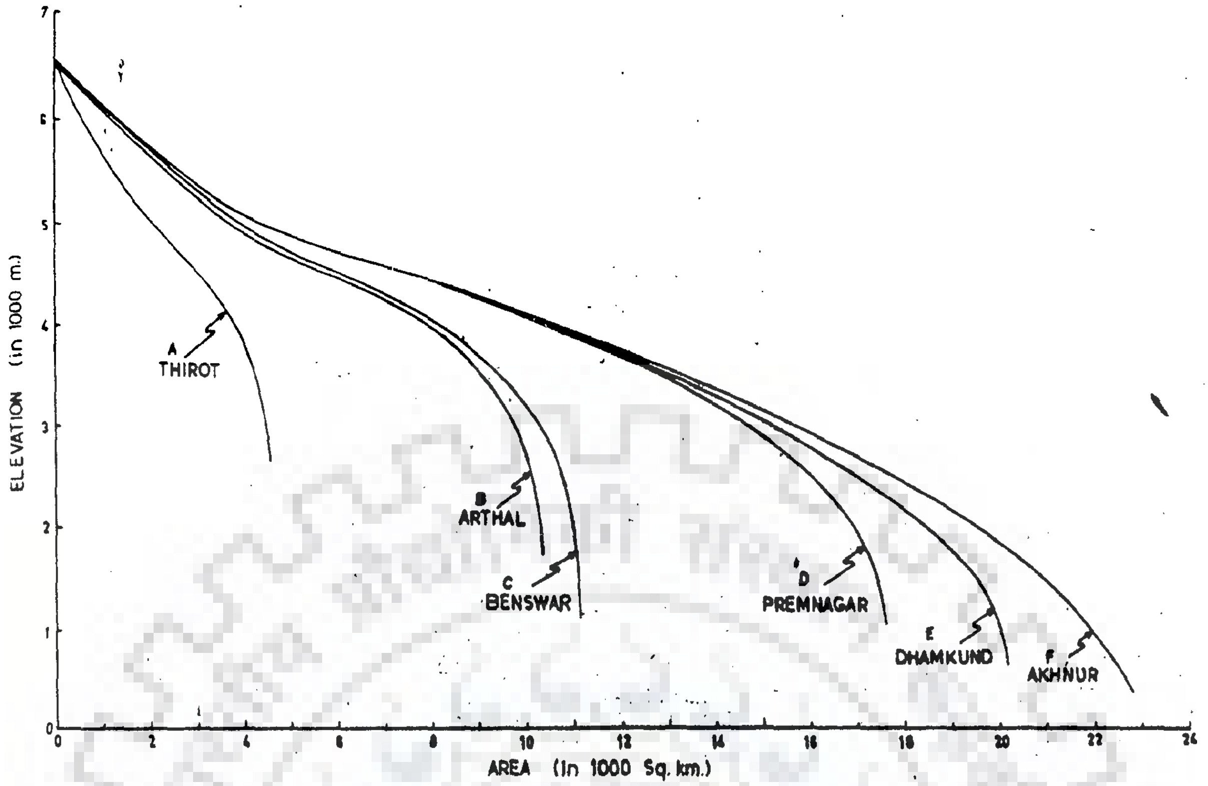
5.3 DATA ANALYSIS

5.3.1 Area Elevation Relationships

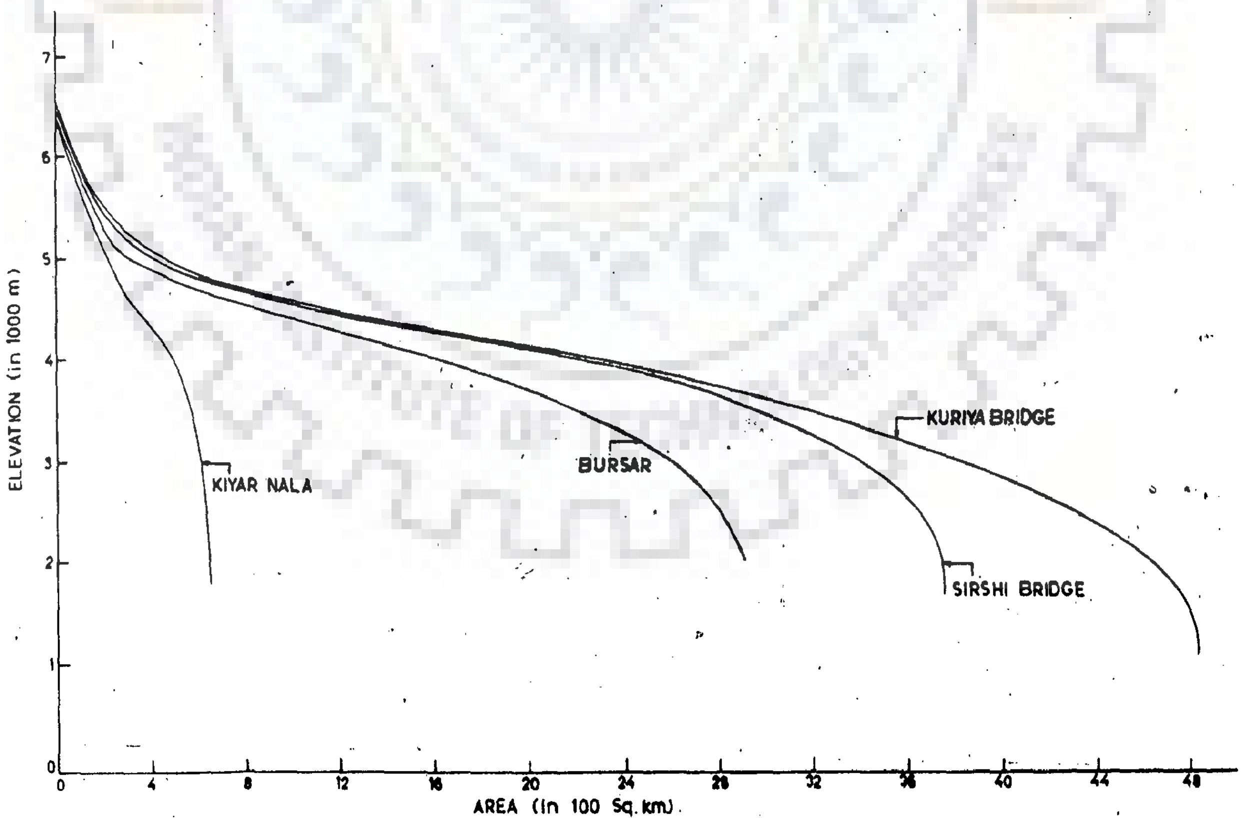
Area between contours at intervals of 1000 meters was measured by planimeter from available topographic maps for each sub-basin. The measured area increasing with the decrease of elevation, starting from maximum elevation was plotted for each sub-basin (Fig. 5.1 and 5.1b).

The decrease of area per each 100 meter decrease of elevation (starting from maximum elevation) of the basin and the decrease of elevation per each 100 sq.km. decrease of the area from the total area of the basin has been determined, using computer program for interpolation. Typical computed values are given in Appendix V-1.

From the computed values of area corresponding to each 500 meter change of elevation, the weighted mean elevation for each of the sub-basins has been computed and the values are given in Table 5.5 :



5·1 (a)



5·1 (b)

Fig. 5·1 Area Elevation Characteristics of Sub-basins

TABLE-5.5 : RELATIONSHIP BETWEEN THE VARIATION OF MELT-RATE AND WEIGHTED MEAN ELEVATION OF THE SUB-BASIN

Parameters	SUB - BASINS					
	Premnagar	Benswar	Kuriya-Bridge	Sirshi Bridge	Bursar	Kiyar-Nala
Estimated values of melt-rate mm/deg-day	0.02430	0.03516	0.0144	0.0189	0.0106	0.03116
Weighted mean elevation (m)	4192.6	4564.7	3848.3	4076.2	4105.6	4380.3
Graphical values of melt-rate used in the model	0.02430	0.03516	0.0144	0.0206	0.0215	0.0296

5.3.2 Temperature Characteristics

(a) Mean and Standard Deviation of Daily Temperature Values:

The average values of daily temperature data(Sec.5.2.2b) has been used in this study. Computations have been made using computer program to find out the statistical parameters, like mean, standard deviation and skewness of the daily values for each day of record during March to September(Appd. V-2). Five alternate daily temperature series, have also been computed for use in the study of variation of melt with the possible variation of temperature pattern, as follows:

(i)(mean daily temperature), (ii) (mean-1.0 Standard deviation), (iii) (mean-0.5 standard dev.), (mean + 0.5 St.dev.), (v)(mean + 1.0 St. dev.).

(b) Lapse Rate:

Lapse rate is the rate of change of temperature with elevation. This parameter enables determination of the temperature at any elevation from the given temperature at base station. The review of studies by Martinec (1981) and Bagchi (1983) indicate that for the study of snowmelt runoff in the Himalayan catchments, the lapse rate of temperature equal to 0.0065°C per meter change in elevation, is appropriate value for this region. The temperature would thus decrease by 0.0065°C for each meter increase of elevation.

(c) Base Temperature:

Base temperature is specified as a constant for a watershed (°C). This specifies the limit of temperature for snowmelt and if the air temperature at particular elevation exceeds this base temperature, then snowmelt takes place. Base temperature value equal to 0°C has been considered appropriate for the present study for Chanab basin. The base temperature of 0°C has also been used in SSARR model study for the U.S. catchments, and by Martinec (1981) in the study for Himalayan catchments.

(d) Rain Freeze Temperature:

Rainfreeze temperature is also a limiting value of temperature. The precipitation is considered to be in the form of snow, when the air temperature at a particular elevation is less than the rainfreeze temperature, and there will be no flow contribution from rain from the catchment area above the elevation corresponding to rainfreeze temperature. The rain freeze temperature value of 0.56°C has been used in the studies using SSARR model for U.S. basins (SSARR Model revised manual, 1975) and the same value was adopted for the present study.

5.3.3 Subdivisions of Drainage Area

Drainage area is the total area of the basin contributing runoff from snowmelt and rainfall. According to the different types of contributions and snow cover conditions the drainage area of high altitude mountainous watershed in Himalayas can be divided into following three sub-divisions, viz.:

i) Permanent snow covered area, which is the area of the basin located above the permanent snow line elevation of the basin. The permanent snow-line elevation is the elevation corresponding to the highest position of the snow line at the beginning of snow fall season, sometimes in the month of October or so,

ii) Temporary snow covered area is the area located between the lowest position of snow line as observed/estimated and the maximum possible position of snow line (i.e. permanent snow line position).

iii) Snow free area is the area of basin below temporary snow line position, which is complementary of the temporary snow covered area.

These parameters representing different categories of basin subdivisions were measured from the topographic maps, and the study of the repetetive landsat images at the beginning of the snowmelt period and at the end of monsoon snowmelt season. The division of the total area into permanent snow covered and the remaining area for some of the sub-basins is given in Table (5.6).

TABLE-5.6 : DIVISION OF SUB-BASIN AREAS IN TO PERMANENT SNOW COVERED AND REMAINING AREAS

Areas sq.km	SUB-BASINS					
	Premnagar	Benswar	Kuriya-Bridge	Sirshi Bridge	Bursar	Kiyar Nala
Total area	17622.46	11162.19	4812.62	3388.12	2896.34	554.99
Permanent snow area	7059.04	5787.58	1160.31	1053.00	829.78	223.22
Remaining area	10563.42	5374.61	3652.31	2535.12	2066.56	331.77

5.3.4 Snow cover Depletion Relationship

The satellite images of snow covered areas show that, the snow covered area of any basin decreases during the snowmelt season due to depletion resulting from melting of the snow under the effect of solar energy and other energy inputs.

The analysis of snow covered area and the corresponding runoff as discussed in Chapter IV shows that there is a relationship between depletion of snow covered area and the snowmelt runoff contributions for the basin. This finding is supported by studies reported by different authors (see Chapter IV).

Analytic approach for this relationship was employed by the Army Corps of Engineers (Snow Hydrology, 1956) in SSARR model, expressing the relationship between snow cover depletion of any basin and corresponding snowmelt runoff as:

$$\frac{SCA}{100} = 1.00 - \left(\frac{\Sigma Q_{gen}}{100}\right)^n \qquad \ldots(5.1)$$

where, SCA = the snow covered area excluding permanent snow covered area as a percentage of (total catchment area minus permanent snow covered area).

ΣQ_{gen} = accumulated generated runoff from snowmelt from the beginning of melt season as a percentage of total seasonal snowmelt runoff (SSR)

n = an index, which is a basin characteristic for the snow cover depletion.

5.3.5 Determination of Parameters 'n' 'SSR' Values and the Variation of Melt Rate

To evaluate the parameters 'n' and seasonal snowmelt runoff (SSR) a computation procedure was developed using information from satellite images, runoff and temperature data. The steps of the procedure followed for these computations are illustrated for Premnagar basin for 1977 as a typical example in Table (5.7), are as follows:

(a) Snow line elevation for each year obtained from the available Landsat images during the snowmelt season was plotted against the date of observation and a smooth curve was drawn through the observed points for each year of observation (Fig. 5.2). The period from March to September has been considered as the period during which snowmelt contribution is expected from the snow covered area as indicated by the study of snow covered area from the repetitive Landsat images. In the studies of snowmelt runoff carried out by Ramanathan et al (1976), for the Satluj basin adjoining to the Chenab basin, it was also rightly inferred that the presumption regarding the snowmelt contribution to runoff in July-August to be insignificant is not correct, and the period should be taken from March to September.

(b) The snow line elevation at the end of each month from February to September was obtained from the fitted curve for snow line v/s date mentioned above. The values of snow covered and snow free area were calculated from the area elevation relationship, assuming that the area of the sub-basins above snow line elevation as snow covered, and below it as snow free area.

(c) The values of monthly precipitation depth were multiplied by snow free area and a runoff factor (assumed to vary

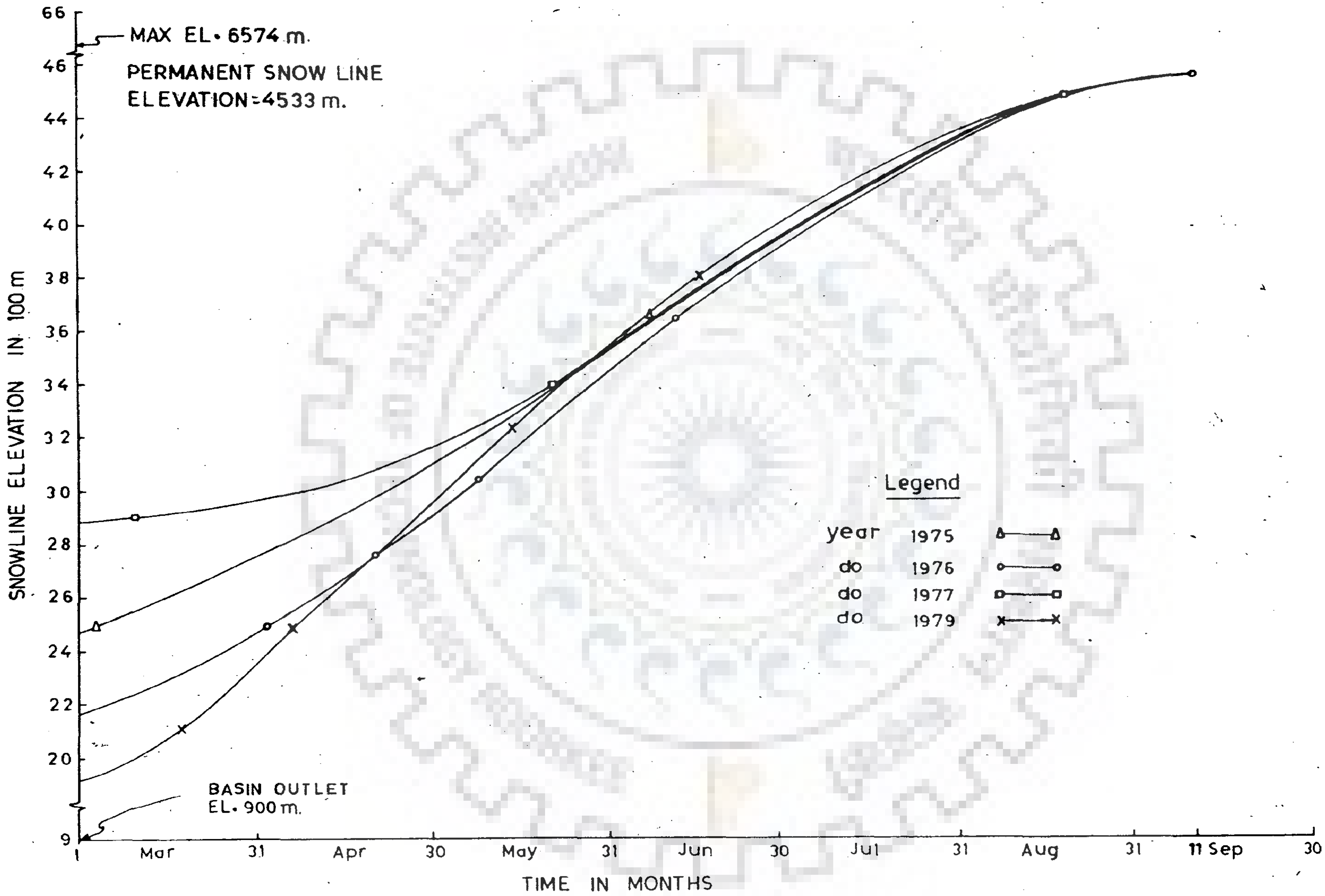


Fig. 5.2 Relationship Between Snow line Elevation and Time for Premnagar Sub-basin

TABLE-5.7 : TYPICAL EXAMPLE OF DETERMINATION OF HYDROLOGICAL PARAMETERS AND BASIN CHARACTERISTICS USING DATA OF 1977 FOR PREMNAGAR

End of Months	Snow-Elev. (m)	Snow-free Area (km^2)	Average Snow-free Area (km^2)	Rain-fall Over Snow-free Area (mm)	Runoff factor	Runoff Due to Rain-fall (m^3/sec)	Base Flow m^3/sec	Total Observed Flow m^3/sec	Snow-melt Runoff m^3/sec	Depth of Snowmelt Runoff Over Temp. (mm)
Feb.	2880.0	2602.8								0.00
March	2940.0	2726.9	2664.8	37.70	0.35	407.0	2480.0	5476	2589	21.18
April	3160.0	3536.6	3131.8	199.60	0.40	2894.0	2400.0	7559	2265	18.53
May	3518.0	5006.9	4271.8	116.41	0.45	2590.0	2480.0	15684	10614	86.82
June	3940.0	6841.9	5924.4	70.01	0.50	2400.0	2400.0	33831	29031	237.46
July	4300.0	9042.4	7942.2	62.84	0.55	3177.0	2480.0	56065	50408	412.31
Aug.	4520.0	10437.10	9740.0	66.15	0.60	4474.0	2480.0	43053	36099	295.27
Sept.	4540.0	10546.0	10500.0	62.25	0.65	4917.0	880.0	11490	5693	46.57
									136699	1118.14

Table-5.7 : Contd.

End of Months	Cumulative Snowmelt Runoff (mm)	Col.12 in %	Temporary Snow cover Area (km^2)	Col.14 in %	Corresponding Elevation for Area in Col.14 (m)	Total D.Day at Base Stn. (C^o)	Total D.day at Elev. of Col.16 (C^o)	Melt-rate Col.11/ Col.18 mm/D.day
Feb.	0.0	0.0	7960.22	75.36				
March	21.18	1.89	7898.22	74.77	2909.27	416.30	158.53	0.134
April	39.71	3.55	7431.22	70.35	3064.27	428.00	148.32	0.13
May	26.53	11.32	6291.32	59.56	3333.65	506.85	163.56	0.53
June	363.99	32.55	4638.62	43.91	3727.53	618.00	208.98	1.14
July	776.30	69.43	2620.82	24.81	4131.17	717.20	213.21	1.94
August	1071.57	95.84	823.02	7.79	4408.99	688.65	128.68	2.29
Sept.	1118.14	100.00	63.02	0.60	4529.60	228.10	20.78	2.24

from 35% to 65% from March to September), to obtain the estimated values of monthly runoff due to rainfall. The monthly snowmelt runoff was obtained by subtracting the base flow and estimated runoff due to rainfall from the total flow of each month as observed at the outlet of the basin.

(d) As mentioned above, knowing the snow line elevation (5.3.4(c)), the corresponding snow covered area has been computed. The snow covered area of the sub-basin below the permanent (highest) position of snow line was taken as temporary snow covered area, and above that as the permanent snow covered area.

The highest elevation for permanent snow line for this study on the basis of available information from satellite images and in view of limitation of data availability, was taken as position of snow line approximately on 11th September 1976 for each sub-basin. It was assumed that the snow line elevation would reach to the same position of permanent snow line elevation every year on 11th September. Using this approach, the temporary and permanent snow covered areas for sub-basins have been estimated.

(e) The percentage of variation of temporary snow covered area in different months was averaged from the available period of record for different years in each sub-basin. Similarly the percentage of snowmelt runoff depth over the temporary area for each months was averaged from the available records for different years for each sub-basin.

(Tables 5.8 and 5.9). The values are marked in Figs.(5.3). The cumulative sum of snowmelt runoff expressed as depth over temporary snow covered area from 1st March to 11th September has been termed as seasonal snowmelt runoff (SSR), see (Table-5.10).

The relationship between percentage of snow cover depletion and the corresponding percentage of SSR as the generated runoff has been found using the relationship of the form given by equation 5.1 for evaluating the parameter 'n'.

5.3.5.1 Determination of Parameter 'n':

To evaluate the best possible value of parameter 'n', the following steps were followed:

Analysis was made to find the minimum values of least squaresfunction F, by using different trial values of 'n', with the following relationship:

$$F_1 = (SCA_{obs} - SCA_{comp})^2 \qquad \ldots(5.2)$$

where, SCA_{obs}, is the observed snow cover, (Sec. 5.3.5e) and SCA_{comp}, is the computed snow cover from equation (5.1) for trial value of n. The 'n' value for each sub-basin was found corresponding to minimum value of function F_1, shown in (Fig. 5.3) as given in Table (5.11). These computed values of 'n' were plotted against modified Hickok et al Parameter ($A/S_c\sqrt{D_d}$) as shown in (Fig. 5.4) and a straight line regional graphical relation indicating general increase of 'n' with decrease in value of the Hickok parameter has been obtained.

TABLE-5.8 : TEMPORARY SNOW COVERED AREA IN % AND CORRESPONDING VALUES OF ACCUMULATED SNOWMELT RUNOFF IN % FOR FEB. TO SEPT. FOR PREMNAGAR CATCHMENT

Year	Temporary Snow Covered Area (SCA, %)					Accumulated Snowmelt Runoff in (%) of Seasonal Snowmelt Runoff (SSR)				
Month	1975	1976	1977	1979	Average	1975	1976	1977	1979	Average
Feb.	85.26	94.72	75.36	98.24	90.86	0.00	0.00	0.00	0.00	0.00
March	81.70	88.14	74.77	92.90	84.38	0.08	0.65	1.89	1.38	1.00
April	72.92	79.94	70.35	81.03	76.06	4.96	6.45	3.55	7.34	5.58
May	59.14	64.87	59.56	62.57	61.54	17.72	21.18	11.32	14.03	16.06
June	56.26	45.60	43.91	43.29	47.26	45.15	43.48	32.55	37.11	39.57
July	43.26	25.32	24.81	23.38	29.19	74.18	78.92	69.42	69.26	72.94
Aug.	7.19	7.79	7.79	6.58	7.34	94.80	97.77	95.84	94.18	95.65
Sept.	0.60	0.60	0.60	0.60	0.60	100.00	100.00	100.00	100.00	100.00

NOTE:- Graph between average of percentage of snow covered area and accumulated snowmelt runoff for different months was plotted to develop mathematical relationship.

TABLE-5.9 : TEMPORARY SNOWCOVERED IN % AND CORRESPONDING VALUES OF ACCUMULATED SNOWMELT RUNOFF IN % FOR FEB. TO SEP. FOR OTHER BASINS USED FOR DETERMINATION OF PARAMETER 'n'

Basins	Benswar		Kuriya-Bridge		Sirshi-Bridge		Bursar		Kiyar-Nala	
Months	SCA %	SMR IN (%) of (SSR)	SCA(%)	SMR in (%) of (SSR)	SCA(%)	SMR in (%) of (SSR)	SCA(%)	SMR in (%) of (SSR)	SCA(%)	SMR in (%) of (SSR)
Feb.	93.70	0.00	92.87	0.00	96.25	0.00	96.62	0.00	92.40	0.00
March	91.07	0.24	84.07	0.60	92.63	0.71	94.82	0.66	91.01	0.25
April	85.43	1.83	75.32	5.85	87.17	3.83	88.36	4.07	85.90	1.98
May	74.26	9.55	60.36	22.65	73.15	15.80	73.91	18.18	77.92	8.63
June	55.24	29.77	47.44	48.80	53.80	42.31	55.41	47.94	66.04	25.20
July	33.84	66.42	24.28	78.27	31.13	75.13	39.17	79.26	35.54	67.24
Aug.	15.07	94.04	11.11	96.97	8.86	96.78	16.78	98.75	19.06	94.59
Sept.	0.00	100.00	2.31	100.00	0.00	10.00	0.00	100.00	0.00	100.00

NOTE:- Using the values given in above table graphs has been plotted in Fig. 5.3 to determine the depletion characteristics 'n' for different sub-basins.

