RAINFALL RUNOFF MODELLING IN THE MOUNTAINOUS CATCHMENTS

1.0 INTRODUCTION

Modelling of rainfall runoff for the mountainous regions is considered more difficult than the plain regions. The complexity increases as the altitude increases because of significant variability in meteorological variables used in the model. Further nonavailability of required data is also one of the severe problem for the mountainous watersheds. The network becomes poorer and poorer as the altitude increases. Installation and maintenance of hydrometeorological instruments at high altitude regions is one of the challenging problem in the mountain areas. This lecture deals with the application of the UBC (University of British Columbia) Watershed model to one of the Indian mountainous basin. Attempts are made to describe the structure of the UBC watershed model. Basic problems related with modelling of rainfall-runoff are discussed.

2.0 UBC WATERSHED MODEL AND IT'S STRUCTURE

This model has been developed for mountainous areas where data is usually scarce, particularly at higher elevations and designed to give a computational representation of watershed behaviour using daily values of maximum and minimum temperatures and precipitation. The model calculates the time distribution of streamflow leaving the catchment as a result of rainfall. Given continuous meteorological input data, the model operates continuously and produces estimates of daily streamflows. However, the model is able to compute the contribution from snow and glaciers also, but this presentation is restricted to only a rain fed basin or rain fed part of the basin. Other aspects of this moisture budget status are soil moisture, evaporation and the quantities of water in the various runoff storage systems. For calibration and verification purposes, the model uses the daily records of measured streamflow as reference data and calculates performance statistics of volume and shape reconstitution.

A major aspect of this model is therefore its capability to interpret meteorological data at a point in terms of basin wide conditions. Assumptions must be made concerning temperature and precipitation distribution by elevation and by area. Algorithms are described which carry out these functions and an important part of model calibration is the determination of suitable control parameter values to describe these processes.

The basic structure of the model depends on a division of the watershed into a number of elevation bands. The elevation increment for each band is the same and an area for each band is specified. The model has been used for watersheds ranging from a few square kilometers up to areas of several thousand square kilometers. The factors influencing choice of watershed size are the available streamflow reference data for calibration and the available meteorological data base. The general structure of the Watershed Model is indicated in the flow chart in Fig.1.

3.0 METEOROLOGICAL DATA DISTRIBUTION ALGORITHMS

As discussed above, in general, the meteorological data base is sparse for most of the mountainous regions modelled. In the majority of situations the meteorological data is from valley stations. Moreover, meteorological data are available as point values at given elevations in a watershed. As a result of these data constraints, an important aspect of the Watershed Model is the elevation distribution of data. Therefore, before watershed response calculations can be made, these meteorological data at a point must be distributed to the mid-elevation points of elevation bands.

Functional relationships are specified describing the variability of temperature lapse rates.

