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HYDROLOGICAL MODELLING USING GIS

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ABSTRACT

In hydrological analysis and design, precipitation-runoff relations are useful to extrapolate or interpolate runoff records from the precipitation records and to estimate the runoff of ungauged catchments. Estimates of hourly, daily, monthly, seasonal or annual runoffs may be required for operational purposes or to have efficient flood forecasting or to provide a database for evaluating reservoir storage requirements. Precipitation-runoff models are classified as lumped and distributed models. Lumped models are developed to get rough estimate of runoff peaks. But the distributed models are developed to represent the complete catchment to get runoff hydrographs.

NASMO model is a rainfall - runoff model developed by Dr. Ing. A.Stodter, Leichtweiss Institute for Hydraulic Engineering, TU Braunschweig, Germany. In this model, the US SCS method is used to find effective rainfall, the linear reservoir method is used to route the runoff over land and the Modified Puls method is used to route the runoff in the stream.

The NASMO model is used to parameterise the following values:

1. The deviation from the soil moisture content
2. Interception
3. Ratio of overland flow (the ratio between effective precipitation to overland flow from direct runoff)
4. Factors to time of concentration for overland flow, interflow and base flow
5. Base flow
6. Factor to travel time in channel (Retention time)
7. Storage coefficient of base flow

GIS ARC/INFO and ILWIS were used to get characteristics of the subcatchment like size, slope, area and landuse details and the length of the stream.

The catchment of Malaprabha upto Khanapur (515.297 sq.km) in Karnataka State was selected and the toposheets were digitised to get the catchment characteristics. The catchment was divided into 39 subcatchments. Three storms 1987 (1st to 31st July), 1988 (9th to 26th July) and 1990 (1st to 31st July) and the corresponding hydrographs were selected for parameter fitting. The parameters were fitted systematically by trial and error process. Best-fitted parameters were arrived for all the storms. The parameters for storms are presented in tabular form. The averaged parameter values are presented in the conclusion. The averaged best-fitted parameters were evaluated using the storm 1991 (1st to 31st July) and the corresponding hydrograph. The output of the model for all the storms are presented in graphical form. It is observed from the results that this model can be used to predict runoff peaks from Indian catchment with more number of storms for parameter fitting.

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CHAPTER 1
INTRODUCTION

The water resources projects play a key role in the development of a country. These projects need careful planning and the planning of water resources projects require adequate reliable hydrological and hydrometeorological data after their completion. Hydrology, which treats all phases of the earth's water, is a subject of great importance for people and their environment. The practical applications of hydrology are found in such tasks as the design and operation of hydrologic structures, water supply, wastewater treatment and disposal, irrigation, drainage, hydropower generation, flood control, navigation, erosion and sediment control, salinity control, pollution abatement, recreational use of water, and fish and wild life protection. The hydrology of a region is determined by its weather patterns and by physical factors such as topography, geology and vegetation. Human activities gradually encroach on the natural water environment, altering the dynamic equilibrium of the hydrologic cycle and initiating new processes and events.

If the surface and soil of a watershed are examined in great detail, the number of possible flow paths becomes enormous. Along any path, the shape, slope, and boundary roughness may be changing continuously from place to place and these factors may also vary in time as the soil becomes wet. Also, precipitation varies randomly in space and time. Because of these great complications, it is very difficult to describe some hydrologic processes with exact physical laws. By using the system concept, effort is directed to the construction of a model relating inputs and outputs rather than to the extremely difficult task of exact representation of the system details, which may not be significant from a practical point of view or may not be known. Nevertheless, knowledge of the physical system helps in developing a good model and verifying its accuracy.

Generally, models can be classified as either prototype or mathematical. Mathematical models are classified as deterministic, probabilistic, conceptual and parametric. A deterministic model is formulated by using laws of physical or chemical processes, as described by differential equations. A probabilistic model, whether statistical or stochastic, is governed by laws of chance or probability. Statistical models deal with observed samples, whereas stochastic models focus on the random properties of certain hydrologic time series-for instance, daily streamflows. A conceptual model is a simplified representation of the physical processes, obtained by lumping spatial and/or temporal variations, and described in terms of either ordinary differential equations or algebraic equations. A parametric model represents hydrologic processes by means of algebraic equations that contain kev parameters to be determined by empirical means.

In principle, deterministic models mimic physical processes and should, therefore, be closest to reality. In practice, however, the inherent complexity of physical phenomena generally limits the deterministic approach to well-defined cases for which a clear cause-effect relationship can be demonstrated. Probabilistic methods are used to fit measured data (i.e., statistical hydrology) and to model random components (stochastic hydrology) in cases where their presence is readily apparent.

Hydrologic models can be either lumped or distributed. Lumped models can describe temporal variations but cannot describe spatial variations. A typical example of a lumped hydrologic model is the unit hydrograph, which describes a catchment's unit response without regard to the response of individual subcatchments. Unlike lumped models, distributed models have the capability to describe both temporal and spatial variations. Distributed models are much more computationally intensive than lumped models and are therefore ideally suited for use with a computer. A typical example of a distributed hydrologic model is an overland flow computation using routing techniques. In this case, equations of mass and momentum (or surrogates thereof) are used to compute temporal variations of discharge and flow depth at several locations within a catchment.

Solutions to hydrologic models can be either analytical or numerical. Using classical tools of applied mathematics, such as Laplace transforms, perturbation theory, and the like obtain analytical solutions. Numerical solutions are obtained by discretizing differential equations into algebraic equations and solving them, usually with the aid of a computer. Examples of analytical solutions are the linear models used in hydrologic systems analysis. Examples of numerical solutions abound, such as those used in hydrologic routing techniques and in the computer models in current use.

All hydrologic models are approximation of reality, so the output of the actual system can never be forecast with certainty. Further, hydrologic phenomena vary in all three-space dimensions, and in time, but the simultaneous consideration of all five sources of variation (randomness, three space dimensions, and time) has been accomplished for only a few idealised cases. A practical model usually considers only one or two sources of variation.

In most hydrologic studies concerned with design, river forecasting, landuse, etc., it is necessary to develop relations between precipitation and runoff, possibly using other factors as parameters. The efficient operation of many irrigation, power, and flood-control developments requires the estimation of the streamflow, which is expected during the coming month, season, or year. Here again, runoff relations serve the purpose. Moreover, precipitation records are generally longer than those of discharge and, therefore, precipitation-runoff relations can be used to extrapolate or interpolate discharge records. Precipitation-runoff models are developed to describe the various surface water processes vary through time during a storm.

1.1 PURPOSE AND SCOPE OF THIS REPORT

The purpose of this report is to apply the NASMO to the Malaprabha basin and to find out the suitability of the model to the Indian basins. NASMO is a deterministic distributed rainfall-runoff model. It has seven parameters. These parameters are varied systematically to match the observed runoff hydrograph to the calculated runoff hydrograph. This model has been developed by Dr Ing. A.Stodter, Leichtweiss Institute for Hydraulic Engineering, TU Braunschweig, Germany. Three storms 1987 (1st to 31st July), 1988 (9th to 26th July) and 1990 (1st to 31st July) and the corresponding hydrographs were selected for model application and the parameters were fitted systematically by trial and error process. Best-fitted parameters were arrived for all the storms. The results are presented in tabular form. The averages of best-fitted parameters for the three storms were taken. The averaged parameter values are presented in the conclusion. The averaged best-fitted parameters were evaluated using the storm 1991 (1st to 31st July) and the corresponding hydrograph. The graphical representation of observed and calculated runoff hydrographs indicates the applicability of the model. It is observed from the results that this model can be used to predict runoff peaks with more number of storms for parameter fitting.

The runoff computation by Curve Number Method, channel routing, catchment routing and the NASMO model are described in Chapter 2. The applicability of GIS ARC/INFO and ILWIS in hydrological problems is explained briefly in Chapter 3. The application of GIS ARC/INFO and ILWIS in RAINFALL-RUNOFF MODELLING (NASMO) for MALAPRABHA basin is explained in Chapter 4. The conclusions are given in Chapter 5.

CHAPTER 2
RAINFALL-RUNOFF MODELS

2.1 INTRODUCTION

The quantity of runoff from a given storm is determined by (1) the moisture deficiency of the basin at the beginning of rainfall and (2) the storm characteristics such as rainfall amount, intensity, and duration. The storm characteristics can be determined from an adequate network of recording and nonrecording precipitation gauges. However, the direct determination of moisture conditions throughout the basin at the beginning of the storm is extremely difficult. While reliable point observations of moisture are possible, three-dimensional measurements are required in a medium recognised for its marked physical discontinuities further emphasised by cultivation and variations in vegetal cover. Also, any complete accountability of moisture within a basin must include consideration of conditions above the soil surface, notably the storage capacity of surface depressions and vegetal cover (interception). Thus, in addition to variations in soil moisture, there is also a seasonal variation in surface storage resulting from changes in vegetal cover, farming practices and other factors.

Soil moisture measurements can be used to represent moisture conditions within the basin, but such observations are generally so limited with respect to areal coverage and length of record that a more indirect index must usually be employed. Stream discharge prior to the beginning of the storm is found to be a good index to moisture deficiency in humid and subhumid areas. Storm runoff is the difference between precipitation and basin recharge. Basin recharge has often been called loss in surface water modelling, because it represents loss to runoff. Many factors used as parameters in runoff relations are related to the basin recharge than to runoff. Consequently, many correlations are presently being made in terms of basin recharge. Knowing the recharge and rainfall, runoff can be computed directly.

2.1.1 CATCHMENT PROPERTIES

A catchment can range from as little as 1 ha (or acre) to hundreds of thousands of square kilometres (or square miles). Small catchments (small watersheds < 50 sq.km) are those where runoff is controlled by overland flow processes. Large catchments (river basins > 5000 sq.km) are those where runoff is controlled by storage processes in the river channels. Between small and large catchments, there is a wide range of catchment sizes with runoff characteristics falling somewhere between those of small and large catchments. Depending on their relative size, midsize catchments are referred to as either watersheds or basins.

The hydrologic characteristics of a catchment are described in terms of the following properties: area, shape, relief, linear measures and drainage patterns.

2.1.2 RUNOFF

Runoff consists of water from three sources: surface flow, interflow, and groundwater flow. Surface flow is effective rainfall, i.e., total rainfall minus hydrologic abstractions. It, also called as direct runoff, has the capability to produce large flow concentrations in a relatively short period of time. Therefore, it is largely responsible for flood flows.

Interflow have got two portions. The flow that reaches the streams or rivers within few hours depending upon the soil condition and topography is called quick interflow. The flow that reaches the streams or rivers after few days or months is called slow interflow.

Groundwater flow includes the portion of infiltrated volume that has reached the water table by percolation from the overlying soils. Groundwater flow may be intercepted by streams and rivers and discharge into them where the groundwater table is close to the surface.

In flood hydrology, baseflow is used to separate surface runoff into direct and indirect runoff. Indirect runoff is surface runoff originating in interflow and groundwater flow. Baseflow is a measure of indirect runoff.

The direct runoff (surface flow) is a function of antecedent precipitation index (API) which is defined as the initial level of soil moisture. The average moisture level in a catchment varies daily, being replenished by precipitation and depleted by evaporation and evapotranspiration.

A basic linear model of rainfall-runoff is the following:

$$Q = b\,(P - P_a) \qquad \text{.......(2.1)}$$

in which Q = runoff depth, P = rainfall depth, P_a = rainfall depth below which runoff is zero, and b = slope of runoff to rainfall when the rainfall and runoff values are plotted on x and y axis respectively. Rainfall depths smaller than P_a is completely abstracted by the catchment, with runoff start as soon as P exceeds P_a. The simplicity of the above equation precludes it from taking into account other important runoff producing mechanisms such as rainfall intensity, infiltration rates, or antecedent moisture. In practice, the correlation usually shows a wide range of variation, limiting its predictive ability.

The effect of infiltration rate and antecedent moisture on runoff is widely recognised. Several models have been developed in an attempt to simulate these and other related processes. Typical of such models is the SCS runoff curve number model, which has had wide acceptance in engineering practice. The SCS model is explained in the next section.

2.2 RUNOFF CURVE NUMBER METHOD

The runoff curve number method is a procedure for hydrologic abstraction developed by the USDA Soil Conservation Service. In this method, runoff depth (i.e., effective rainfall depth) is a function of total rainfall depth and an abstraction parameter referred to as runoff curve number, curve number, or CN. The curve number varies in the range 1 to 100, being a function of the following runoff-producing catchment properties: hydrologic soil type, land use and treatment, ground surface condition, and antecedent moisture condition.

The runoff curve number method was developed based on 24-h rainfall-runoff data. It limits to the calculation of runoff depth and does not explicitly take into account temporal variations of rainfall intensity. The temporal rainfall distribution is introduced at a later stage, during the generation of the runoff hydrograph, by means of the convolution of the unit hydrograph.

In the runoff curve number method, actual runoff is referred to as Q, and potential runoff (total runoff) is represented by P, with $P \geq Q$. The actual retention after runoff begins is $P - Q$. The potential (or potential maximum retention) is S, with $S \geq P - Q$.

The method is based on an assumption of proportionality between retention and runoff:

$$\frac{P - Q}{S} = \frac{Q}{P} \qquad ....(2.2)$$

which states that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff. This assumption underscores the conceptual basis of the runoff curve number method.

For practical applications, Eq. 2.2 is improved by reducing the potential runoff by an amount equal to the initial abstraction. The initial abstraction consists mainly of interception, infiltration, and surface storage, all of which occur before runoff begins.

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \qquad \text{.......(2.3)}$$

in which I_a = initial abstraction.

Solving for Q from Eq. 2.3

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad \text{.......(2.4)}$$

which is physically subject to the restriction that $P \geq I_a$ (i.e., the potential runoff minus the initial abstraction can not be negative).