TABLE-5.10 : ESTIMATED VALUES OF SEASONAL SNOWMELT RUNOFF (SSR) FOR DIFFERENT SUB-BASINS

Years Basins	1975		1976		1977		1979	
	m^3/sec	mm	m^3/sec	mm	m^3/sec	mm	m^3/sec	mm
Premnagar	153126	1207.5	134640	1101.28	136699	1118.14	181670	1485.94
Benswar	112230	1804.17	107962	1735.55	115366	1853.56	-	-
Kuriya-Bridge	45125	1132.79	47021	1112.33	42857	1013.84	-	-
Sirshi-Bridge	38953	1327.55	36362	1240.00	30645	1044.41	-	-
Bursar	21494	898.62	19514	815.86	16166	675.86	-	-
Kiyar Nala	-	-	6152	1602.00	7483	1775.00	-	-

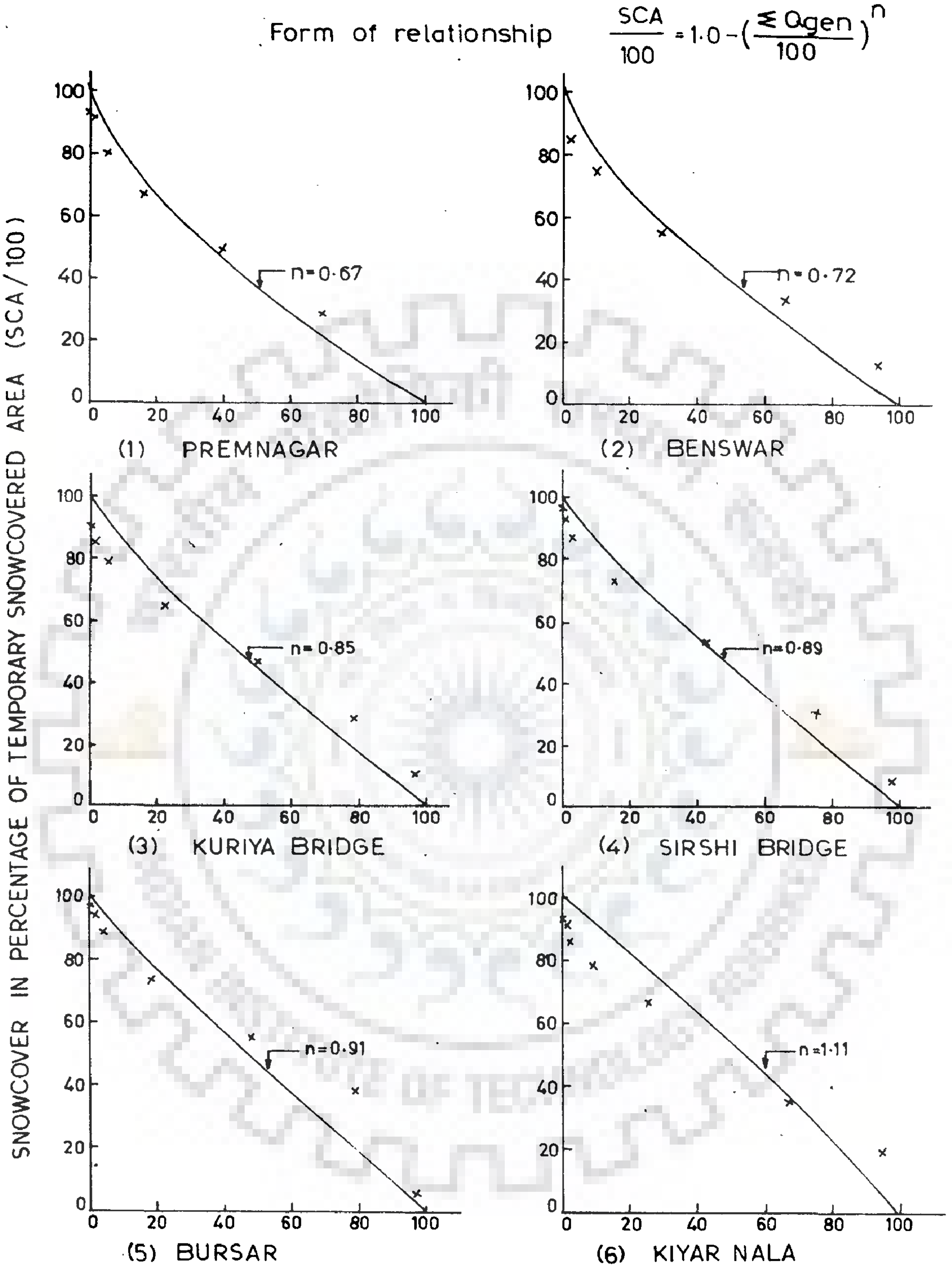


Fig 5.3 Relationship Between Snow cover in percentage of Temporary Snowcovered area and Snowmelt Runoff as Percentage of Seasonal Total Using Minimised values of (n)

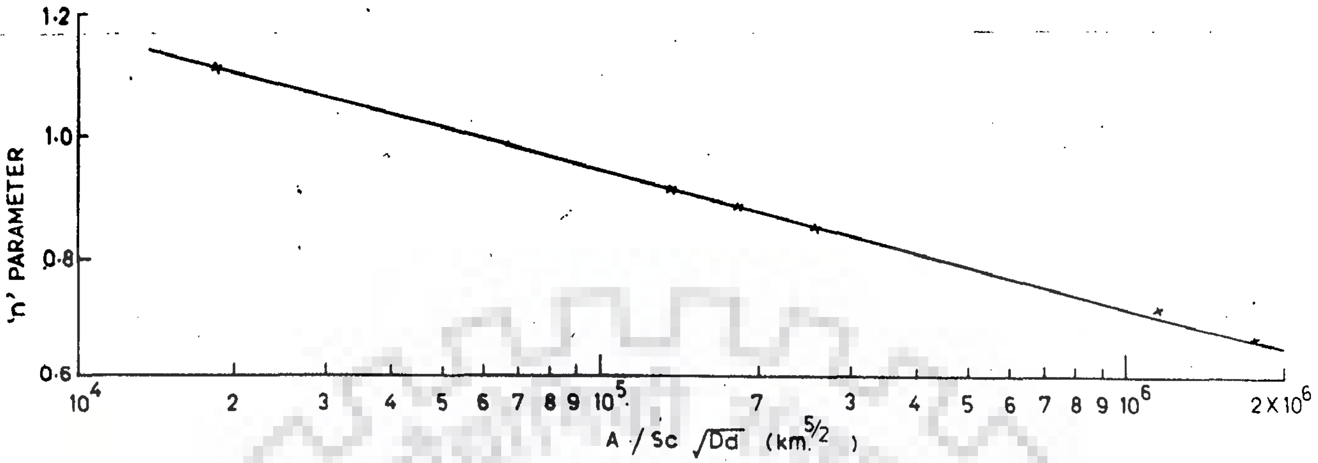


Fig 5.4 Relationship Between 'n' Parameter and Hickok et al Parameter

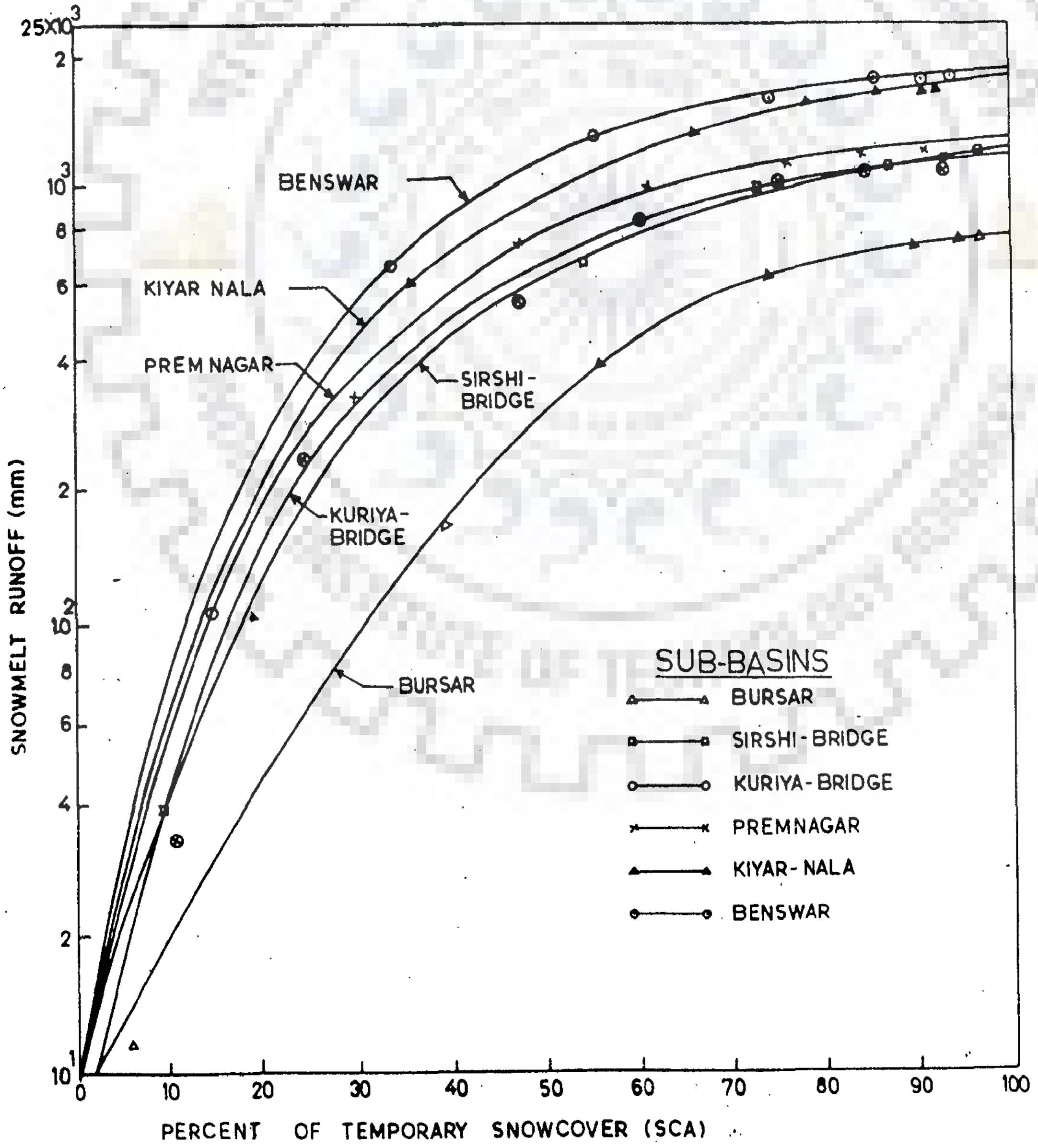


Fig. 5.5 Relationship Between Snowmelt Runoff and Temporary Snowcovered Area

TABLE-5.11 : COMPUTED VALUES OF PARAMETER

Sub-basin	Hickok Parameter $A/S_c\sqrt{D_d}$ (10^2 km$^{5/2}$)	Computed Value of 'n' for Individual Sub-basin
1. Premnagar	17454.3	0.67
2. Benswar	10155.4	0.72
3. Kuriya-bridge	2520.8	0.85
4. Sirshi-bridge	1773.0	0.89
5. Bursar	1383.9	0.91
6. Kiyar Nala	186.3	1.11

5.3.5.2 Seasonal Snowmelt Runoff (SSR):

The average subsequent snowmelt runoff (SSMR) in (mm) over the catchment area excluding permanent area for each month from February to September were estimated as discussed above using available data for different years. Average values (Table 5.12) were plotted against the percentage of temporary snow covered (SCA) (Tables 5.8 and 5.9) for each sub-basin (Fig. 5.5). The resulting curve have been considered to be the generalized regional graphical relationship between snow covered area and the subsequent snowmelt runoff. These relationship has been used to estimate the values of SSR at the beginning of computer run corresponding to SCA values obtained from satellite images (Table 5.13). The date of beginning of season has been taken depending upon the

TABLE-5.12 : ESTIMATED VALUES FOR SUBSEQUENT SNOWMELT RUNOFF (SSMR) OVER TEMPORARY AREA FOR EACH SUB-BASIN (mm)

Basin	Premnagar					Benswar	Kuriya Bridge	Sirshi-Bridge	Bursar	Kiyar-Nala
Dates	1975	1976	1977	1979	Average	Average	Average	Average	Average	Average
Feb.	1207.5	1101.3	1118.2	1485.9	1228.2	1860.9	1107.1	1204.0	796.8	1775.1
March	1206.5	1904.1	1097.0	1465.5	1215.8	1856.5	1100.6	1195.8	791.9	1770.6
April	1147.6	1030.2	1078.4	1376.9	1158.3	1828.4	1041.9	1157.6	746.4	1741.7
May	993.6	868.0	991.6	1277.5	1032.7	1690.6	853.4	1011.6	644.1	1633.6
June	662.3	622.4	754.2	934.5	753.4	1327.0	654.3	689.4	398.1	1337.2
July	311.8	232.2	341.8	456.8	335.6	668.2	240.0	300.0	165.3	617.1
Aug.	62.7	24.55	46.6	86.4	55.1	108.9	33.6	40.0	11.2	105.2
Sept.	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE-5.13 : ESTIMATING SEASONAL SNOWMELT RUNOFF (SSR)

Sub-basin/ Year	Date of Beginning of Season from	SCA %	From graph SSR(mm)	Initial Snowmelt Runoff(mm)
1. Premnagar				
1975	3rd March	84.54	1285	0.34
1976	2nd April	84.70	1290	7.14
1977	10th March	74.84	1180	1.05
1979	18th March	94.17	1400	6.76
2. Benswar				
1975	3rd March	94.49	1910	0.06
1976	2nd April	92.89	1870	1.53
1977	10th March	84.41	1840	1.53
3. Kuriya Bridge				
1975	3rd March	90.15	1200	0.40
1976	2nd April	87.33	1185	17.34
1977	10th March	79.19	1100	1.32
4. Sirshi-Bridge				
1975	3rd March	95.92	1295	0.31
1976	2nd April	95.59	1285	4.94
1977	10th March	90.53	1180	1.77
5. Bursar				
1975	3rd March	98.71	810	0.08
1976	1st March	100.00	820	0.54
1977	10th March	92.48	765	0.54
6. Kiyarnala				
1976	2nd April	93.58	1860	5.23
1977	10th March	88.17	1790	1.30

availability of satellite images. However, since melting season has been considered to commence from 1st March, the amount of snowmelt runoff (mm) from 1st March upto beginning of season has been separately estimated from available flow data and added to SSR to obtain corrected values of SSR.

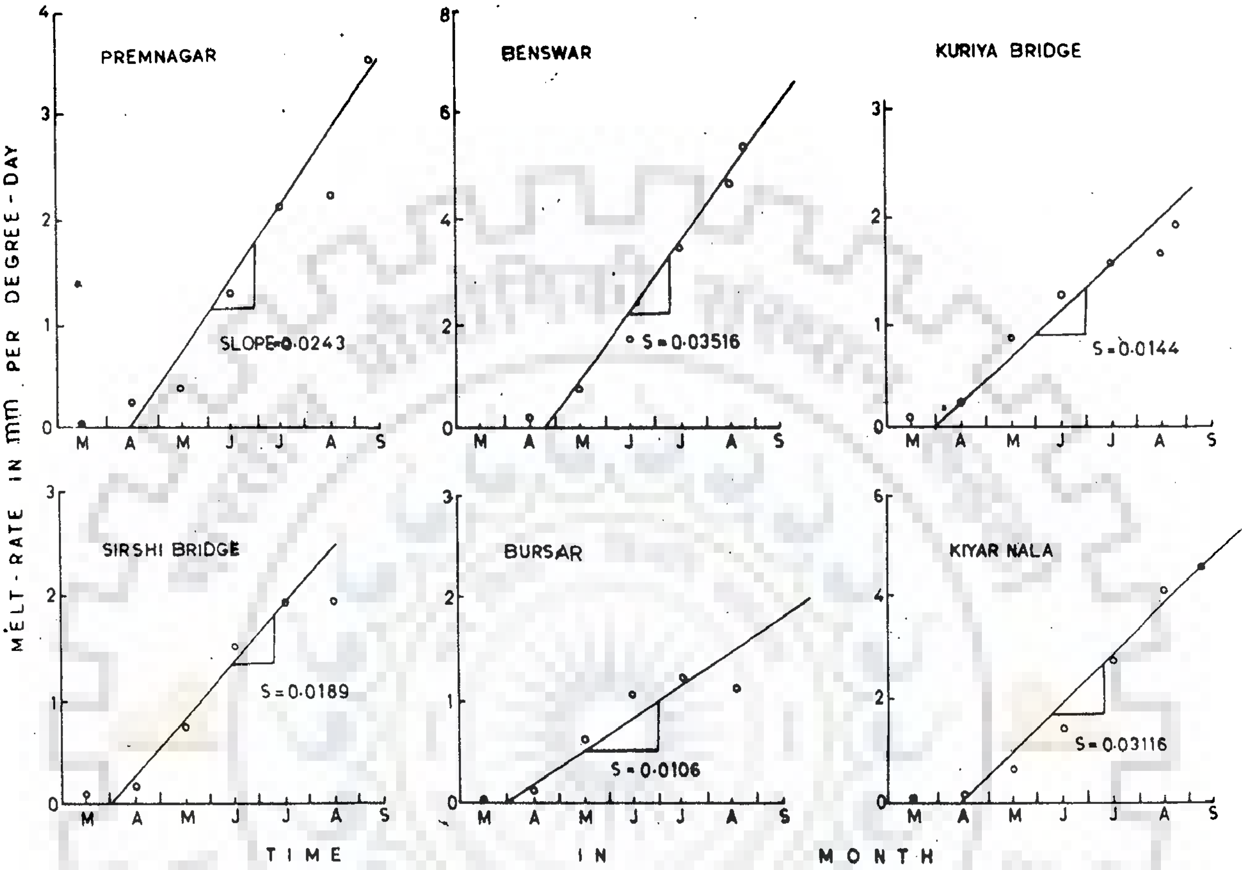
5.3.5.3 Melt Rate Variation:

The estimated values of monthly snowmelt in mm and corresponding sum of degree days for the month for the sub-basin, (Table-5.14), lapsed corresponding to the melting elevation were plotted against time (months) for the period from March - September (Fig. 5.6). The slope of the resulting line indicates the general increase of melt rate during the snowmelt season. The computed values of the rate of increase of melt rate for each sub-basin have been plotted against the weighted mean elevation for each sub-basin (Fig. 5.7). The graphical relation of rate of increase of melt rate plotted against the weighted mean elevation of each sub-basin is the indication of the variation of increase of melt rate for different sub-basins. This regional graphical relationship was used to determine the melt rate variation for each sub-basin of the Chenab catchment corresponding to the mean elevation of the sub-basin for use in model study (Table-5.15):

TABLE-5.14 : MONTHLY SNOWMELT RUNOFF (mm/Deg.Day) FOR MARCH TO SEPTEMBER FOR DIFFERENT SUB-BASINS

Basin	MELT-RATE IN (mm/Deg. Day)									
	Premnagar					Benswar	Kuriya-Bridge	Sirshi-Bridge	Bursar	Kiyar-Nala
Month	1975	1976	1977	1979	Average	Average	Average	Average	Average	Average
March	0.02	0.05	0.13	0.15	0.09	0.03	0.04	0.06	0.04	0.04
April	0.30	0.27	0.13	0.30	0.25	0.13	0.25	0.18	0.14	0.18
May	0.71	0.84	0.53	0.56	0.66	0.73	0.83	0.75	0.61	0.67
June	1.64	1.13	1.14	1.37	1.32	1.75	1.28	1.51	1.07	1.44
July	2.49	1.78	1.93	2.27	2.12	3.49	1.56	1.95	1.21	2.79
Aug.	2.30	1.61	2.29	2.76	2.24	4.66	1.65	1.94	1.11	4.06
Sept.	3.47	4.35	2.24	4.08	3.53	5.30	1.94	2.45	0.89	4.53

NOTE:- The average melt-rate given in above table has been plotted against the corresponding months. The slope of the straight line fitted by eye to the plotted points(Fig.5.6) is the representative of variation of melt-rate with respect to time, during the snowmelt season, in different sub-basins.



NOTE: SLOPE OF THE LINE, (S) IS THE MELTRATE VARIATION IN MM PER DEGREE DAY/DAY.

Fig. 5.6 Relationship Between Melt-rate and Time in Different Sub-basins

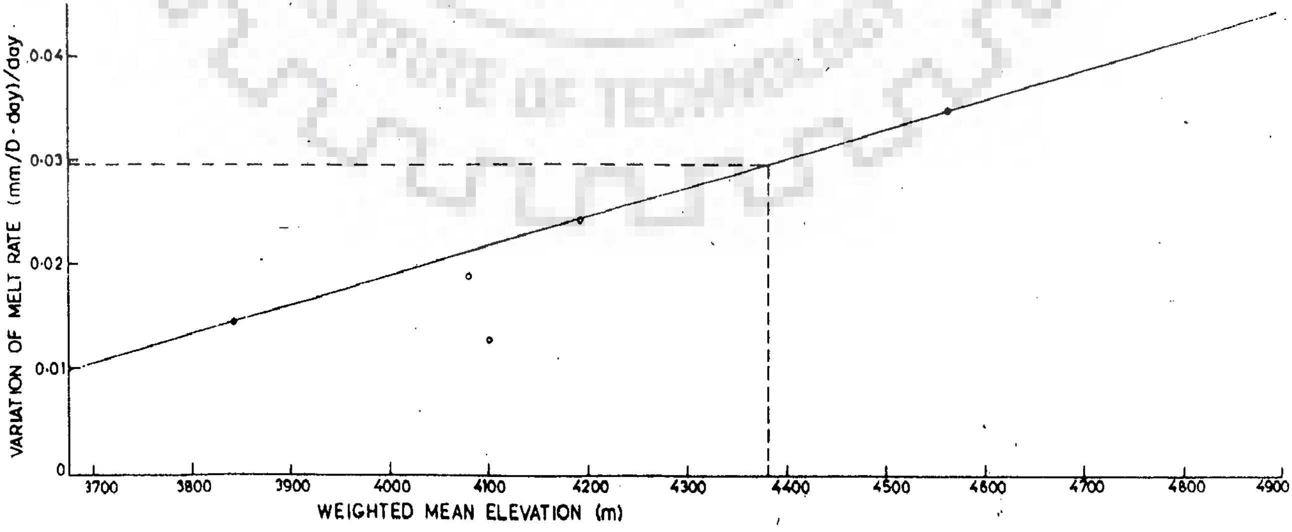


Fig. 5.7 Relationship Between Melt-rate Variation and the Weighted Mean Elevation

TABLE-5.15 : COMPUTED RATE OF VARIATION OF MELT RATE

Sub-basin	Rate of variation of melt rate for individual sub-basin (mm/deg. day/day)	Weighted mean elevation (m)	Computed rate of variation of melt rate from graph (mm/deg.day/day)
1. Premnagar	0.02430	4192.6	0.02430
2. Benswar	0.03516	4564.7	0.03516
3. Kuriya bridge	0.01440	3848.3	0.01440
4. Sirshi-bridge	0.01890	4076.2	0.02060
5. Bursar	0.01060	4105.6	0.02150

5.4 THE MODEL

As discussed earlier, after review of literature and analysis of available data of hydromorphological characteristics, satellite images, meteorological and hydrological parameters, it is seen that the rain and snowmelt runoff process in Himalayan catchments is highly complex. However, it is feasible to develop a watershed model for simulation of daily runoff for Himalayan basins during snowmelt season (premonsoon and monsoon months) from March to September.

The analysis of data of the Chenab basin has clearly indicated that there is a systematic pattern of relationship between extent of snow cover and resulting snowmelt runoff and suitable relationships have been developed for the same.

These studies have also indicated that for modelling of the runoff in Himalayan basins, it is necessary to divide the catchments into zones of permanent snow, temporary snow and snow free areas. In some studies mostly in Europe reported in literature, orographic effect has been considered for both temperature as well as precipitation gradients. However, a review of literature related to Himalayan basin and preliminary analysis of available data has indicated that, in the absence of relevant data of measurement of precipitation at higher elevations, it may not be worthwhile to consider orographic effects on precipitation. Moreover, any arbitrary assumptions of orographic effects on precipitation may lead to unnecessary errors in the estimation of parameters of the model. For modelling of daily runoff of the Chenab basin, orographic influences only on temperature have been considered and the change of temperature with elevation has been considered using the lapse rate of 6.5°C per 1000 meter change in elevation.

5.4.1 Simple Model Structure

The problem of developing a model structure could be tackled by two different approaches. One is to start from a complete general model representing all the complex processes and their intersections, and then to calibrate/test it for given/assumed catchment conditions. The other approach is to start from a simple model within the framework of known physical behaviour of the given catchment and add new components if their need becomes apparent after testing the performance. Keeping in view, the limitations of data, both with respect to availability and accuracy, for the region, a simple model structure has been considered appropriate for the Chenab basin.

The model structure has to consider and be based on the following:

i) Use of constant values of lapse rate, base temperature and rainfreeze temperature.

ii) Distribution of catchment into three types of zones viz. permanent snow covered, temporary snow covered and snow free.

iii) Use of information about extent of snow cover/snow line position as estimated from satellite images.

iv) Use of daily rainfall, daily temperature and daily direct runoff (total runoff-base flow) data.

v) Use of regional relationships as described in previous sections for

a) Parameter, 'n' (in the relationship between snow-cover area and snowmelt runoff) with parameter $A/S_c\sqrt{D_d}$.

b) Constant value of degree day factor of 0.38 mm/deg($^\circ$C) day on first March and linear variation (increase) of melt rate during melt season, with rate of variation of degree day factor being a function of weighted mean elevation for the basin

c) Total seasonal snowmelt runoff being the function of snow covered area(SCA) for the basin.

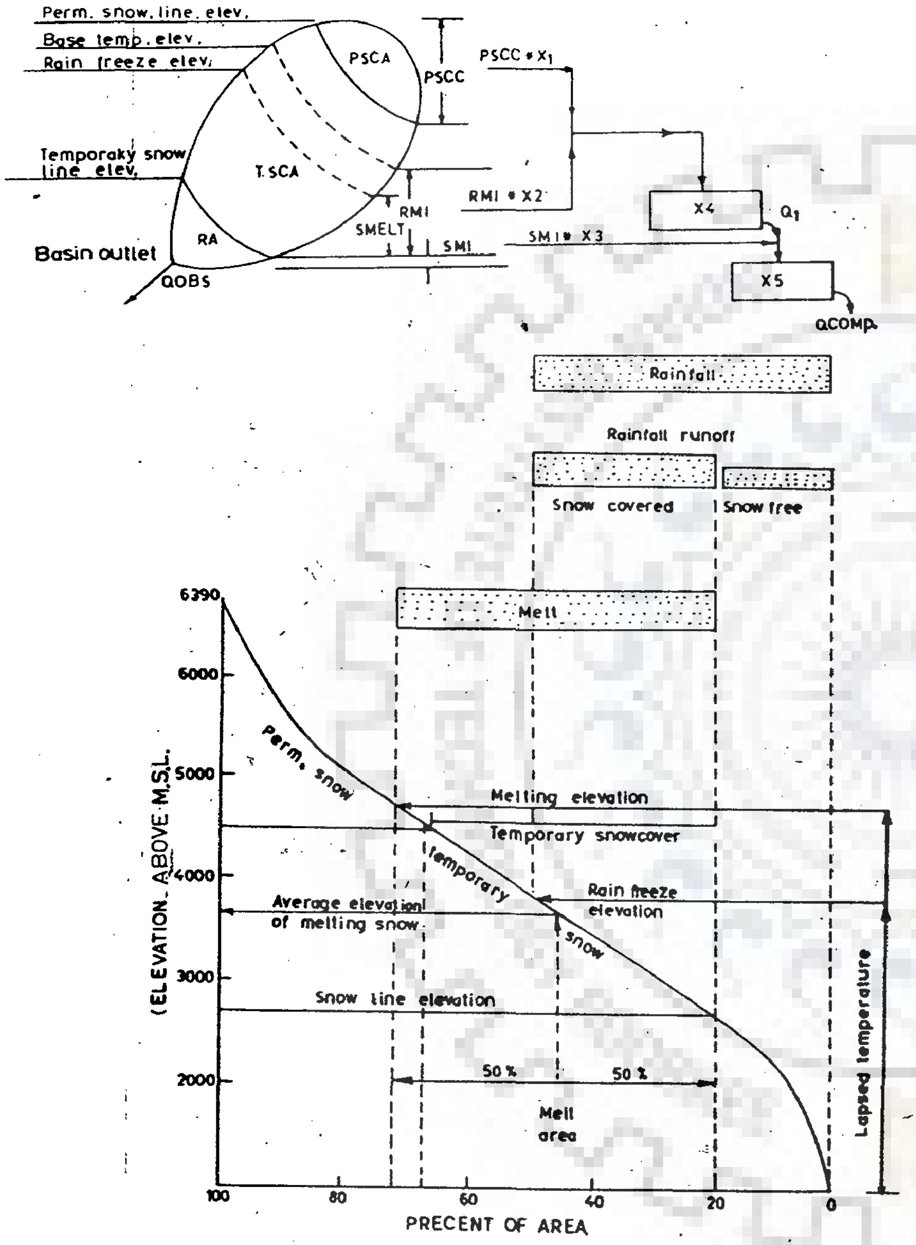
vi) Use of area-elevation and elevation-area relationships obtained from topographic maps and interpolation programme.

With the above requirements and assumptions suitably incorporated in the model, the model structure would be suitable for application not only in the Chenab basin, but also in other basins in the Himalayas.

5.4.2 Split Watershed Approach

The model has been developed using the limited data based on split watershed modelling approach, on the lines similar to those adopted in SSARR model of North Pacific Division of U.S.Army Corps of Engineers(1975). In this approach, the snow covered and snow free areas are treated as two separate watersheds, each with its own characteristics and parameters. The snow free area is the complement to snow covered area derived from the snow cover depletion function for computing snowmelt runoff. As shown in (Fig. 5.8), the catchment area using the split watershed in this study is divided into snow free, temporary snow covered and permanent snow covered areas, using the informations about snow line elevation. The snow covered area under temporary snow cover is further divided into melt area and non-melt areas using the data of temperature, elevation and value of base temperature assumed as $0^{o}C$. When the elevation corresponding to base temperature level is higher than permanent snow line elevation, the melt occurs from permanent snow cover.