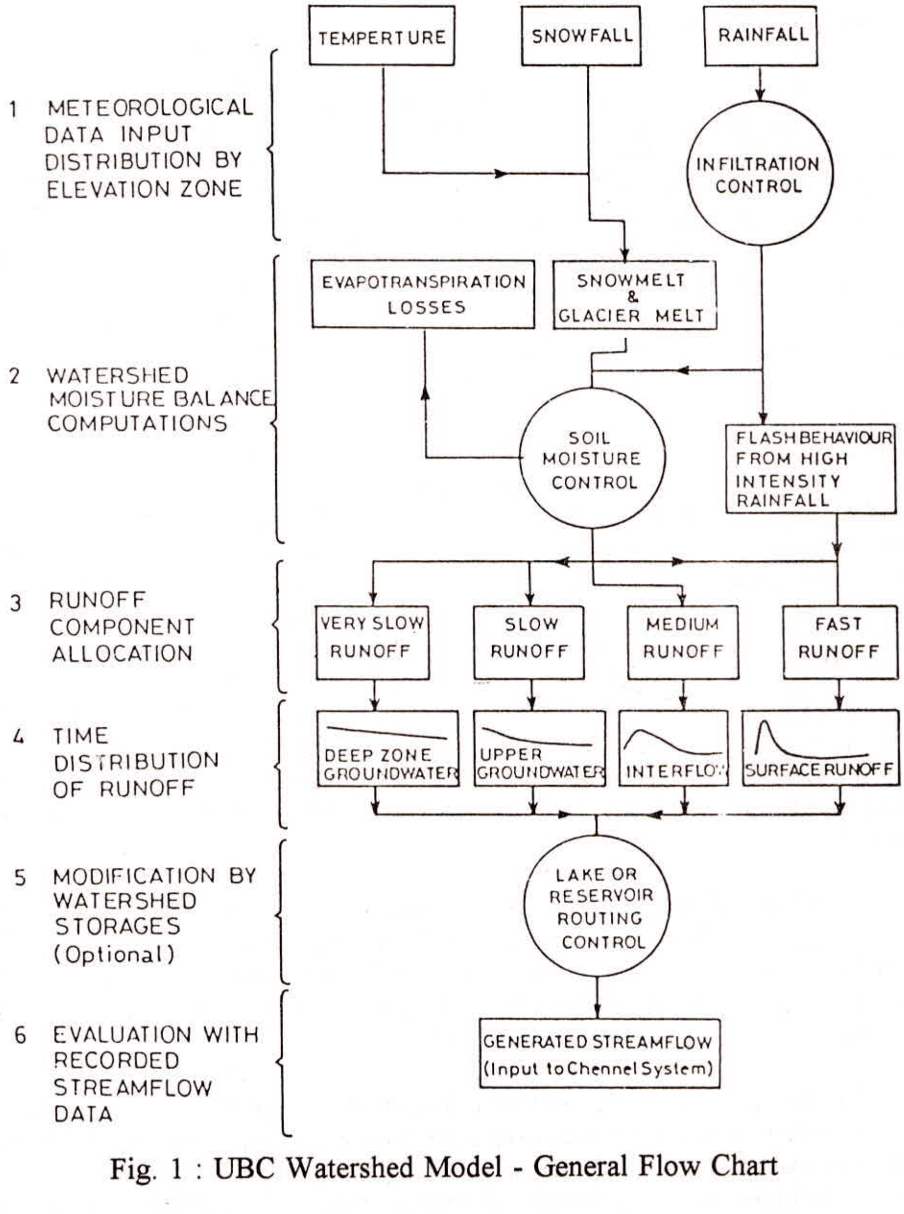

Fig. 1 : UBC Watershed Model - General Flow Chart

Precipitation inputs are made functionally dependent on elevation and on temperature regime. This functional variation of precipitation automatically recognizes that precipitation undergoes greater orographic enhancement in winter than it does during warm summer rainstorms. The importance of these temperature and precipitation gradients is illustrated in the Watershed calibration examples.

a) Temperature lapse rate

The temperature lapse rate is a key relationship because it influences the evaporation losses from the different parts of the basin. Lapse rates are known to be quite variable, ranging from high values of about the dry adiabatic lapse rate to low values representing inversion conditions. A complete and detailed representation of this lapse rate variability is not possible, but the main features of lapse rate can be represented as a function of daily temperature range.

The following major features of lapse rate variation are recognised in the temperature lapse rate algorithm:

i) During continuous rainstorm conditions the lapse rate will approximate the saturated adiabatic rate. Under these conditions the daily temperature range will tend to be zero or very low.

ii) Under clear sky, dry weather conditions, the lapse rate during the warm part of the day will tend to the dry adiabatic rate. During the night, under these clear sky conditions, radiation cooling will cause the temperatures to fall to the dew point temperature, and this is particularly true for a moist air mass. As a result, night-time lapse rates under clear skies will tend to be quite low, and at times even zero lapse rates will occur.

Based on these considerations, two lapse rates are specified in the model, one for the maximum temperature and one for the minimum temperature. The lapse rate is calculated for each day using the daily temperature range (diurnal range) as an index.

(b) Precipitation-elevation gradients

The enhancement of precipitation as a moist air mass is driven by wind across mountain barriers is an important aspect of mountain watershed modelling. Orographic precipitation is influenced by three main factors, the slope of the mountain side, the mountain barrier height and the stability of the air mass. To generalise, the steeper the mountain side, the more rapid the increase in orographic precipitation. However, this increase in precipitation with elevation does not continue indefinitely, but tends to decrease after a certain height. Such trends have been found in the Himalayan regions also (Loukas and Quick, 1993, 1996 ; Singh et. al, 1995; Singh and Kumar, 1997).

(c) Form of precipitation

The model must distinguish between precipitation in the form of snow and precipitation falling as rain and this distinction must be made for each elevation band. Snow is stored until melted whereas rain is immediately processed by the soil moisture model. The form of precipitation is controlled by logical statements and the temperature, T, used in these statements is normally the mean daily temperature in each band. However, it can be specified to be the maximum or the minimum daily temperature in each band.