To simplify Eq. 2.4, initial abstraction is related to potential maximum retention as follows:

$$I_a = 0.2S \qquad \text{.......(2.5)}$$

This relation was obtained based on rainfall-runoff data from small experimental watersheds. The coefficient 0.2 has been subjected to wide scrutiny. V.M.Ponce (1989) has indicated that Springer et al. evaluated small humid and semiarid catchments and they found that the coefficient in Eq. 2.5 varied in the range 0.0 to 0.26. Nevertheless, 0.2 is the standard initial abstraction coefficient recommended by SCS. For research applications and particularly when warranted by field data, it is possible to consider the initial abstraction coefficient as an additional parameter in the runoff curve number method. In general:

$$I_a = KS \qquad \text{......(2.6)}$$

in which K = initial abstraction.
With Eq. 2.5, Eq. 2.6 reduces to

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{......(2.7)}$$

which is subject to the restriction that $P \geq 0.2S$.

Since potential maximum retention varies widely, it is more appropriate to express it in terms of a runoff curve number, an integer varying in the range 1 to 100, in the following form:

$$S = \frac{1000}{CN} - 10 \qquad \text{......(2.8)}$$

in which CN is the runoff curve number (dimensionless) and S, 1000 and 10 are given inches. To illustrate, for CN = 100, S = 0; and for CN = 1, S = 990 in. Therefore, the catchment's capability for rainfall abstraction is inversely proportional to the runoff curve number. For CN

= 100 no abstraction is possible, with runoff being equal to total rainfall. On the other hand, for CN = 1 practically all rainfall would be abstracted, with runoff being essentially equal to zero.

With Eq. 2.8, 2.7 can be expressed in terms of CN:

$$Q = \frac{[CN\,(P+2) - 200\,]^2}{CN\,[CN\,(P-8) + 800]} \qquad \text{......(2.9)}$$

which is subject to the restriction that P ≥ (200/CN)-2. In Eq. 2.9 P and Q are given in inches. In SI units, the equation is:

$$Q = \frac{R\,[CN\,(P/R+2) - 200\,]^2}{CN\,[CN\,(P/R-8) + 800]} \qquad \text{......(2.10)}$$

which is subject to the restriction that P ≥ R[(200/CN)-2]. With R = 2.54 in Eq. 2.10, P and Q are given in centimetres.

For a variable initial abstraction, Eq. 2.9 is expressed as follows:

$$Q = \frac{[CN\,(P+10K) - 1000K\,]^2}{CN\,\{CN\,[P - 10(1-K)] + 1000(1-K)\}} \qquad \text{......(2.11)}$$

which is subject to the restriction that P ≥ (1000K/CN)-10K. An equivalent equation in SI units is:

$$Q = \frac{R\,[CN\,(P/R+10K) - 1000K\,]^2}{CN\,\{CN\,[P/R - 10(1-K)] + 1000(1-K)\}} \qquad \text{......(2.12)}$$

which is subject to the restriction that P ≥ R[(1000K/CN)-10K] .

A graph of Eqs. 2.9 and 2.10 is shown in Fig. 1. This figure is applicable only for the standard initial abstraction value, $I_a = 0.2S$. If this condition is relaxed, as in Eqs. 2.11 and 2.12, Fig. 1 has to be modified appropriately.

Estimation of Runoff Curve Number from Tables

With rainfall P and runoff curve number CN; the runoff Q can be determined by either Eq. 2.9 and 2.10 or from Fig. 1

For ungauged watersheds, estimates of runoff curve numbers are given in tables supplied by federal agencies (SCS, Forest Service) and city local and county departments. Tables of runoff curve numbers for various hydrologic soil-cover complexes are widely available. The hydrologic soil-cover complex describes a specific combination of hydrologic soil group, land use and treatment, hydrologic surface condition, and antecedent moisture condition. All these have a direct bearing on the amount of runoff produced by a watershed. The hydrologic soil group describes the type of soil. The land use and treatment describes the type and condition of vegetative cover. The hydrologic condition refers to the ability of the watershed surface to enhance or impede direct runoff. The antecedent moisture condition accounts for the recent history of rainfall, and consequently it is a measure of the amount of moisture stored by the catchment.

Hydrologic Soil Group

All soils are classified into four hydrologic soil groups of distinct runoff-producing properties. These groups are labelled A, B, C, and D.

Group A consists of soils of low runoff potential, having high infiltration rates even when wetted thoroughly. They are primarily deep, very well drained sands and gravels, with a characteristically high rate of water transmission.

Group B consists of soils with moderate infiltration rates when wetted thoroughly, primarily moderately deep to deep, moderately drained to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

Group C consists of soils with slow infiltration rate when wetted thoroughly, primarily soils having a layer that impedes downward movement of water or soils of moderately fine to fine texture. These soils have a slow rate of water transmission.

Group D consists of soils of high runoff potential, having very slow infiltration rates when wetted thoroughly. They are primarily clay soils with high swelling potentials, soils with a permanent high water table, soils with a clay layer near the surface, and shallow soils overlying impervious material. These soils have a very slow rate of water transmission.

Land use and Treatment

The effect of the surface condition of a watershed is evaluated by means of land use and treatment classes. Land use pertains to the watershed cover, including every kind of vegetation, litter and mulch, fallow (bare soil), as well as non-agricultural uses such as water surfaces (lakes, swamps and so on), impervious surfaces (roads, roofs, and the like), and urban areas. Land treatment applies mainly to agricultural land uses, and it includes mechanical practices such as contouring or terracing and management practices such as grazing control and crop rotation. A class of land use/treatment is a combination often found in a catchment.

The runoff curve number method distinguishes between cultivated land, grasslands, and woods and forests. For cultivated lands, it recognises the following land uses and treatments: fallow, row crop, small grain, close-seed legumes, rotations (from poor to good), straight-row fields, contoured fields, and terrace fields.

Hydrologic Condition

Grasslands are evaluated by the hydrologic condition of native pasture. The percent of areal coverage by native pasture and the intensity of grazing are visually estimated. A poor hydrologic condition describes less than 50 percent areal coverage and medium grazing. A good hydrologic condition describes more than 75 percent areal coverage and light grazing.

Woods are small isolated groves or trees being raised for farm or ranch use. The hydrologic condition of woods is visually estimated as follows: (1) poor-heavily grazed or regularly burned woods, with very little litter and few shrubs, (2) fair-grazed but not burned, with moderate litter and some shrubs, and (3) good-protected from grazing, with heavy litter and many shrubs covering the surface.

Antecedent Moisture Condition

The runoff curve number method has three levels of antecedent moisture, depending on the total rainfall in the 5-d period preceding a storm. The dry antecedent moisture condition (AMC I) has the lowest runoff potential, with the soils being dry enough for satisfactory ploughing or cultivation to take place. The average antecedent moisture condition (AMC II) has an average runoff potential. The wet antecedent moisture condition (AMC III) has the highest runoff potential, if the watershed practically saturated from antecedent rainfalls. The AMC can be estimated from information such as that of Table 1 or other similar regionally derived tables. Tables of runoff curve numbers for various hydrologic soil cover complexes are in current use. Table 2(a) shows runoff curve numbers for urban areas, Table 2(b) shows them for cultivated agricultural areas, Table 2(c) shows them for other agricultural lands, and Table 2(d) shows them for arid and semiarid range lands. Runoff curve numbers shown in these Tables are for the average AMC II condition. Corresponding runoff curve numbers for AMC I and AMC III conditions are shown in Table 3.

Using Eq. 2.8, Hawkins et al (1985) have expressed the values in Table 3 in terms of potential maximum retention. They correlated the values of potential maximum retention for AMC I and III with those of AMC II and found the following ratios to be a good approximation:

$$\frac{S_I}{S_{II}} \cong \frac{S_{II}}{S_{III}} \cong 2.3 \qquad \text{......(2.13)}$$

This led to the following relationships:

$$CN_I = \frac{CN_{II}}{2.3 - 0.013\,CN_{II}} \qquad \text{......(2.14)}$$

$$CN_{III} = \frac{CN_{II}}{0.43 - 0.0057\,CN_{II}} \qquad \text{......(2.15)}$$

which can be used in lieu of Table 3 to calculate runoff curve numbers for AMC I and AMC III in terms of the AMC II values.

Estimation of Runoff Curve Numbers from Measured Data

The runoff curve number method was developed primarily for design applications in ungauged catchments and was not intended for simulation of actual recorded hydrographs. However, where rainfall-runoff data are available, estimations of runoff curve numbers can be obtained directly from data. These values compliment and in certain cases may even replace the information obtained from Tables.

To estimate runoff curve numbers from data, it is necessary to assemble corresponding sets of rainfall-runoff data for several events occurring individually. As far as possible, the selected events should be of constant intensity and should uniformly cover the catchments. A recommended procedure is to select events that correspond to annual floods. Inclusion of events of greater frequency may lead to more conservative (higher) values of runoff curve numbers. The selected sets should encompass a wide range of antecedent moisture conditions, from dry to wet. For each event, a value of P, total rainfall depth, is identified. The associated direct runoff hydrograph is integrated to obtain the direct runoff volume. This runoff volume is divided by the catchment area to obtain Q, the direct runoff depth (in centimetres or inches). The values of P and Q are plotted on Fig. 1 and a corresponding value of CN is identified. The procedure is repeated for all events, and a CN value is obtained for each event, as shown in Fig. 2. In theory, the AMC II runoff curve number is that which separates the data into two equal groups, with half of the data plotting above the line and half below it. The AMC I runoff curve number is the curve number that envelopes the data from below. The AMC III runoff curve number is the curve number that envelops the data from above. (see Fig. 2)

2.3 ROUTING OF RUNOFF

The storage concept is well established in flow routing theory and practice. The storage routing is used not only in reservoir routing but also in stream channel and catchment routing. Techniques for storage routing are invariably based on the differential equation of water storage. This equation is founded on the principle of mass conservation, which states that the change in flow per unit length in a controlled volume is balanced by the change in flow area per unit time. In partial differential form:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \qquad ......(2.16)$$

in which Q = flow rate, A = flow area, x = space(length), and t = time.

The differential equation of storage is obtained by lumping spatial variations. For this purpose, Eq. 2.16 is expressed in finite increments.

$$\frac{\Delta Q}{\Delta x}+\frac{\Delta A}{\Delta t}=0 \qquad ......(2.17)$$

With $\Delta Q = O - I$, in which O = outflow and I = inflow; and $\Delta S = \Delta A\ \Delta x$, in which ΔS = change in storage volume, Eq. 2.17 reduces to

$$I - O=\frac{\Delta S}{\Delta t} \qquad ......(2.18)$$

in which inflow, outflow, and rate of change of storage are expressed in L^3T^{-1} units. Furthermore, Eq. 2.18 can be expressed in differential forms leading to the differential equation of storage:

$$I - O=\frac{dS}{dt} \qquad ......(2.19)$$

Equation 2.19 implies that any difference between inflow and outflow is balanced by a change of storage in time. In a typical reservoir routing application, the inflow hydrograph (upstream boundary condition), initial outflow and storage (initial conditions), and reservoir physical and operational characteristics are known. Thus, the objective is to calculate outflow hydrograph for the given initial condition, upstream boundary condition, reservoir characteristics, and operational rules.

Stream channel routing uses mathematical relations to calculate outflow from a stream channel inflow, lateral contributions, and channel characteristics are known. Stream channel routing usually implies open channel flow condition, although there are exceptions, such as storm sewer flow, for which mixed open channel, closed conduit flow condition may prevail. Channel reach refers to a specific length of stream channel possessing certain translation and storage properties. The hydrograph at the upstream end of the reach is the inflow hydrograph; the hydrograph at the downstream end is the outflow hydrograph. Lateral contributions consist of point tributary inflows and/or distributed inflows (i.e. interflow and groundwater flow).

2.3.1 STORAGE INDICATION METHOD (CHANNEL ROUTING)

The storage indication method is also known as the Modified Puls method. It is used to route stream flows through actual reservoirs, for which the relationship between outflow and storage is usually of a non-linear nature. A small section of the channel is considered as a reservoir. The method is based on the differential equation of storage, Eq. 2.19. The discretization of this equation on the xt plane leads to the following equation.

$$O = (2/3)[(2/3)g]^{1/2} Z H^{3/2} \qquad \text{......(2.20)}$$

where O = outflow

Z = variable representing cross sectional area or length of the channel

H = hydraulic head above outlet elevation

In the storage indication method, Eq. 2.20 is transformed to its equivalent form:

$$\frac{2S_2}{\Delta t} + O_2 = I_1 + I_2 + \frac{2S_1}{\Delta t} - O_1 \qquad \text{......(2.21)}$$

in which the unknown values (S_2 and O_2) are on the left side of the equation and the known values (inflows initial outflows and storage) are on the right side. The left side of Eq. 2.21 is known as the storage indication quantity. In the storage indication method, it is first necessary to assemble geometric and hydraulic reservoir data in suitable form. For this purpose, the following curves (or tables) are prepared: (1) elevation-storage, (2) elevation-out flow, (3) storage-outflow, and (4) storage indication-outflow. For computer applications, tables of elevation-outflow-storage-storage indication quantities replace these curves.

The elevation-storage relation is determined based on topographic information. The minimum elevation is that for which storage is zero, and maximum elevation is the minimum elevation of the outlet crest.

The elevation-outflow relation is determined based on the hydraulic properties of the outlet. In the typical application, the reservoir pool elevation provides a head over the outlet, and outflow can be calculated using an equation such as the following equation.

$$O = C_d Z H^y \qquad ......(2.22)$$

where C_d = discharge coefficient

Elevation-storage and elevation-outflow relations lead to the storage-outflow relation. In turn, the storage-outflow relation is used to develop the storage indication-outflow relation. The storage indication variable is the left side of the Eq. 2.21. In general, the storage indication quantity is $[(2S/\Delta t)+ O]$, with S = storage, 0 = outflow and Δt = time interval. To develop the storage indication-outflow relation it is first necessary to select a time interval such that the resulting linearization of the inflow hydrograph remains a close approximation of the actual nonlinear shape of the hydrograph. For smoothly rising hydrographs, a minimum value of $t_p/\Delta t = 5$ is recommended, in which t_p is time to peak of the inflow hydrograph. In practice, a computer-aided calculation would normally use a much greater ratio, say 10-20.

2.3.2 CATCHMENT ROUTING

Catchment routing refers to the calculation of flow in time and space within a catchment. The objective of catchment routing is to transform effective rainfall into streamflow. This is accomplished in a lumped mode or in a distributed mode.

Methods for catchment routing are similar to those of reservoir and stream channel routing. In fact, many techniques used in reservoir and channel routing are also applicable to catchment routing. For instance, the concept of linear reservoir is in both reservoir and catchment routing.