The extent of area on which rainfall occurs as rain is



Split watershed Snowcover Depletion

Fig. 5·8 Diagram Expressing Runoff Model Working Procedure

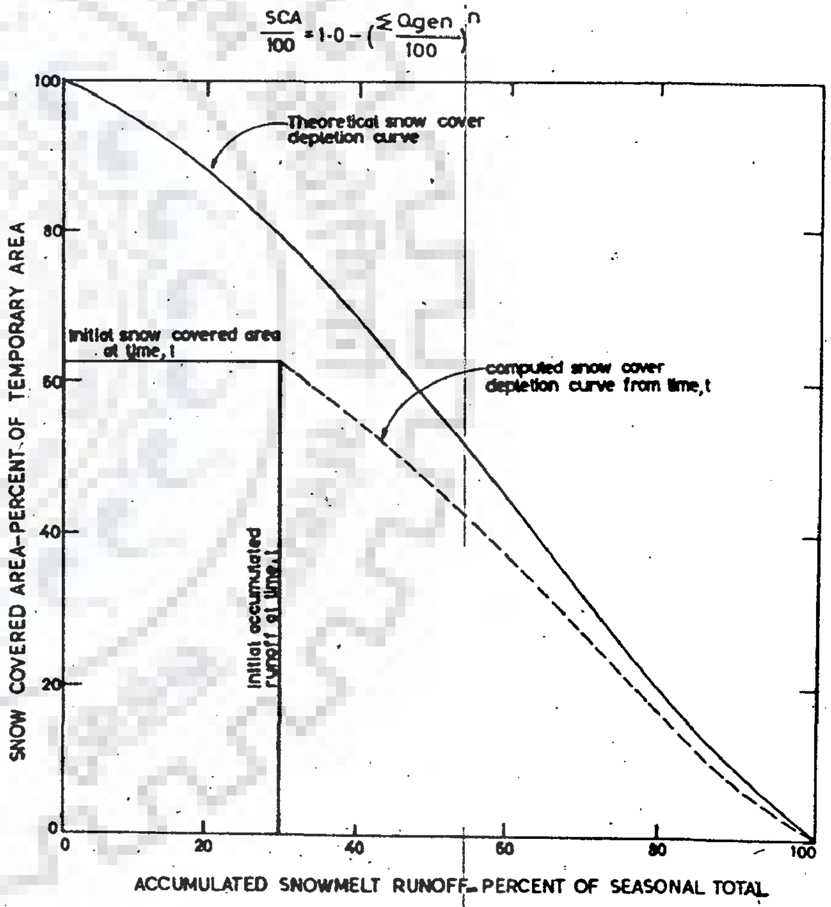


Fig. 5·9 Snowcover Depeletion Curve

identified by considering the rainfreeze temperature specified as a constant for watershed and taken as 0.56°C in this study. The melt of snow is computed using simple degree day approach. The losses are assumed to occur at different constant rates, using three coefficients X(1), X(2) and X(3) respectively, from the melt of permanent snow, from the melt of temporary snow and rain falling on snow and from rainfalling on snow-free area.

The excess water thus generated from permanent snowcovered and temporary snowcovered areas is combined together and is routed through a linear reservoir with storage constant X(4). The output of this linear reservoir is combined with excess **runoff** generated from snowfree area and is routed through another linear reservoir with storage constant X(5) to simulate total daily direct runoff at the catchment outlet.

The salient features of the model and the various relationships which have been used are given in subsequent sections.

5.4.3 Snowcover Depletion Process

The computation of daily snowmelt runoff in this model is based on variation of snowcover area of the basin which depletes during the snowmelt season depending upon the quantity of snowmelt runoff contribution due to the effect of temperature. Occasional observation of snowcover area is sufficient to estimate the quantity of the snowmelt contribution using snowcover depletion relationship.

Fig. 5.9 illustrates the snowcover depletion curve as given by the equation (5.1) as a typical example. To utilize the above relationship for the daily snowmelt runoff computation by the model, it is required to specify, the initial snowcovered area (SCA), temporary snowcover (CA), permanent snowcover (APSC), seasonal snowmelt runoff (SSR), and the initial accumulated runoff. The model program uses these specified values to compute the initial percent of accumulated generated runoff(ΣQ_{gen}) and consequently, it determines the ratio (RSC) of the actual initial snowcovered area to the theoretical snowcovered area. In the example shown in Fig. 5.9,RSC is approximately 61.2/80.0. The daily computed snowmelt increment converted to the mm of depth over the basin on the basis of that day's snowcover is added to the initial accumulated generated runoff in order to determine the next day's theoretical snowcover by applying the RSC value. The same process is continued upto the end of the computer run.

In hilly areas, such as the Chenab basin under study, the snowcovered and snowfree areas are easily distinguished by a snowline, which usually follows the contour elevation of the basin,the area above the snowline elevation is considered to be full of snow and below which is snowfree area. Runoff contribution is generated from snowcovered area due to snowmelt and rain, and snowfree area due to rainfall. Freshly fallen snow during the computation period is not incorporated automatically in the program, since it is not that significant for the area under study. In case there is any significant snowmelt during the snowmelt season, it can be incorporated suitably in the model by modifying the value of accumulated generated runoff.

5.4.4 Model Relationships and Steps

The steps followed in the model are given in the flowchart (Appendix : V - 3).

The model program reads the daily temperature (TEMPA(I)) and the elevation of the temperature station (AVELEV), the daily precipitation, (PRCP (I), and the specified values for the Lapse rate, (ALR), rainfreeze temperature (RTF) base temperature (BTEMP): initial (FA) and final (FB) values of the meltrate,seasonal snowmelt runoff (SSR); initial snowcovered area (SCA)· temporary snowcovered area (CA); permanent snowcovered area (APSC) and the area-elevation curve.

The precipitation on each day is assumed to fall in the form of snow on the areas located above the rainfreeze temperature elevation and as rainfall below that elevation. The rainfreeze temperature elevation is the elevation where temperature is equal to rainfreeze temperature of 0.56^{o}C.

Snowmelt is assumed to occur from the area between the snowline elevation and the base temperature elevation (BTEMPE). The base temperature elevation is the elevation, where the temperature becomes equal to base temperature adopted as $0.^{\circ}C$ in this study.

Average daily temperature for each day is lapsed at the rate of $6.5^{\circ}C$ per 1000 m increase of elevation from the Banihal station (Elev. = 1630 m above, m. s.l.) to determine the rainfreeze and base temperature elevations (Fig. 5.8).

The quantity of runoff contribution from the above three zones is computed by the program as follows :

a) Contribution from the Snowfree area (SMI):

The program determines the percentage of snowfree area and applies it to the average rainfall depth by the following relationship

$$SMI = (\%RA)\ (PRCP) \qquad ..(5.2)$$

b) Contribution from Temporary Snow melt area (RMI):

i) Snowmelt (SMELT) due to temperature; The percent of the snowmelt area (MA) located between snowline and the base temperature elevation applies to the total degree day at the medium elevation(AMETE) of the melt area and the melt-rate of the same day: The medium elevation of the melt area can be determined from the area-elevation curve against the (AMET) area ;where

$$AMET = \%\ RA + MA/2 \qquad ..(5.3)$$

The total degree-day (TAMETE) at the median elevation is computed by:

$$\text{TAMETE} = \text{TEMPA(I)} - (\text{AMETE} - \text{AVELV}) * \text{ALR} \qquad ..(5.4)$$

So $$\text{SMELT} = \%\ \text{MA} * \text{TAMET} * \text{MR} \qquad ..(5.5)$$

ii) Snowmelt (RMELT) due to the effect of rainfall:

The percentage of the area between snowline and the rainfreeze temperature elevation (ABRFE) is applied to the precipitation depth of the same day. The rainfreeze elevation is computed by the following equation

$$\text{RFE} = \text{AVELV} + (\text{TEMPA(I)} - \text{RTF})/\text{ALR} \qquad ..(5.6)$$

The area corresponding to the rainfreeze elevation (RFE) is computed from the area elevation curve.

For the (RMELT) computation

$$\text{RMELT} = \%\ (\text{ABRFE-RA})\ (\text{PRCP}) \qquad ..(5.7)$$

The snowmelt, $$\text{RMI} = \text{SMELT} + \text{RMELT} \qquad ..(5.8)$$

c) Contribution from Permanent Snowcovered Area (PSCC)

In some days during the computation period when the daily average temperature increases, the base temperature elevation may rise above the permanent snowline elevation. Under such a condition there is some snowmelt contribution from the permanent snowcovered area. The quantity of this contribution depends upon the total degree - day (TAMET) affecting on the median elevation of the area between permanent snowline and the base temperature elevation, the percent of the melting area (APS) with respect to the total permanent snowcovered area, and the value of the melt-rate (MR) of the same day.

$$PSCC = (\%APS)\ (TAMET)\ (MR) \qquad ..(5.9)$$

d) Routing of Runoff Contributions :

As stated earlier and shown in flow diagram, the snowmelt contribution from permanent snow covered area is multiplied by coefficient X(1) to obtain excess water from this area. The snowmelt contribution as well as rain on temporary snowcovered area is multiplied by X(2) to obtain excess water from this area. For snowfree area coefficient X(3) is used to obtain excess water from total rain on the area, as below :

Runoff from perm . snowcovered area,

$$RPS = X(1) * PSCC \qquad ..(5.10)$$

Runoff from temp.snowcovered area ,

$$RCS = X(2) * RMI \qquad ..(5.11)$$

Runoff from snowfree area,

$$RCR = X(3) * SMI \qquad ..(5.12)$$

The routing equations for Ist and 2nd linear reservoirs having storage coefficients X(4) and X(5) respectively are as follows in general form .

$$(ARCS)_{n,n-1} = (RPS)_{n,n-1} + (RCS)_{n,n-1} \qquad ..(5.13)$$

$$Q_n = C_A (ARCS)_{n,n-1} + C_B\, Q_{n-1} \qquad ..(5.14)$$

$$C_A = \frac{\Delta t}{X(4)+0.5\Delta t}, \quad C_B = \frac{X(4)-0.5(\Delta t)}{X(4)+0.5(\Delta t)} \qquad ..(5.15)$$

$$(BRCS)_{n,n-1} = (RCR)_{n,n-1} + Q_n \qquad ..(5.16)$$

$$Q_{F(n)} = D_A (BRCS)_{n,n-1} + D_B Q_{F(n-1)} \qquad ..(5.17)$$

$$D_A = \frac{\Delta t}{X(5)+0.5\,\Delta t} \;, \quad D_B = \frac{X(5)-0.5\,\Delta t}{X(5)+0.5\,\Delta t} \qquad ...(5.1\;\;)$$

where $(ARCS)_{n,n-1}$ is excess water from permanent and temporary snowcover during unit time interval $\Delta t = 1$ day between $(n-1)^{th}$ and n^{th} intervals,

C_A and C_B are routing coefficients for first linear reservoir

D_A and D_B are routing coefficients for second linear. reservoir

Q_n is outflow from 1st linear reservoir

$Q_{F(n)}$ is outflow from 2nd linear reservoir, which is also the computed value of direct runoff using the model i.e. Q_{comp}.

The excess water from permanent snowcovered area and temporary snowcovered area for the computation time interval (one day in this case) is routed through Ist reservoir with storage coefficient X(4). The output from this reservoir, combined with contribution from snowfree area is routed through second linear reservoir with storage coefficient X(5). The output of second linear reservoir gives estimated/computed value of daily direct runoff for given trial values of perameters X(1), X(2), X(3), X(4) and X(5).

5.5. OPTIMISATION

As described above these are five parameters X(1), X(2) , X(3), X(4) and X(5) which are to be optimised for each sub-basin using available data for the snowmelt season (March - September) for the year. To estimate these parameters for calibrating the model and also to test the relative performance and adequacy of the model structure, the following procedure has been adopted. Basically it involves fitting of the model to observed and estimated data using snow covered area, daily rainfall and daily temperature as input data and calculating the daily direct runoff as output. The five parameters listed above are evaluated by the optimisation technique, so that the observed and calculated values of daily direct runoff agree for the period of record used in calibration and compare satisfactorily.

5.5.1 Rosenbrock Technique :

The Rosenbrock technique of optimisation has been adopted. This technique gives after an initial exploration, an acceleration in both the direction and distance of movement in the multivariable numerical approach of optimisation. The main features of the technique is to align one of the search direction in the most favourable direction of search based upon the information gained from previous exploration. Other directions of search are selected to be orthogonal to the first direction and at the same time oriented in a favourable direction.

Every improvement in the objective function is counted as a success and then a move in that direction in the next search is made at accelerated rate, by increasing the step size to three times the distance last moved. When the objective function deteriorates in a particular direction, then the search is a failure and in the next cycle when this particular direction is searched, the step size is reduced to half its previous length and the movement is made in opposite direction.

Rosenbrock technique has the provision for putting constraints i.e. lower and upper limits on the parameter values, so that after calibration, the parameter values obtained lie within the realistic limits.

5.5.2 Objective Criterion for Optimisation Technique :

The objective function, F for the evaluation of parameters for optimisation adopted for these study is the minimization of the sums of squares of the differences between the observed and computed values of daily runoff. The objective function, F is given by the following expression :

$$F = \sum_{i=1}^{N} \sqrt{[Q_{obs}(I) - Q_{comp}(I)]^2} \quad \ldots(5.18)$$

where

Q_{obs} = daily observed flow (mm), direct runoff in this study.

Q_{comp} = daily computed flow (mm), direct funoff in this study.

5.5.3 Performance Criterion

While the objective function described above was used for calibration optimisation runs, the following performance criterian were used to judge the performance of the calibrated model. These are :

1. STD.ERROR in (cumec days) $= \sqrt{\dfrac{\sum_{i=1}^{N} (DSRO(I)-QEST(I))^2}{N}}$ ..(5.19)

where DSRO(I) is the daily observed direct runoff Q_{EST} is the computed values of daily flow, N is the number of days used for the computer run

2. EFFICIENCY in (%) $= \dfrac{F_o - F_1}{F_o} \times 100$ ..(5.20)

$$\text{where } F_o = \sum_{i=1}^{N} (DSRO(I) - DMEAN)^2$$

$$F_1 = \sum_{i=1}^{N} (DSRO(I) - Q_{EST}(I))^2$$

$$D_{MEAN} = \frac{1}{N} \sum_{i=1}^{N} DSRO(I)$$

3. AVERAGE ABSOLUTE ERROR (Cumec-days)

$$= \sum_{i=1}^{N} \frac{|DSRO(I) - QEST(I)|}{N} \quad ..(5.21)$$

4. PERCENTAGE AVERAGE ABSOLUTE ERROR

$$= \frac{1}{N} \sum_{i=1}^{N} \frac{|DSRO(I) - QEST(I)|}{N} \times 100 \quad ..(5.22)$$

5. Comparison of computed snow line elevation with observed snowline elevation on specific dates as obtained from Satellite images.

6. Comparison of computed and observed monthly flows and total seasonal flows.

To judge the performance of the model, the above mentioned parameters have also been used, so that while least squares objective function is minimum, the snowline position and monthly flows are also simulated well and the efficiency of the model is satisfactory.

5.5.4 Computer Program

Computer program was developed for the model to read the information as mentioned in the previous sections and do the required computations, incorporating standard Rosenbrock (1960) search routine for optimisation of five parameters, and various functions to be evaluated. The program was run on DEC-2050 system of Roorkee University (RURCC) Regional Computer Centre. Details of the various parameters used for performance criterion are given in the previous section. The limits and step-size for parameters of losses and values of parameters used for limiting the time required for computer runs are listed in (Table- 5.16).

TABLE 5.16 : MODEL PARAMETERS :

a) Constant Parameters

1. ALR, Lapse rate = 0.0065 °C/m
2. BTEMP, Base temperature = 0.0 °C
3. RTF, Rainfreeze temperature = 0.56 °C

b) Fixed in Each Sub-basin

1. TCA, Total drainage area (km^2)
2. APSC, Permanent snow covered area (km^2)
3. CA, Temporary snow covered area (km^2)
4. n, Basin characteristic (Refer Section 5.3.5.1)
5. MR, the rate of change of melt (D.day/day) (Refer Sec. 5.3.5. 3)

c) Fixed for Each Basin for Each Year

1. SSR, Seasonal snowmelt runoff (mm) (Refer Sec. 5.3.5.2)
2. SCA, initial snowcovered area (km^2)
3. ARUN, initial accumulated runoff (mm)
4. TEMPA, Average daily temperature (°C)
5. DSRO, Direct surface runoff (m^3/sec)
6. RAIN, Daily average rainfall (mm)
7. BFLO, Base flow (m^3/sec.)

d) Parameters to be optimised for Each Basin for Each Year

1. X(1) Runoff coefficient for permanent snowcovered area
2. X(2) Runoff coefficient for temporary snowcovered area

3. X)3) ,Runoff coefficient for snow-free area
4. X(4) ,Storage coefficient for first linear reservoir
5. X(5) ,Storage coefficient for second linear reservoir.

e) Variables Used as Performance Criterion.

1. Objective function (mm^2)
2. Snowline elevation (m)
3. Monthly flows (cumecs)
4. Total seasonal
5. Efficiency (%)
6. Standard error (cumecs-day)
7. Percentage absolute error(%)

f) Initial Parameter Values for Optimisation

I. Parameters for Rosenbrock Technique

II.

Parameter	Limit	Initial values	Step size (EPS)
1, X_1	0.8 to 1.0	0.8 dimension	0.010
2, X_2	0.8 to 1.0	0.8 -do-	0.010
3, X_3	0.2 to 1.0	0.2 -do-	0.010
4, X_4	0.0 to -	0.10 day	0.010
5, X_5	0.0 to -	0.01 day	0.001

III. Limits and Stopping Criteria

a: Limits

1, MAXK = 1000

2, MKAT = 30

3, MCYC = 50

4, EPSY = 0.00001

where,

MAXK is maximum value or limit for function evaluations.

MKAT is maximum value or limit for No.of stages.

MCYC is maximum number of cycles in a stage.

EPSY is minimum difference between present and immediate previous value of objective.

b) The Program Steps:

i) If number of function evaluations exceeds MAXK

ii) if number of stages exceeds MKAT

iii) if difference between present and immediate previous value of objective function is less than EPSY.

5.6 PRESENTATION AND DISCUSSION OF RESULTS

5.6.1 Introduction

The snowmelt runoff model described in earlier sections was used with data of different sub-basins in the Chenab basin for calibration and testing studies. In order to get an idea of effectiveness of the optimisation technique in evaluating the five model parameters, sensitivity run was made using data of Sirshi bridge for 1976. This involves use of the given data for obtaining the parameter values through a calibration run, and then using the computed runoff values as a typical set of error free data for a repeat calibration run. The efficacy of optimisation techniques was judged by the number of function evaluations required, and the parameter values obtained in comparison to the parameter values used for computing the synthetic data set.

The sub-basins for which data has been used in the study include Premnagar, Benswar, Sirshi Bridge, Kuriya Bridge and Kiyar Nala sub-basins. For the Premnagar sub-basin, the studies involved calibration runs for each of the 1975, 1976 and 1977 seasons using appropriate information regarding position of snowline and total estimated seasonal snowmelt at the beginning of the season. For calibration with data of a particular season and sub-basin, many trial runs were made using different trial values of 'n' parameter and initial melt rate. While selecting these trial values for parameter 'n', the general form of graphical relationship between parameter 'n' and Hickok et al parameter $(A/S_c\sqrt{D_d})$ was maintained. As discussed in previous section 5.3.5.1 initial trial values of 'n' for the five sub-basins were taken as follows:

(i) Premnagar - 0.67, (ii) Benswar - 0.72, (iii) Bursar - 0.91, (iv) Sirshi Bridge - 0.89, and (v) Kuriya Bridge - 0.85. For alternative trial values of initial melt rate for 1st March also, different values between 0.2 to 0.6 were used, but the general pattern of rate of variation of melt rate as given by its graphical relationship with weighted mean elevation was maintained for the sub-basin. The performance of these calibration runs was judged on the basis of objective function, efficiency, error parameters, reproduction of monthly flows, and reproduction of snow line position. On the basis of optimised parameter values obtained after calibration runs, average parameters were computed and prediction runs were made for each of the

3 seasons in order to judge performance of the model with average parameters for the sub-basin. Using the average parameters for the sub-basin test run was also made for the Premnagar sub-basin using independent data of 1979 season, for judging the applicability of model and the average parameter values.

The calibration runs and runs with average parameters on similar lines were also made using data of 1975, 1976 and 1977 for 4 sub-basins viz. Benswar, Bursar, Sirshi Bridge, Kuriya Bridge. These runs were made to judge the applicability of the model structure for different sub-basins and suitability of average parameters for respective sub-basins of the Chenab basin.

Using the average values of 5 parameters X(1), X(2), X(3), X(4) and X(5) for the 5 sub-basins mentioned above, regional pattern was studied and overall parameters were computed by taking arithmetic average in the case of parameters X(1), X(2) and X(3) and relating the parameters X(4) and X(5) to catchment characteristics.

The overall regional pattern thus evolved was tested using independent data of KiyarNala sub-basin for 1976 and 1977 seasons, for testing the applicability and judging the performance of regional overall parameters to any sub-basin in the Chenab basin.

5.6.2 Calibration and Sensitivity Runs Using Data of Sirshi Bridge for 1976 Season

The efficacy of optimisation technique in evaluating five parameters of the snowmelt model was judged by using synthetic runoff values as a typical error free data set for 1976 season at Sirshi Bridge. Using given data of daily rainfall, runoff, temperature etc. the calibration run was made to obtain the parameter values for five parameters X(1), X(2), X(3), X(4) and X(5). These values were then used in simulation model to obtain computed runoff values, which were taken as synthetic error free data set for sensitivity run.

As could be seen from results given in Table 5.17, only 376 function evaluations were made to achieve a near zero objective function value of 0.0979 and an efficiency of 99.99% . The corresponding values for error parameters and monthly and total seasonal values of computed runoff also show that the optimisation technique was able to achieve almost a complete reproduction. The parameter values obtained in sensitivity run are also nearly same as those used for computing synthetic data set. The computer program was then used for calibration and test runs using data of different sub_basins as discussed in subsequent sections.

TABLE-5.17 : SENSITIVITY TEST OF THE MODEL WITH CALIBRATED OUTPUT OF SIRSHI-BRIDGE (1976)

Items	Calibrated Run	Sensitivity Run
Parameters		
X_1	0.93039667	0.92181759
X_2	0.84955948	0.85172325
X_3	0.55311794	0.55194667
X_4	4.80930590	4.82995440
X_5	4.48988660	4.54038180
Judging Criteria		
Total No. of stages	10	20
Total No. of function evaluation	1000	376
Objective function (mm^2)	266.1361	0.0979
Standard error(cumec-day)	53.603	1.018
Efficiency (%)	87.25	99.99
AU. Abs.error(cumec-days)	38.905	0.374
Abs. error (%)	31.87	0.21
Flows (Cumec-days)		
From 2nd April (Part)	1474.11	1470.80
May	5980.53	5981.91
June	10272.75	10282.32
July	13214.95	13204.28
August	9438.66	9441.09
To 11th September(Part)	2250.95	2249.31
Total	42631.96	42629.71

5.6.3(a) Calibration Runs Using Data of Premnagar for 1975, 1976 and 1977 Seasons

Separate calibration runs involving number of trial runs were made for Premnagar sub-basin using data for 1975, 1976 and 1977 seasons for 193, 163 and 186 days respectively. The results of final calibration runs are summarised in Tables 5.18 to 5.20. It is seen that parameter values for X(1), X(2) and X(3) are nearly of the same order, while those for X(4) and X(5) differ in the three runs. The overall reproduction of daily flows is satisfactory as indicated by efficiency values of 80.8% to 86.10%, however, time distribution of computed daily values does not exactly match the observed values as shown in Fig. 5.10 and also reflected by values of error function. But keeping in view data limitations and simplicity of model, this performance is quite encouraging. Total seasonal flows are reproduced well, though monthly flows for March, April, May, and June (Premonsoon months) are somewhat over estimated, while those monsoon months of June, July, August, September are somewhat under estimated.

Inspite of some difference in parameter values for individual years, on average they are similar and their arithmetic averages were taken for use in simulation runs for Premnagar sub-basin, as indicated in the subsequent section.

5.6.3(b) Prediction Runs Using Average Parameters for 1975, 1976 and 1977 Seasons

Using average values of parameters X(1), X(2), X(3),

TABLE-5.18 : COMPUTED PARAMETERS FOR THE SUB-BASINS FOR CALIBRATION RUN AND SIMULATION RUNS

Sub-Basins	Years	P A R A M E T E R S				
		X_1	X_2	X_3	X_4(days)	X_5(days)
Premnagar	1975	0.8840	0.8777	0.6478	0.9088	2.4079
	1976	0.9447	0.9024	0.5301	4.9987	3.7147
	1977	0.8980	0.8879	0.5808	4.0318	1.1796
Average parameters		0.9089	0.8893	0.5862	3.3131	2.4341
Overall parameters		0.9100	0.8915	0.4965	5.7000	2.3000
Benswar	1975	0.9096	0.8783	0.5099	2.0104	1.1898
	1976	0.9035	0.8700	0.3328	8.0012	2.0663
	1977	0.8998	0.9108	0.5524	7.8661	2.0474
Average parameters		0.9043	0.8864	0.4650	5.9592	1.7479
Overall parameters		0.9100	0.8915	0.4965	5.4400	2.2600
Kuriya-Bridge	1975	0.9813	0.8900	0.3726	1.5931	1.2398
	1976	0.9152	0.9038	0.7046	3.8517	0.8054
	1977	0.8983	0.8863	0.6073	4.0155	0.9929
Average parameters		0.9316	0.8934	0.5615	3.1534	1.0127
Overall parameters		0.9100	0.8915	0.4965	4.4000	1.8000
Sirshi-Bridge	1975	0.8721	0.8750	0.6389	1.3781	2.098
	1976	0.9257	0.8826	0.5320	2.2914	3.6247
	1977	0.9035	0.8700	0.3328	8.0169	2.0107
Average parameters		0.9003	0.8759	0.5012	3.8955	2.5779
Overall parameters		0.9100	0.8915	0.4965	4.1000	1.7000

Table-5.18 : Contd.

Sub-Basins	Years	PARAMETERS				
		X_1	X_2	X_3	X_4(days)	X_5(days)
Bursar	1975	0.9115	0.8935	0.3640	7.9073	3.0194
	1976	0.9071	0.9140	0.4756	8.0128	2.2326
	1977	0.8965	0.9300	0.2664	4.0887	1.0209
Average parameters		0.9050	0.9125	0.3686	6.6696	2.0910
Overall parameters		0.9100	0.8915	0.4965	3.9000	1.6000

TABLE-5.19 : JUDGING CRITERIA FOR CALIBRATION RUNS AND SIMULATION RUNS USING AVERAGE AND OVERALL PARAMETERS

Items Sub-basins	Years	Parameters used	Objective function sq.mm	Efficiency (%)	Error Functions (Cumec-days)		
					Standard error	Av.Absolut. error	Absolut. error(%)
1	2	3	4	5	6	7	8
Premnagar	1975	Calibration	438.70	80.81	316.89	224.42	77.71
		Average	-	79.57	327.00	236.97	72.15
		Overall	-	78.63	334.38	235.57	62.87
	1976	Calibration	187.66	80.84	227.44	170.51	21.11
		Average	-	74.12	264.32	211.99	25.93
		Overall	-	77.00	249.18	190.18	22.21
	1977	Calibration	189.83	86.10	246.17	193.69	56.22
		Average	-	86.87	239.29	189.08	56.05
		Overall	-	86.43	243.23	184.67	50.09
Benswar	1975	Calibration	974.46	74.82	290.27	202.25	132.72
		Average	-	77.42	274.92	184.90	113.41
		Overall	-	77.48	274.59	184.54	135.38
	1976	Calibration	323.39	82.97	227.77	164.57	40.92
		Average	-	80.85	241.53	186.53	50.30
		Overall	-	81.71	236.03	180.82	47.19
	1977	Calibration	486.39	85.64	241.64	193.15	93.82
		Average	-	85.51	243.62	198.99	94.11
		Overall	-	85.80	240.62	197.61	95.71

TABLE-5.19 : Contd.