(d) Precipitation representation factors

Each meteorological station has precipitation representation factor associated with it. This factor is introduced because precipitation measured at a point is not always representative of the areal distribution of precipitation. For example, a meteorological station may be in a rain shadow situation, or it may be in a narrow valley where it is receiving precipitation which is more representative of the mountain side some thousands of feet higher than the station. These representation factors can be determined by comparing long term volumes of runoff with computed values.

(e) Evapotranspiration

Evapotranspiration estimation can be subdivided into three processes. In the first process estimates are made of the daily potential evapotranspiration for the lowest meteorological station in the watershed (EVAP). In the second process this EVAP value is distributed to each elevation mid-band level and is designated by PET. In the third process these PET values are used in conjunction with the calculated soil moisture deficit values to yield and actual evapo-transpiration value for each band (AET). EVAP is computed using the following equation:

$$EVAP = K*MK \{10*(TX-14.5)/64 - 10*(TN-14.5)/64\}$$

where K is an evaporation constant MK is a factor which is specified internally in the model as a monthly factor. It accounts for the seasonal variation of EVAP. The bracket [10*(TX-14.5)/64 - 10*(TN-14.5)/64] represents the variation of the saturated vapour pressure curve as a function of maximum and minimum temperature. It is assumed that the minimum temperature is a good approximation for the dew point temperature.

$$PET(L) = [(TX(L)-32)/(TEX-32)]*EVAP$$

This calculation is carried out for each band L, where TX(L) is the maximum temperature in each band and TEX is the maximum temperature for Meteorological station number 1.

4.0 SOIL MOISTURE MODEL

The response of the watershed to rainfall is controlled by a soil moisture model. The soil moisture status of each area elevation band controls the subdivision of the total rain input into the various components of watershed runoff response. These components of runoff can be characterized as fast, medium, slow and very slow runoff, and they may be conceptually thought of as representing surface runoff, interflow, and superficial and deep groundwater components. The total rain input to each watershed band is subdivided on a priority basis, for example, a first priority is the satisfying of any soil moisture deficit, a deficit which arises continuously because of evaporative demand. The various priorities of the components of run-off are described in the detailed outline of model behaviour.

Each component of runoff undergoes delay before reaching the outflow point of the watershed. These delays, or time distribution of runoff, are achieved by using unit hydrograph convolution. As explained later, the various delay processes, or time distribution processes, can be thought of in terms of cascades of linear reservoirs.

The Watershed Model contains certain logical statements which decide how input are subdivided between evaporation loss, and fast, medium, slow and very slow runoff.

The central control parameter for the subdivision of total watershed input is the SOIL MOISTURE DEFICIT. Note that rather than attempting to specify a total soil moisture capacity, the model operates from a lack of soil moisture. When this soil moisture deficit reaches zero, the watershed reaches its maximum runoff potential, except for FLASH runoff which will be discussed later.

A diagrammatic representation of the soil moisture model is shown in Fig. 2, and is described below in terms of the priorities of runoff.

(a) First Priority: Impermeable percentage - fast runoff control

Part of each elevation band can be specified to be impermeable, so that any input of water to this area will enter the fast runoff component. Such runoff can be thought of in terms of surface runoff or very superficial percolation through coarse sediments.

The impermeable percentage of the watershed can be made to vary with soil moisture deficit. The algorithm which describes this process is:

Impermeable fraction = MXIMP * 10**(-BSD/AREGEN)

MXIMP is the maximum impermeable fraction when the soil is fully saturated. BSD is the soil moisture deficit in an elevation band and AREGEN is a constant which regulates how sensitive the impermeable area is to changes in soil moisture.