CASCADE OF LINEAR RESERVOIRS

A linear reservoir has a diffusion effect on the inflow hydrograph. If an inflow hydrograph is routed through a linear reservoir, the outflow hydrograph has a reduced peak and an increased time base. This increase in time base causes a difference in the relative timing of inflow and outflow hydrographs, referred to as the lag. The amount of diffusion (and associated lag) is a function of the ratio $\Delta t/K$, a larger diffusion effect corresponding to smaller values of $\Delta t/K$. K is defined as Storage Coefficient.

The cascade of linear reservoirs is a widely used method of hydrologic catchment routing. As its name implies, the method is based on the connection of several linear reservoirs in series. For N such reservoirs, the outflow from the first would be taken as inflow to the second, the outflow from the second as inflow to the third, and so on, until the outflow from the (N - 1)th reservoir is taken as inflow to the Nth reservoir. The outflow from the Nth reservoir is taken as the outflow from the cascade of linear reservoir. Admittedly, the cascade of reservoirs to simulate catchment response is an abstract concept. Nevertheless, it has proven to be quite useful in practice.

Each reservoir in the series provides a certain amount of diffusion and associated lag. For a given set of parameter Δt/K and N, the outflow from the last reservoir is a function of the inflow to the first reservoir. In this way, a one-parameter linear reservoir method (Δt/K) is extended to a two-parameter catchment routing method. Moreover, the basic routing formula and routing coefficients remain essentially the same.

The basic routing formula and routing coefficients are given as follows:

$$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1 \qquad ......(2.23)$$

in which C_0, C_1 and C_2 are routing coefficients defined as follows:

$$C_0 = \frac{\Delta t/K}{2 + (\Delta t/K)} \qquad ......(2.24)$$

$$C_1 = C_0 \qquad ......(2.25)$$

$$C_2 = \frac{2 - (\Delta t/K)}{2 + (\Delta t/K)} \qquad ......(2.26)$$

Since $C_0 + C_1 + C_2 = 1$, the routing coefficients are interpreted as weighting coefficients. These routing coefficients are a function of Δt/K, the ratio of time interval to storage constant.

The addition of the second parameter (N) provides considerable flexibility in simulating a wide range of diffusion and associated lag effects. However, the conceptual basis of the method restricts its general use, since no relation between either of a parameter to the physical problem can be readily envisaged. Notwithstanding this apparent limitation, the method has been widely used in catchment simulation, primarily in applications involving large gauged river basins. Rainfall-runoff data can be used to calibrate the method, i.e. to determine a set of parameter $\Delta t/K$ and N that produces the best fit to the measured data.

2.4 NASMO MODEL

NASMO model is a rainfall-runoff model developed by DR Ing A.Stodter of Leichtweiss Institute for Hydraulic Engineering, TU Braunschweig, Germany. U.S. Soil Conservation Service method is used to find out the direct runoff from rainfall using rainfall data and watershed characteristics. Curve number is calculated on the basis of the procedure explained by U.S. SCS method.

2.4.1 RUNOFF CALCULATION

The following formulae are involved in finding out the runoff from rainfall.

$$\frac{N_{eff}}{N - I_a} = \frac{F}{S} \quad ; \quad N \succ I_a \qquad \text{.......(2.27)}$$

where N = rainfall in mm

I_a = interception in mm

N_{eff} = effective rainfall in mm

F = infiltration in mm

S = potential infiltration in mm

$$F = N - I_a - N_{eff} \qquad \text{.......(2.28)}$$

$$N_{eff} = \frac{(N - I_a)^2}{(N - I_a) + S} \quad ; \quad N \succ I_a \qquad \text{.......(2.29)}$$

Where $I_a = 0.2S$

The potential infiltration is explained in terms of curve number as follows

$$S = \frac{25400}{CN} - 254 \qquad \text{.......(2.30)}$$

Where S = potential infiltration in mm

CN = Curve number

$$CN_{moisturecontent} = \frac{1000}{\frac{1000}{CN} - \frac{moisturecontent}{25.4}} \quad for \ CN \prec 100 \qquad \text{.......(2.31)}$$

$$CN_{moisturecontent} = 100 \quad for \ CN = 100 \qquad \text{.......(2.32)}$$

where moisture content in mm and CN is the curve number for AMC II. The moisture content is adjusted to have correct potential infiltration. Total runoff is calculated by calculating the groundwater flow, surface flow and interflow for each landuse and time interval.

$$N_{eff,u(t,b)} = \frac{S(b\,)^2}{(\Sigma(t) - I_a(b) + S(b)\,)^2} . N(t) \qquad \text{.......(2.33)}$$

$$N_{eff,o(t,b)} = (N(t) - N_{eff,u(t,b)}).anto \qquad \text{.......(2.34)}$$

$$N_{eff,i(t,b)} = (N(t) - N_{eff,u(t,b)}).(1 - anto) \qquad \text{.......(2.35)}$$

where $N_{eff,u(t,b)}$ = groundwater flow in mm

$N_{eff,o(t,b)}$ = surface flow in mm

$N_{eff,i(t,b)}$ = interflow in mm

N(t) = rainfall in mm

ΣN(t) = total rainfall in mm

$I_a(b)$ = interception for a landuse in mm

S(b) = potential infiltration for a landuse in mm

anto = ratio of surface flow to interflow

The ratio of surface flow to interflow is adjusted to match the observed runoff
The runoff is calculated in m^3/s using the following formulae

$$Q(t) = S(t)/k \qquad \text{......(2.36)}$$

where Q(t) = runoff for a time period t in m^3/s

S(t) = storage volume for a time period t in m^3

k = storage constant in s

The above formula is written for a small period of time as follows

$$\Delta S/\,\Delta t = \Delta Q/\Delta t \qquad \text{......(2.37)}$$

$$I_w(t).A - Q(t) = k.\ \Delta Q/\Delta t \qquad \text{......(2.38)}$$

where $I_w(t)$ = rainfall intensity in m/s

A = watershed area in m^2

The runoff per unit length of watershed is calculated by the following formula

$$u(t) = \frac{A}{\Delta t} . (e^{(\Delta t - t)/k} - e^{-t/k)} \qquad \text{......(2.39)}$$

where u(t) = runoff ordinate in $m^3/(s.m)$

Δt = time interval in s

The k value is calculated as a sum of travelling time (t_y+t_x) on surface and river channel as follows:

$$k = \frac{0.5\, b_{Tfl}}{v_y.3600} + \frac{l_{Tfl}}{v_x.3600} \qquad \text{......(2.40)}$$

where k = storage constant in s

b = width of the catchment in m

l = length of the catchment in m

v_x = velocity of flow in main stream

v_y = velocity of over land flow

b_{Tfl} = 1.00 A_{Tfl}/l_{Tfl} for rectangular subcatchment

b_{Tfl} = 1.33 A_{Tfl}/l_{Tfl} for triangular subcatchment

b_{Tfl} = 1.28 A_{Tfl}/l_{Tfl} for circle subcatchment

$$v_x = v_{x0}\left(\frac{k_{st}}{k_{st0}}\right)^a . \left(\frac{J_x}{J_{x0}}\right)^b \qquad \text{......(2.41)}$$

$$v_{x0} = 0.12 + 0.086.\ln(AE_0) \quad for \quad AE_0 \geq \_\, 1.0\ km^2 \qquad \text{......(2.42)}$$

$$v_{x0} = 0.12 \quad for \quad AE_0 \prec 1.0\ km^2 \qquad \text{......(2.43)}$$

where v_x = flow velocity in channel in m/s

v_{x0} = flow velocity parameter, depending on upstream area

J_x = slope of channel [0/00]

J_{x0} = slope parameter: 1 [0/00]

k_{st} = STRICKLER-roughness in channel in $m^{1/3}/s$

k_{st0} = roughness parameter in $m^{1/3}/s$ (30 $m^{1/3}/s$)

a and b are constants where a = 0.73 and b = 0.35

AE_0 = area of subcatchment in km2

$$v_y = (J_y / J_{y0})^b \qquad \text{......(2.44)}$$

v_y = velocity of overland flow in m/s

J_y = slope of land surface [0/00]

J_{y0} = slope of land surface: 1 [0/00]

For parameter-fitting k is multiplied with each storage factor such as surface flow, interflow and groundwater flow. Mean storage time is calculated for surface, inter and groundwater flow separately.

2.4.2 CALCULATION OF TIME OF CONCENTRATION

In NASMO model three options are given for calculating time of concentration

2.4.2.1 ROTHER METHOD

The value v_x found earlier is used to find out the time of concentration using the following formula

$$t_F = \frac{l_F}{v_x} \qquad \text{......(2.45)}$$

where t_F = concentration time in s

v_x = velocity of flow in stream in m/s

l_F = travel length in m

2.4.2.2 KIRPICH METHOD

The following formula by Kirpich is used to find out the time of concentration

$$t_c = \frac{0.0662\,(l_F)^{0.77}}{\sqrt{J^{0.77}}} \qquad \text{......(2.46)}$$

where t_c = concentration time in hour

l_F = travel length in km

J = slope m/m

2.4.2.3 SCS FORMULA

The following formula is used by U.S. Bureau of Reclamation to find out the time of concentration

$$t = \left[\frac{11.9\, l_F^{3}}{H}\right]^{0.385} \qquad \text{......(2.47)}$$

$$H = J\, l_F \,.10000 \qquad \text{......(2.48)}$$

where t_c = time of concentration in hour

l_F = travel length in km
J = slope in m/m

2.4.3 ROUTING OF RUNOFF THROUGH CHANNEL AND OVER LAND

The over land flow is routed by linear storage method by using the following formula

$$Q_a(t+\Delta t) = Q_a(t) + C.(Q_z(t) - Q_a(t)) + 0.5\, C.(Q_z(t+\Delta t) - Q_z(t) \qquad \text{......(2.49)}$$

where t = observation time in hour
Δt = routing interval in hour
Q_z = inflow in m^3/s
Q_a = outflow in m^3/s
C = substitution parameter = $\Delta t/(k+0.5.\ \Delta t)$ where k = storage constant in hour

The flow is routed through channel by Modified Puls method as explained by the following formula

$$S(t+\Delta t)/\ \Delta t + Q_a(t+\Delta t)/2 = (S(t)/\ \Delta t + Q_a(t)/2) - Q_a(t) +(\ Q_z(t) + Q_z(t+\Delta t)) \qquad \text{......(2.50)}$$

where t = observation time in hour
Δt = routing interval in hour
S = storage volume for t and $t+\Delta t$ in m^3
Q_z = inflow in m^3/s
Q_a = outflow in m^3/s

The calculation is carried out backwardly for each subcatchment and the final runoff hydrograph is arrived at last at the excess subcatchment by adding.

2.4.4 MODEL STRUCTURE

The NASMO model is written in PASCAL language. This model consists of 5 input files

1) TFL - catchment characteristics

2) GGN - rainfall values (storm)
3) GGQ - observed runoff values
4) ORG - organisation file
5) PCD - procedure file

Catchment characteristics include

1) name of the subcatchment
2) identification of flow into one downstream subcatchment
3) identification of flow into two downstream subcatchment
4) rainfall station number
5) print option
6) symbol of subcatchment where runoff is measured
7) shape of the subcatchment
    The shape of the subcatchment is defined as follows
    3 is for triangle
    4 is for rectangle
    0 is for circle
8) area of the subcatchment
9) length of main stream
10) slope in streamflow direction
11) slope in overland flow direction
12) Mannings coefficient
13) Darcy's coefficient
14) soil group
15) number of landuses
16) landuse area in proportion
    The landuse classification is defined as follows
    1 - paddy field
    2 - grass
    3 - forest
    4 - village
    5 - city
    6 - water (if there is water area)
17) details of parameters file

Rainfall value file contains

1) total number of records
2) number of stations
3) station number
4) number of records per station
5) beginning time
6) rainfall values

Runoff value file contains

1) total number of records
2) number of stations
3) name of the subcatchment where runoff is measured
4) symbol of subcatchment where runoff is measured
5) number of records per station 6) beginning time
7) runoff values

In the organisation file the input and output files are organised systematically. The details of the records are given as follows a) beginning time b) beginning date c) time interval d) total duration in hours. The method to calculate the time of concentration is also given. The option 01 is for German catchment by Rother. The option 02 is for other catchment by Kirpich. The option 03 is SCS method. It also contains the organisation of all input and output files.

Procedure file contains the parameter values as follows: i) the deviation from the soil moisture content, ii) interception, iii) ratio of overland to interflow, iv) factors to time of concentration for overland flow, interflow and base flow, v) baseflow value (base flow value, storage coefficient of the base flow, maximum and minimum velocity of base flow), vi) factor to travel time in channel (retention time), vii) ratio of flow from subcatchment which has got two downstream subcatchment.

The NASMO model working structure is represented by Fig 3.

2.4.5 APPLICATIONS OF NASMO

As per the Manual of NAMSO, the applications are listed as follows:

a) to estimate the water level along bridges
b) to estimate the sediment loads
c) to estimate the water levels and flow rates for flood protection
d) to investigate the effect of landuse alterations in the catchment
e) to simulate water flow in catchments where no measuring gauge is available
f) to design and operate the hydraulic structures

CHAPTER 3

GEOGRAPHIC INFORMATION SYSTEM (GIS) ARC/INFO AND ILWIS

GIS is described as an organised collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information. In a simple way, GIS is defined as a computer system capable of holding and using data describing places on the earth's surface. A GIS typically links data from different sets. Exact matching occurs when the information of the file about many geographic features and additional information in another file about the same set of features have got stored in the computer. The operation to bring them together is easy, achieved by using a key common to both files. So, the record in each file, if the same name is expected and the two are joined and stored in another file.

Applications for GIS technology developed around the world. Today, the number and variety of applications for GIS are impressive. The amount of geographic data that has been gathered is staggering and includes volumes of satellite imagery collected from space. Local governments use GIS for planning and zoning, property assessment and land records, parcel mapping, public safety, and environmental planning. Resource managers rely on GIS for fish and wildlife planning; management of forested, agricultural, and coastal lands; and energy and mineral resource management.