1	2	3	4	5	6	7	8
Bursar	1975	Calibration	765.99	66.72	67.42	45.34	62.08
		Average	-	68.71	65.38	46.14	73.04
		Overall	-	67.31	66.83	48.26	89.42
	1976	Calibration	66.84	88.58	30.28	21.05	-
		Average	-	89.07	29.62	21.06	-
		Overall	-	85.84	33.72	24.84	
	1977	Calibration	266.24	61.49	51.93	38.90	92.42
		Average	-	60.98	52.27	40.03	48.94
		Overall	-	57.19	54.75	41.54	95.41
Sirshi-Bridge	1975	Calibration	766.63	78.24	85.16	61.05	83.57
		Average	-	77.87	85.89	61.56	62.97
		Overall	-	78.06	85.52	61.37	68.70
	1976	Calibration	306.07	85.39	57.37	46.42	33.08
		Average	-	84.76	58.61	47.64	31.86
		Overall	-	83.22	61.49	50.18	35.26
	1977	Calibration	415.21	83.22	62.93	47.33	54.74
		Average	-	82.77	63.76	47.81	63.63
		Overall	-	81.19	66.62	50.15	66.51
Kuriya-Bridge	1975	Calibration	836.91	73.02	117.19	87.96	58.71
		Average	-	65.20	133.91	95.26	66.39
		Overall	-	70.87	122.52	90.54	58.90
	1976	Calibration	177.08	77.61	87.83	68.40	25.95
		Average	-	80.08	82.85	63.35	23.64
		Overall	-	79.23	84.59	67.29	24.71
	1977	Calibration	335.90	74.93	96.68	70.23	52.94
		Average	-	75.52	95.54	68.66	52.82
		Overall	-	77.74	91.10	69.61	48.99

TABLE-5.20 : MONTHLY OBSERVED AND COMPUTED RUNOFF (Cumec-days) FOR CALIBRATION AND SIMULATION RUNS (USING AVERAGE AND OVERALL PARAMETERS)

Sub-basins Date Month Year	PREMNAGAR				BENSWAR			
	Drainage area (17622-46 km^2		Perm.snow area (7059.44 km^2)		Drainage area (11162.19 km^2)		Perm. snow area (5787.58 km^2)	
	Obs.	Calib.	Simulation using		Obs.	Calib.	Simulation using	
			Average Parameters	Overall Parameters			average Parameters	Overall Parameters
1	2	3	4	5	6	7	8	9
1975								
March(3rd)	2362	5968	5068	4401	538	1932	1590	1865
April	8742	14551	13027	11748	2587	7988	6578	6615
May	20872	26177	25742	24825	11912	17170	16036	16222
June	41478	35421	35054	34008	27150	27460	25700	25922
July	52602	48222	48294	47158	40303	32985	33776	34284
August	51052	44172	44874	43990	37170	29427	30565	30885
Sept.(11th)	10834	9119	9058	9112	8339	5718	61100	6226
TOTAL	187942	183630	181187	175243	127999	122730	120343	122020
1976								
April(2nd)	8545	8702	10765	9347	2909	4029	4720	4430
May	21877	26325	27616	26364	11459	16288	17533	17193
June	32068	38669	38043	37763	21782	27565	28144	28146
July	51622	51612	52663	51328	44466	40253	41474	42068
August	40893	37171	34811	35002	-	-	-	-
Sept.(11th)	10179	9301	9398	9176	-	-	-	-
TOTAL	165184	171780	173297	168980	80616	88135	91821	91836

Table-5.20 : Contd.

1	2	3	4	5	6	7	8	9
1977	PREMNAGAR				BENSWAR			
March(10^{th})	1788	3146	2990	2545	655	1167	1252	1256
April	5156	11737	11570	10845	1691	7165	7039	7148
May	13204	16623	16622	15223	5317	9364	9498	9585
June	31431	34161	33813	32008	22708	23213	23892	24022
July	53585	48454	48929	48710	48130	40862	40292	40713
August	40523	33497	33926	34676	37524	30786	29207	29428
Sept.(11^{th})	10610	10550	10146	10056	8335	8777	8313	8345
TOTAL	156297	158268	157998	154063	124360	121333	119494	120496
1975	BURSAR*				SIRSHI-BRIDGE**			
March(3^{rd})	187	278	316	371	396	766	642	665
April	796	1826	2094	2455	1604	3440	2859	2990
May	3023	4555	4831	4899	5357	6626	6478	6469
June	7478	6142	6609	6725	12624	9443	9133	9140
July	7438	6476	6771	6799	12494	11854	11593	11628
August	6574	5960	6353	6702	12073	10413	10327	10404
Sept.(11^{th})	1552	1444	1430	1474	2404	2353	2282	2238
TOTAL	27048	26681	28405	29425	46952	44895	43314	43534
1976								
March	96	191	207	253	-	-	-	-
April	1066	1729	1854	2147	1364	2087	1998	2124
May	4228	5030	5134	5347	5423	6653	6509	6731
June	6268	6870	6752	6649	9273	9901	9779	9959
July	-	-	-	-	13393	12815	12614	12821
August	-	-	-	-	10457	8526	8417	8362
Sept. (11^{th})	-	-	-	-	2730	2102	2114	2112
TOTAL	11658	13821	13948	14397	42640	42082	41431	42109

*Drainage Area = 2896.34 km^2
perm.snow area= 829.78 km^2

**

**Drainage Area = 3588.12 km^2
perm.snow area = 1053.00 km^2

Table-5.20 : Contd.

1	2	3	4	5	6	7	8	9
	BURSAR				SHRSHI-BRIDGE			
1977								
March(10th)	196	491	358	467	407	433	570	619
April	762	2517	2390	2530	1150	2901	3237	3323
May	2270	3563	3208	3480	3383	3821	4222	4369
June	5078	6855	6531	6729	7261	8131	8873	9152
July	6563	7444	7684	7567	12749	11973	12220	12334
August	3957	4163	4621	4439	8005	8407	8159	8186
Sept. (11th)	977	1216	1321	1436	2147	2397	2451	2532
TOTAL	19803	26248	26113	26648	35102	38045	39732	40515

TABLE-5.20 : MONTHLY OBSERVED AND COMPUTED RUNOFF (Cumec-Days) FOR CALIBRATION AND SIMULATION RUNS (USING AVERAGE AND OVERALL PARAMETERS)

Sub-basins Date Month, Year	KURIYA BRIDGE Drainage Area (4812.42 km^2) Obs.	 Calib.	Permanent Snow Area (1160.31 km^2) Simulation Using Average Parameters	 Overall Parameters
1975				
March(3rd)	679	1577	1746	1571
April	3066	5232	5040	4453
May	8496	8596	8851	8775
June	15165	11132	11117	10856
July	16511	15081	14240	15816
August	15934	14398	16238	15652
September	3383	2771	3097	3245
TOTAL	63234	58787	62329	60368
1976				
April (2nd)	3162	2583	2636	2290
May	9037	8078	8223	7775
June	13266	11868	11859	11664
July	16539	15204	15055	14802
August	-	-	-	-
September(11th)	-	-	-	-
TOTAL	42004	37733	37774	36531
1977				
March(10th)	614	971	1020	852
April	2277	5438	5472	5112
May	5453	5702	5791	5497
June	11350	10510	10725	10229
July	16197	13859	13905	13921
August	11028	9767	9726	9827
September(11th)	2904	3462	3431	3213
TOTAL	49823	49709	50070	48651

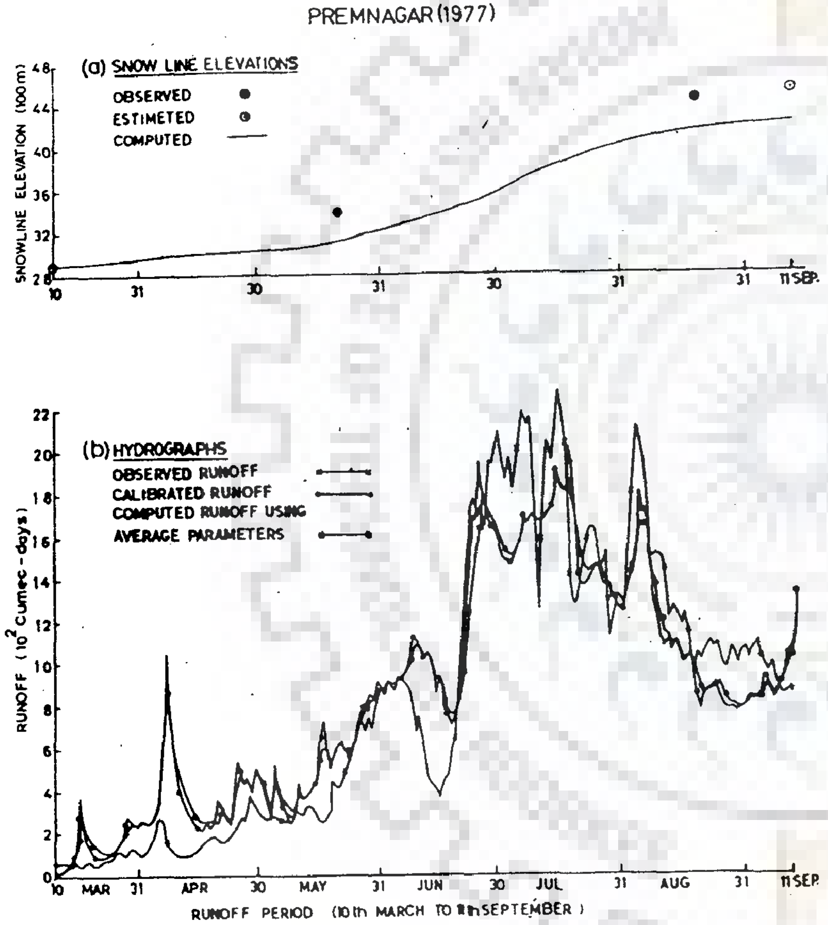


Fig 5.10 (a) Snowline Elevation (b) Hydrographs Using Average Parameters

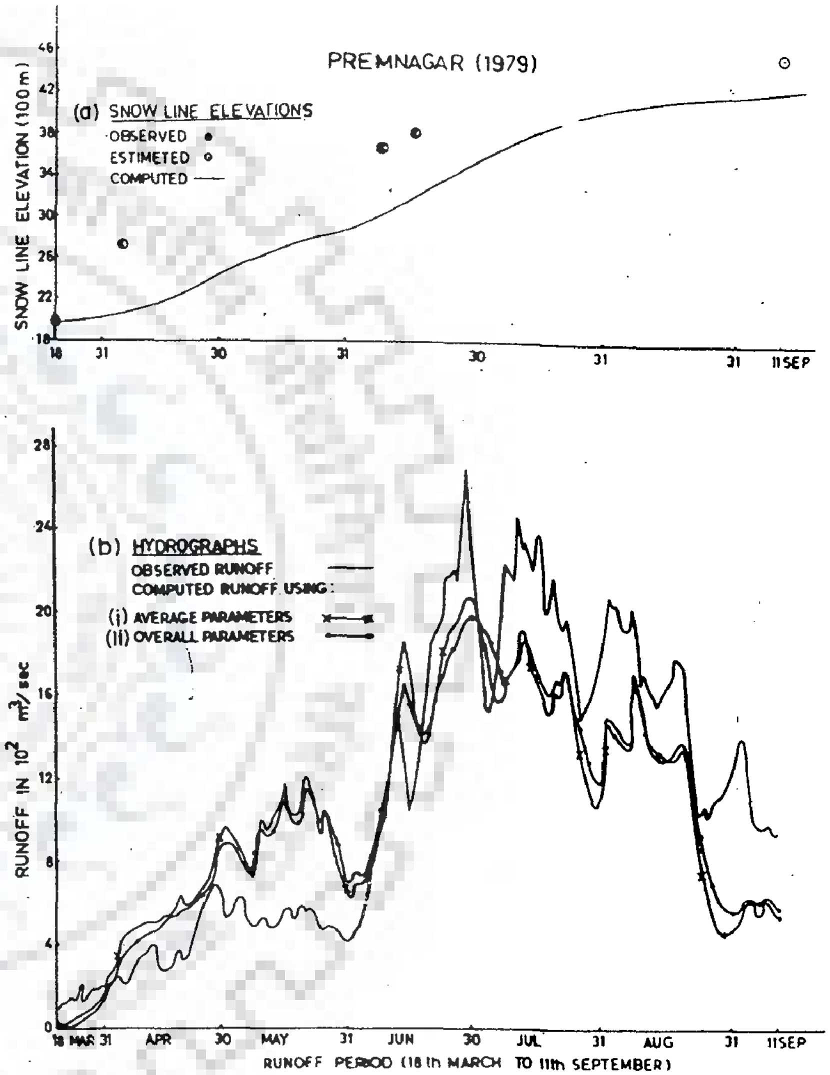


Fig. 5.11 Hydrographs Using Average and Overall Parameters

X(4) and X(5), prediction runs were made. The results of these runs are summarised in Tables 5.18 to 5.20, and plotted in Fig. 5.10 for Premnagar (1977) alongwith those of calibration runs for sake of comparison. It is clearly seen that inspite of averaging, the model performance is quite good as reflected by efficiency values of 74.12% to 86.87% for the years 1975 to 1977. The time distribution of flows also remains nearly similar to that for calibration runs as reflected by values of error functions, and also daily flow hydrograph. The total seasonal flows are reproduced very well within 3 to 4% variation and even monthly flow simulation is quite satisfactory, when compared with results for calibration runs.

These results have thus showed applicability of average values of five parameters for Premnagar sub-basin, on the same data which was used for calibration runs. The model performance was further tested with independent data set for 1979 season for Premnagar sub-basin as discussed in the next section.

5.6.3(c) Test Run with Average Parameters Using Independent Data of 1979 Season (Premnagar)

The performance of test run with independent data set is quite encouraging as indicated by results summarised in Table-5.21 and plotted in (Fig. 5.11), inspite of the fact that only three seasons data has been used in obtaining the average parameters. The efficiency value of 71.23 % has been achieved and total seasonal flows have been reproduced satisfactorily. The plots in Fig. 5.11, indicate a general

TABLE-5.21 : RESULT OF THE TEST RUNS FOR PREMNAGAR (1979)

JUDGING CRITERIA

Items	Efficiency (%)	Error Functions		
		Standard Error Cumec-days	Average Abs. Error (Cumec-days)	Average Error (%)
Average parameters	71.23	384.39	329.73	43.70
Overall parameters	74.28	363.41	310.09	40.32

MONTHLY FLOWS (Cumec-days)

Months	Observed Flow	Computed Flow Using	
		Average Parameters	Overall Parameters
March(18th)	2146	1123	887
April	11277	17505	15952
May	16118	29776	29400
June	43477	44386	41636
July	60225	50481	51710
August	48880	36462	37405
September(11th)	12085	6225	6518
TOTAL	1,94,208	1,85,958	1,83,507

SNOW LINE ELEVATION (m)

Date	18-March	5-April	7-June	16-June	11-Sep.
Observed	2099	2752	3668	3801	4540 (test)
Comp. using overall parameters	2099	2169	3078	3255	4257

overestimation of flows during premonsoon months(March,April May and June). and a general under estimation during monsoon months (July-September). This seems to be due to data limitations and simplified model structure involving assumption of linear increase in melt rate. The computed position of snow line is somewhat lower than positions for corresponding dates as estimated from satellite images. However, keeping in view the large size of catchment (17622.46 km^2) and use of toposheets in deriving area elevation relationships, the results are satisfactory.

5.6.4(a) Calibration Runs Using Data of (i) Benswar (ii) Bursar (iii) Sirshi Bridge, and (iv) Kuriya Bridge Sub-basins for 1975, 1976 1977 Seasons

Separate calibration runs involving number of trial runs were made for the four sub-basins using data for 1975, 1976 and 1977 seasons. These have different catchment areas, viz. Benswar-11162.19 km^2, Bursar - 2896.34 km^2, Sirshi Bridge-3588.12 km^2 and Kuriya Bridge-4812.62 km^2. The results of the final calibration runs are given in a summarised form in Tables 5.18 to 5.20.

For the Benswar sub-basin, it is seen that parameter values X(1), X(2), X(3) are nearly of the same order for three seasons. However, parameter values for X(4) and X(5) for 1975 differ from those for 1976 and 1977, which are of the same order. The overall performance of the model as judged by efficiency values ranging from 74.82% to 85.54%

and reproduction of total seasonal flows, is quite good. The pattern of reproduction of monthly flows is on the same lines as for Premnagar, with general overestimation for pre-monsoon months and understimation for monssoon months. Due to simplicity of model structure and data limitations, time distribution of daily flows is not fully reproduced, as indicated by values of error functions.

For Bursar sub-basin, for 1975 and 1977, efficiency is somewhat lower as indicated by values of 66.72% and 61.49% There is also a general over prediction of monthly flows and total seasonal flows in 1977. A comparison of data sets for 1975, 1976 and 1977 for Bursar sub-basin indicated possible reasons for somewhat lower efficiencies for 1975 and 1977. It is seen that base flow separated for these two years is 9.42% and 14.46% respectively of total runoff, while for 1976 it is 18.02% (Table-5.4) and the precipitation values are also lower for these two years. (Table-5.22). For the Sirshi-Bridge and Kuriya-Bridge sub-basins, also the general pattern of results is similar to that for Benswar and Premnagar sub-basins. The results of calibration runs for these sub-basins are given in summarised form in Tables-5.18 to 5.20.

Thus, inspite of data limitations and simple model structure, the model has performed satisfactorily for five sub-basins of different sizes. The values of parameters X(1), X(2), X(3), X(4), X(5) for different seasons for each of the sub-basins, inspite of some variation in values of X(4) and X(5), on average are similar and their arithematic

TABLE-5.22 : PRECIPITATION DEPTH (mm) DURING PREMONSOON AND MONSOON PERIOD

Sub-Basins	Runoff Period	Precipitation(mm)		Total Pre-cipitation (mm)
		Pre monsoon	Mon-soon	
1. Premnagar				
	3,Mar-11,Sept'75	436.8	615.9	1052.70
	2,Apr-11,Sept'76	243.2	581.5	824.7
	10,Mar-11,Sept'77	423.7	192.2	615.9
	18,Mar-11,Sept'79	383.8	118.9	502.7
2. Benswar				
	3,Mar-11,Sept.'75	735.2	481.0	1216.2
	2,Apr-31,Jul. '76	308.6	75.6	384.2
	10,Mar-11,Sept '77	531.5	173.7	705.2
3. Kuriya-Bridge				
	3,Mar-11,Sept '75	646.0	673.6	1319.6
	2,Apr-31,Jul. '76	259.7	87.8	347.5
	10,Mar-11,Sept.'77	482.7	196.3	679.0
4. Sirshi-Bridge				
	3,Mar-11,Sept.'75	678.5	483.9	1162.4
	2,Apr-11,Sept.'76	278.4	337.4	615.8
	10,Mar-11,Sept.'77	495.8	189.1	684.9
5. Bursar	3,Mar-11,Sept.'75	555.7	484.7	1040.4
	1,Mar-30,June '76	416.2	-	416.2
	10,Mar.11,Sept.'77	465.9	205.1	671.0
6. Kuriya-Bridge				
	2,Apr-31,July '76	251.4	75.6	327.0
	10,Mar-11,Sept.'77	424.0	700.1	1124.1

averages were taken for each sub-basin for use in simulation runs as discussed in next section.

5.6.4(b) Prediction Runs Using Average Parameters for (i) Benswar (ii) Bursar (iii) Sirshi Bridge and (iv) Kuriya Bridge Sub-basins for 1975, 1976 and 1977 Seasons

The average parameter values for the Premnagar sub-basin and four sub-basins were computed as discussed in previous sections (Table 5.14).

It is clearly seen that the values of parameters X(1), X(2) and X(3) are nearly of same order for all the five sub-basins, while X(4) and X(5) vary from sub-basin to sub-basin. Prediction runs were made using these average parameters for four sub-basins viz. Benswar, Bursar, Sirshi-Bridge and Kuriya-Bridge on the same lines as for Premnagar sub-basin, as discussed in Section-5.6.3(b) for 1975, 1976 and 1977 seasons. The summarised results of these runs are given in Tables 5.18 to 5.20 alongwith the results for calibration runs for sake of comparison. Inspite of averaging of parameters, the model performance is quite good for all the four sub-basins for each of the seasons. The model efficiency varies between 77.42% to 85.51%for Benswar, 60.98% to 89.07% for Bursar, 77.87% to 84.76% for Sirshi-Bridge and 65.20% to 80.08% for Kuriya-Bridge; and these values differ in general by about 1% to 2% from corresponding values for calibration runs. However, for Kuriya-Bridge sub-basin for 1975 and 1976 seasons, this averaging of parameters results in decrease in efficiency by 8% and 5%, respectively. This seems to be mostly due to difference in calibrated parameter values for X(3), X(4) and X(5) for these seasons for this sub-basin. Inspite of this the results are quite reasonable.

Similar, generally good pattern of performance of average parameters is indicated by values of error functions and simulated monthly and total seasonal flows.

The values of average parameters for the five sub-basins were used to develop overall regional parameters/ relationship for Chenab basin as discussed in next section.

5.6.5(a) Overall Regional Parameters for the Chenab Basin

As shown in Section 5.6.4(b), the average parameter values for X(1), X(2) and X(3) are nearly of same order for five sub-basins and as such their mean value was taken to represent overall regional parameter values for the Chenab basin, as X(1) = 0.9100, X(2) = 0.8915, and X(3) = 0.4965.

The parameters X(4) and X(5) are storage coefficients of two linear reservoirs, which respectively simulate travel of the excess water (effective precipitation - abstractions) generated while moving through snow covered and snow free areas of the catchment. The Gray's parameter ($L_c/\sqrt{S_c}$) also represents time of travel through the catchment. The values of parameters X(4) and X(5) were therefore, plotted against values of Grays' parameter for the sub-basins, and graphical relationships were obtained as shown in (Fig. 5.12).

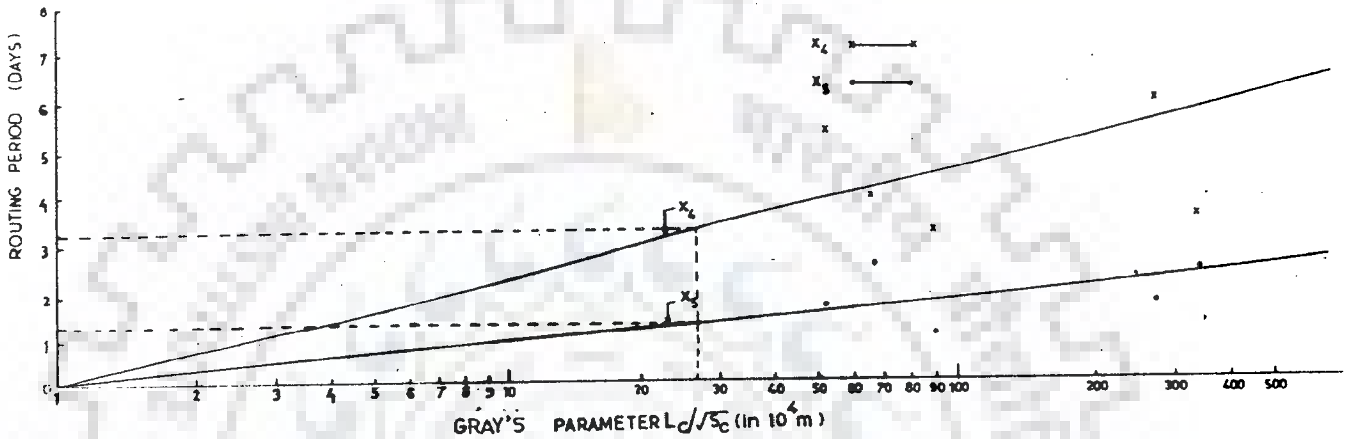


Fig 5.12 Relationship Between Routing Period and Gray's Para meters ($L_c/\sqrt{S_c}$)

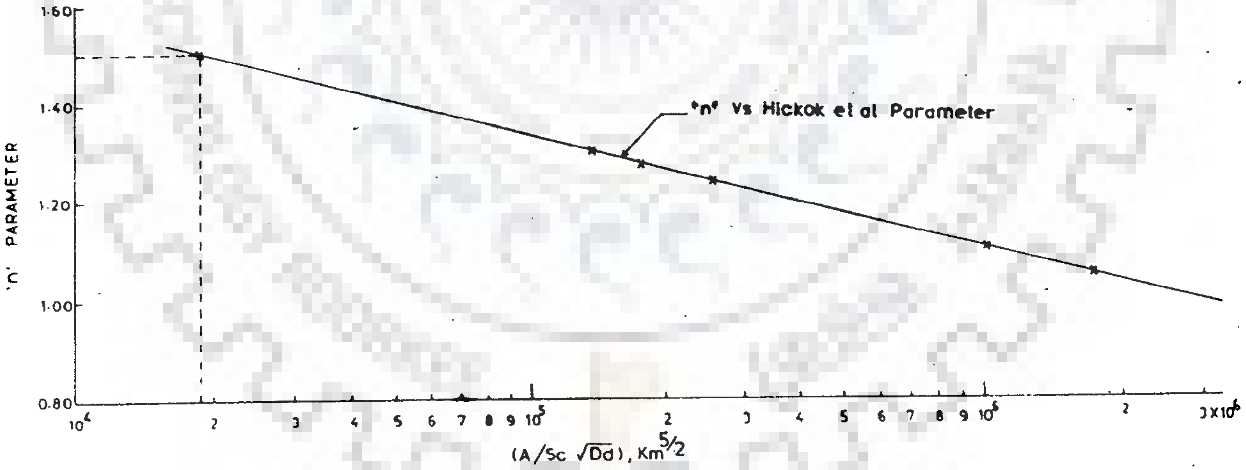


Fig. 5.13 Relationship Between 'n' Parameter and Modified Hickok-Keppel and Rafferty Parameter

The overall parameter values for X(4) and X(5) for five sub-basins whose data has been used in calibration, and also for Kiyar Nala sub-basin were read from the graph. These are given as below (Table-5.23):

TABLE-5.23 : OVERALL PARAMETER VALUES FOR X(4) AND X(5)

Sl. No.	Name of Sub-basin	Value of Gray's Parameter($L_c/\sqrt{S_c}$) (10^4 m)	Overall Parameter Value X(4) (days)	X(5) (days)
1.	Premnagar	331.13	5.70	2.30
2.	Benswar	274.81	5.44	2.26
3.	Bursar	52.38	3.90	1.60
4.	Sirshi Bridge	66.16	4.10	1.70
5.	Kuriya Bridge	89.76	4.40	1.80
6.	Kiyar Nala	26.83	3.23	1.33

As discussed earlier in Section-5.3.5.1, the parameter 'n' was related to Hickok et al parameter ($A/S_c\sqrt{D_d}$) by a graphical relationship and during calibration runs, number of trial runs were made with different values of n, while maintaining general form of this graphical relationship. After the final calibration runs for each of the sub-basins, final values of parameter 'n' for the sub-basins were established, and were used during prediction runs and test runs discussed in previous sections. These values were also used for development of final graphical relationship for the Chenab basin (Fig. 5.13). The values obtained from graph are as below (Table-5.24):

TABLE-5.24 : VALUES OF PARAMETER 'n'

Sl. No.	Name of Sub-basin	Parameter $A/S_c\sqrt{D_d}$	Values of 'n' Obtained from Graph
1.	Premnagar	17454.3	1.05
2.	Benswar	10155.4	1.10
3.	Kuriya Bridge	2520.8	1.24
4.	Sirshi Bridge	1782.0	1.27
5.	Bursar	1383.9	1.30
6.	Kiyar Nala	186.3	1.51

It may be pointed out that, the data of Kiyar Nala was not used in development of relationship and was used only for testing with independent sub-basin data. These values of 'n' have also been used to compute shape of fitted curve for plot between snow cover and snowmelt runoff as shown in Fig. 5.14.

The comparison of Fig. 5.14 with Fig. 5.3 indicate the relative change in shape of curve between percentages of snow cover area and snowmelt runoff, after final calibration runs.