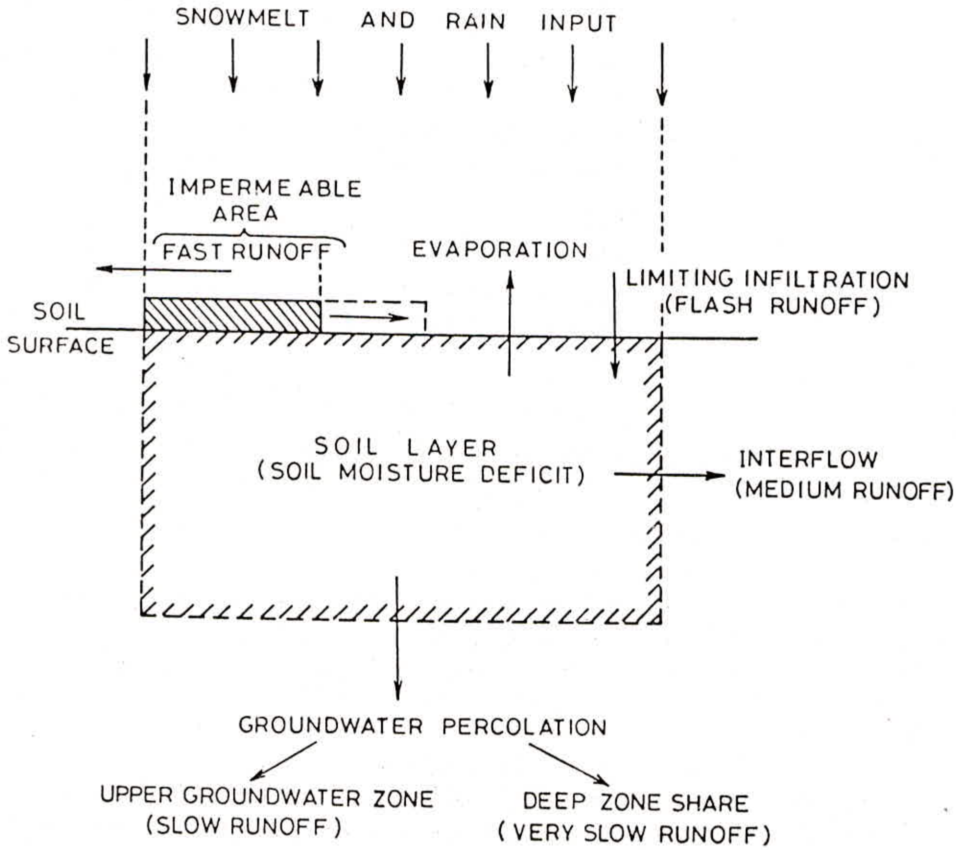

Fig. 2 : Model of soil layer and subdivision of runoff components.

(b) Second Priority: soil moisture and actual evapotranspiration

Before any further runoff can occur, other than fast runoff, the soil moisture deficit must be satisfied. While soil moisture deficits are being satisfied by incoming water from rain, there is also an evaporative demand which is continually building up a deficit.

Potential evapotranspiration has been described earlier. On any given day, in any given elevation band, there will exist a specified potential evapotranspiration. The soil moisture deficit which exists in that band will represent the actual evapotranspiration capability of that band. The algorithm describing this relationship is:

AET = PET* 10**(-BSD/AETGEN)

AET is the actual evapotranspiration
PET is the potential evapotranspiration
BSD is the current value of the band soil moisture deficit

AETGEN is a specified constant which controls the rate at which BSD influences PET.

This actual evapotranspiration demand will only influence the area of the watershed which is not impermeable.

For each day a new value of soil moisture deficit is computed:

New value of BSD = BSD-PRN-AET

Where PRN is rain input. If the band soil moisture deficit reaches zero, any excess water inputs can be subjected to further priorities.

(c) Third Priority: Groundwater percolation

Groundwater percolation accepts any water excess up to a fixed limit (GWPERC). Any excess above this limit goes to the fourth priority, medium runoff. Water which percolates to groundwater is assumed to be divided into specifiable fractions which go to the two groundwater components, the upper groundwater and the deep zone groundwater components.

(d) Fourth Priority: Medium runoff

Any excess moisture input now remaining is assigned to medium runoff, or interflow. Although this is the lowest priority, it is also frequently the most significant runoff component during rain storms. In the model, interflow is considered to be a large reservoir which receives inflows day by day during rain. These inflows are the excesses remaining after satisfying soil moisture and groundwater abstractions. This reservoir releases a certain fraction each day, but the volume of water released does not immediately appear in the downstream channel system. Instead, this released water undergoes a convolution very similar to the fast component unit hydrograph. This release from an interflow storage reservoir and convolution before reaching the channel outflow point, produces a much more sluggish response for this medium runoff component.

5.0 WATERSHED ROUTING

Water allocated to each of the components of runoff, namely fast, medium, slow and very slow components, are subjected to a routing procedure which produces a time distribution of runoff. The routing procedure for each component is based on the same underlying concept, namely the linear storage reservoir. The fast and medium components of runoff are subjected to a cascade of reservoirs which is essentially identical to unit hydrograph convolution. The slower components of runoff simply use a single linear reservoir, thus avoiding the necessity to convolute for the final outflow. The resulting outflow from the nth reservoir at time t from a unit instantaneous inflow can be written as:

$$u(t) = \frac{1}{K^n} \cdot \frac{t^{n-1}}{(n-1)!} \cdot e^{-t/k}$$

where,

k is the linear storage constant for each of reservoirs in the cascade,
n is the number of linear reservoirs in the cascade
t is the time after occurrence of input