GIS supports the daily activities of automated mapping and facilities management with applications for electricity, water, sewer, gas, telecommunications, and cable television utilities, using capabilities such as load management trouble call analysis, voltage drop, baseman generation and maintenance, line system analysis, siting, network pressure and flow analysis, leak detection, and inventory. Demographers use GIS for target market analysis, facility siting, address matching and geocoding, as well as product profiles, forecasting, and planning. GIS also has an increasing role in supporting education and research in the classroom, the computer lab, the research institute, and the public library.

The most important point to note is that these diverse applications are carried out using similar software and techniques - a GIS is truly a general-purpose tool.

A GIS is not simply a computer system for making maps, although it can create maps at different scales in different projections, and with different colours. A GIS is an analytical tool. The major advantage of a GIS is that it allows identifying the spatial relationships between map features.

A GIS does not store a map in any conventional sense; nor does it store a particular image or view of a geographic area. Instead, a GIS stores the data from which one can draw a desired view to suit a particular purpose.

A GIS links spatial data with geographic information about a particular feature on a map. The information is stored as attributes of the graphically represented feature. For example, the centre line that represents a road on a map does not tell much about the road except its location. To find out the road's width of pavement type, query of the data base is must. Using the information stored in the database, a display symbolising the roads according to the type of information that needs to be shown can be created.

A GIS also uses the stored feature attributes to compute new information about map features; for example, to calculate the length of a particular roads segment or to determine the total area of a particular soil type.

Essentially, a GIS gives the ability to associate information with a feature on a map and to create new relationships that can determine the suitability of various sites for development, evaluate environmental impacts, calculate harvest volumes, identify the best location for a new facility, and so on.

3.1 HYDROLOGICAL APPLICATIONS OF GIS ARC/INFO AND ILWIS

GIS ARC/INFO Version 7.0 is a Geographical Information System with advance capabilities developed by Environmental Systems Research Institute, INC., 380 New York Street, Redlands, CA 92373, USA. ARC/INFO TIN, ARC/INFO NETWORK, ARC/INFO COGO AND ARC/INFO GRID are extensions to ARC/INFO. These extensions are provided to have advanced analysis in GIS.

ILWIS 2.1 is another Geographical Information System developed by International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands. The abbreviation of ILWIS is Integrated Land and Water Information System.

Both of the systems mentioned above are used as tool in solving hydrological problems as mentioned below.

a) **Topographical information** - It is required in developing rainfall-runoff models. The topographical informations are size and slope of the catchment and drainage pattern. These are collected either from satellite imageries or digitised data through GIS systems. Digital Elevation models (DEM) are developed to extract these informations.
b) **Derivation of landuse pattern** – It is again used in rainfall-runoff modelling. This can be derived from digitised data or satellite imageries. The derivation of landuse is useful in designing optimal landuse pattern according to the available resources
c) **Ground water flow modelling** -- The flow equations are solved with GIS modelling technique and the streamlines and potential lines are plotted for further use.
d) **Ground water pollution modelling** – The pollution level of the ground water can be modelled through GIS and the dispersion pattern can be plotted to locate safe wells for many purposes.
e) **Snow mapping** – GIS can do Snow mapping. The topographical informations derived are used in snow mapping.
f) **Flood mapping** – GIS can do flood mapping with the modelling of flood rise over the area in desired duration.
g) **Reservoir sedimentation studies** – GIS can be used in reservoir sedimentation studies also.
h) **Data analysis** – The GIS can be used to analyse the data of hydrological studies.

The work book and the manuals of GIS ARC/INFO version 7 and ILWIS are to be referred to know how to digitise, manage and present the maps of any kind.

CHAPTER 4

APPLICATION OF GIS ARC/INFO AND ILWIS IN RAINFALL - RUNOFF MODELLING (NASMO)

As discussed in earlier Chapters the development of relations between precipitation and runoff is necessary for hydrologic design, river flow forecasting, landuse investigation etc. Runoff relations enable to estimate the streamflow to be expected during a period to operate irrigation, power, and flood-control structures. Parameters are fitted to match the observed outflow hydrograph to calculated hydrograph. In NASMO (rainfall-runoff) model the parameters are as follows i) the deviation from soil moisture content, ii) interception, iii) ratio of overland to interflow, iv) factors to time of concentration for overland flow, interflow and base flow, v) baseflow (base flow value, storage coefficient of the base flow, minimum and maximum velocity of the base flow), vi) factor to travel time in channel (retention time), vii) ratio of flow from subcatchment which has got two downstream subcatchments. These fitted parameters are later used to estimate the streamflow values for given rainfall. This procedure of calculation of runoff from rainfall can be adopted even for ungauged catchments with characteristics similar to the gauged-modelled catchment. As per the NASMO model requirement, the catchment characteristics like length of the stream, size, shape, slope and land use area of the subcatchment are to be calculated. GIS ARC/INFO and ILWIS were used to calculate the catchment characteristics.

4.1 DESCRIPTION OF THE STUDY AREA

4.1.1 MALAPRABHA CATCHMENT

The Malaprabha river is a right bank tributary of river Krishna. The Malaprabha catchment lies between north latitudes $15^{0}00'$ and $16^{0}12'$ and east longitudes $74^{0}14'$ and $76^{0}05'$ comprising the catchment area of the river from its source to its confluence with the Krishna including the catchments of all its tributories. The index map of the sub basin is presented in Fig 4. The location of raingauge station with drainage system is presented in Fig 5.

The Malaprabha originates at Kankumbi in the Western Ghats at an altitude of about 793 m in about 16 km west of Jamboti in Belgaum district of Karnataka. The river flows to east and the north west and joins the Krishna at Kapila sangam in the Bijapur district at an elevation of about 488 m. It traverses a length of 306 km before meeting the river Krishna. The Bennihala and the Hirehalla are the principal tributories of the river Malaprabha. The catchment area of the sub basin lies wholly in the state of Karnataka. The drainage area of the Malaprabha catchment upto Khanapur is 515.297 sq.km.

To harness the waters of the Malaprabha river a dam is constructed at Naviluteerth, Belgaum district to impound 1377 MCM water. The reservoir catchment covers an area of 3300 sq.km.

4.1.2 PHYSIOGRAPHY AND METEOROLOGY

The Malaprabha catchment is approximately triangular in shape. The terrain is flat to gently undulating except for a few hillocks and valleys. The northern boundary is the common ridge between the Malaprabha and the Ghataprabha rivers. The eastern boundary is the common ridge between the Malaprabha, the Krishna and the Tungabhadra rivers. The southern and western boundaries are the common ridge between the Malaprabha and the west flowing rivers. The important rock formations in the sub basin are (1) sedimentary rock formations (Kaladgi group) comprising limestone, shale and quartzites (ii) Schistose rock formations (Dharward super group) comprising granite, gneiss and crystalline rocks.

(a) **Climate**

There are three seasons prevailing in the catchment, the summer from March to April, the monsoon from May to November and the winter from December to February. The climate of the catchment is generally dry except the monsoon months. The maximum and minimum annual mean temperature for Khanapur are 31.7^0 C and 20.1^0 C respectively. The maximum and minimum annual mean relative humidity for Belgaum are 76 % and 57 % respectively. The annual mean windspeed for Belgaum is 9.3 km/hr. The annual mean sunshine for Belgaum is 74.5 %. The annual mean potential evapotranspiration for Belgaum is 1491.3 mm. The annual mean cloud cover for Belgaum at 0830 and 1730 are 3.4 akta and 4.0 akta respectively.

(b) **Rainfall**

The Malaprabha catchment mainly experiences the south-west monsoon. The rainfall in the non-monsoon period is insignificant. The average annual rainfall of the catchment is 770 mm. The rainfall values for 1987, 1988, 1990 and 1991 of six stations were considered for the study. The stations considered were Khanapur, Kankumbi, santibastwad, Desur, Jamboti and Gunji. The rainfall values of Gunji for the year 1988 were missing. The values are presented in

Tables 4, 5, 6 and 7 for the years 1987, 1988, 1990 and 1991 respectively.

4.1.3 LAND USE PATTERN

Malaprabha basin upstream of Khanapur was divided into 39 subcatchments. The main aim of dividing the catchment into number of subcatchments is to account the change in landuses and soil conditions. In some subcatchments there may be more than one landuses with different soil conditions. These subcatchments were labelled according to the model (1.10000, 1.11000, 1.11100, 1.20000 etc.) and the same is presented in Fig 6. The subcatchment name, length of the main stream, area of the subcatchment, main stream slope and average slope of the subcatchment are presented in Table 8. The landuses of these sub catchments were classified into forest, agriculture, shrubs and barren land. As per the NASMO model there is no option for barren land. Barren land is nearer to village land in respect of infiltration characteristics. So barren land is taken as village and in the same way the shrub area is taken as grassland by considering the characteristics of both the type of landuses. The percentage of respective classifications is identified and is presented in Table 9. The land use pattern is presented in Fig 7.

4.1.4 SOILS

As per SCS curve number method all soils are classified into four hydrologic soil groups of distinct runoff producing properties. These soil groups are labelled as A, B, C, and D. After the survey, it is confirmed that the red loamy soils are distributed in the study area. The red loamy soil is a soil with moderate infiltration rates when wetted thoroughly, primarily moderately deep to deep, moderately drained to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission. The soils of the study area were found to be in B group. The input for hydrologic soil group in this model was 2.

4.1.5 OBSERVED RUNOFF HYDROGRAPHS

The observed runoff hydrograph values were available for 1987, 1988, 1990 and 1991. The values were selected for this study according to the selected rainfall values. The values are presented in Tables 10, 11, 12 and 13 for the years 1987, 1988, 1990 and 1991.

4.1.6 BASE FLOW

The observed runoff hydrographs were plotted and the base flow values were separated for the selected values. The values are presented in Table 14.

4.2 DESCRIPTION OF THE STUDY CARRIED OUT

The stream lengths, percentage of landuse pattern, area of the sub-catchment were calculated by digitising the toposheets of 48I/1, 48I/2, 48I/5, 48I/6 of scale 1:50000 of the catchment. The slope of the stream and average slope of the subcatchment were calculated from DEM. The DEM is presented in Fig 8. The following values for each subcatchments were fed to the Model in the file of MALA.TFL:

1. Name of the subcatchment from the schematic diagram of the basin
2. Identification of flow into one downstream catchment from the schematic diagram of the basin
3. Identification of flow into two downstream catchment from the schematic diagram of the basin
4. Rainfall station number from Thiessen polygon
5. Print option
6. Symbol of subcatchment where the runoff is measured
7. Shape of the catchment from the schematic diagram of the basin
8. Area of the catchment in km^2 from the histogram of the digitised map
9. Length of the stream, in m form the histogram of the digitised map
10. Slope of stream flow from the DEM
11. Slope of overland flow from the DEM
12. Mannings coefficient by the nature of stream channel
13. Darcy's coefficient by the soil type
14. Soil group from soil survey details
15. Number of landuses from the digitised landuse map
16. Proportion of each landuses from the histogram of digitised landuse map
17. Details of parameters file

The Strickler's Resistance Formula is written as follows:

$$V = k_s R^{2/3} S_f^{1/2} \qquad \text{......(4.1)}$$

Where k_s is Strickler's constant.

The Manning equation is written as follows:

$$V = \frac{1}{n} R^{2/3} S_f^{1/2} \qquad \text{......(4.2)}$$

Where n is Manning constant.

A comparison of equations 4.1 and 4.2 shows that the Manning and Strickler formulas are similar and that

$$k_s = \frac{1}{n} \qquad \text{......(4.3)}$$

The Strickler coefficient was taken as 25 (The Mannings coefficient was taken as 0.04 because the natural channel is a winding stream and moreover it is a forest area) for the model application. (Applied Hydrology by V.T.chow, D.R.Maidment and L.W.Mays).

The rainfall values in mm were fed in *.GGN (for example MALA_87.GGN) file.

The catchment has got only one runoff station at Khanapur. These runoff values in m^3/sec were fed in *.GGQ (for example MALA_87.GGQ) file.

The input and output files were organised in *.ORG file. The input files were as follows:

1. MALA.TFL - catchment characteristics
2. *.GGN - rainfall values
3. *.GGQ - runoff values
4. *.PCD - procedure file
5. *.ORG - calculated runoff hydrograph characteristics
6. NASMO.ERR - error file

The output files were as follows:

1. *.ERG - result of calculation
2. MALA.TAB - catchment characteristics and the result of concentration time in each sub-

catchment

3. MALA.REC - special feature of each sub-catchments and the annotation
4. MALA.CTL - control information and control output
5. MALA.MON - The output of process in order of sub-catchments
6. MALA.QSV - The observed runoff

The output file *.ERG was very important to fit the parameters among the six output files because it contains observed and calculated runoff values.

The details like beginning date, time, interval and duration in hour for calculated hydrograph were also fed in *.ORG file.

The option 2 (KIRPICH Method) for the method of calculation of time concentration was also fed. In the *.PCD the following values were fed:

1. The deviation form the soil moisture content in mm
   The AMC II is considered for calculating the curve numbers. SCS method assumes average soil moisture content according to this AMC II by considering the total 5-d antecedent seasonal rainfall limits. But the real AMC may be plus or minus to the assumed value. The curve number is calculated by assuming plus or minus value to this average soil moisture content.
2. Interception in mm
3. Ratio of overland flow (the ratio between effective precipitation to overland flow from direct runoff)
4. Factors to time of concentration for overland flow, interflow and base flow with maximum and minimum limit in hour
5. Base flow in l/(s.km^2)
6. Factor to travel time in channel (Retention time) in hour
7. Storage coefficient of the base flow in hour

The above mentioned values are considered as parameters in this model. These values were changed and the model was run repeatedly to match the observed hydrograph with the calculated hydrograph.