5.6.5(b) Prediction Runs Using Overall Parameters

The prediction runs were made for five sub-basins, in order to compare the performance of overall parameters with that of average and calibrated parameters for data of different seasons:

Form of relationship $\frac{SCA}{100} = 1.0 - \left(\frac{\Sigma Qgen}{100}\right)^{n}$

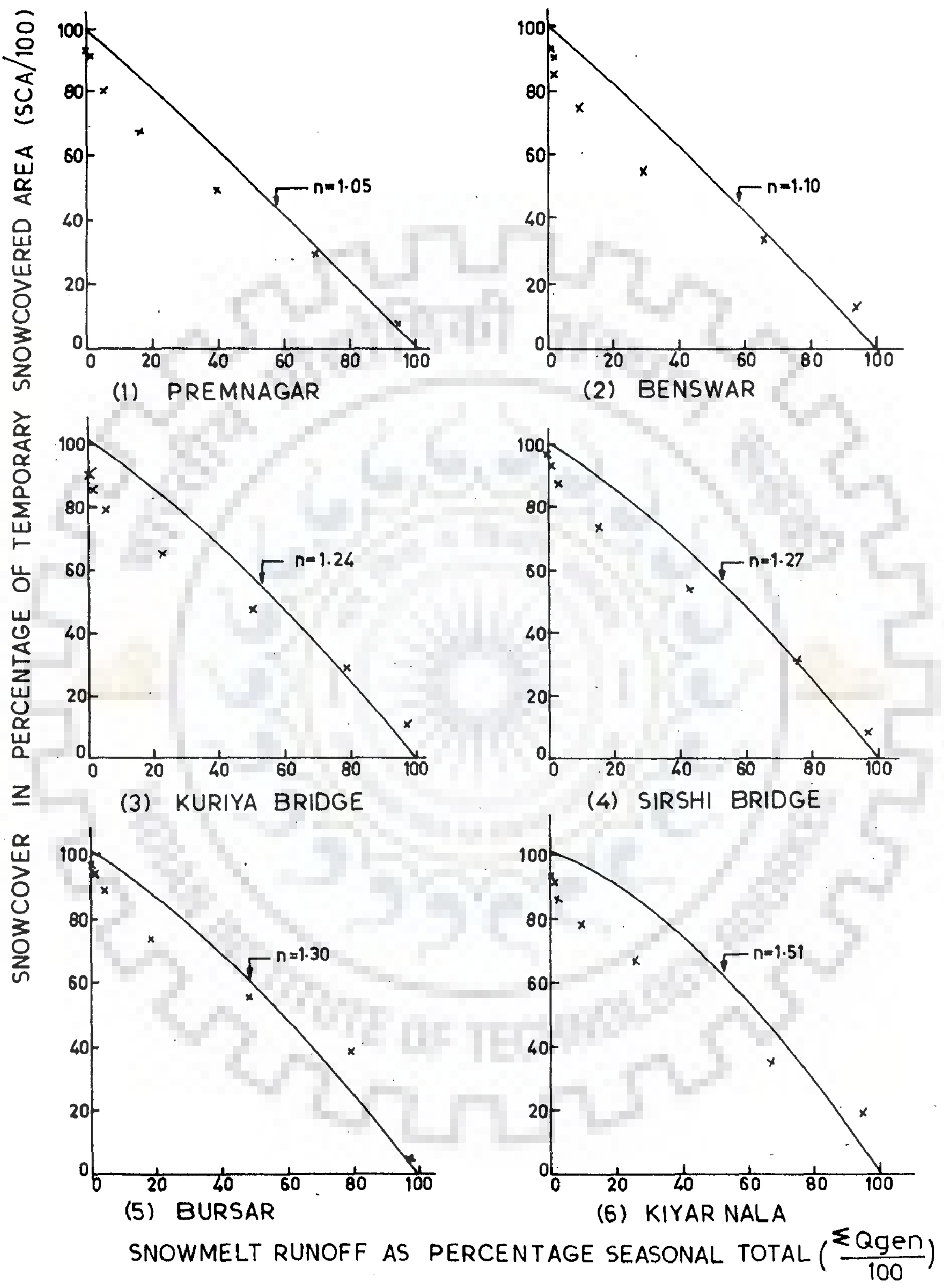


Fig. 5·14 Relationship Between Snowcover in percentage of Temporary Snowcovered area and Snowmelt Runoff as Percentage of Seasonal Total with final values of 'n' After Calibration.

i) For 1975, 1976, 1977 and 1979 seasons for Premnagar;

For the 1975, 1976 and 1977 seasons for which data was used in calibration, the use of overall parameters resulted in change in range of efficiency values from 77.0% to 86.43% which compares well with corresponding values of 74.12% to 86.87% for average parameters and 80.81% to 86.10% for calibrated parameters. The summarised results are given in Tables-5.18 to 5.20 and computed hydrographs are plotted in Figs. 5.15 to 5.17, which clearly indicate good performance of overall parameters.

For the independent data set of 1979 season, the use of overall parameters gave a higher efficiency value of 74.28% in comparison to 71.23% for average parameter values (Table-5.21, Fig. 5.11). Inspite of only 3 seasons data used, the performance on independent data set is very good as indicated by values of error parameters, total seasonal flows, monthly flows and computed position of snow line.

ii) For 1975, 1976 and 1977 seasons for Benswar, Bursar, Sirshi Bridge and Kuriya Bridge.

The results of prediction runs for three seasons for these sub-basins are also summarised in Tables-5.18 to 5.20 and 5.25 alongwith the results for calibration runs and prediction runs with average parameters.

In general, the overall parameters gave a good performance (Figs. 5.18-5.21), both on the basis of comparison with observed values, and also with results of calibration runs and prediction runs with average parameter.

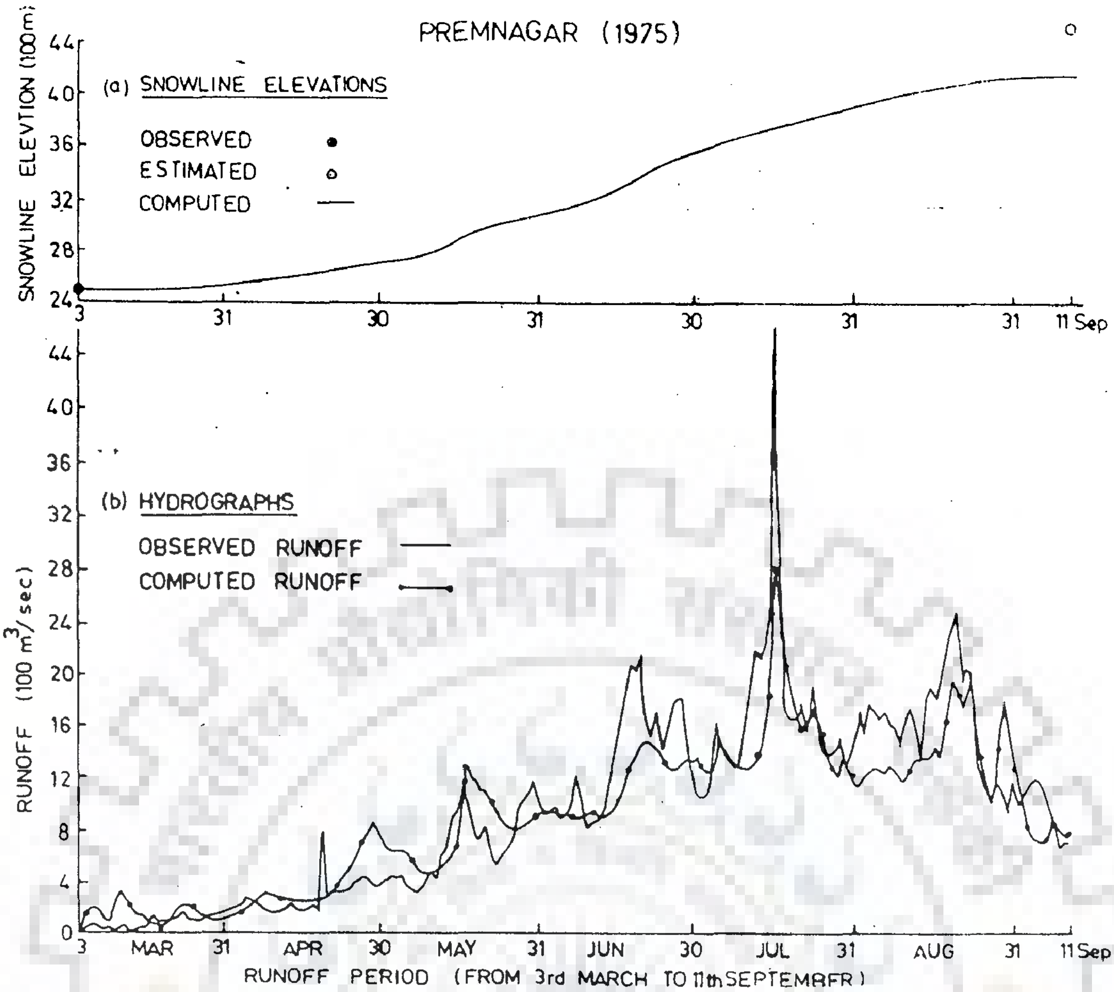


Fig. 5.15 (a) Snowline Elevations (b) Hydrographs Using Overall Parameters

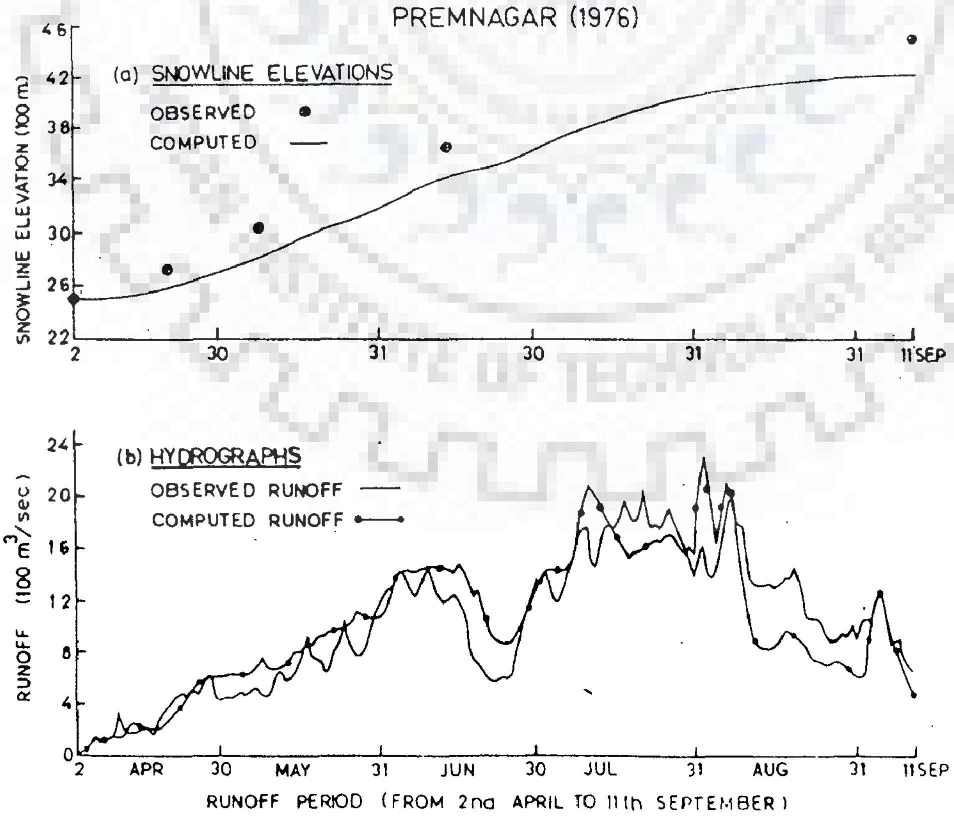


Fig. 5.16 (a) Snowline Elevations (b) Hydrographs Using Overall Parameters.

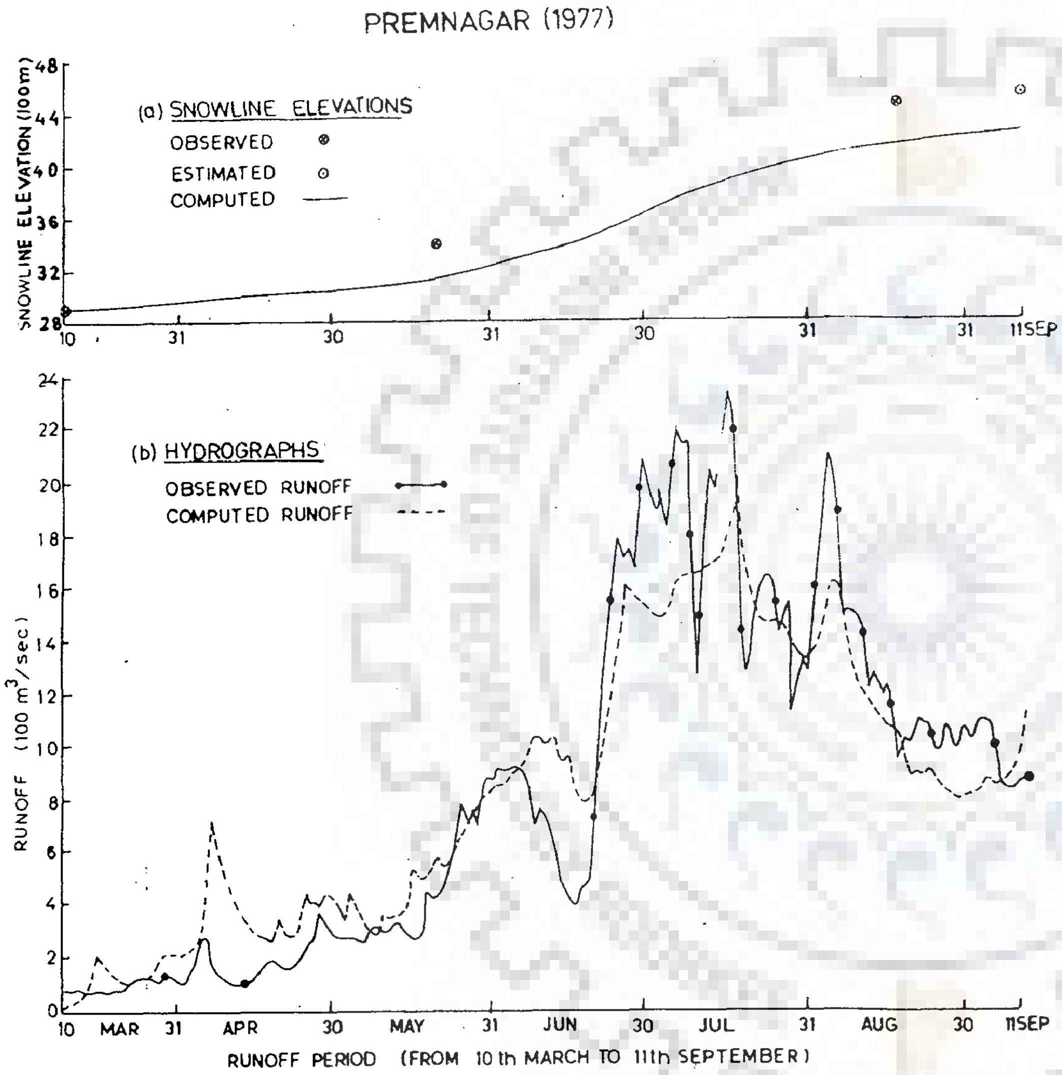


Fig.5.17 (a) Snowline Elevations(b) Hydrographs Using Overall Parameters

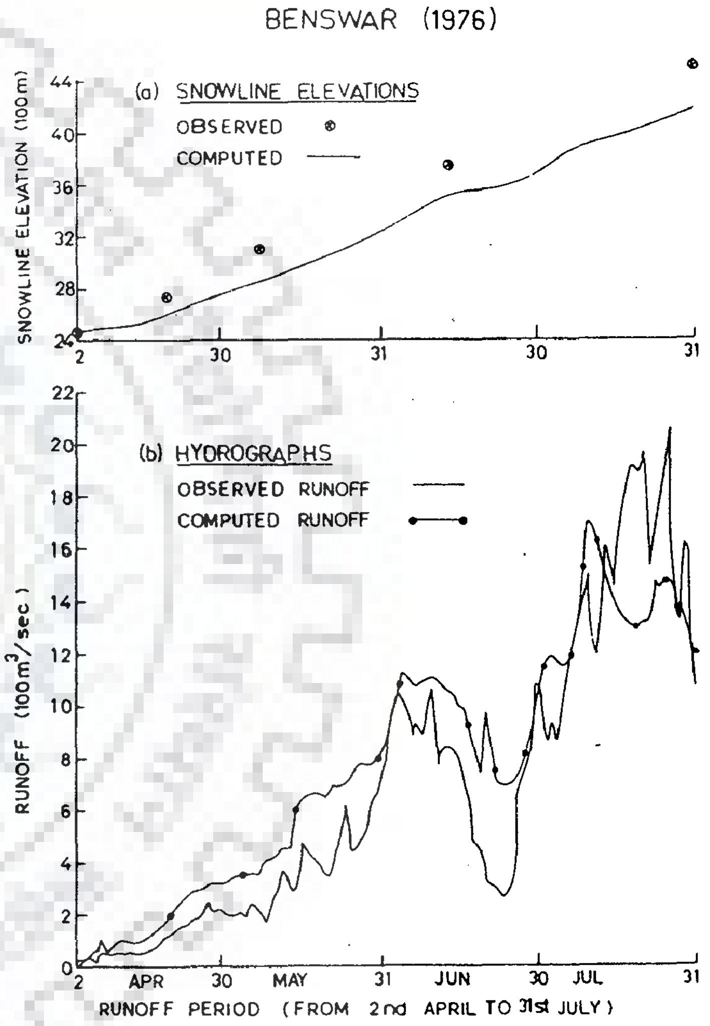


Fig.5.18 (a) Snowline Elevations (b) Hydrographs Using Overall Parameters

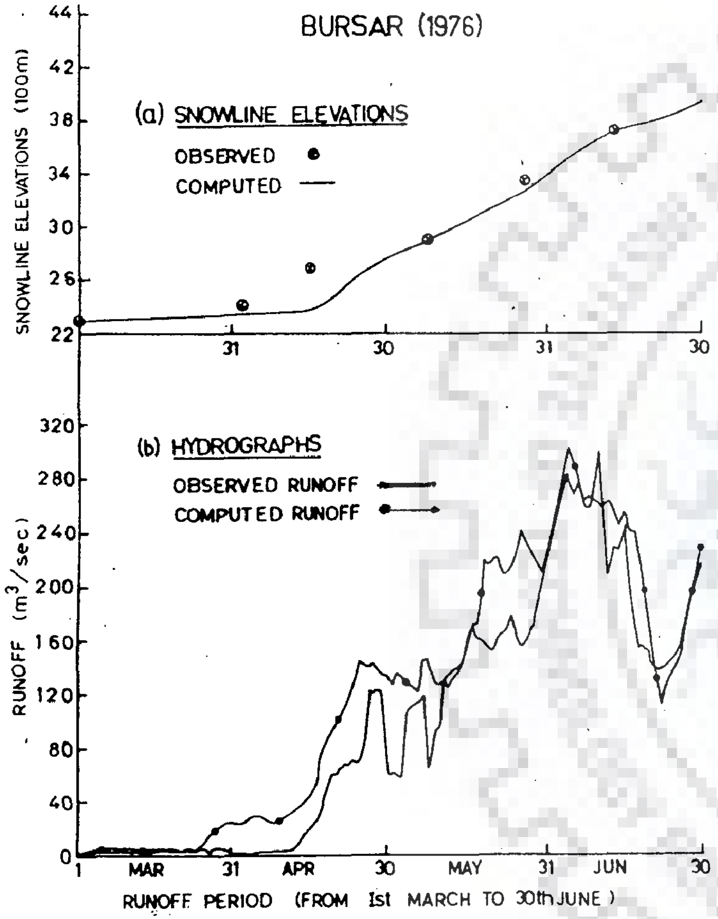


Fig.5.19(a)Snowline Elevations (b) Hydrographs Using Overall Parameters

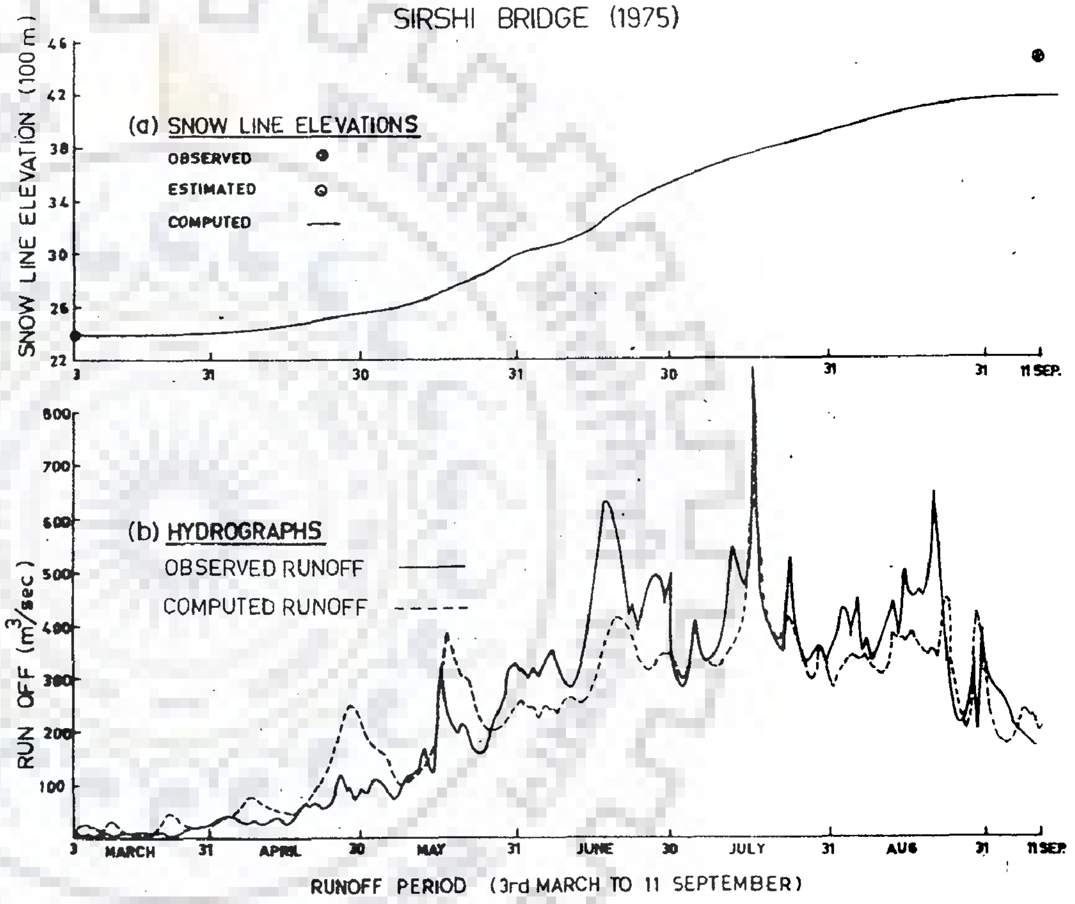


Fig. 5.20 (a) Snowline Elevations(b) Hydrogrphs Using Overall Parameters.

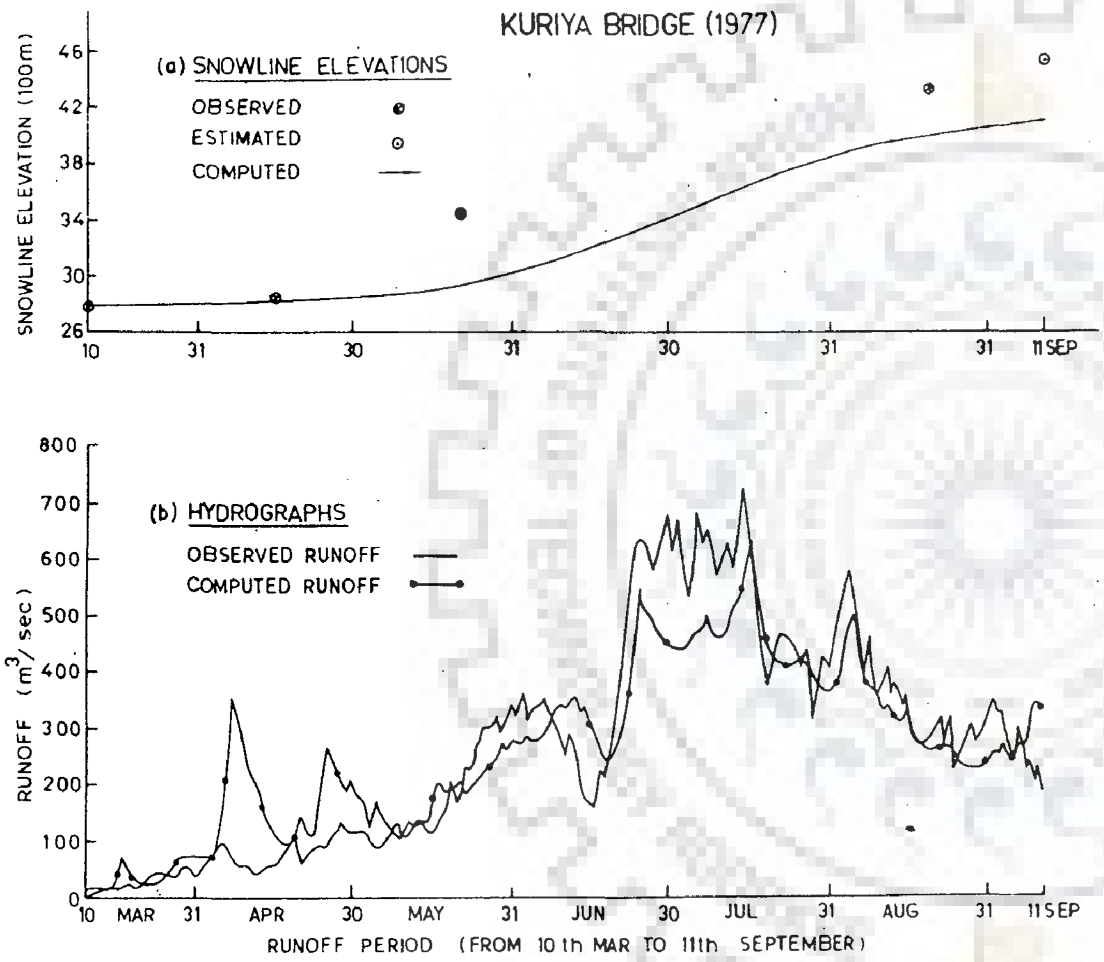


Fig.5·21 (a) Snowline Elevations (b) Hydrographs Using Overall Parameters

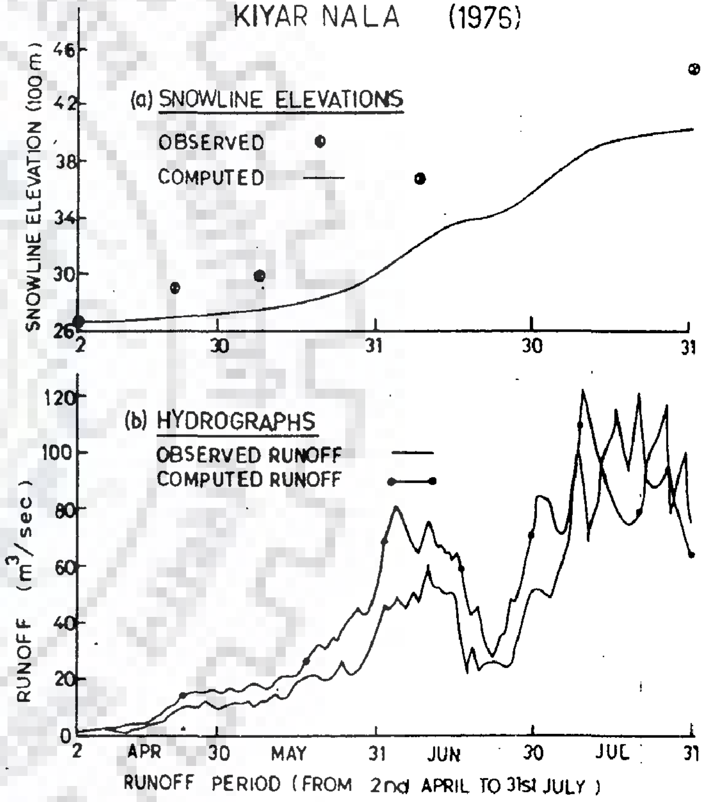


Fig.5·22 (a) Snowline Elevations (b) Hydrographs Using Overall Parameters for Independent Data

TABLE-5.25 : OBSERVED AND COMPUTED SNOW LINE ELEVATION(m) IN DIFFERENT SUB-BASINS USING OVERALL PARAMETERS

Sub-basins	Premnagar		Benswar		Bursar		Sirshi-Bridge		Kuriya-Bridge	
Date	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.	Obs.	Comp.
3-3-75	2499	2499	2298	2298	2396	2396	2396	2396	2320	2320
9-4-75	-	-	-	-	2827	2428	-	-	-	-
11-9-75	4540 (est.)	4185	4530 (est.)	4258	4530 (est.)	4365	4489 (est.)	4189	4529 (est.)	4036
1-3-76	-	-	-	-	2300	2300	-	-	-	-
2-4-76	2493	2493	2474	2474	2424	2319	2421	2421	2458	2458
20-4-76	2749	2573	2740	2572	2707	2459	2629	2487	2713	2477
8-5-76	3042	2783	3113	2848	2897	2887	2850	2691	2855	2604
27-5-76	-	-	-	-	3351	3246	-	-	-	-
13-6-76	3653	3416	3747	3500	3725	3703	3712	3411	3610	3712
30-6-76	-	-	-	-	-	3934	-	-	-	-
31-7-76	-	-	-	4126	-	-	-	-	-	-
11-9-76	4540	4211	-	-	-	-	4489	4230	4529	3860
10-3-77	2906	2906	2986	2986	2780	2780	2699	2699	2792	2792
15-4-77	-	-	3160	3041	3031	2887	3001	2754	2843	2829
21-5-77	3391	3107	3434	3144	3450	3085	3462	2944	3440	2912
19-8-77	4470	4145	4494	4212	4505	4359	4427	4179	4388	3976
11-9-77	4540 (est.)	4242	4530 (est.)	4299	4530 (est.)	4426	4489 (est.)	4266	4529 (est.)	4098

The range of efficiency values obtained are given below for the sake of comparison (5.26):

TABLE-5.26 : RANGE OF EFFICIENCY VALUES

Sl. No.	Name of sub-basins	Range of Efficiency Value (%)		
		Calibration runs	Prediction with average parameters	Prediction with overall parameters
1.	Benswar	74.82-85.64	77.42-85.51	77.47-85.80
2.	Bursar	61.49-88.58	60.98-89.07	57.19-85.84
3.	Sirshi Bridge	78.24-85.39	77.87-84.76	78.06-83.22
4.	Kuriya Bridge	73.02-77.61	65.20-80.08	70.87-79.23

The reproduction of monthly and seasonal flows and snow line position also compare well with corresponding results for calibration runs and prediction runs using average parameters.