6.0 APPLICATION OF UBC WATERSHED MODEL TO A MOUNTAINOUS CATCHMENT

The UBC Watershed Model was applied to one of the Himalayan basin (Satluj basin). Becuase this lecture deals with only rainfall runoff modelling, therefore discussions are restricted only for the lower part of the basin namely Bakhra local watershed. The Bhakra local watershed extends from Rampur to the Bhakra reservoir and has an area of 4459 km^2. The elevation range is from 500 m to 3300m, but is mainly below 2000m. The watershed lies between the front range of the Himalayas, the Pir-Panjal range and the start of the Great Himalayan range. Heavy monsoon rains penetrate into this region, but rarely penetrate further into the Great Himalayan region itself. The map of the Satluj River system showing the sub-watersheds is given in Fig. 3.

Six meteorological stations have been used to characterize the rainfall and temperatures in this region, and they are listed below:

1. Bhakra dam (518 m)
2. Suni (625 m)
3. Kasol (661 m)
4. Kahu (649 m)
5. Berthin (657 m)
6. Rampur (1066 m)

The first five stations all exists at low elevations near the south end of the catchment. The data for these five stations has been averaged to give a reasonable estimate of the precipitation across this lower part of the catchment. The sixth station, Rampur, is at the northern end of the catchment and is more characteristic of the drier, hotter upstream valley region, and has been used to characterize the upper part of the catchment.

The model results indicate that major runoff events can be quite well modeled from the rain measurements. Some of the lesser runoff events are not so well modeled because rainfall is more variable for these events. The results are presented in Figures 4(a), (b), (c).

The summary statistics for three years 1987 to 1990 show that the total volumes of runoff are estimated within some 3 to 8%, except for the annual volumes in 1988 and 1989, when the winter flows, especially groundwater, were over estimated. The Nash shape statistics indicate values of about 60 to 80%, which is quite good for the very flashy rainfall runoff which occurs in this watershed. These analyses confirm that the total runoff in this sub-watershed is essentially from monsoon rainfall and any snowmelt input is quite minor.

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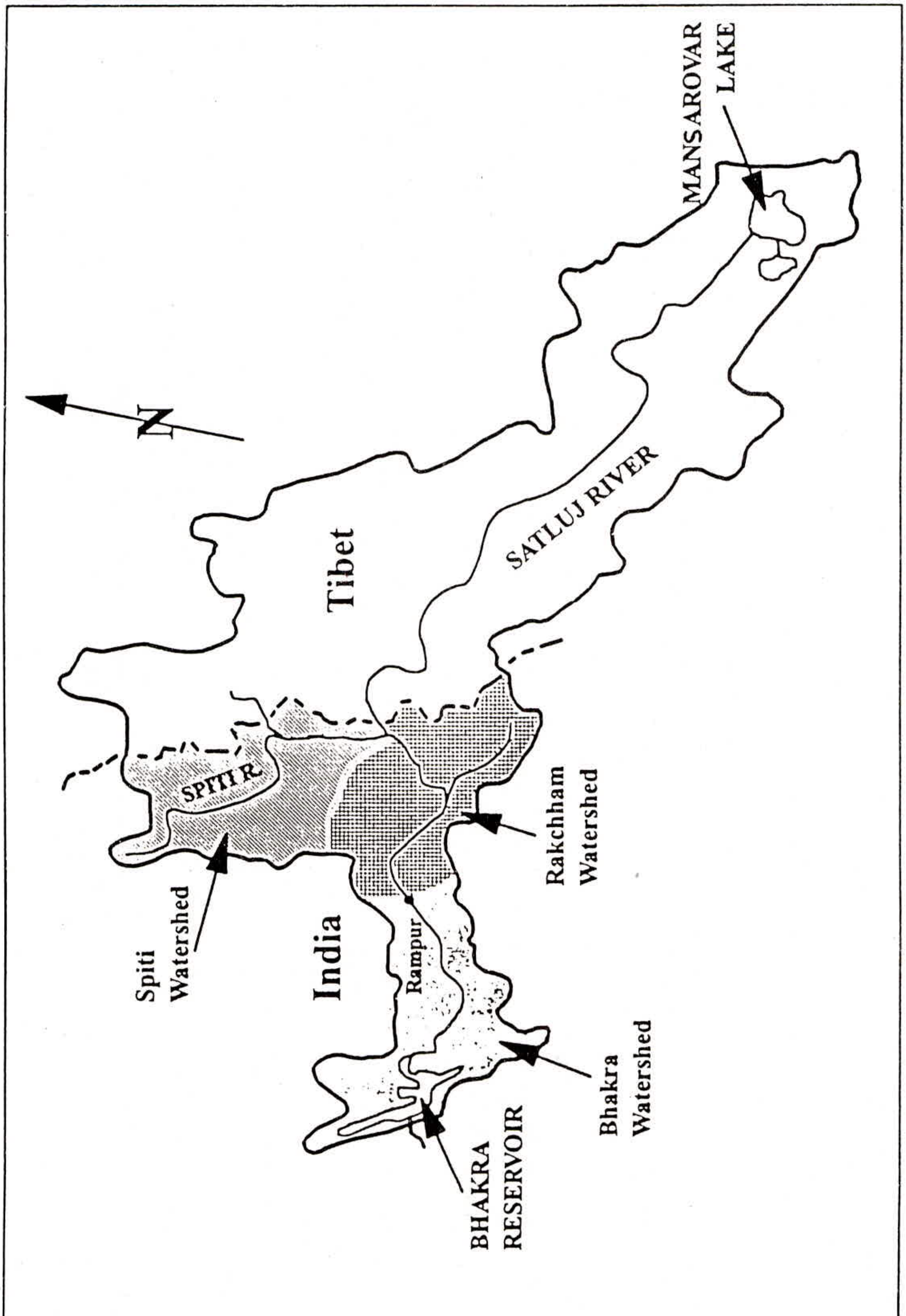