4.3 RESULTS

The parameter values are assumed according to the soil condition, landuse pattern and physical characteristics of the basin in the first run. Three storms 1987(1st to 31st July), 1988 (9th to 26th July) and 1990 (1st to 31st July) were selected for the parameter calibration. In the first run of storm for 1987 the highest peak of the calculated hydrograph was too much higher than the peak of the observed hydrograph. Then the parameter values, factors to time of concentration for surface flow, interflow and base flow, were changed systematically to reduce the difference between the peak of the calculated hydrograph and the peak of the observed hydrograph. After the last run the highest peak of the calculated hydrograph is 0.39 times higher than the peak of the observed hydrograph. The observed hydrograph contains four peaks. Only one peak of the calculated hydrograph is 0.35 times lower than the observed hydrograph. All other peaks of calculated hydrograph are higher from 0.7 to 2.0 times approximately than observed hydrograph. The last peak of the calculated hydrograph is 2.0 times higher than the peak of the observed hydrograph. The peaks of the calculated hydrograph occur at the same time as the observed hydrograph. The parameter value, factor to travel time in channel, was taken as 0.001 because the outlet of each stream is very nearer to the beginning of the stream. The parameter values are given in tabular form later in this section.

In the first run of storm for 1988 also the highest peak of the calculated hydrograph was higher than the peak of the observed hydrograph. Then the parameter values, factors to time of concentration for surface flow, interflow and base flow, were changed systematically to reduce the difference between the peak of the calculated hydrograph and the peak of the observed hydrograph. After the last run the calculated hydrograph is matching approximately with the observed hydrograph upto 70 hours of simulation. The observed hydrograph contains three peaks. Only one peak of the calculated hydrograph is 0.32 times lower than the observed hydrograph. The highest peak of calculated hydrograph is 0.004 approximately higher than observed hydrograph. The last peak of the calculated hydrograph is 0.19 times higher than the peak of the observed hydrograph. The peaks of the calculated hydrograph occur approximately 2 hours after the observed hydrograph except the first peak. The parameter value, factor to travel time in channel, is taken as 0.001 because the outlet of each stream is very nearer to the beginning of the stream. The parameter values are given in tabular form later in this section.

In the first run of storm for 1990 the highest peak of the calculated hydrograph was much higher than the peak of the observed hydrograph. Then the parameter values, factors to time of concentration for surface flow, interflow and base flow, were changed systematically to reduce the difference between the peak of the calculated hydrograph and the peak of the observed hydrograph. The observed hydrograph contains three peaks. Only one peak of the calculated hydrograph is 0.07 times lower than the observed hydrograph. All other peaks of calculated hydrograph are higher from 0.008 to 0.018 times approximately than observed hydrograph. The last peak of the calculated hydrograph is 0.018 times higher than the peak of the observed hydrograph. The peaks of the calculated hydrograph occur approximately 2 hours after the observed hydrograph. The parameter value, factor to travel time in channel, is taken as 0.001 because the outlet of each stream is very nearer to the beginning of the stream. The parameter values are given in tabular form later in this section.

Item	1987	1988	1990
Deviation for the moisture content in mm	0	0	30.0
Interception in mm	20.0	20.0	20.0
Ratio of overland flow	0.25	0.36	0.50
Factor to time of concentration for overland flow in hour	5.0	3.0	3.0
Factor to time of concentration for interflow in hour	60.0	70.0	70.0
Factor to time of concentration for baseflow in hour	1500.0	1500.0	1500.0
Base flow in $l/(s.km^2)$	20.0	20.0	50.0
Factor to travel time in channel (Retention time) in hour	0.00	0.00	0.00
Storage Coefficient of the base flow in hour	1500.0	1500.0	1500.0

The parameters for all the three storms were averaged at last and the average values are given in the conclusion.

The averaged parameters are evaluated using the storm 1991 (1st to 31st July) and the corresponding hydrograph. The calculated hydrograph is approximately matching with observed hydrograph upto 360 hours of simulation. The observed hydrograph contains 3 peaks. The highest peak of the observed hydrograph is 0.006 times higher than the calculated hydrograph. All other peaks of calculated hydrograph are higher from 0.009 to 0.27 times approximately than observed hydrograph. The highest peak of calculated hydrograph occurs at the peak of the observed hydrograph. The other peaks of the calculated hydrograph occur before 10 to 19 hours of the peaks of the observed hydrograph. The Figures 9, 10, 11 and 12 for the years 1987, 1988, 1990 and 1991 respectively indicate the matching of observed and calculated outflow hydrographs.

CHAPTER 5
CONCLUSIONS

NASMO is a rainfall-runoff model in which the US SCS curve number method is used to calculate effective rainfall in a catchment. The unit hydrograph technique is used to get outflow hydrograph. The overland flow is routed by linear reservoir method and streamflow is routed by Modified Puls method. It is an articulated model for which the degree of the discretization can be chosen on the need for discharge calculations at specific points. It can be used to represent small to midsize catchments and discretization schemes with very efficient memory administration on a PC. Approximately 1000 calculation intervals using 750 subareas are the upper limit for PC usage when a normal density of rainfall and gauging stations are used. Other platforms must be used for larger models or for finer discretizations. It has a modular design, enabling addition of programs to answer new questions with a minimum expense. The basin parameters can be generated with a Geographic Information System. It has seven parameters, which are fitted systematically by trial and error process. This model is in German language. So it is difficult to understand and correct the errors while running the model. The whole executive version of the model should be translated into English for wider use.

The package GIS ARC/INFO and ILWIS were used to digitise the toposheets of Malaprabha catchment up to Khanapur (515.297 sq.km) in Karnataka State to get catchment characteristics like shape, size, slope and landuse patterns. Rainfall values of 6 stations and one runoff station values were used in the model.

The parameter values were fitted for three rainfall storms: 1987 (1st to 31st July), 1988 (9th to 26th July) and 1990 (1st to 31st July) and the corresponding hydrographs. The following are best-fitted average values for this catchment according to the data available. As per the catchment characteristics, rainfall storms and the corresponding runoff hydrograph, landuse patterns and soiltypes, the best-fitted parameters are in the reasonable range.

1. The deviation from the soil moisture content – 10.00 mm
2. Interception – 20 mm
3. Ratio of overland flow (the ratio between effective precipitation to overland flow from direct runoff) – 0.37
4. Factor to time of concentration for overland flow – 3.67 hour

Factor to time of concentration for interflow – 66.67 hour

Factor to Time of concentration for base flow – 1500.00 hour

5. Base flow – 30 litres/(second.km^2)
6. Factor to travel time in channel (Retention time) – 0.001 hour
7. Storage Coefficient of the base flow – 1500.00 hour

The averaged best-fitted parameters are evaluated using the data of the storm of 1991 (1st to 31st July) and the corresponding hydrograph. The highest peak of the calculated hydrograph matches very closely with the peak of the observed hydrograph. All other peaks of the calculated hydrograph are also closely matching with the peaks of the observed hydrograph.

Based on the results, it is concluded that the NASMO can be used to predict the runoff from Indian catchment. The error in the fitted parameter values will be reduced if more number of storms are used for parameter fitting. For effective use of this model for Indian catchments, it is required to have complete details regarding landuses and soil conditions of each subcatchments. The channel characteristics are also to be provided for the use of this model.

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Table 1 Seasonal Rainfall Limits for Three Level of Antecedent Moisture Condition (AMC)

AMC	Total 5-d Antecedent Rainfall (cm)	
	Dormant Season	Growing Season
I	Less than 1.3	Less than 3.6
II	1.3 to 2.8	3.6 to 5.3
III	More than 2.8	More than 5.3

Note: This table was developed using data from the midwestern United States. Therefore, caution is recommended when using the values supplied in this table for AMC determinations in other geographic or climatic regions.

Table 2(a) Runoff Curve Number for Urban areas[1]

Cover Description		Curve Numbers for Hydrologic Soil Group:			
Cover Type and Hydrologic Condition	Average Percent Impervious Area[2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover less than 50%)		68	79	86	89
Fair condition (grass cover 50 to 75%)		49	69	79	84
Good condition (grass cover greater than 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curves and storm sewers (excluding right-of-way)		98	98	98	98
Paved, open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-in. sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
$\frac{1}{8}$ ac. or less (town houses)	65	77	85	90	92
$\frac{1}{4}$ ac.	38	61	75	83	87
$\frac{1}{3}$ ac.	30	57	72	81	86
$\frac{1}{2}$ ac.	25	54	70	80	85
1 ac.	20	51	68	79	84
2 ac.	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[5]		77	86	91	94
Idle lands (curve numbers (CNs) are determined using cover types similar to those in Table 5-2(c)).					

Notes.

[1] Average antecedent moisture condition and $I_a = 0.2S$.

[2] The average percent impervious area shown was used to develop the composite *CN*s. Other assumptions are as follows: Impervious areas are directly connected to the drainage system; impervious areas have a $CN = 98$; and pervious areas are considered equivalent to open space in good hydrologic condition. *CN*s for other combinations of conditions may be computed using Fig. 5 or 6

[3] CNs shown are equivalent to those of pasture. Composite *CN*s may be computed for other combinations of open space cover type.

[4] Composite *CN*s for natural desert landscaping should be computed using Figs. 5 or 6 based on the impervious area percentage ($CN = 98$) and the pervious area *CN*. The pervious area *CN*s are assumed equivalent to desert shrub in poor hydrologic condition.

Composite *CN*s to use for the design of temporary measures during grading and construction should be computed using Figs 5 or 6 , based on the degree of development (impervious area percentage) and the *CN*s for the newly graded pervious areas.

Table 2(b) Runoff Curve Numbers for Cultivated Agricultural lands[1]

Cover Description			Curve Numbers for Hydrologic Soil Group:			
Cover Type	Treatment[2]	Hydrologic Condition[3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured and terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

Notes:

[1] Average antecedent moisture condition and $I_a = 0.2S$.

[2] *Crop residue cover* applies only if residue is on at least 5% of the surface throughout the year.

[3] Hydrologic condition is based on combination of factors that affect infiltration and runoff, including: (1) density and canopy of vegetated areas; (2) amount of year-round cover; (3) amount of grass or close-seeded legumes in rotation; (4) percent of residue cover ~~on the~~ land surface (good hydrologic condition is greater than or equal to 20%); and (5) degree of surface roughness. *Poor:* Factors impair infiltration and tend to increase runoff. *Good:* Factors encourage average and better than average infiltration and tend to decrease runoff.

Table 2(c) Runoff Curve Numbers for Other Cultivated Agricultural lands[1]

Cover Description		Curve Numbers for Hydrologic Soil Group:			
Cover Type	Hydrologic Condition	A	B	C	D
Pasture, grassland, or range-continuous forage for grazing[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow-continuous grass, protected from grazing and generally mowed for hay	—	30	58	71	78
Brush—brush-weed grass mixture with brush being the major element[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[4]	48	65	73
Woods—grass combination (orchard or tree farm)[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods.[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30[4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

Notes:

[1] Average antecedent moisture condition and $I_a = 0.2S$.

[2] *Poor:* less than 50% ground cover on heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: more than 75% ground cover and lightly or only occasionally grazed.

[3] *Poor:* less than 50% ground cover.
Fair: 50 to 75% ground cover.
Good: more than 75% ground cover.

[4] Actual curve number is less than 30; use $CN = 30$ for runoff computations.

[5] *CN*s shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the *CN*s for woods and pasture.

[6] *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table 2(d) Runoff Curve Numbers for Arid and Semiarid Rangelands[1]

Cover Description		Curve Numbers for Hydrologic Soil Group:			
Cover Type	Hydrologic Condition[2]	A[3]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbrush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

Notes:

[1] Average antecedent moisture condition and $I_a = 0.2S$. For range in humid regions, use Table 2(c).

[2] *Poor:* less than 30% ground cover (litter, grass, and brush overstory).
Fair: 30 to 70% ground cover.
Good: more than 70% ground cover.

[3] Curve numbers for group A have been developed only for desert shrub.

Table 3 Corresponding Runoff Curve Numbers for three AMC conditions

AMC II	AMC I	AMC III	AMC II	AMC I	AMC III
100	100	100	60	40	78
99	97	100	59	39	77
98	94	99	58	38	76
97	91	99	57	37	75
96	89	99	56	36	75
95	87	98	55	35	74
94	85	98	54	34	73
93	83	98	53	33	72
92	81	97	52	32	71
91	80	97	51	31	70
90	78	96	50	31	70
89	76	96	49	30	69
88	75	95	48	29	68
87	73	95	47	28	67
86	72	94	46	27	66
85	70	94	45	26	65
84	68	93	44	25	64
83	67	93	43	25	63
82	66	92	42	24	62
81	64	92	41	23	61
80	63	91	40	22	60
79	62	91	39	21	59
78	60	90	38	21	58
77	59	89	37	20	57
76	58	89	36	19	56
75	57	88	35	18	55
74	55	88	34	18	54
73	54	87	33	17	53
72	53	86	32	16	52
71	52	86	31	16	51
70	51	85	30	15	50
69	50	84			
68	48	84	25	12	43
67	47	83	20	9	37
66	46	82	15	6	30
65	45	82	10	4	22
64	44	81	5	2	13
63	43	80	0	0	0
62	42	79			
61	41	78			

Table 4 Cumulative Rainfall values for 1987

Date	Time	Cumulative Rainfall values (mm)					
		Khanapur	Kankumbi	Santibast wad	Despur	Jamboti	Gunji
01071987	0830	07.00	103.40	08.90	05.00	12.40	18.40
02071987	0830	55.10	211.20	38.50	31.00	30.80	58.40
03071987	0830	92.90	305.60	82.10	100.00	134.80	120.40
04071987	0830	99.90	365.80	88.30	104.00	158.80	133.60
05071987	0830	112.60	432.60	91.10	107.00	177.20	155.60
06071987	0830	122.10	504.80	97.10	142.00	222.20	157.00
07071987	0830	176.70	612.40	126.10	186.00	324.20	207.20
08071987	0830	253.30	754.00	167.70	211.00	430.20	282.20
09071987	0830	304.80	903.80	213.70	266.00	596.40	447.60
10071987	0830	306.00	968.40	216.50	266.00	598.80	459.80
11071987	0830	317.50	1047.00	218.50	266.00	609.20	469.10
12071987	0830	320.10	1086.00	219.40	266.00	623.30	470.50
13071987	0830	338.30	1122.60	220.60	275.00	657.50	489.50
14071987	0830	341.50	1208.40	229.20	281.00	705.50	492.80
15071987	0830	347.60	1298.40	238.60	296.00	750.50	505.10
16071987	0830	351.00	1347.00	240.00	300.00	778.90	515.10
17071987	0830	353.30	1365.80	240.00	301.00	782.90	520.10
18071987	0830	360.00	1392.80	240.00	302.00	800.90	528.10
19071987	0830	375.20	1472.80	243.30	304.00	822.90	537.40
20071987	0830	379.70	1509.80	245.50	307.00	830.90	540.70
21071987	0830	380.00	1517.00	245.90	307.00	830.90	540.70
22071987	0830	380.30	1529.40	246.30	307.00	832.90	540.70
23071987	0830	381.30	1534.40	246.30	307.00	832.90	540.70
24071987	0830	381.80	1542.00	246.70	307.00	832.90	540.70
25071987	0830	382.30	1552.20	246.70	307.00	840.10	540.70
26071987	0830	395.00	1655.60	259.40	307.00	863.10	570.90
27071987	0830	395.80	1669.00	261.20	318.00	865.50	570.90
28071987	0830	395.80	1693.40	261.20	318.00	868.50	570.90
29071987	0830	395.80	1694.20	261.20	318.00	868.50	570.90
30071987	0830	395.80	1694.20	261.20	318.00	868.50	570.90
31071987	0830	396.10	1694.20	261.20	318.00	868.50	570.90