(c) Test Runs Using Independent Data of Kiyar Nala for 1976 and 1977 Seasons

The performance of regional overall parameters for the Chenab basin was tested using independent data sets for Kiyar Nala sub-basin. The values of five parameters X(1)=0.9100, X(2)=0.8915, X(3)=0.4965, X(4)=3.23, X(5)=1.33 and also value of , n = 1.51 (as obtained from regional relation for the Chenab basins), were used.

The variation of melt rate for Kiyar Nala sub-basin was also taken from graphical relationship with weighted mean elevation as discussed in Section 5.3.5.3. For weighted mean elevation of 4380.3 m, this value was obtained as 0.0296, (Fig. 5.7) and was used in prediction runs.

The values of seasonal snowmelt runoff parameter (SSR) for Kiyar Nala sub-basin were taken from graphical relationship between SSR and observed percentage of snow covered area for this sub-basin as discussed in Section 5.3.5.2, (Fig.5.5) for 1976 and 1977 seasons. (Table-5.27)

TABLE-5.27 : VALUES OF PARAMETER (SSR)

Season	Observed % of Snow covered area	Value of SSR (mm)
1976	93.58	1860
1977	88.17	1790

The summarised results of prediction runs for 1976 and 1977 are as follows (5.28):

TABLE-5.28: SUMMARISED RESULTS OF PREDICTION RUNS

Month	Flows (Cumec.days) April to July(1976)		March to Sept. (1977)	
	Observed	Computed	Observed	Computed
1. March(part)	-	-	36	74
2. April	154	257	126	380
3. May	582	898	328	567
4. June	1241	1743	159	1581
5. July	2660	2627	3022	2402
6. Aug.	-	-	2245	1654
7. Sept.	-	-	552	1476
Total	4637	5525	6468	8134

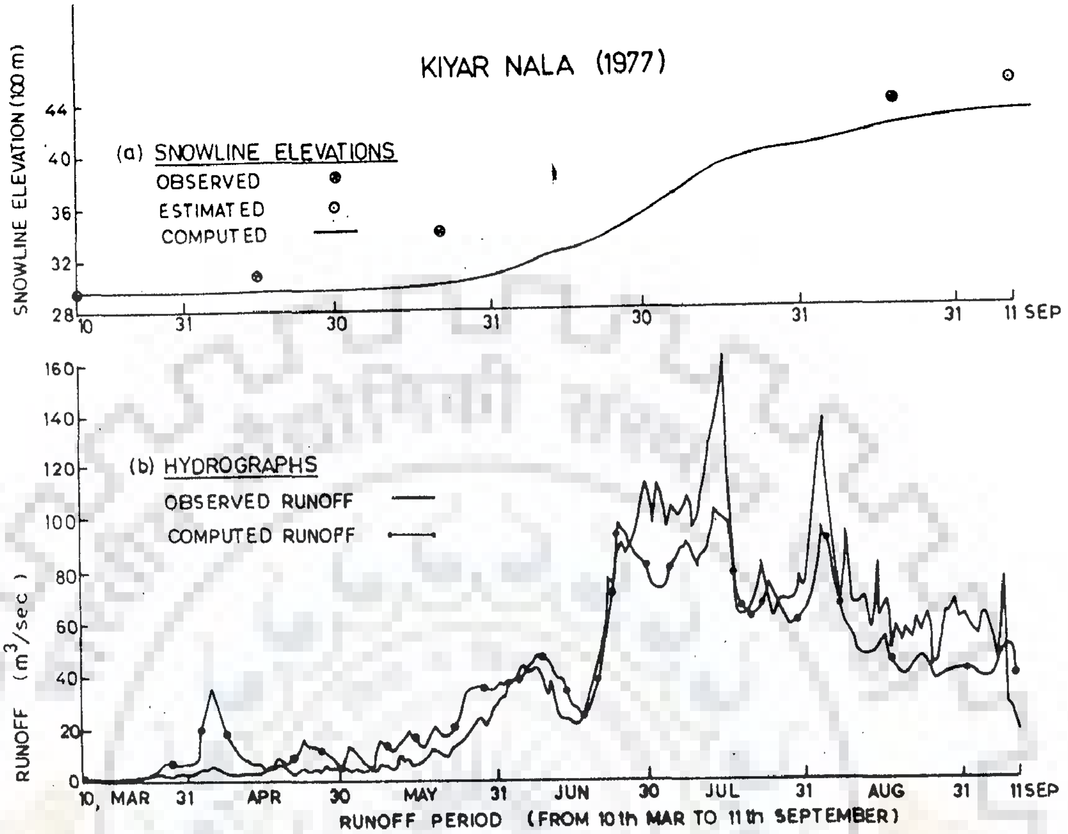


Fig. 5.23 (a) Snowline Elevations (b) Hydrographs Using Overall Parameters For Independent Data

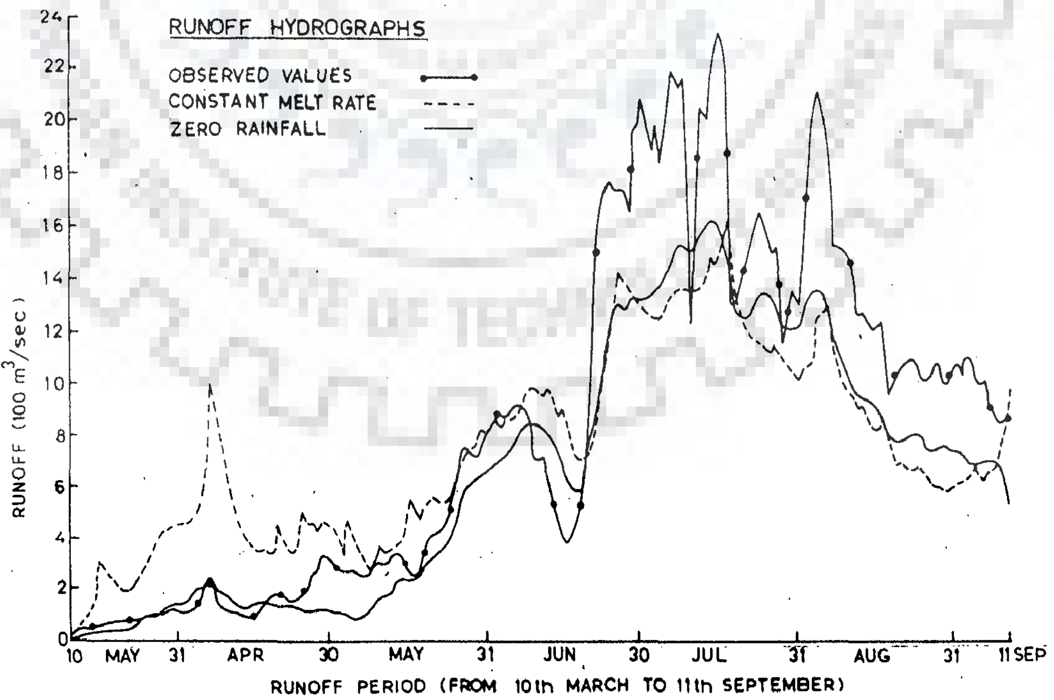


Fig.5.24 Hydrographs At Premnagar (1977) Using Overall Parameters and Constant Melt - Rate

The observed and computed hydrographs and snow line positions for 1976, 1977 season are plotted in Figs. 5.22 and 5.23. The results clearly indicate very good reproduction of flows, and also good reproduction of snow line positions for independent sub-basin data. The snow line position as estimated from available satellito images and as given by model - runs for specific dates is as follows (Table-5.29):

TABLE-5.29 : SNOWLINE POSITIONS ESTIMATED AND COMPUTED FOR KIYAR NALA

	1976 Season			1977 Season		
	Snow line elevation(m)			Snow line elevation(m)		
	Date	Observed	Computed	Date	Observed	Computed
1.	20-4-76	2903	2670	10-3-77	2951	2951
2.	8-5-76	2990	2748	15-4-77	3080	2964
3.	13-6-76	3708	3338	21-5-77	3431	3006
4.	11-9-76	4530	4060	19-8-77	4387	4203
5.	-	-	-	11-9-77	4530	4298

5.6.6 General Remarks About Model Performance

The results of calibration runs using data of 3 seasons (1975, 1976, 1977) for five sub-basins (Premnagar, Benswar, Bursar, Sirshi Bridge, Kuriya Bridge), prediction runs using average with parameters, test with independent data for 1979 season for Premnagar and prediction runs using overall parameters have all indicated reasonably good performance of the model. The use of overall parameters and regional relationships for prediction test runs with independent data sets for Kiyar Nala has further confirmed good performance of the model. A general feature of results is somewhat over-prediction of flows during premonsoon months (March, April, May and June and under prediction of flows during monsoon months (July, Aug., Sept.). It seems to be mainly due to assumption of linear increase in melt rate starting from 1st March, adopted in the model for the sake of simplification and non-availability of reasonable information. The daily rainfall and variation of daily temperature pattern also have some effect on simulation pattern of flows. These have been examined in the typical runs using overall parameters, as discussed in subsequent sections.

5.6.7 Results of Typical Runs

(a) Runoff from snow covered and snow free areas from Prediction runs assuming zero rainfall:

Using overall parameters for Premnagar, Benswsr and Sirshi Bridge sub-basins and data for 1975, 1976, 1977 (also 1979 for Premnagar) seasons, prediction runs were made using overall parameters and assuming rainfall as zero. The comparison of these results with corresponding results of previous runs with rainfall, provided estimates of runoff contributions from various parts of the catchment and also indication of rainfall contributions to total runoff during premonsoon and monsoon months. The percentage of each contribution results from various parts of the individual catchments are summarised in Table 5.30 and the hydrograph of the snowmelt runoff (zero rainfall) for Premnagar(1977) is shown in Fig. 5.24.

TABLE-5.30 : PERCENTAGE CONTRIBUTIONS TO TOTAL RUNOFF

Sl. No.	Name of Sub-basin and season	Total runoff (Cumec-days)	% Contributions From			
			Permanent snow area	Snowmelt temp. snow area	Rain on temp. snowmelt area	Rain on snow-free area
1.	<u>Premnagar</u>					
(a)	1975 Premonsoon	74982	5.2	68.1	19.0	7.7
	Monsoon	100260	14.6	51.4	11.7	22.3
	Total	175242	10.6	58.5	14.8	16.1
(b)	1976 Premonsoon	73475	7.9	74.3	13.1	4.7
	Monsoon	95506	21.6	53.9	3.4	21.1
	Total	168981	15.6	62.8	7.6	14.0
(c)	1977 Premonsoon	60620	5.8	62.9	20.0	11.3
	Monsoon	93443	25.5	59.8	5.2	9.5
	Total	154063	17.8	61.0	11.0	10.2
(d)	1979 Premonsoon	87875	7.1	70.1	17.6	5.2
	Monsoon	95632	28.8	62.0	3.0	6.2
	Total	183507	18.5	65.8	10.0	5.7
2.	<u>Benswar</u>					
(a)	1975 Premonsoon	50294	7.9	71.3	17.6	3.2
	Monsoon	71392	22.1	55.6	9.8	12.5
	Total	121623	16.3	62.1	13.0	8.6
(b)	1976 Premonsoon	49768	11.3	75.3	10.1	3.3
	Monsoon	-				
	Total	-				
(c)	1977 Premonsoon	42011	8.5	63.7	21.1	6.7
	Monsoon	78485	32.0	58.9	4.2	4.9
	Total	120496	23.8	60.6	10.1	5.5
3.	<u>Sirshi Bridge</u>					
(a)	1975 Premonsoon	19264	4.9	65.6	26.1	3.4
	Monsoon	24270	14.1	54.0	15.0	16.9
	Total	43534	10.1	59.1	19.9	10.9
(b)	1976 Premonsoon	18814	7.4	73.2	16.2	3.2
	Monsoon	23294	20.0	54.8	6.9	18.3
	Total	42108	14.4	63.0	11.1	11.5
(c)	1977 Premonsoon	17463	5.2	61.6	28.0	5.2
	Monsoon	23052	23.8	61.4	6.1	8.6
	Total	40515	15.8	61.5	15.6	7.1

TEMPERATURE CHARACTERISTICS

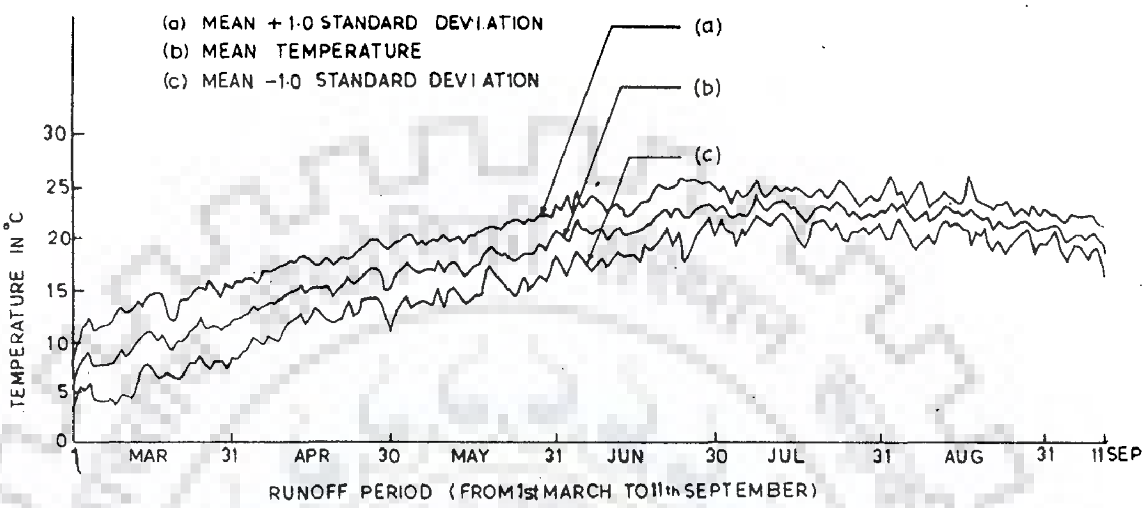


Fig. 5·25 Variation of Mean Temperature During Runoff Period.

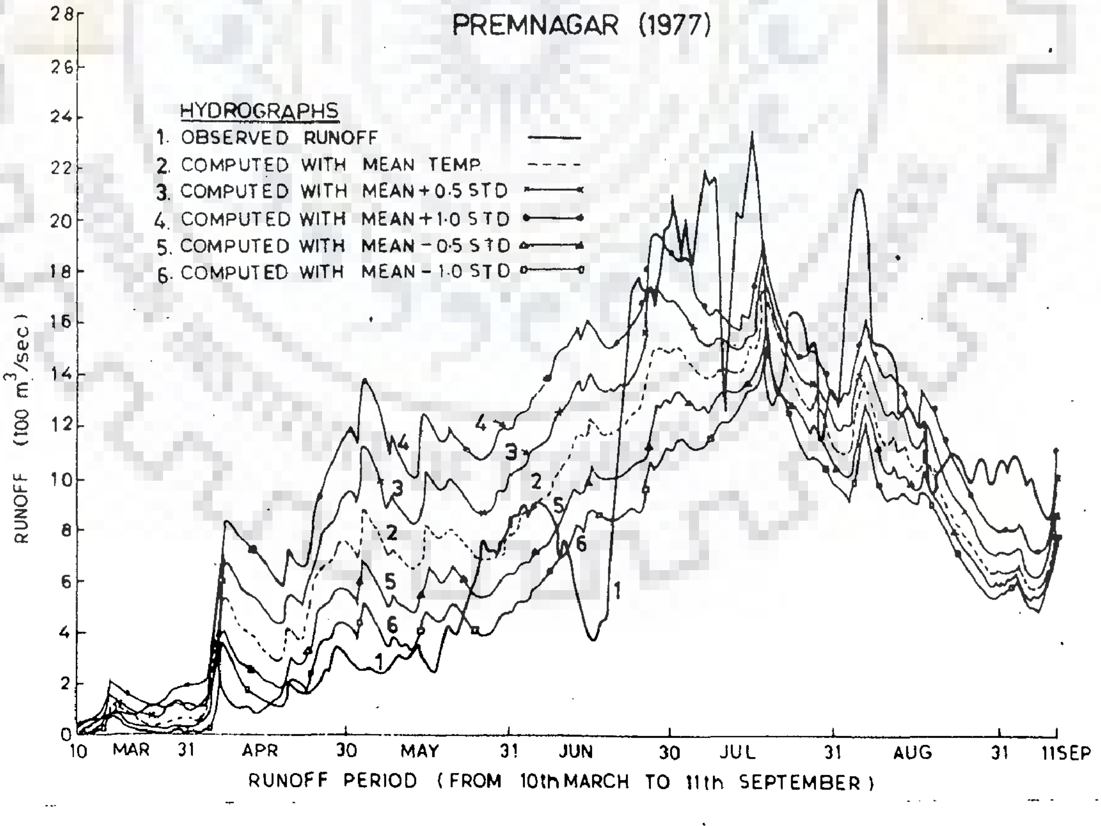


Fig. 5·26 Hydrographs of the Observed and Computed Runoff with the Change of Temperature.

It is seen that rainfall contributions, both from temporary snow area and snow free area are quite significant in both premonsoon and monsoon seasons varying between 10% to 34% . In view of limitations of rainfall data availability, there is possibility of some seasonality introduced in the results, leading to overprediction during premonsoon months and under prediction during monsoon months.

(b) Effect of rainfall pattern on runoff

The effect of rainfall pattern on runoff was also studied with typical sensitivity run using overall parameters and data for 1977 season for Premnagar. Two prediction runs were made : (i) all daily rainfall values were increased by 20% , (ii) all daily rainfall values were decreased by 20% . The summary of results is as follows for these two cases and also for corresponding zero rainfall case discussed in previous section(Table -3.31)

TABLE-5.31 : RESULTS OF PREDICTION RUNS FOR EFFECT OF RAINFALL PATTERN(PREMNAGAR-1977)

Typical Cases	Premonsoon flows (cumec-days)	Monsoon flow (cumec-days)	Total flows (cumec days)
i. Observed flows	51579	104718	156297
ii. With rainfall	60621	93442	154063
iii. Rainfall zero	41685	80432	122118
iv. 1.2 times rainfall	64407	96045	160452
v. 0.8 times rainfall	56834	90840	147674

It can be seen that decrease of rainfall in premonsoon months and increase in rainfall in monsoon months tends to give flows nearer to observed values. The effect of limited availability of rainfall data on simulation of observed flows, thus becomes obvious.

5.6.8 Results of Typical Runs for Studying Effect of Temperature Pattern On Computed Runoff

For the purpose of this study, alternative patterns of daily temperature series were considered as follows, based on estimated means and standard deviations for the daily temperature values for each day for the data of temperature station.

i) Mean series
ii) (Mean + 0.5 x standard deviation) series
iii) Mean + 1.0 x standard deviation) series
iv) (Mean-0.5 standard deviation) series
v) (Mean-1.0 standard deviation) series.

The series (i), (iii) and (v) are also plotted in Fig.(5.25). Using the temperature patterns as above, five prediction runs were made using overall parameters and data for Premnagar sub-basins for 1977 season. The five computed daily runoff hydrographs plotted alongwith observed runoff hydrograph in Fig. 5.26 , clearly show the effect of temperature pattern on flows, with all other conditions remaining same. The predicted values of monthly flows for the five cases and corresponding observed values are as follows (Table-5.32):

TABLE-5.32 : PREDICTED AND OBSERVED VALUES OF MONTHLY AND SEASONAL FLOWS DUE TO EFFECT OF TEMPERATURE

Month	Flows (in cumec days)					
	Observed	Case 1 mean-1.0x Stan.dev.	Case 2 mean-0.5x St.dev.	Case 3 mean	Case 4 mean+ 0.5x St.dev.	Case 5 mean+ 1.0x St. dev.
1. March(part)	1788	538	834	1052	1736	2714
2. April	5156	6073	8663	11849	15791	20492
3. May	13204	13017	17742	23156	29482	36008
4. June	31431	23835	29019	34616	40611	46744
Premonsoon total	51579	43463	56258	70673	87620	105958
5. July	53585	37301	40630	43742	46898	50224
6. Aug.	40523	26583	28657	31158	34174	37770
7. Sept.	10610	6439	6836	7359	8058	8977
Monsoon total	104718	70323	76123	82259	89130	96971
Total seasonal	156297	113786	132381	152932	176750	202929

It can also be seen from these results, that change of temperature by 0.5 standard deviation (Case 2 and Case 4) from the mean (Case 3) results in 20.4 to 24 % change in flows in premonsoon months and 7.5 to 8.4% change in monsoon months. This also indicates possibility of some seasonality introduced in the results due to limitations of temperature data.

5.6.9 Results of Typical Runs for Studying Effect of Melt Rate Variation on Computed Runoff

In the model structure, the melt rate has been assumed to vary linearly at the different rates for sub-basins depending upon the weighted mean elevation of the sub-basins. These have been taken as ranging from 0.01440mm per degree per day for Kuriya Bridge to 0.03516 mm per degree day per day for Benswar, starting from 1st March as the beginning of melt season, with melt rate as 0.38 mm per degree day. In order to study the effect of melt rate variation on computed runoff some typical prediction runs were made using overall parameters and data for 1977 season for Premnagar sub-basin.

Case-1:- Constant melt rate of 2.85 mm/degree day as an average of melt rates assumed earlier (Fig. 5.24).

Case-2:- Constant melt rate of 0.38 mm/degree day for March and April, linear increase to 5.12 mm/degree day on 31st August and constant rate of 5.12 mm/degree day for September.

The results of these two cases are given as follows along-with corresponding results for prediction run using overall parameters involving linear melt rate variation from 0.38 on 1st March to 5.12 mm/degree day on 11th September.

TABLE-5.33 : PREDICTED AND OBSERVED VALUES OF MONTHLY AND SEASONAL FLOWS DUE TO EFFECT OF MELT-RATE VARIATION.

Month	Flows in cumec days			Partly constant partly increasing melt rate
	Observed	Increasing melt rate	Constant melt rate	
1. March	1788	2545	5343	1838
2. April	5156	10845	15099	7703
3. May	13204	15223	15646	10835
4. June	31431	32008	29194	27394
Monsoon Total	51579	60621	65282	47770
5. July	53585	48710	39708	49606
6. August	40523	34676	26730	39181
7. September	10610	10056	7824	11467
Monsoon total	104718	93442	74262	100254
Seasonal total	156297	154063	139544	148024

These results clearly indicate the significance of melt rate on computed flows. The over prediction during premonsoon months and under prediction during monsoon months for the case of increasing melt rate gets still worst when constant melt rate is assumed. However, for the case of constant melt rates for March and April and increasing melt rates for May, June, July, Aug. and constant for September gives improved results; though total seasonal flows get somewhat reduced.

5.7 CONCLUDING REMARKS

On the basis of these results, with limited data of only three seasons and simplified assumptions involved in formulation of the model structure, reasonably good procedure has been provided for daily runoff modelling in the sub-basins of the Chenab basin, which mainly involves use of the following:

i) Graphical relationship between parameter 'n' with parameter $A/S_c\sqrt{D_d}$ (Fig. 5.13)

ii) Graphical relationship between seasonal snowmelt runoff with observed percentage of snow covered area (Fig. 5.5).

iii) Graphical relationship between rate of variation of melt rate and weighted mean elevation (Fig. 5.7).

iv) Graphical relationship between parameters X(4) and X(5), and Gray's parameter $L_c/\sqrt{S_c}$ (Fig. 5.12).

v) Overall regional values of parameters X(1) = 0.9100, X(2) = 0.8915, X(3) = 0.4965.

vi) Constant initial melt rate of 0.38 mm/deg°C day on 1st March, and lapse rate value of 6.5°C per 1000 m change in elevation.

vii) Data of daily rainfall, daily temperature, satellite images for estimation of position of snow line, and topographic maps for estimation of area-elevation relationships and hydromorphometric parameters.

The model provides following useful information as output:

i) Daily contributions from permanent snow covered area, temporary snow covered area and snow free area and daily runoff.

ii) Daily position of snowline

iii) Monthly and seasonal totals of runoff and monthly contributions from three portions of catchment, viz., permanent snow covered, temporary snow covered and snow free.

It is also seen that in case reasonable data is available for specifying the pattern of melt rate variation, it is possible to further improve the performance of the model.

CHAPTER - VI

CONCLUSIONS

The present study has focussed on systematic analysis and interpretation of limited available data of the Chenab basin (area 22250 sq.km) a typical Himalayan basin, for the development of (i) suitable relationships between flood/ flow characteristics and hydromorphometric characteristics, (ii) relationship between snowmelt runoff and extent of snow cover and (iii) model of daily runoff from snowmelt and rainfall during snowmelt season (March-June) and monsoon season (July-September). The available meteorological and hydrological data (for 1965-81 period) like daily temperature, daily rainfall, daily discharge (at different sites) and information derived from toposheets and satellite images (for 1975-81 period) have been used in the study. Computer Programs for determination of statistical parameters multiple regression analysis, daily runoff model involving us of Rosenbrock optimization technique have been extensively used and were run on the DEC-2050 computer system of Roorkee University Regional Computer Centre (RURCC). Considerable effort has been made in deriving morphometric and snow cover information from toposheets (scale 1:250,000 and 1:50,000) and interpretation of Landsat MSS 5 images (0.6-0.7 μ wavelength). The important findings and conclusions drawn from the study are summarised below:

1. Hydromorphometric Analysis

The study of hydromorphometric characteristics indicate that the various laws of drainage composition are valid only in a broad sense for the Chenab basin on a regional scale. The basin characteristics like bifurcation ratio, length ratio, area ratio, slope ratio etc. which are supposed to be nearly constant for a basin, have been found to vary from the upper reaches to lower reaches. The upper reaches have very high relief and are marked by parallel drainage pattern, higher bifurcation ratio, shorter mean stream length, low drainage density and high overland flow. The middle and lower reaches exhibit rectangular, rectilinear, contorted and barbed drainage patterns indicating strong geological control. In these reaches, the bifurcation ratios are relatively low and mean stream length very high.