Figure 3. Map of Satluj River System showing the Sub-watersheds

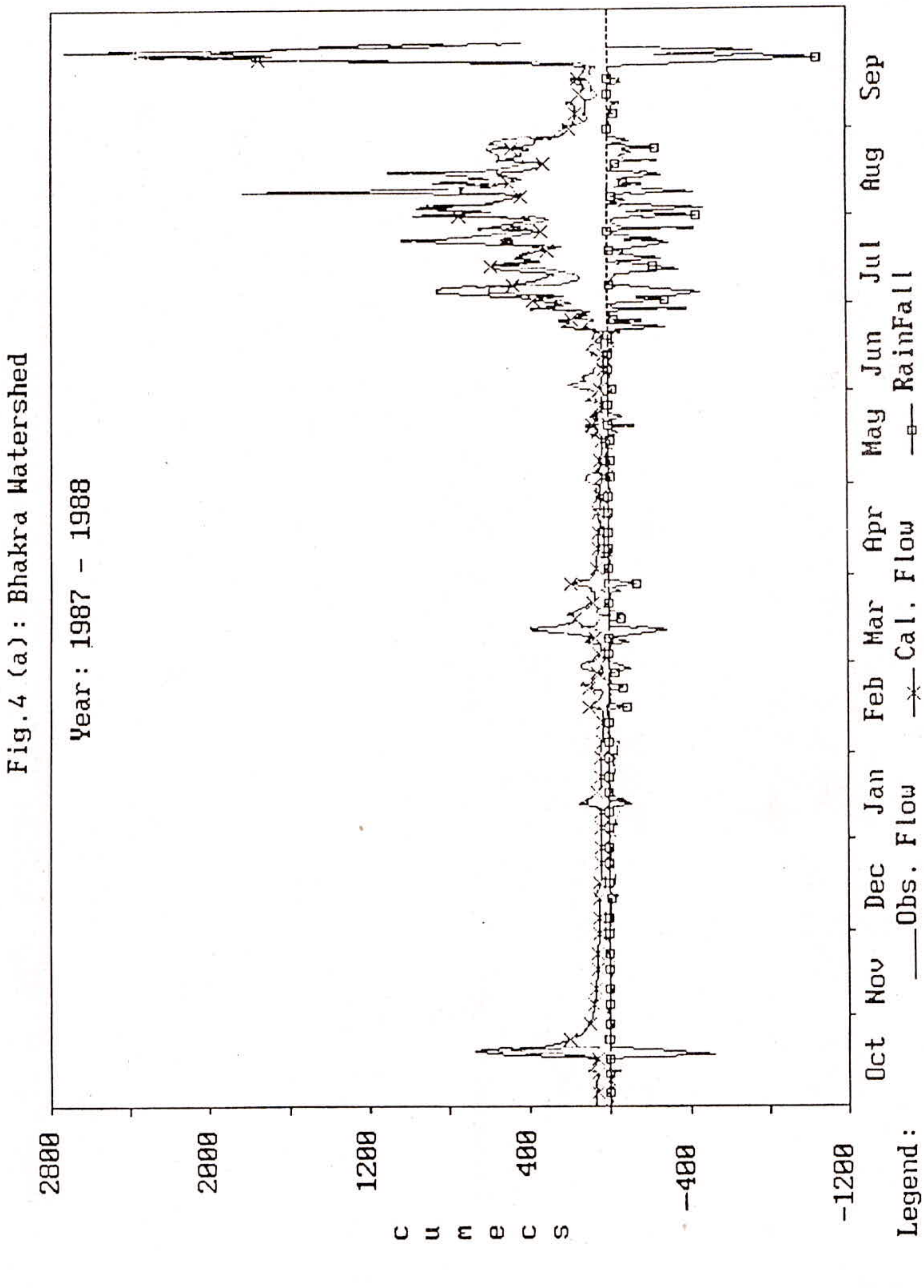
Fig.4 (a): Bhakra Watershed
Year: 1987 - 1988
2800
2000
1200
400
-400
-1200
cumecs
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
Legend: —Obs. Flow —*— Cal. Flow —□— RainFall