Table 5 Cumulative Rainfall values for 1988

Date	Time	Cumulative Rainfall values (mm)					
		Khanapur	Kankumbi	Santibast wad	Despur	Jamboti	Gunji
09071988	0830	00.00	27.60	00.00	00.00	01.20	-
10071988	0830	00.00	29.60	00.00	00.00	01.20	-
11071988	0830	00.00	65.40	00.00	00.00	01.20	-
12071988	0830	09.60	90.40	00.50	00.00	11.20	-
13071988	0830	26.60	164.80	14.50	19.00	20.30	-
14071988	0830	111.10	407.20	95.50	79.00	121.40	-
15071988	0830	167.70	502.80	121.30	95.00	191.40	-
16071988	0830	256.50	639.20	207.90	173.00	295.40	-
17071988	0830	304.00	899.20	306.30	239.00	415.40	-
18071988	0830	451.00	1211.60	466.30	304.00	587.70	-
19071988	0830	553.30	1334.00	506.30	376.00	699.00	-
20071988	0830	594.80	1427.80	524.30	411.00	775.00	-
21071988	0830	601.10	1508.60	530.30	426.00	794.00	-
22071988	0830	608.60	1581.60	545.60	434.00	817.00	-
23071988	0830	652.40	1767.20	598.40	479.00	881.10	-
24071988	0830	659.80	1817.20	608.80	498.00	902.30	-
25071988	0830	666.00	1830.80	611.80	514.00	914.60	-
26071988	0830	677.50	1855.40	619.90	520.00	935.80	-

Table 6 Cumulative Rainfall values for 1990

Date	Time	Cumulative Rainfall values (mm)					
		Khanapur	Kankumbi	Santibast wad	Despur	Jamboti	Gunji
01071990	0830	46.40	76.40	04.00	20.40	32.60	24.20
02071990	0830	64.40	186.20	18.50	49.60	65.40	56.30
03071990	0830	215.10	416.20	118.50	89.60	231.40	95.50
04071990	0830	261.50	572.20	143.70	154.00	321.00	119.60
05071990	0830	278.20	632.20	149.70	176.20	352.60	127.80
06071990	0830	295.20	652.20	153.20	183.20	363.60	129.90
07071990	0830	312.00	676.60	159.20	187.40	375.40	135.10
08071990	0830	317.10	695.60	163.70	193.40	386.80	136.30
09071990	0830	327.50	735.60	185.70	233.40	413.20	139.40
10071990	0830	334.00	770.20	188.70	235.40	435.80	141.60
11071990	0830	340.40	808.00	200.70	242.40	445.40	142.80
12071990	0830	350.80	896.00	203.70	245.80	460.80	151.00
13071990	0830	351.30	927.40	205.20	246.80	465.20	155.40
14071990	0830	361.40	1047.60	220.70	255.00	497.60	162.60
15071990	0830	378.70	1223.20	229.70	274.20	553.60	168.00
16071990	0830	403.40	1323.20	238.70	281.20	582.00	170.70
17071990	0830	438.40	1418.20	259.30	304.60	638.80	185.90
18071990	0830	462.50	1568.20	289.50	359.80	712.20	208.00
19071990	0830	482.70	1640.20	296.00	369.20	740.80	224.20
20071990	0830	489.70	1681.60	300.50	373.40	758.40	232.40
21071990	0830	527.30	1766.00	310.30	379.80	808.80	235.50
22071990	0830	543.00	1856.20	334.70	393.40	837.60	242.70
23071990	0830	553.50	2001.20	350.20	408.80	870.20	252.90
24071990	0830	587.30	2202.20	373.20	428.80	945.60	272.10
25071990	0830	595.30	2260.00	378.20	432.20	960.20	278.20
26071990	0830	597.40	2304.60	379.40	433.20	967.60	281.40
27071990	0830	599.60	2347.60	381.90	433.20	972.20	283.60
28071990	0830	608.40	2359.60	383.40	433.20	982.20	284.80
29071990	0830	616.60	2367.60	384.00	435.40	987.20	285.90
30071990	0830	623.70	2386.60	385.00	435.40	994.80	288.10
31071990	0830	629.50	2428.00	390.00	439.40	1004.60	294.20

Table 7 Cumulative Rainfall values for 1991

Date	Time	Cumulative Rainfall values (mm)					
		Khanapur	Kankumbi	Santibast wad	Despur	Jamboti	Gunji
01071991	0830	0.00	7.80	0.00	2.00	0.00	0.00
02071991	0830	2.00	25.80	5.10	5.20	11.00	3.90
03071991	0830	3.70	66.00	9.60	10.20	18.40	6.20
04071991	0830	11.50	108.80	16.60	16.40	28.20	8.10
05071991	0830	14.70	139.80	21.60	28.40	37.20	11.40
06071991	0830	18.20	178.40	22.10	29.40	48.20	14.30
07071991	0830	23.60	223.80	25.90	31.40	59.20	17.40
08071991	0830	26.60	286.80	27.40	31.40	67.20	21.10
09071991	0830	28.00	302.40	29.90	36.00	72.20	22.60
10071991	0830	29.30	337.40	30.50	37.00	77.20	24.90
11071991	0830	34.30	355.80	33.00	37.00	87.20	27.00
12071991	0830	44.30	375.60	42.00	43.00	99.20	37.30
13071991	0830	64.30	445.60	58.30	52.00	137.80	46.20
14071991	0830	106.10	494.60	84.20	66.20	203.40	59.50
15071991	0830	216.80	697.60	121.70	111.60	308.20	85.20
16071991	0830	294.90	824.60	169.70	159.60	442.20	109.40
17071991	0830	357.00	1009.80	207.10	194.80	528.80	142.70
18071991	0830	414.60	1120.00	245.20	223.00	619.60	176.10
19071991	0830	446.90	1193.00	249.20	228.00	660.60	184.40
20071991	0830	453.00	1230.60	253.10	231.40	681.40	193.30
21071991	0830	465.80	1291.40	265.00	237.40	704.40	201.70
22071991	0830	499.00	1398.00	285.00	264.40	772.00	217.60
23071991	0830	517.40	1458.80	294.40	274.60	812.00	229.40
24071991	0830	533.30	1514.80	296.30	276.60	827.00	237.80
25071991	0830	542.10	1620.20	306.80	279.60	860.00	245.70
26071991	0830	615.30	1732.40	332.60	305.50	941.60	276.10
27071991	0830	787.50	2123.20	441.30	405.50	1211.60	309.40
28071991	0830	844.80	2403.20	509.00	451.50	1358.60	352.80
29071991	0830	867.30	2518.20	543.90	473.90	1394.60	380.90
30071991	0830	885.50	2643.80	553.30	479.10	1420.20	396.30
31071991	0830	901.50	2708.80	559.80	486.70	1456.20	411.50

Table 8 Subcatchment details of Malaprabha

Sl.no	Subcatchment	Area (Sqkm)	Main Stream length (m)	Main stream Slope (m/km)	Average subcatchment slope (m/km)
1	1.10000	1.940	484.6	2.066	4.103
2	1.11000	0.741	1535.7	1.954	3.385
3	1.11100	4.234	3555.2	5.626	20.852
4	1.12000	15.488	6392.4	2.000	29.727
5	1.13000	18.688	4432.2	4.964	46.914
6	1.14000	6.908	1915.2	2.000	13.919
7	1.15000	6.072	4957.4	1.412	39.042
8	1.15100	18.334	6056.1	44.088	84.859
9	1.16000	17.297	4600.3	1.956	43.407
10	1.17000	17.116	2180.7	2.000	44.337
11	1.18000	26.778	6398.5	2.969	61.681
12	1.19000	24.278	3668.7	2.000	70.507
13	1.20000	26.539	4863.3	2.000	66.543
14	1.21000	34.106	6591.3	3.034	28.794
15	2.10000	2.407	3684.0	2.000	3.160
16	2.11000	5.170	3161.9	3.795	12.670
17	2.11100	9.690	7855.5	7.893	20.959
18	2.12000	11.836	5934.1	8.257	19.548
19	2.12100	13.450	5786.7	8.986	13.188
20	3.10000	7.874	4514.3	2.000	12.473
21	3.11000	7.269	1821.8	2.000	12.492
22	3.11100	9.855	5816.2	24.243	51.765
23	3.12000	4.794	1345.7	2.000	14.105
24	3.12100	1.400	1638.4	2.000	23.079
25	3.12200	2.513	1957.2	2.000	11.863
26	3.12210	3.315	3075.0	22.114	26.343
27	3.12300	3.546	1512.0	2.000	15.880
28	3.12310	11.400	5882.1	34.001	54.243
29	3.12400	19.659	7338.9	44.557	55.553
30	3.13000	12.080	4398.7	1.591	23.639
31	3.13100	17.325	6322.0	11.389	51.135
32	3.14000	14.063	2232.1	2.000	52.563
33	3.15000	22.772	4481.4	2.000	56.586
34	4.10000	17.904	5930.9	4.721	24.375
35	4.11000	11.699	4011.7	2.000	6.422
36	4.12000	19.846	3041.3	4.274	25.246
37	4.13000	22.173	8681.7	6.796	46.119
38	4.13100	21.612	6040.9	1.324	27.154
39	4.13200	23.179	4829.6	10.146	38.359

Table 9 Landuse details of Malaprabha

Sl.no	Subcatchment	Landuse in percentage				
		Agriculture	Grass	Forest	Village	City
1	1.10000	0.00	0.98	0.00	0.02	0.00
2	1.11000	0.00	1.00	0.00	0.00	0.00
3	1.11100	0.00	0.53	0.47	0.00	0.00
4	1.12000	0.00	0.46	0.54	0.00	0.00
5	1.13000	0.00	0.08	0.92	0.00	0.00
6	1.14000	0.00	0.11	0.89	0.00	0.00
7	1.15000	0.00	0.00	1.00	0.00	0.00
8	1.15100	0.00	0.00	1.00	0.00	0.00
9	1.16000	0.00	0.01	0.99	0.00	0.00
10	1.17000	0.00	0.00	0.98	0.02	0.00
11	1.18000	0.11	0.00	0.89	0.00	0.00
12	1.19000	0.09	0.00	0.91	0.00	0.00
13	1.20000	0.01	0.00	0.99	0.00	0.00
14	1.21000	0.17	0.00	0.83	0.00	0.00
15	2.10000	0.00	1.00	0.00	0.00	0.00
16	2.11000	0.00	1.00	0.00	0.00	0.00
17	2.11100	0.04	0.94	0.02	0.00	0.00
18	2.12000	0.20	0.80	0.00	0.00	0.00
19	2.12100	0.58	0.42	0.00	0.00	0.00
20	3.10000	0.00	0.05	0.95	0.00	0.00
21	3.11000	0.00	0.00	1.00	0.00	0.00
22	3.11100	0.00	0.00	1.00	0.00	0.00
23	3.12000	0.20	0.00	0.80	0.00	0.00
24	3.12100	0.00	0.00	1.00	0.00	0.00
25	3.12200	0.00	0.00	1.00	0.00	0.00
26	3.12210	0.00	0.00	1.00	0.00	0.00
27	3.12300	0.00	0.00	1.00	0.00	0.00
28	3.12310	0.00	0.00	0.98	0.02	0.00
29	3.12400	0.00	0.00	1.00	0.00	0.00
30	3.13000	0.20	0.00	0.80	0.00	0.00
31	3.13100	0.19	0.00	0.81	0.00	0.00
32	3.14000	0.16	0.00	0.84	0.00	0.00
33	3.15000	0.00	0.00	1.00	0.00	0.00
34	4.10000	0.18	0.73	0.09	0.00	0.00
35	4.11000	1.00	0.00	0.00	0.00	0.00
36	4.12000	1.00	0.00	0.00	0.00	0.00
37	4.13000	0.99	0.01	0.00	0.00	0.00
38	4.13100	0.51	0.23	0.00	0.26	0.00
39	4.13200	0.02	0.77	0.21	0.00	0.00

Table 10 Observed Discharge at Khanapur for 1987

Date	Time	Observed Discharge (Cumec)
01071987	0830	11.03
02071987	0830	60.17
03071987	0830	103.81
04071987	0830	65.77
05071987	0830	57.92
06071987	0830	45.03
07071987	0830	105.18
08071987	0830	148.98
09071987	0830	197.84
10071987	0830	136.05
11071987	0830	130.76
12071987	0830	92.71
13071987	0830	93.29
14071987	0830	83.22
15071987	0830	104.86
16071987	0830	85.70
17071987	0830	76.56
18071987	0830	74.87
19071987	0830	81.24
20071987	0830	73.05
21071987	0830	66.16
22071987	0830	45.76
23071987	0830	39.74
24071987	0830	35.63
25071987	0830	39.34
26071987	0830	47.42
27071987	0830	38.12
28071987	0830	35.80
29071987	0830	27.92
30071987	0830	27.00
31071987	0830	21.36