The relationship between cumulative stream length and stream order shows a general decrease in cumulative stream length with increasing stream order. However, some anomalous situation also occur due to effect of channelization of streams along geologically weak plains and tectonic uplift. The basin configuration, studied by computation of circularity ratio, elongation ratio and form factor, is found highly elongated type, as a result of strong structural influence. The study of relief has indicated very high values of relief ratio and ruggedness number. The hypsometric analysis has also indicated a relatively youthful stage of development of the basin, creating lack of hydromorphometric maturity and geometric similarity.

2. Relationships Between Flood/Flow and Hydromorphometric Characteristics

Gross flow/flood characteristics (obtaibed from limited data available) viz. average peak discharge Q_p (m^3/sec), maximum peak discharge Q_{mp} (m^3/sec) and average annual flow Q_{AV} (m^3/sec), each considered as dependent variable, have been related to selected morphologic parameters obtained from analysis of topographic information for 10 sub-basins in the Chenab basin. The multiple regression analysis approach involving use of 'F' test and 't' test has indicated that morphologic parameters like drainage area A (km^2) channel slope S_c (%), drainage density D_d (km^{-1}) and length of main stream channel L_c (km) have significant relationships with flood/flow parameters. Hickok et al parameter ($A/S_c \sqrt{D_d}$) and Gray's parameter ($L_c/\sqrt{S_c}$) are combinations of the above parameters. The drainage area A has also given significant relationships for all three flow/flood parameters. The selected relationships are as below:

(a) In terms of drainage area A

$$Q_p = 0.39701\,(A)^{0.9148}$$

$$Q_{mp} = 0.47241\,(A)^{0.9504}$$

$$Q_{AV} = 41.09\,(A)^{0.8816}$$

(b) In terms of other parameters

$$Q_p = 4.1829 \left[A/S_c \sqrt{D_d}\right]^{0.6726}$$

$$Q_{mp} = 0.862 \left(L_c\right)^{1.456}$$

3. Relationship Between Snowmelt Runoff and Snow Cover Area

The information about extent of snow cover obtained from the Landsat MSS images for months of March to June has been related to snowmelt runoff assumed as total flow minus base flow during these months for different sub-basins in the Chenab basin. A general linear relationship has been obtained using a semilog plot. It has been found that as the catchment size increases the regression lines, fitted for snow cover area and subsequent premonsoon cumulative runoff, are successively right shifted along the X axis. There is also a systematic variation in the slope of the regression lines for different sub-basins. This is related to interplay of several factors like catchment area, permanent snow cover area, average altitude of the sub-basin, relief and channel slope, all of which can be generally considered together in terms of a single parameter i.e. stream order.

The relationships obtained after the analysis of available information about snow cover from satellite images should be useful in predicting subsequent snowmelt runoff in sub-basins of the Chenab basin cummulated upto June 30, if the snow cover area is known at any stage after the end of snow accumulation season i.e. during March to June. The methodology adopted in this analysis is equally applicable for other basins in Himalayas.

4. Modelling of Daily Runoff During March-September Season

The review of important studies of snowmelt process, Himalayan basins and simple snowmelt runoff models indicated some salient features and significant developments. These included: (i) presence of permanent and temporary snow covers in Himalayan basins, (ii) applicability of simple degree day approach under limited data availability condition, (iii) good correlation between snowmelt runoff and snow cover area, (iv) useful information availability from satellite images for difficult terrain situations, (v) contributions from snowmelt to river flows commencing from March and continuing upto September, (vi) change of melt rate with progress of melt season due to various processes including increase in snow density, and (vii) desirability to develop simple model structure with reasonable physical base for Himalayan basins.

The analytic approach of SSARR model of the following form has been found appropriate for expressing the relationship between snow cover depletion of any sub-basin and corresponding snowmelt runoff:

$$\frac{SCA}{100} = 1.00 - \left(\frac{\Sigma Q_{gen}}{100}\right)^{n}$$

The parameter 'n' of this relationship has been found to be related by a straight line relationship with Hickok et al parameter $(A/S_c\sqrt{D_D})$, indicating general increase of 'n' with decrease in value of the Hickok parameter, for the sub-basins of the Chenab basin. Generalised graphical relationships have also been developed between seasonal snowmelt runoff (SSR) in mm over the catchment area excluding permanent snow area and the percentage of temporary snow covered area (SCA) for each sub-basin. The rate of increase of melt rate during melt period from 1st March to 11th September for each sub-basin of the Chenab basin has been found to be related to mean elevation of the sub-basin.

The simple model structure based upon split watershed approach, sub-dividing it into permanent snow covered, temporary snow covered and snow free areas, and also dividing into melt and nonmelt areas using daily data of temperature lapsed at a rate of 6.5°C per 1000 m change in elevation; has given a very good performance in simulating daily flows. Base temperature of 0°C and rain freeze temperature of 0.56°C have been found appropriate. The melt of snow has been computed using simple degree day approach, assuming initial melt rate on 1st March as 0.38 mm/deg° day and varying (increasing) it linearly using appropriate rate for the sub-basin. The model has five parameters to be calibrated by optimization technique using least squares objective criterion, viz. X(1), X(2), and X(3) coefficients to simulate losses from melt water/rain water and X(4), X(5) storage coefficients of linear reservoirs for routing of excess water to catchment outlet.

The results of calibration runs using data of 3 seasons (1975, 1976, 1977) for five sub-basins (Premnagar, Benswar, Bursar, Sirshi-Bridge, Kuriya-Bridge), prediction runs using average parameters for the sub-basins, independent data for 1979 season for Premnagar and using overall regional parameters have all indicated good efficiency and performance of the model. The overall regional values adopted for $X(1) = 0.9100$, $X(2) = 0.8915$ and $X(3) = 0.4965$, are constant for entire basin, while parameters X(4) and X(5) have been found to vary with value of Gray's parameter ($L_c/\sqrt{S_c}$) for the sub-basins. The overall regionalisation of parameters, when tested with independent data sets for Kiyar Nala sub-basin, has further confirmed good performance of the model. In all the cases, the model has given very good reproduction of total seasonal flows for March to September period, however, a general over prediction of flows during premonsoon (March April, May, June) and under prediction of flows during monsoon (July, Aug. Sept.) is indicated. This has been found to be mainly due to poor data base for rainfall and temperature, and assumption of linear increase of melt rate starting from 1st March based upon limited information available, as shown also by typical prediction runs using overall parameters with zero rain fall, % change in rainfall, change in temperature pattern, and change in pattern of variation of melt rate. Though no specific control involving soil moisture modelling has been used for losses from melt water and rain water, comparison of the total losses with baseflows have been found to be reasonable.

The results of analysis of hydromorphometry, satellite images, and use of simple model structure for complex terrain conditions of the Chenab basin with limited data base, have been found to be quite encouraging and would provide useful procedure for systematic studies of snowmelt runoff in this region. With improvement in data availability, it would be possible to further improve the performance of the model.

APPENDIX-I.1

PRECIPITATION STATIONS AVAILABLE IN CHENAB BASIN

Sl. No.	Name of stations	Elevation above m.s.l. (m)	Average annual precipitation (mm)	Sl No.	Name of stations	Elevation above m.s.l. (m)	Average annual precipitation (mm)
1.	Koksar	3204	658.3	8.	Qazigund	1956	1269.4
2.	Gundla	3144	1011.4	9.	Kulgam	1902	769.1
3.	Kyelong	3166	566.1	10.	Banihal	1630	1526.8
4.	Bhadarwa	1643	1399.6	11.	Ramban	945	1194.1
5.	Phalgam	1960	1230.1	12.	Chenani	1122	1470.0
6.	Kokarnagh	1960	970.8	13.	Reasi	585	1484.3
7.	Vernagh	1964	1252.7	14.	Akhnur	331	1215.4

APPENDIX-I.2

SUB-DIVISION OF CHENAB BASIN

Sl. No.	Name of discharge sites	Catchment area (Sq.km.)	Sl. No.	Name of discharge sites	Catchment area (Sq.km.)
1.	Thirot	4537.98	6.	Sirshi-Bridge	3588.12
2.	Arthal	10330.51	7.	Kuriya-Bridge	4812.62
3.	Benswar	11162.19	8.	Premnagar	17622.46
4.	Kiyar Nala	554.99	9.	Dhamkund	20172.64
5.	Bursar	2896.34	10.	Akhnur	22846.96

APPENDIX-II.1

NOTATIONS USED FOR HYDROMORPHOLOGICAL PARAMETERS

A	Drainage area
Au	Area of stream order u
$\bar{A}_u$**	Mean value of A_u
$D.A_c$	Diameter of circle with same area of the basin Under consideration
Dd	Drainage density of the catchment
Du	Drainage density of the basin of stream order,u
F	Form factor
F_s	Stream frequency
H	Elevation difference between the peak and the outlet point
h	Relative height of the particular point of contour above the outlet point
K	Stream order of the trunk segment
L_b	Basin length
L_c	Main channel length
L_t	Cumulative stream length of all the orders
L_{tu}	Cumulative stream length of order u
L	Length of overland flow
Lu	Stream channel segment for order u
No	Total number of stream segments.
Nu	Total number of stream segments of the order u
P	Perimeter
R	Basin relief
R_a	Area ratio
R_b	Bifurcation ratio
R_c	Circularity ratio
R_e	Basin elongation ratio
R_h	Relief ratio
R_l	Length ratio
S_b	Basin shape factor
S_c	Main channel slope
S_g	Ruggedness number
S_u	Channel slope of Stream segment Order u
u	Stream order

* Alphabetic order has been followed in this listing

$\bar{A}_u$** A bar over the notation indicates mean value of the parameter.

APPENDIX-II.2

MEASURED AND COMPUTED HYDROMORPHOMETRIC CHARACTERISTICS OF THE CHENAB BASIN (Scale of Study 1:250,000)

Region 1	u* 2	N_u 3	Lt_u (km) 4	$\bar{L}_u$ (km) 5	$\bar{A}_u$ (km^2) 6	R_b 7	R_1 8	R_a 9
Thirot (A)	1st	748	1400.73	1.88	3.50	6.50	1.86	6.61
	2nd	115	401.70	3.49	23.12	6.05	2.05	4.79
	3rd	19	136.54	7.19	110.83	6.33	6.69	9.74
	4th	3	144.10	48.04	1097.82	3.00	1.10	4.20
	5th**	10	52.28	52.288	4537.98			
Arthal (B)	1st	1909	3944.83	2.07	3.28	6.47	1.71	6.64
	2nd	295	1040.68	3.52	21.77	5.57	2.01	4.85
	3rd	53	375.83	7.09	105.55	5.89	3.65	7.26
	4th	9	232.88	25.88	766.54	4.50	3.62	4.75
	5th	2	187.45	62.48	3643.34	2.00	0.52	2.87
	6th**	1	49.06	49.06	10330.51			
Benswar (C)	1st	2075	4338.33	2.09	3.05	6.18	1.62	6.85
	2nd	336	1138.79	3.39	20.88	5.60	1.98	4.73
	3rd	60	403.50	6.73	98.67	5.45	3.69	6.69
	4th	11	272.70	24.79	660.27	5.50	3.78	5.52
	5th	2	178.80	62.48	3643.34	2.00	0.99	3.25
	6th**	1	93.15	93.15	11191.49			
Prem-nagar (D)	1st	3090	6917.01	2.24	3.16	6.12	1.58	6.37
	2nd	505	1788.63	3.54	20.13	5.21	2.30	5.24
	3rd	97	788.93	8.13	105.46	5.39	2.70	5.90
	4th	18	395.98	22.00	621.89	4.50	3.32	5.17
	5th	4	291.12	72.78	3214.37	4.00	1.87	5.49
	6th**	1	136.01	136.01	17651.71	4.00		

Appendix-II.2 : Contd.

1	2	3	4	5	6	7	8	9
Dhum-kund (E)	1st	3653	8358.33	2.28	3.34	6.00	1.57	5.69
	2nd	609	2188.65	3.59	19.02	5.08	2.23	5.11
	3rd	120	960.01	8.00	97.21	4.80	2.43	5.22
	4th	25	485.29	19.41	507.40	4.17	3.15	5.31
	5th**	5	306.20	61.24	2695.42	6.00	3.08	7.52
	6th	1	188.43	20283.02	6.00	3.08		
Akhnur (F)	1st	4180	9924.73	2.37	3.33	5.62	1.50	5.35
	2nd	743	2687.15	3.62	17.81	4.76	2.28	4.70
	3rd	156	1162.55	7.45	83.77	4.87	2.32	5.27
	4th	32	565.76	17.68	441.21	5.33	3.03	5.51
	5th	6	342.68	57.11	2433.17	6.00	4.87	9.40
	6th	1	278.40	22878.66	22876.66			

** Representing incomplete regime

* Notations as in Appendix-III.1

APPENDIX-II.3

MEASURED AND COMPUTED CHARACTERISTICS OF THE SELECTED SUB-BASINS
(Scale of Study - 1:50,000)

Sub-basin	u	N	Lt_u (km)	$\bar{L}_u$ (km)	$\bar{A}_u$ (km_2)	$\bar{S}_u$ (m/km)	R_b	R_1	R_a	R_s
1	2	3	4	5	6	7	8	9	10	11
I	1st	126	80.1	0.60	0.24	491.34	8.40	2.30	5.79	1.46
	2nd	15	22.0	1.47	1.39	336.74	3.75	2.46	15.24	3.49
	3rd	4	14.5	3.62	21.19	96.55	4.00	1.25	4.20	0.52
	4th	1	4.4	4.40	89.07	186.67				
II	1st	273	152.3	0.56	0.21	535.25	7.38	1.82	8.24	2.20
	2nd	37	37.6	1.02	1.73	243.00	7.40	2.55	9.65	2.13
	3rd	5	13.0	2.60	16.69	114.23	5.00	4.23	7.62	2.82
	4th	1	11.0	11.00	127.15	40.55				
III	1st	4681	3101.8	0.60	0.21	632.65	5.72	1.33	3.88	1.42
	2nd	818	716.4	0.88	0.81	443.97	5.84	2.72	12.71	2.09
	3rd	140	334.4	2.39	10.35	211.88	5.60	2.28	5.64	1.78
	4th	25	147.1	5.45	58.37	118.69	5.00	1.63	3.30	3.28
	5th	5	44.4	8.85	192.35	36.22	5.00	12.50	12.84	2.83
	6th	1	111.0	111.00	2468.85	12.79				
IV	1st	9986	6651.3	0.67	0.23	660.66	5.47	1.34	4.48	1.40
	2nd	1827	1638.3	0.90	1.03	470.54	5.82	2.42	8.44	1.66
	3rd	314	684.0	2.18	8.61	282.51	6.61	2.45	5.92	2.16
	4th	56	299.1	5.34	50.97	130.60	5.60	1.94	4.35	2.62
	5th	10	103.8	10.38	221.87	49.77	5.00	7.27	9.40	3.62
	6th	2	151.0	75.50	2084.18	14.79	2.00	0.32	2.18	2.26
	7th	1	24.5	24.50	4550.41	6.53				

Append.-II.3 :   Contd.

1	2	3	4	5	6	7	8	9	10	11
V	1st	1857	1334.4	0.72	0.23	718.66	5.84	1.22	4.44	1.51
	2nd	321	282.3	0.88	1.20	476.83	6.06	3.09	6.14	1.98
	3rd	53	142.3	2.69	7.37	240.00	5.30	1.56	3.63	1.50
	4th	10	42.0	4.20	63.58	159.88	10.00	13.61	15.85	5.86
	5th	1	57.2	57.17	1008.22	27.25				
VI	1st	360	363.5	0.73	0.33	592.90	5.71	1.62	4.91	1.36
	2nd	63	74.0	1.18	1.62	435.74	4.50	1.52	7.81	2.20
	3rd	14	25.0	1.79	12.65	198.10	4.67	2.42	4.24	2.15
	4th	3	13.0	4.33	66.30	92.31	3.00	2.77	3.74	0.86
	5th	1	12.0	12.00	247.99	107.17				
VII	1st	555.	304.9	0.55	0.24	690.35	5.34	1.47	2.71	1.27
	2nd	104	84.4	0.81	0.65	541.87	5.47	2.04	15.07	1.39
	3rd	19	31.4	1.65	9.80	390.57	3.80	1.39	1.28	1.66
	4th	5	11.4	2.29	12.51	235.58	5.00	5.82	9.49	2.46
	5th	1	12.4	13.32	118.66	95.85				
VIII	1st	23714	15662.1	0.66	0.23	713.97	5.14	1.36	4.13	1.28
	2nd	4617	4158.9	0.90	0.97	555.64	5.75	2.25	7.89	1.68
	3rd	8803	1628.8	2.03	7.63	331.04	5.21	2.29	5.65	1.95
	4th	154	715.8	4.65	43.14	169.53	5.92	2.41	4.92	2.72
	5th	26	291.4	11.21	212.23	62.33	6.50	4.28	7.62	3.11
	6th	4	191.9	47.97	1616.18	20.	4.00	3.32	6.40	2.68
	7th	1	145.0	144.99	10335.85	7.46				

APPENDIX-II.4

CHANNEL SLOPE DRAINAGE DENSITY, STREAM FREQUENCY AND LENGTH OF OVERLAND

Region	N	L_t(km)	h(m)	L_c(km)	S_c(m/km)	D_d(km^{-1})	F_s(Km^{-2})	L_o(km)
Part A : - Scale of Study, 1:250000								
A	886	3139.00	3165	160.50	19.72	0.47	0.19	1.06
B	2270	5830.82	4086	280.99	14.54	0.56	0.22	0.89
C	2487	4633.92	4760	330.00	14.42	0.57	0.21	0.88
D	3718	10317.67	4965	379.00	13.10	0.58	0.21	0.86
E	4417	12485.91	5288	448.15	11.67	0.62	0.22	0.81
E	5122	14961.30	5550	542.80	10.22	0.65	0.22	0.77
F								
Part B : - Scale of Study 1:50000								
I	146	121.03	1536	14.50	105.93	1.36	1.64	0.37
II	316	212.85	1265	15.00	84.33	1.68	2.48	0.30
III	5672	4455.03	2992	136.00	22.00	1.79	2.28	0.28
IV	12196	9551.95	3165	160.50	19.72	2.10	2.68	6.24
V	2242	1858.22	3550	75.42	44.42	1.84	2.22	0.27
VI	441	387.50	3543	28.50	124.32	1.58	1.78	0.32
VII	684	445.51	3258	17.82	182.81	3.76	5.76	0.13
VIII	29319	22793.76	4086	280.99	14.54	2.21	2.84	0.23

APPENDIX-II.5

FACTORS EXPRESSING BASIN CONFIGURATION (Scale of Study - 1:250000)

Notation	Derived By	Source	REGIONS					
			Thirot	Arthal	Benswar	Premnagar	Dhamkund	Akhnur
$A(km^2)$	Measured	S.O.I. Toposheets	4537.99	10330.51	11162.19	17622.46	20172.64	22846.96
$L_b(km)$	-do-	-do-	97.41	186.58	223.50	218.03	267.47	290.06
P (km)	-do-	-do-	397.89	621.41	681.79	885.58	1011.77	1263.72
R (m)	-do-	-do-	3570.00	4491.00	5165.00	5370.00	5833.00	5955.00
$R_h(m/m)$	-do-	-do-	0.03665	0.02407	0.02311	0.02463	0.02106	0.02053
S_g	$D_d(R)$	Horton (1945)	1.68	2.51	2.95	3.11	3.50	3.87
R_c	$\frac{4\pi A}{P^2}$	Miller (1953)	0.36	0.34	0.30	0.28	0.25	0.18
Re	$D.A_c/L_b$	Schumm (1956)	0.82	0.59	0.56	0.62	0.57	0.49
F	$A/(L_b)^2$	Horton (1932)	0.48	0.30	0.22	0.37	0.28	0.27
S_b	L_b^2/A	Horton (1932)	2.08	2.33	4.54	2.70	3.57	3.70

APPENDIX-II.6

HYPSOMETRIC CHARACTERISTICS OF THE CHENAB CATCHMENT

Above M.S.L. (m)	Relative Height (above outlet point) h (m)	Area (above the elevation) (a)(km^2)	Height Ratio ($\frac{h}{H^*}$)	Area Ratio ($\frac{a}{A^{**}}$)
6517 (heighest point in the catchment)	6202	0.00	1.00	0.0
5000	4685	4534.93	0.7554	0.1982
4000	3685	10449.07	0.5942	0.4567
3000	2685	15387.24	0.4329	0.6726
2000	1685	19626.68	0.2717	0.8579
1000	685	22008.3	0.1104	0.9620
315 (elevation of outlet point)	0	22846.96	0	1.000

[*] H - Total height difference between the heighest peak and the outlet point (= 6202 m)

[**] A - Total drainage area of the catchment(= 22846.96 km^2).

APPENDIX-III.1

SPECIFIC METHOD FOR JUDGEMENT CRIETERIA FOR THE REGRESSION RELATIONSHIPS

(i) Parameter Estimation:

The parameters of the multiple regression are estimated by method of least squares for [illegible] the sum of squares of residuals. The sum of squares of residuals is given by the following equation:

$$\epsilon^2 = \sum_{i=1}^{N} (X_1 - X_1')^2 \qquad \ldots(3.7)$$

where,

X_1 = observed value of dependent variable

X_1' = estimated value of dependent variable

Estimated value of the dependent variable is given by:

$$X_1 = B_1 + B_2X_2 + B_3X_3 + \ldots . + B_mX_m \qquad \ldots(3.8)$$

For $\epsilon^2 = 0$

$$[Y] = [X][B]$$

$$[X]^T[Y] = [X]^T[X][B]$$

$$[X^TX]^{-1}[X]^T[Y] = [X^TX]^{-1}[X][B][X]^T$$

$$[B] = [X^TX]^{-1}[X]^T[Y]$$

where,

[B] = Matrix containing M regression coefficients

[X] = (NxM) matrix containing independent variables

[Y] = (Nx1) matrix containing dependent variable

(ii) Statistics Calculated in the Program for Multiple Regression

Formulae used for the calculation of various statistics are given in subsequent sections:

(a) Mean of the variable (dependent or independent)

$$\bar{X} \quad \frac{\sum\limits_{i=1}^{N} X_i}{N} \qquad \ldots(3.9)$$

where

$\bar{X}$ = mean

X_i = i^{th} value of variable

N = total number of observations

(b) Standard deviation

$$\sigma = \left(\frac{\sum\limits_{i=1}^{N} (X_i - \bar{X})^2}{N-1}\right)^{1/2} \qquad \ldots(3.10)$$

where,

σ : Standard deviation

(c) Correlation X v/s Y

$$r_{x,y} = \frac{S_{xy}}{S_x \; S_y}$$

$$= \frac{\sum\limits_{i=1}^{N} (X_i . \bar{X})(Y_i - \bar{Y})/N-1}{\sqrt{\frac{1}{N-1} \sum\limits_{i=1}^{N} (X_1 - \bar{X})^2} \; \sqrt{\frac{1}{N-1} \sum\limits_{i=1}^{N} (Y_i - \bar{Y})^2}}$$

$$= \frac{\sum\limits_{i=1}^{N} (X_i - \bar{X})(Y_i - \bar{Y})}{\left(\sum\limits_{i=1}^{N} (X_i - \bar{X})^2 \; \sum\limits_{i=1}^{N} (Y_i - \bar{Y})^2 \right)^{1/2}} \qquad \ldots(3.11)$$

where,

$r_{x,y}$ = Correlation X v/s Y

(d) Regression coefficient

Regression coefficients are calculated by the method of least squares

(e) Standard error of regression coefficient

$$S_{b_i} = \frac{S_1}{S_i}\sqrt{\frac{1}{(N - M)(1-R_1^2)}} \qquad \ldots(3.12)$$

where

S_{b_i} Standard error of i^{th} regression coefficient

S_1 = Standard deviation of residuals

S_i = Standard deviation of X_i

R_i = Multiple correlation coefficient of X_i with respect to all variables except the variable X_i

(f) T value

$$\text{T value} = \frac{\text{regression coefficient}}{\text{standard error of regression coefficient}} \qquad \ldots(3.13)$$

(g) Sum of squares due to regression

$$SSDR = \sum_{i=1}^{N} (X_1' - \bar{X}_1)_1^2 \qquad \ldots(3.14)$$

where, SSDR = Sum of squares due to regression

X_1' = Estimated value of dependent variable

$\bar{X}_1$ = Mean of dependent variable

(h) Sum of squares from regression:

$$SSFR = \sum_{i=1}^{N} (X_1 - X')^2 \qquad \ldots(3.15)$$

Where, SSFR : Sum of square from regression

X_1 : Observed value of dependent variable

(i) Mean squares due to regression

$$\text{Mean squares due to regression} = \frac{\text{Sum of squares due regression}}{\text{Number of degrees of freedom}} \quad \ldots(3.16)$$

Number of degrees of freedom will be equal to number of independent variables

(i) Mean squares from regression

$$\text{Mean squares from regression} = \frac{\text{Sum of squares from regression}}{\text{Number of degrees of freedom}} \quad \ldots(3.17)$$

Number of degrees of freedom will be equal to N-M

(k) Multiple correlation coefficient

This is the square root of coefficient of determination.

$$\text{Multiple correlation coefficient} = \sqrt{R^2}$$

$$= \sqrt{\frac{\text{Sum of squares due to regression}}{\text{Sum of squares about mean}}}$$

$$= \sqrt{\frac{\sum_{i=1}^{N} (X_1-\bar{X}_1)^2}{\sum_{i=1}^{N} (X_1-\bar{X}_1)^2}} \quad \ldots(3.18)$$

Sum of squares about the mean is the sum of squares due to regression and sum of squares from the regression.

(l) Standard error of estimate

$$\text{Standard error of estimate} = \sqrt{\text{Mean square from regression}}$$

$$= \sqrt{\sum_{i=1}^{N} (X_1-X_1')^2/(N-M)} \quad \ldots 3.19)$$

(m) F value

$$\text{F value} = \frac{\text{Mean squares due to regression}}{\text{Mean squares from regression}} \quad ...(3.20)$$

(iii) Tests of Hypothesis:

F-Tests : A test of the hypothesis that the regression equation is not explaining a significant amount of variation in X_1 can be made by calculating the F value, which is the ratio of mean squares due to regression to mean squares from regression.

The hypothesis is rejected if F value for the regression equation exceeds $F_{1-\alpha, M-1, N-M}$ where $(1-\alpha)$ is the confidence level. In other words regression equation explains significant amount of variation in X_1 if F value is greater than $F_{1-\alpha, M-1, N-M}$.

T-Test: A test of hypothesis that the i^{th} independent variable is not contributing significantly to explain the variation in dependent variable is made by calculating the T-value. The hypothesis is rejected at $1-\alpha$ probability level if t-value exceeds $t_{1-\alpha/2, N-M}$. In other words i^{th} variable is significant at $1-\alpha$ level if t value is greater than $t_{1-\alpha/2, N-M}$.

The values of cumulative F distribution for ν_1 (numerator (M-1) and ν_2 (denominator (N-M)), and percentile values ($t_{\alpha,}$) for the t distribution with degrees of freedom are given in the statistical tables (Pearson 1976).

APPENDIX-IV. 1

AVAILABLE LANDSAT IMAGES ON CHENAB BASIN

Sl. No.	Date	Path and Row	Sun Elevation (Degree)	Azimate Angle (Degree)	Cloud Cover %
1	2	3	4	5	6
1.	3-3-75	159-037	38	134	10
2.	10-11-75	-do-	33	148	00
3.	2-4-76	-do-	48	125	10
4.	20-4-76	-do-	53	118	10
5.	8-5-76	-do-	57	111	10
6.	13-6-76	-do-	59	100	10
7.	11-9-76	-do-	48	126	10
8.	10-3-77	-do-	38	128	00
9.	15-4-77	-do-	49	117	30
10.	21-5-77	-do-	56	103	10
11.	19-8-77	-do-	49	111	30
12.	18-3-79	-do-	41	128	10
13.	5-4-79	-do-	48	122	10
14.	7-6-79	-do-	60	102	10
15.	16-6-79	-do-	59	99	10
16.	12-4-81	-do-	51	122	02
17.	18-5-81	-do-	60	102	05
18.	5-6-81	-do-	59	108	05
19.	9-4-75	160-036	50	126	10
20.	4-1-76	-do-	24	146	00
21.	22-1-76	-do-	26	143	10
22.	9-2-76	-do-	30	139	20
23.	27-2-76	-do-	35	135	10
24.	27-5-76	-do-	59	107	10
25.	18-10-76	-do-	32	141	00
26.	5-11-76	-do-	32	145	00
27-	16-1-76	-do-	24	142	10

Appendix-IV.1 : Contd.