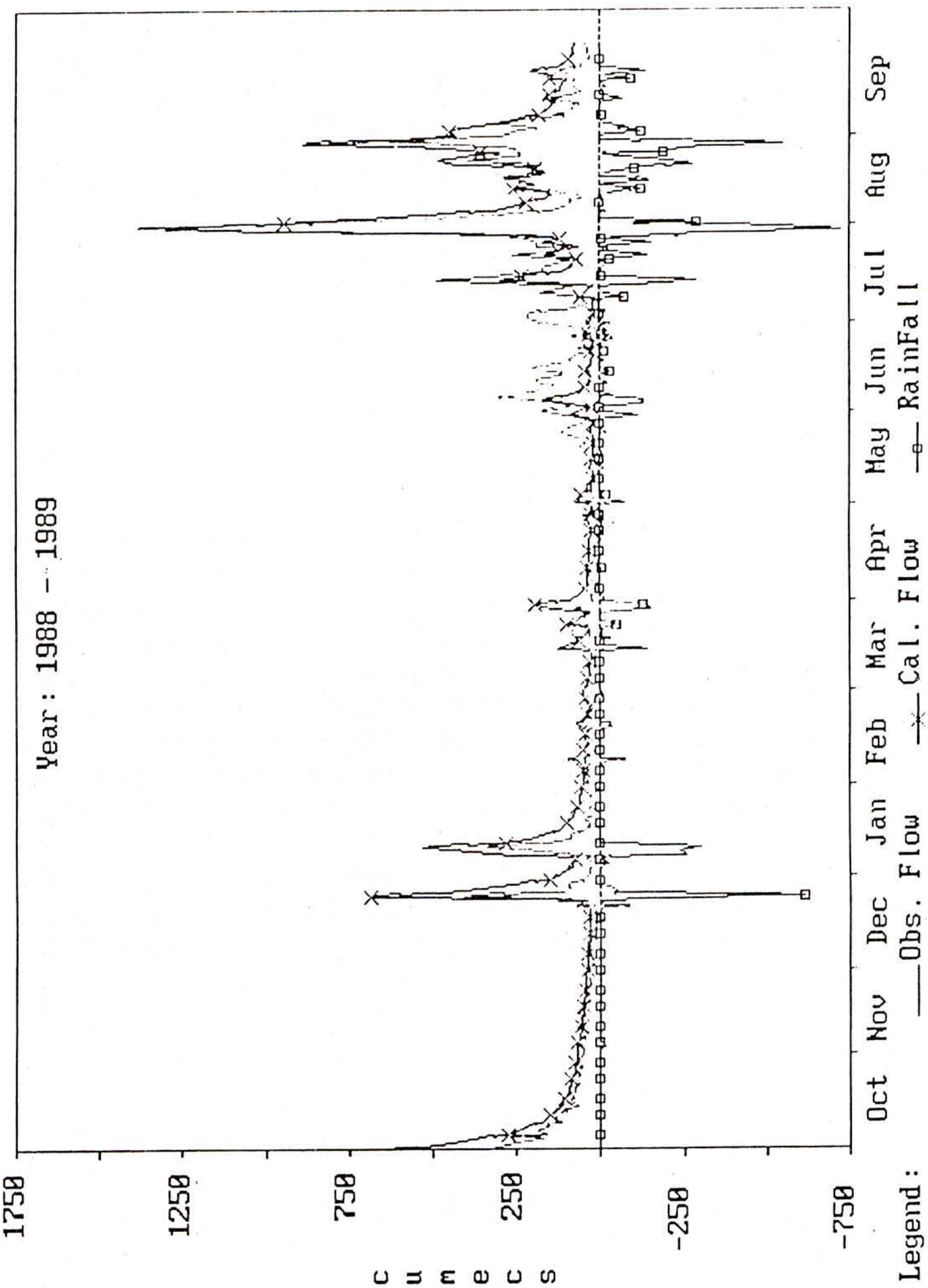

Fig. 4 (b): Bhakra Watershed