Table 11 Observed Discharge at Khanapur for 1988

Date	Time	Observed Discharge (Cumec)
09071988	0830	11.55
10071988	0830	11.68
11071988	0830	20.13
12071988	0830	11.94
13071988	0830	51.82
14071988	0830	235.38
15071988	0830	142.38
16071988	0830	232.20
17071988	0830	267.15
18071988	0830	510.00
19071988	0830	295.90
20071988	0830	227.63
21071988	0830	218.41
22071988	0830	143.28
23071988	0830	271.96
24071988	0830	187.23
25071988	0830	111.77
26071988	0830	105.06

Table 12 Observed Discharge at Khanapur for 1990

Date	Time	Observed Discharge (Cumec)
01071990	0830	101.77
02071990	0830	109.95
03071990	0830	309.56
04071990	0830	183.32
05071990	0830	133.33
06071990	0830	89.94
07071990	0830	65.42
08071990	0830	50.20
09071990	0830	67.55
10071990	0830	50.97
11071990	0830	55.59
12071990	0830	61.41
13071990	0830	62.89
14071990	0830	85.60
15071990	0830	109.00
16071990	0830	121.67
17071990	0830	160.64
18071990	0830	278.53
19071990	0830	162.83
20071990	0830	121.00
21071990	0830	138.87
22071990	0830	124.76
23071990	0830	157.15
24071990	0830	271.21
25071990	0830	142.11
26071990	0830	97.81
27071990	0830	73.51
28071990	0830	61.29
29071990	0830	53.09
30071990	0830	48.56
31071990	0830	45.38

Table 13 Observed Discharge at Khanapur for 1991

Date	Time	Observed Discharge (Cumec)
01071991	0830	05.84
02071991	0830	05.95
03071991	0830	06.52
04071991	0830	08.95
05071991	0830	11.24
06071991	0830	20.73
07071991	0830	21.99
08071991	0830	29.31
09071991	0830	28.01
10071991	0830	25.14
11071991	0830	21.33
12071991	0830	23.00
13071991	0830	31.93
14071991	0830	94.10
15071991	0830	220.35
16071991	0830	291.34
17071991	0830	246.03
18071991	0830	268.70
19071991	0830	265.55
20071991	0830	155.55
21071991	0830	169.10
22071991	0830	175.51
23071991	0830	182.55
24071991	0830	153.47
25071991	0830	163.82
26071991	0830	284.98
27071991	0830	311.20
28071991	0830	328.71
29071991	0830	319.11
30071991	0830	247.78
31071991	0830	216.80