1	2	3	4	5	6
28.	16-4-77	160-036	49	118	10
29.	22-6-78	-do-	56	109	10
30.	26-3-81	-do-	41	129	20
31.	1-5-81	-do-	56	117	02
32.	19-5-81	-do-	59	110	02
33.	5-6-81	-do-	60	105	05
34.	13-5-75	158-037	59	110	00
35.	18-6-75	-do-	60	100	10
36.	14-3-76	-do-	41	138	10
37.	1-4-76	-do-	47	125	00
38.	9-3-77	-do-	37	128	10
39.	27-3-77	-do-	43	123	10
40.	2-5-77	-do-	53	110	20
41.	18-8-77	-do-	49	110	20
42.	11-8-78	-do-	60	102	20
43.	29-6-78	-do-	60	100	20
44.	22-4-79	-do-	53	116	10
45.	11-4-81	-do-	51	122	02

```
                                   APPENDIX:V(1)            PAGE: 1

    AREA-ELEVATION RELATIONSHIP FOR PREM NAGAR SUB-BASIN
   *******************************************************
          AREA(SQ. KM)
 17622.46  17413.40  17204.34  16995.28  16786.22  16577.16
 16352.26  16082.26  15812.26  15542.26  15272.26  14994.46
 14694.46  14362.99  14021.59  13680.19  13270.67  12667.27
 12066.46  11415.79  10766.46  10156.06   9516.06   8876.06
  8223.45   7566.86   6980.70   6595.02   6143.74   5671.74
  5222.36   4837.36   4442.44   4019.28   3596.13   3172.97
  2803.95   2589.00   2374.05   2109.66   1829.66   1566.30
  1350.30   1134.30    953.90    784.75    629.72    514.87
   400.02    305.58    217.58    145.85    120.44     95.03
    69.62     44.21     18.80      0.00
          ELEVATION(METRE)
  6574.00   6474.00   6374.00   6274.00   6174.00   6074.00
  5974.00   5874.00   5774.00   5674.00   5574.00   5474.00
  5374.00   5274.00   5174.00   5074.00   4974.00   4874.00
  4774.00   4674.00   4574.00   4474.00   4374.00   4274.00
  4174.00   4074.00   3974.00   3874.00   3774.00   3674.00
  3574.00   3474.00   3374.00   3274.00   3174.00   3074.00
  2974.00   2874.00   2774.00   2674.00   2574.00   2474.00
  2374.00   2274.00   2174.00   2074.00   1974.00   1874.00
  1774.00   1674.00   1574.00   1474.00   1374.00   1274.00
  1174.00   1074.00    974.00    900.00
    AREA-ELEVATION RELATIONSHIP FOR BENSWAR SUB-BASIN
   *************************************************
          AREA(SQ. KM)
 11162.19  10943.62  10725.05  10506.45  10287.92  10069.35
  9821.37   9567.37   9313.37   9059.37   8805.37   8540.86
  8272.15   7999.29   7726.44   7453.59   7077.96   6680.19
  6269.19   5835.86   5305.69   4777.27   4253.27   3789.68
  3448.75   3107.81   2780.01   2489.59   2269.59   2049.59
  1788.09   1518.09   1343.08   1187.53   1031.98    876.43
   754.44    639.32    339.75    471.75    403.75    349.03
   297.03    245.29    194.07    142.85    115.23     92.45
    73.89     63.89     53.89     41.22     28.03     14.80
     1.59      0.00
```

```
        ELEVATION(METRE)
 6517.00   6417.00   6317.00   6217.00   6117.00   6017.00
 5917.00   5817.00   5717.00   5617.00   5517.00   5417.00
 5317.00   5217.00   5117.00   5017.00   4917.00   4817.00
 4717.00   4617.00   4517.00   4417.00   4314.00   4217.00
 4117.00   4017.00   3917.00   3817.00   3717.00   3617.00
 3517.00   3417.00   3317.00   3217.00   3117.00   3017.00
 2917.00   2817.00   2717.00   2617.00   2517.00   2417.00
 2317.00   2217.00   2117.00   2017.00   1917.00   1817.00
 1717.00   1617.00   1517.00   1417.00   1317.00   1217.00
 1117.00   1105.00
AREA-ELEVATION RELATIONSHIP FOR KURIYA-BRIDGE SUB-BASIN
********************************************************
        AREA(SQ. KM)
 4812.62   4790.20   4767.78   4745.36   4722.93   4700.51
 4678.09   4655.67   4633.25   4609.14   4565.66   4522.19
 4472.18   4420.32   4364.08   4257.42   4128.52   3983.52
 3792.70   3568.70   3346.86   3146.62   2946.62   2729.98
 2504.11   2310.63   2119.02   1949.42   1784.42   1620.74
 1472.78   1324.78   1201.13   1095.11    988.46    874.48
  760.49    662.91    577.19    491.48    407.29    340.62
  281.00    226.69    173.62    135.61     97.59     59.95
   26.62     10.94      8.09      5.22      2.35      0.00
        ELEVATION(METRE)
 6392.00   6292.00   6192.00   6092.00   5992.00   5892.00
 5792.00   5692.00   5592.00   5492.00   5392.00   5292.00
 5192.00   5092.00   4992.00   4892.00   4792.00   4692.00
 4592.00   4492.00   4392.00   4292.00   4192.00   4092.00
 3992.00   3892.00   3792.00   3692.00   3592.00   3492.00
 3392.00   3292.00   3192.00   3092.00   2992.00   2892.00
 2792.00   2692.00   2592.00   2492.00   2392.00   2292.00
 2192.00   2092.00   1992.00   1892.00   1792.00   1692.00
 1592.00   1492.00   1392.00   1292.00   1192.00   1110.00
```

```
 AREA-ELEVATION RELATIONSHIP FOR SIRSHI-BRIDGE SUB-BASIN
*************************************************************
       AREA(SQ. KM)
3588.12   3488.12   3388.12   3288.12   3188.12   3088.12
2988.12   2888.12   2788.12   2688.12   2588.12   2488.12
2388.12   2288.12   2188.12   2088.12   1988.12   1888.12
1788.12   1688.12   1588.12   1488.12   1388.12   1288.12
1188.12   1088.12    988.12    888.12    788.12    688.12
 588.12    488.12    388.12    288.12    188.12    135.45
 102.12     68.79     37.04     23.55     10.84      7.24
   3.64      0.00
       ELEVATION(METRE)
6392.00   5882.29   5440.00   5200.00   5007.59   4895.00
4791.30   4704.35   4617.39   4561.90   4514.29   4466.67
4419.05   4371.43   4323.81   4280.00   4240.00   4200.00
4150.00   4100.00   4050.80   4001.61   3920.54   3850.00
3775.00   3700.00   3616.67   3533.33   3445.45   3346.00
3231.50   3110.50   3000.60   2773.68   2619.05   2492.00
2392.00   2292.00   2192.00   2092.00   1992.00   1892.00
1792.00   1691.00
AREA-ELEVATION RELATIONSHIP FOR BURSAR SUB-BASIN
**********************************************************
       AREA(SQ. KM)
2896.34   2796.34   2696.34   2596.34   2496.34   2396.34
2296.34   2196.34   2096.34   1996.34   1896.34   1796.34
1696.34   1596.34   1496.34   1396.34   1296.34   1196.34
1096.34    996.34    896.34    796.34    696.34    596.34
 496.34    396.34    296.34    196.34     96.34      0.00
       ELEVATION(METRE)
6392.00   5797.33   5321.43   4990.00   4889.47   4786.36
4696.36   4623.64   4550.91   4482.63   4424.74   4366.84
4308.95   4247.93   4183.78   4119.63   4055.49   3987.51
3895.01   3802.50   3710.00   3608.00   3506.00   3398.75
3286.25   3165.00   3044.75   2870.00   2650.00   2110.00
```

```
 AREA-ELEVATION RELATIONSHIP FOR KIYAR-NALA  SUB-BASIN
*****************************************************************
       AREA(SQ. KM)
 554.99     550.53     546.06     540.65     534.93     529.22
 523.22     516.42     509.62     505.56     502.36     495.66
 478.99     467.35     457.30     447.26     434.82     415.60
 395.03     372.26     346.67     312.80     273.60     234.40
 200.98     196.40     142.37     128.35     116.17     104.57
  93.26      82.76      72.89      64.79      56.70      48.61
  40.84      33.99      27.13      21.99      17.39      13.21
  10.21       7.21       5.31       3.77       2.39       1.52
   0.65       0.00
       ELEVATION(METRE)
6574.00    6474.00    6374.00    6274.00    6174.00    6074.00
5974.00    5874.00    5774.00    5674.00    5574.00    5474.00
5374.00    5274.00    5174.00    5074.00    4974.00    4874.00
4774.00    4674.00    4574.00    4474.00    4374.00    4274.00
4174.00    4074.00    3974.00    3874.00    3774.00    3674.00
3574.00    3474.00    3374.00    3274.00    3174.00    3074.00
2974.00    2874.00    2774.00    2674.00    2574.00    2474.00
2374.00    2274.00    2174.00    2074.00    1974.00    1874.00
1774.00    1700.00
```

TEMPERATURE CHARACTERISTICS AT [illegible],EL=103[illegible] (M)

MONTH :- MARCH

DAY	MEAN	STDEV	SKEW
1	5.99	2.42	-0.5030
2	7.07	2.35	-0.1926
3	6.28	3.27	-0.8359
4	9.1[illegible]	3.35	-0.3810
5	7.75	3.62	-0.3949
6	7.86	3.73	0.0279
7	7.85	3.69	-0.1254
8	7.9[illegible]	3.79	-0.1613
9	7.98	4.35	-0.1240
10	9.13	4.21	-0.1131
11	8.62	4.08	0.0442
12	8.68	[illegible]	0.0546
13	9.74	[illegible]	0.3709
14	10.15	3.25	0.0423
15	10.8[illegible]	3.25	0.1731
16	[illegible]	3.52	0.0591
17	10.33	4.27	-0.3278
18	10.57	3.99	-0.3286
19	9.51	2.69	0.9809
20	9.30	2.65	0.6190
21	10.22	3.77	-0.5595
22	10.22	3.66	0.2602
23	10.93	3.17	0.3797
24	11.09	3.43	-0.3635
25	12.12	3.23	0.3566
26	11.85	3.27	-0.5856
27	11.42	4.26	-0.7492
28	11.62	3.01	-0.8050
29	11.19	3.41	-0.6381
30	11.48	4.08	-0.9216
31	11.09	3.14	-0.1742

MONTH :- APRIL

DAY	MEAN	STDEV	SKEW
1	12.11	3.94	-0.4821
2	12.46	3.30	-0.8101
3	12.68	3.15	0.2636
4	13.41	2.92	0.5849
5	12.93	2.76	-0.2209
6	13.36	3.59	-1.0481
7	13.69	3.15	-0.3199
8	13.61	3.26	-0.8241
9	13.70	3.54	-1.1199
10	1[illegible].54	2.99	-0.6541
11	1[illegible].44	3.[illegible]3	-0.5655
12	15.[illegible]1	2.68	0.1239
13	15.39	2.86	0.0641
14	1[illegible].97	3.28	-1.[illegible]136
15	1[illegible].16	2.36	-1.1122
16	15.[illegible]1	2.[illegible]1	0.1691
17	15.21	2.44	-0.6948
18	15.3[illegible]	3.[illegible]2	-1.0146
19	1[illegible].[illegible]9	2.82	-0.8011
20	15.1[illegible]	3.[illegible]6	-0.3778
21	15.37	3.28	-0.6548
22	15.[illegible]2	2.[illegible]3	0.1249
23	15.52	2.83	0.1825
24	15.[illegible]5	2.99	-0.3673
25	1[illegible].62	2.66	-0.2836
26	17.[illegible]2	2.99	-0.3719
27	17.23	2.76	-0.[illegible]125
28	16.69	3.07	-0.5181
29	15.[illegible]6	2.95	-0.8552
30	15.11	3.10	-1.3965

MONTH :- MAY

DAY	MAX	STDEV	SKEW
1	16.22	3.51	-1.2295
2	16.89	3.03	-1.1919
3	17.01	3.05	-0.3838
4	16.69	3.67	-0.7904
5	16.51	2.82	-1.1613
6	15.95	3.02	-0.9605
7	15.64	2.72	-0.1776
8	16.58	3.24	-0.7991
9	17.36	2.16	-0.2730
10	16.79	3.75	-0.7004
11	17.22	2.48	-0.1767
12	17.51	2.26	-0.4260
13	17.25	2.87	-0.3372
14	15.24	3.10	-0.0108
15	16.32	3.37	-0.0987
16	17.02	2.91	0.2611
17	17.09	2.99	-0.2656
18	18.65	2.31	-1.0027
19	19.26	1.98	-0.2137
20	16.76	2.27	0.1722
21	16.31	2.54	0.2036
22	18.33	3.03	0.0456
23	17.66	3.68	-1.4532
24	19.29	3.59	-0.9455
25	18.65	2.60	-0.3625
26	18.56	3.42	-1.5697
27	19.60	3.21	-0.5377
28	19.24	2.93	-1.2555
29	19.00	3.10	-1.7142
30	19.65	2.37	-0.5982
31	20.77	2.55	-0.1833

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       MONTH   :- JUNE
       --------------------

DAY         MEAN          STDEV         SKEW
----        -----          ----         ----
  1         20.29          2.01        0.5539
  2         20.17          4.05       -0.3341
  3         19.09          2.39        1.2919
  4         21.00          2.93        0.4675
  5         20.58          2.37        0.6908
  6         20.56          3.37       -1.4568
  7         20.03          3.25       -1.7780
  8         20.71          2.46        0.4083
  9         20.65          2.50       -0.3156
 10         19.94          2.59        0.7640
 11         20.73          2.48        1.1973
 12         21.08          2.38        0.9786
 13         20.30          2.15       -1.0230
 14         20.26          2.01       -0.3948
 15         20.55          2.27       -0.1677
 16         20.66          2.99       -0.1132
 17         21.37          2.28       -0.8269
 18         21.02          2.45       -1.3489
 19         22.39          2.91       -2.1191
 20         22.56          2.76       -2.3257
 21         22.87          1.57       -0.5000
 22         22.09          2.90       -0.5256
 23         22.90          2.33       -0.5250
 24         22.01          4.00       -1.6001
 25         21.93          3.82       -2.1423
 26         22.52          3.17       -1.6597
 27         23.07          2.51       -1.2615
 28         23.37          2.03       -1.0982
 29         23.74          1.74       -0.2652
 30         22.55          2.53       -1.8832
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      MONTH    :- JULY
      ------------------

 DAY            MEAN            STDEV           SKEW
 ----           -----           ----            ----
   1            23.22           1.60           -1.0018
   2            22.93           2.10           -1.7543
   3            21.99           1.35            0.0653
   4            22.[illegible]4           2.74           -0.8854
   5            22.1[illegible]           1.59           -0.1887
   6            22.2[illegible]           1.79           -0.6059
   7            23.[illegible]9           1.75            1.[illegible]056
   8            23.[illegible]7           1.67           -0.2250
   9            22.94           1.31           -[illegible].[illegible]399
  10            22.65           1.35           -1.5016
  11            23.42           1.91           -0.1803
  12            23.53           [illegible].97           -[illegible].3319
  13            23.[illegible]2           1.[illegible]           -[illegible].7547
  14            22.[illegible]3           1.68           -1.2002
  15            22.73           2.37           -[illegible].9484
  16            21.87           2.[illegible]2           -1.[illegible]482
  17            21.53           2.71           -[illegible].[illegible]237
  18            22.54           1.[illegible]5           -[illegible].[illegible]172
  19            23.[illegible]7           1.57           -1.7811
  20            23.18           1.57           -0.[illegible]570
  21            22.81           1.13           -0.2191
  22            22.61           2.[illegible]1           -1.1398
  23            23.56           2.[illegible]9           -1.5066
  24            22.62           2.59           -1.6239
  25            22.31           2.74           -0.[illegible]636
  26            22.[illegible]6           1.67           -[illegible].2821
  27            21.96           1.24           -0.0401
  28            22.3[illegible]           1.39           -1.9622
  29            22.31           1.96           -1.4446
  30            22.13           1.51           -0.6751
  31            22.64           1.91           -0.1953
```

DATA :- AUGUST

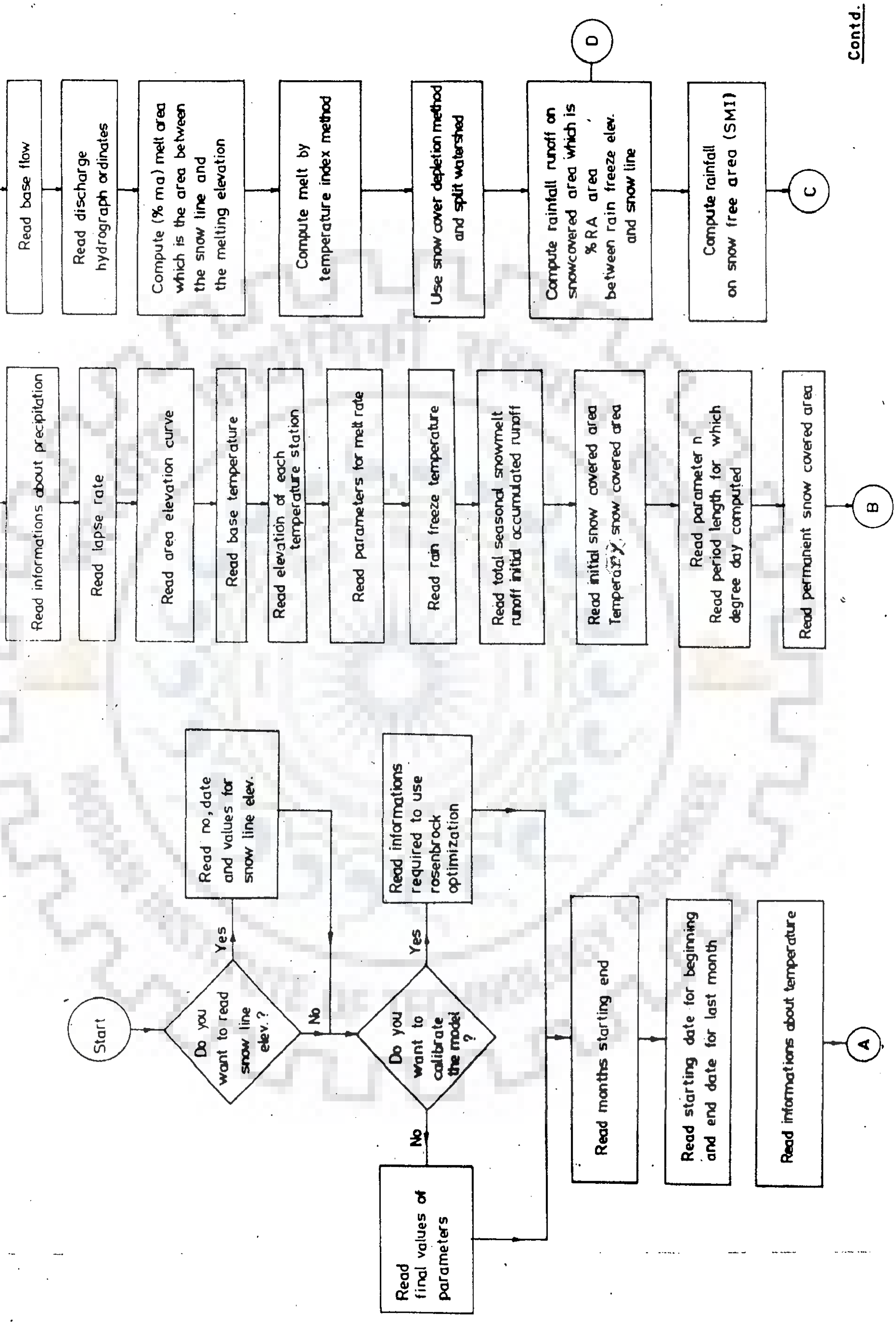
DAY	MEAN	STDEV	SKEW
1	22.78	2.87	-2.1964
2	23.12	3.29	-2.4826
3	22.94	1.32	-1.9712
4	23.49	1.12	-1.4208
5	22.11	1.24	-0.7817
6	21.61	2.58	-0.8865
7	21.96	3.15	-0.7617
8	22.63	2.92	-0.3383
9	21.57	1.26	-1.6899
10	21.63	2.14	-0.2341
11	22.34	1.45	-0.5467
12	23.19	1.44	-0.6495
13	22.51	1.77	-0.4710
14	22.53	1.67	-1.0660
15	22.12	1.37	-0.4748
16	22.23	1.51	-0.1061
17	22.73	3.40	1.3530
18	22.01	1.51	-0.2894
19	21.78	1.47	-0.7878
20	22.03	1.21	-0.6185
21	2[illegible].67	2.[illegible]1	-0.1757
22	21.61	1.68	-0.9479
23	21.12	2.04	0.4281
24	20.97	2.62	0.9623
25	21.73	1.92	-0.1845
26	21.27	1.38	-0.7579
27	21.72	1.05	0.4837
28	21.48	0.82	0.6437
29	20.65	2.49	-1.9633
30	2[illegible].77	1.33	-1.5153
31	21.[illegible]	1.76	[illegible].0848

MONTH :- SEPTEMBER

DAY	MEAN	STDEV	SKEW
1	21.03	1.14	-0.7556
2	21.35	0.87	-0.2204
3	20.01	1.57	0.6873
4	19.04	2.08	-0.2670
5	19.82	2.06	-0.1857
6	20.37	1.25	-1.2906
7	20.19	1.27	0.5797
8	19.71	1.83	-0.7978
9	20.01	1.67	0.4863
10	19.99	1.06	0.6346
11	18.35	2.44	-0.0165
12	19.13	1.10	0.1237
13	19.58	1.18	0.0953
14	19.12	1.52	-1.5851
15	19.55	2.12	-1.0183
16	19.25	1.04	1.3599
17	19.41	2.23	-1.3391
18	18.84	2.02	-0.9907
19	18.56	1.62	-0.2500
20	17.69	2.01	-1.8782
21	18.79	0.92	0.1794
22	18.74	1.54	-1.0326
23	18.82	1.26	-0.0963
24	19.02	1.71	-0.7207
25	19.28	2.20	-2.1453
26	18.27	1.98	-0.3693
27	17.79	1.96	-0.2320
28	18.07	1.34	0.0050
29	17.93	1.57	-0.3480
30	17.97	1.35	0.6502

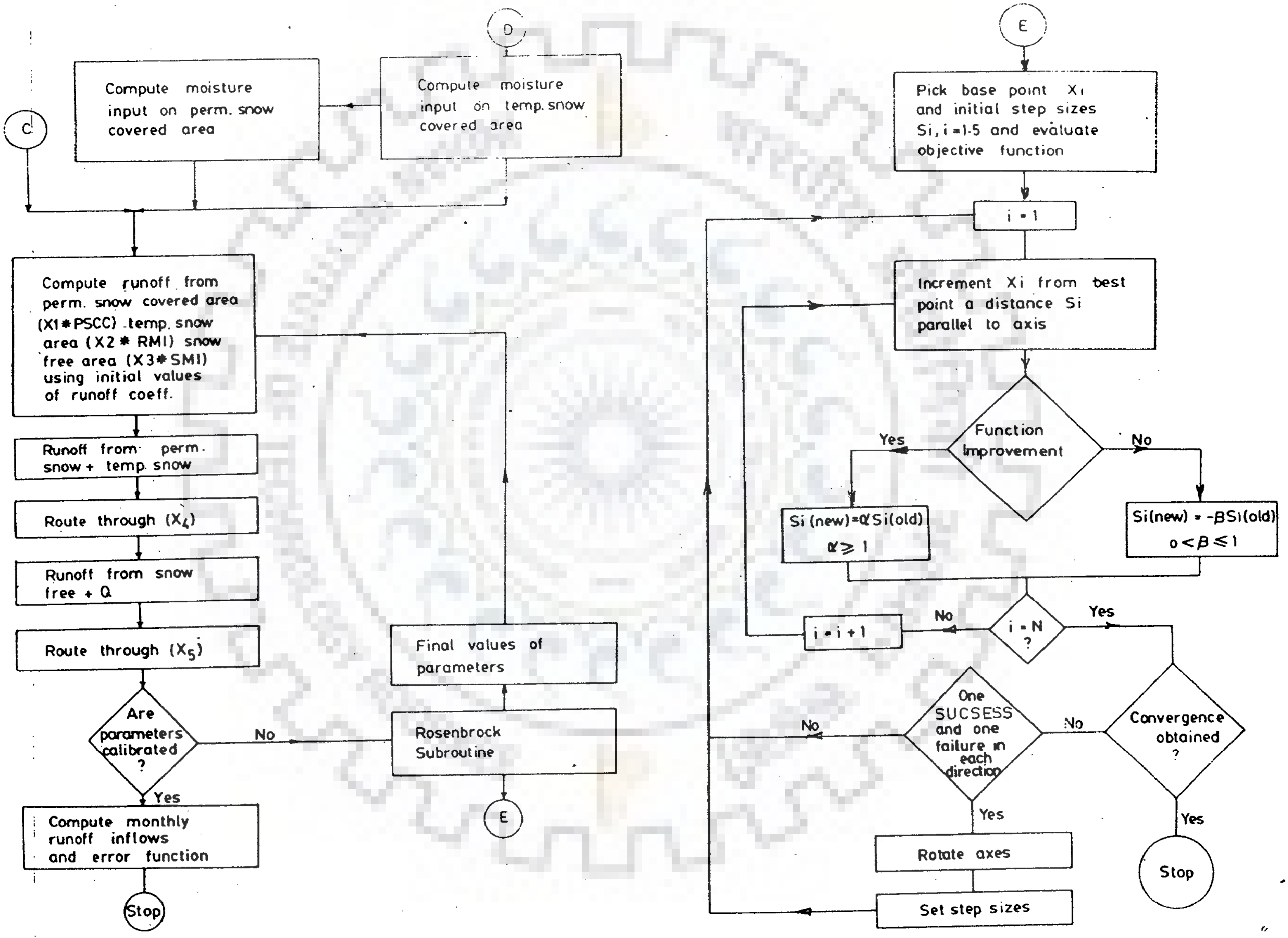
APPENDIX V-3(i)

FLOW CHART FOR RUNOFF MODEL



Contd.

APPENDIX V-3 (ii)



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WILLIAMS, Jr., R.S. and CARTER,W.D.(1976),ERTS-1, A new Window on Our Planet, U.S.Geol.Surv.Prof.Pap.929.

i) For 1975, 1976, 1977 and 1979 seasons for Premnagar;

For the 1975, 1976 and 1977 seasons for which data was used in calibration, the use of overall parameters resulted in change in range of efficiency values from 77.0% to 86.43% which compares well with corresponding values of 74.12% to 86.87% for average parameters and 80.81% to 86.10% for calibrated parameters. The summarised results are given in Tables-5.18 to 5.20 and computed hydrographs are plotted in Figs. 5.15 to 5.17, which clearly indicate good performance of overall parameters.

For the independent data set of 1979 season, the use of overall parameters gave a higher efficiency value of 74.28% in comparison to 71.23% for average parameter values (Table-5.21, Fig. 5.11). Inspite of only 3 seasons data used, the performance on independent data set is very good as indicated by values of error parameters, total seasonal flows, monthly flows and computed position of snow line.

ii) For 1975, 1976 and 1977 seasons for Benswar, Bursar, Sirshi Bridge and Kuriya Bridge.

The results of prediction runs for three seasons for these sub-basins are also summarised in Tables-5.18 to 5.20 and 5.25 alongwith the results for calibration runs and prediction runs with average parameters.

In general, the overall parameters gave a good performance (Figs. 5.18-5.21), both on the basis of comparison with observed values, and also with results of calibration runs and prediction runs with average parameter.