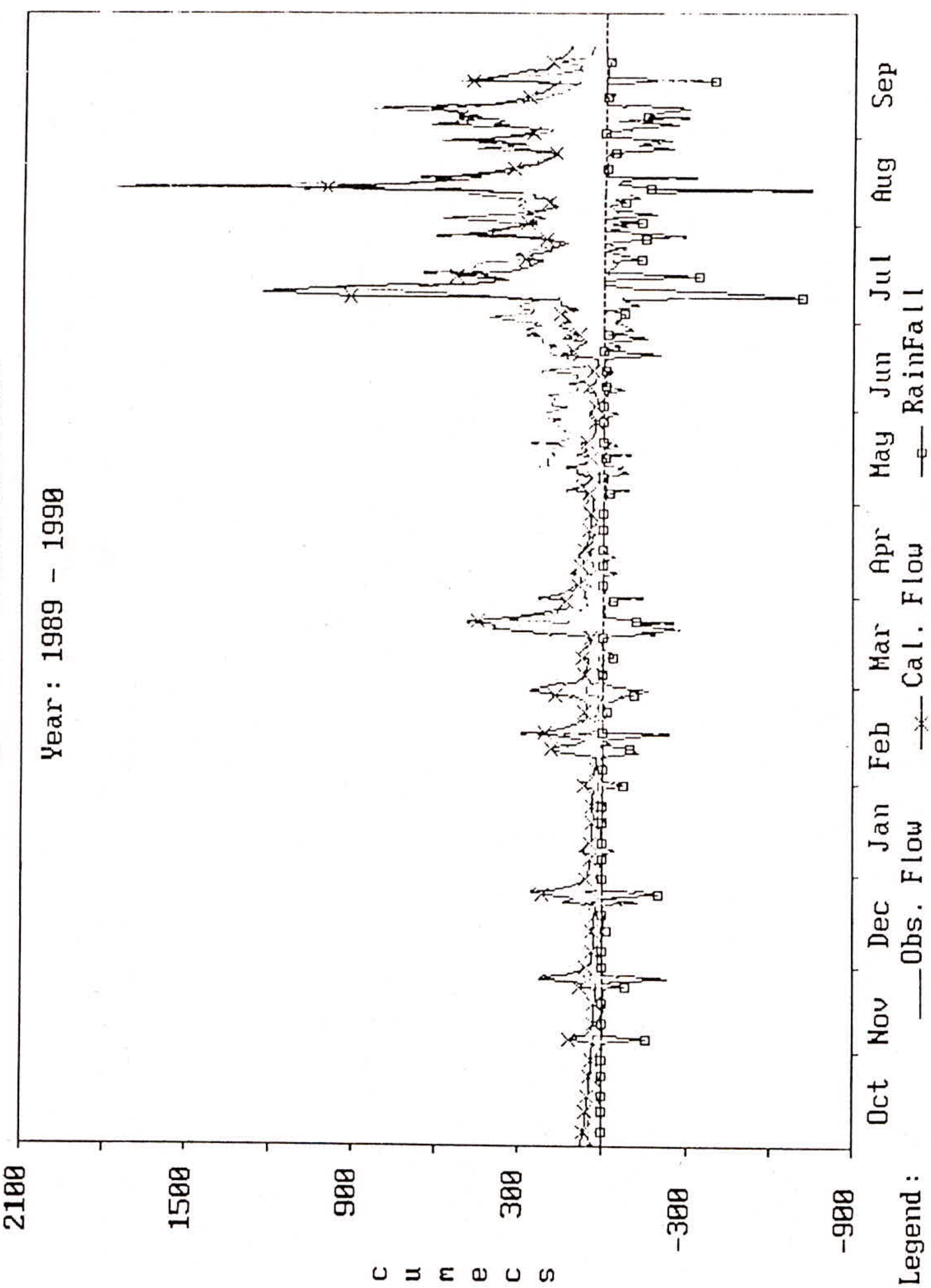

Fig.4 (c): Bhakra Watershed