Table 14 Base flow values for the selected storms

Sl.no	Year	Base flow (l/(s.Km^2))
1	1987	87.39
2	1988	22.41
3	1990	118.94

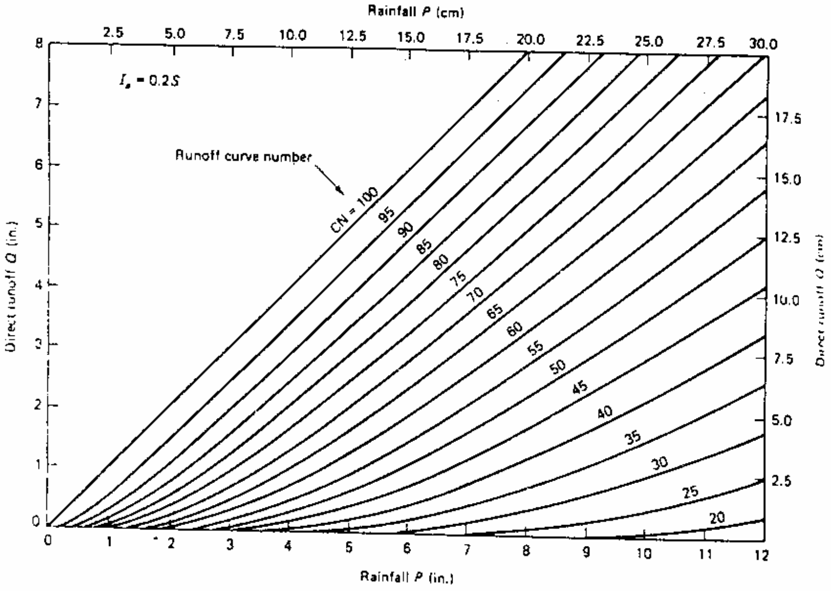

Figure 1 Direct Runoff as a function of Rainfall Curve Number

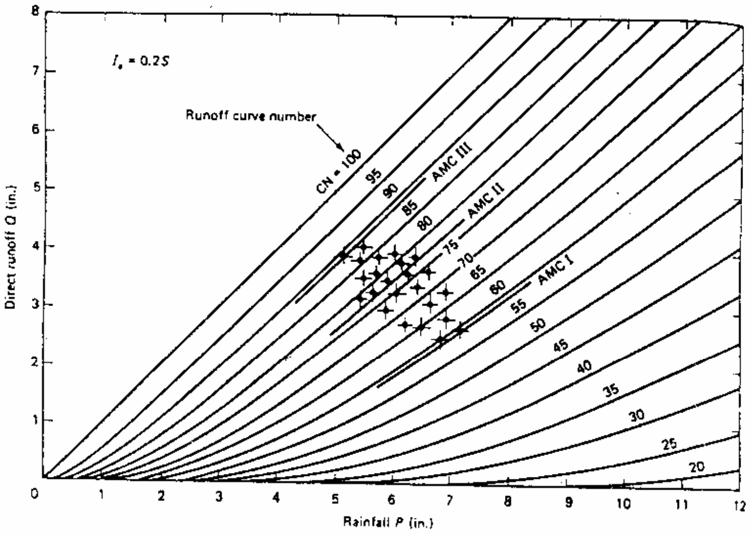

Figure 2 Estimation of Runoff Curve Numbers from Measured data

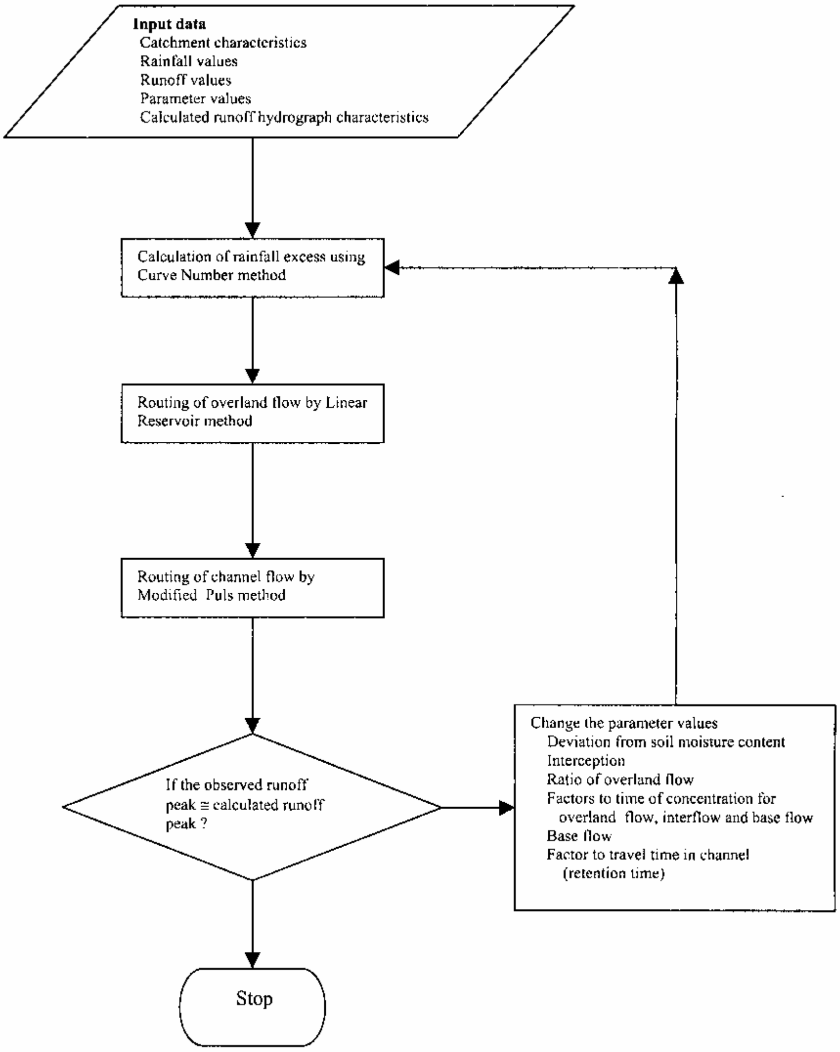

Fig 3 Flow chart representing the working of the NASMO Model

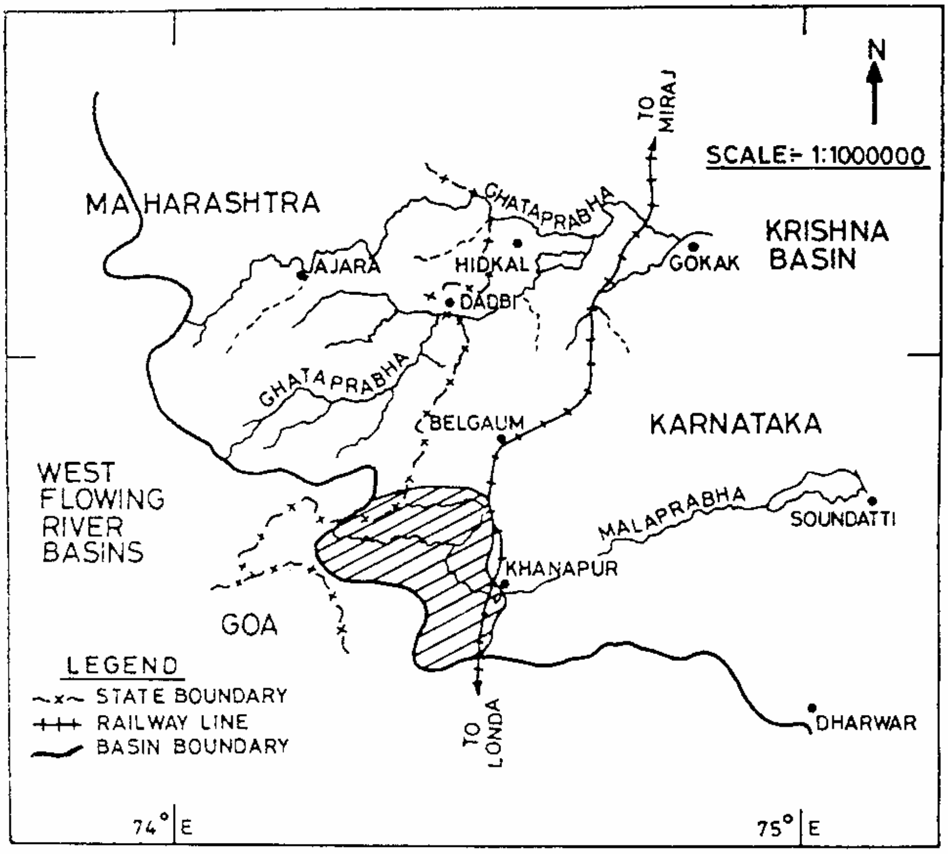

Fig 4 Index Map of the Study Area

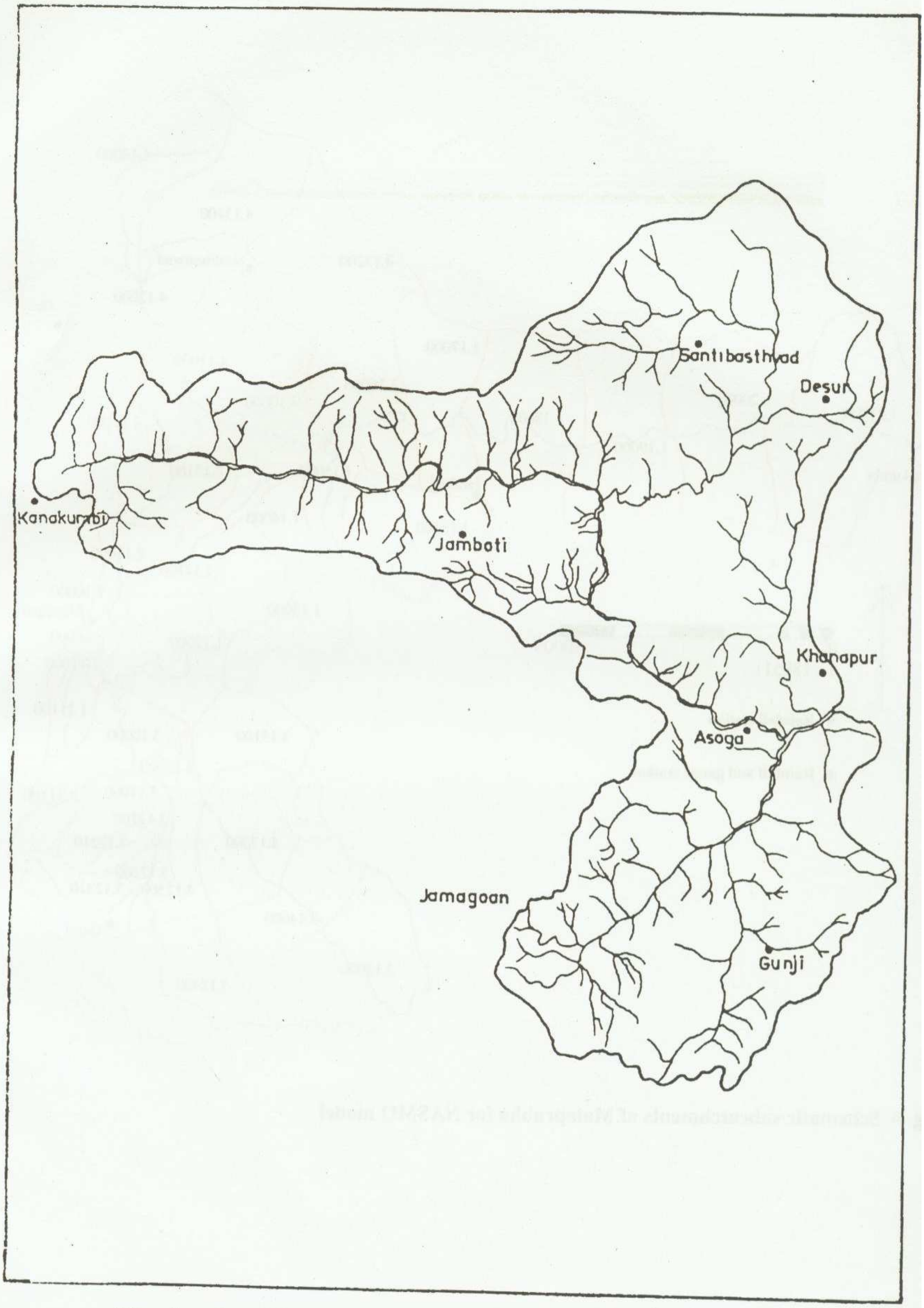

Fig 5 Location of Raingauge Stations and Drainage System

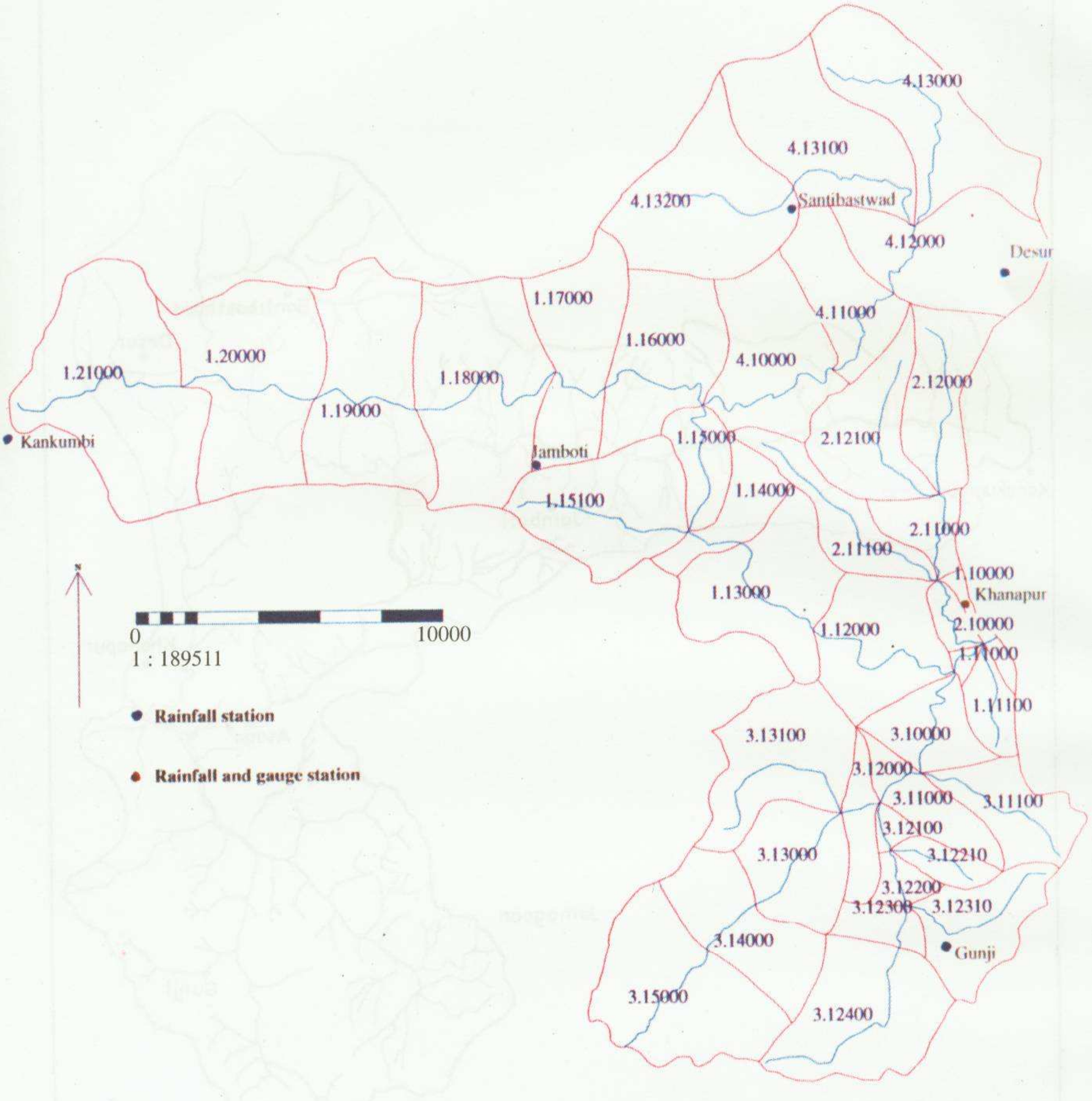

Fig 6 Schematic subcatchments of Malaprabha for NASMO model

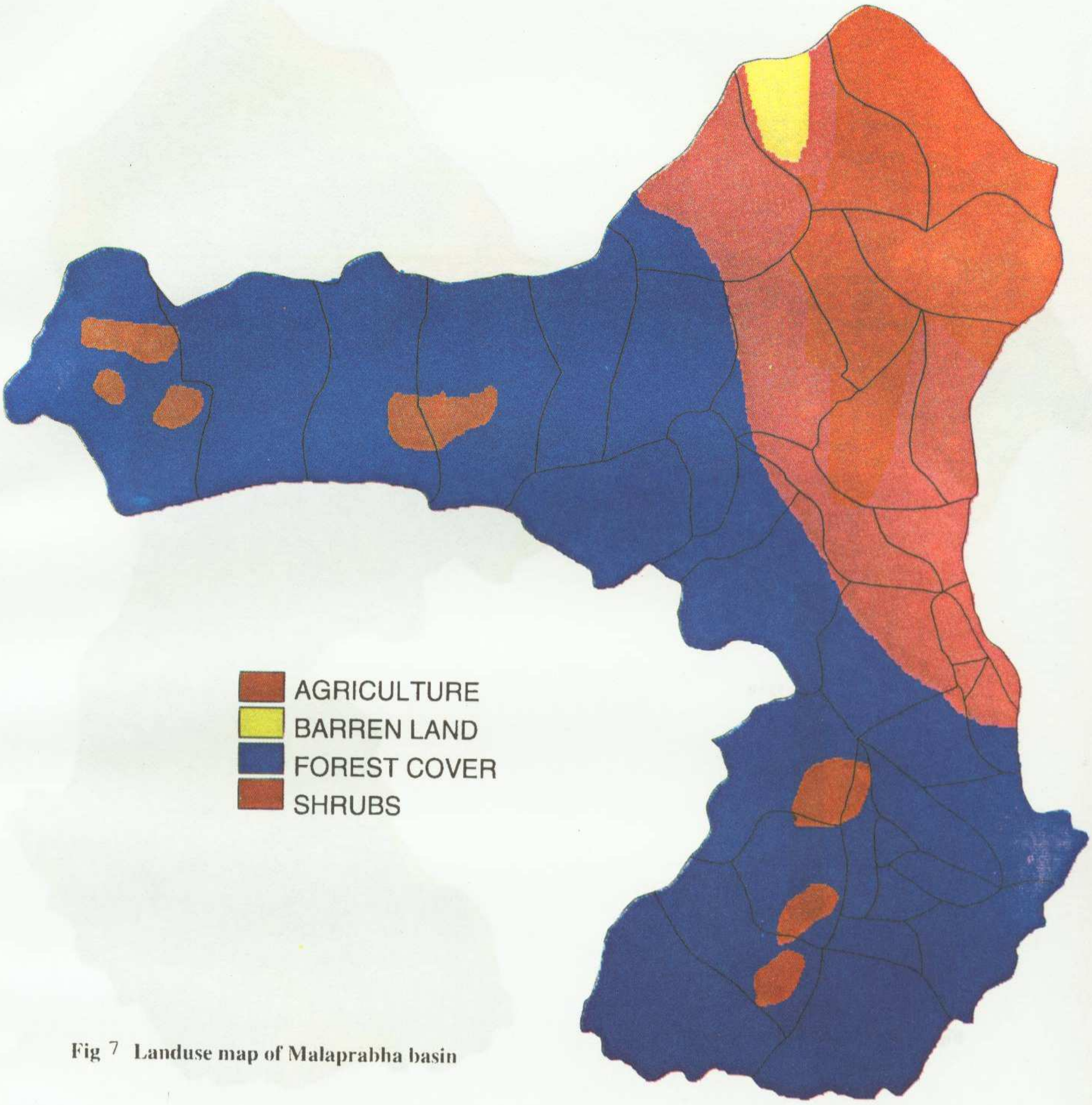

Fig 7 Landuse map of Malaprabha basin

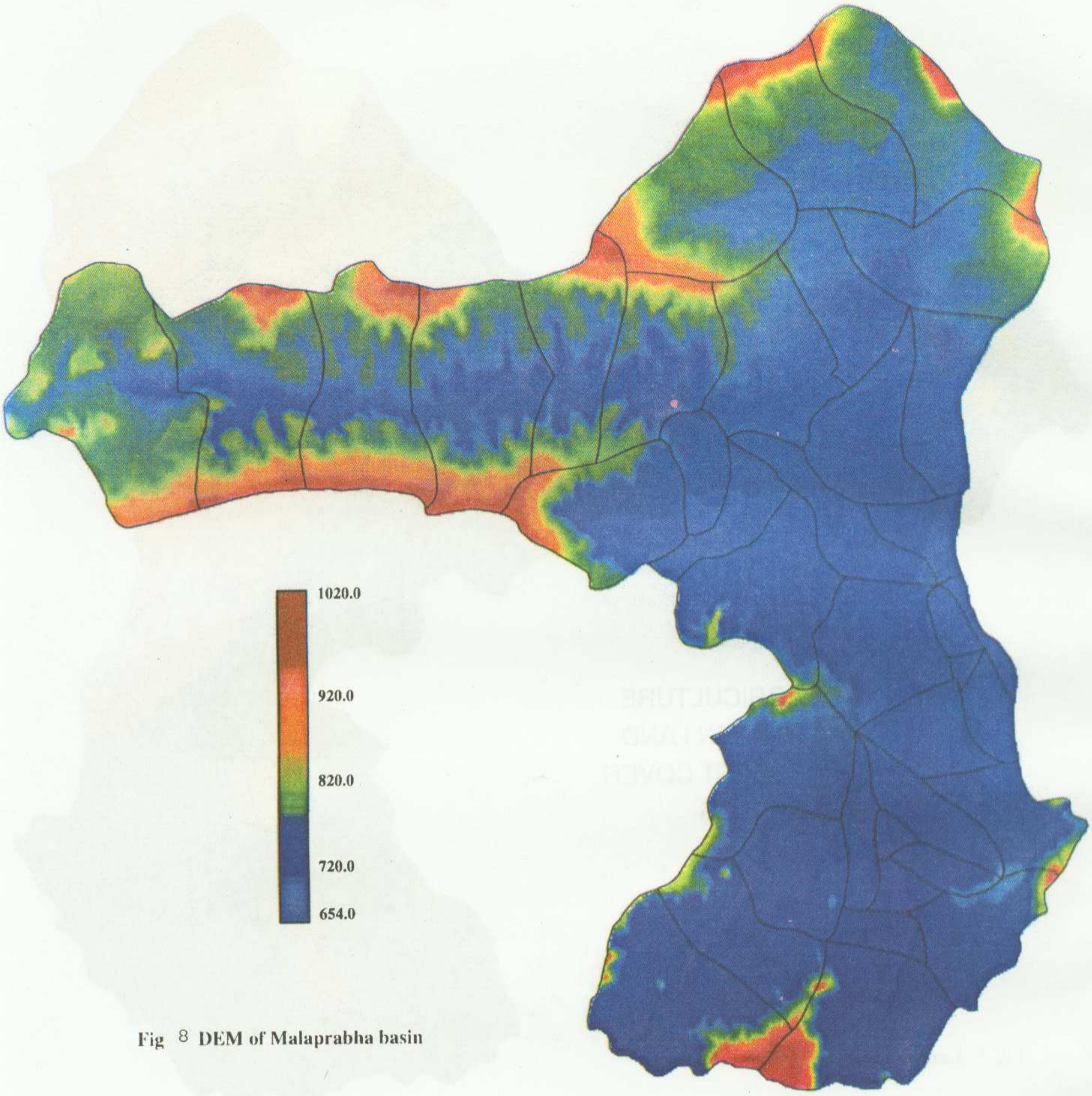

Fig 8 DEM of Malaprabha basin

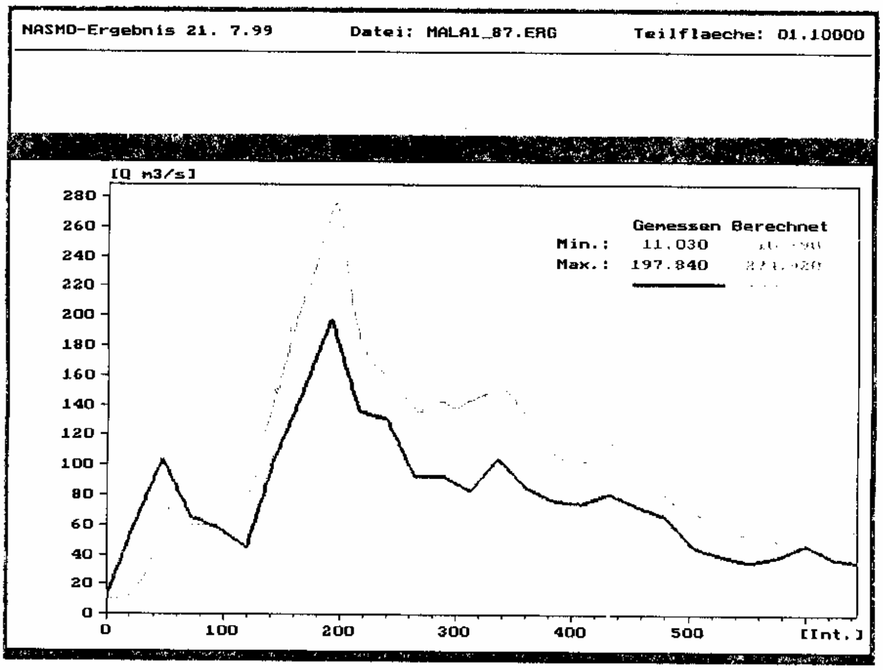

Fig 9 Observed and calculated hydrograph for the year 1987

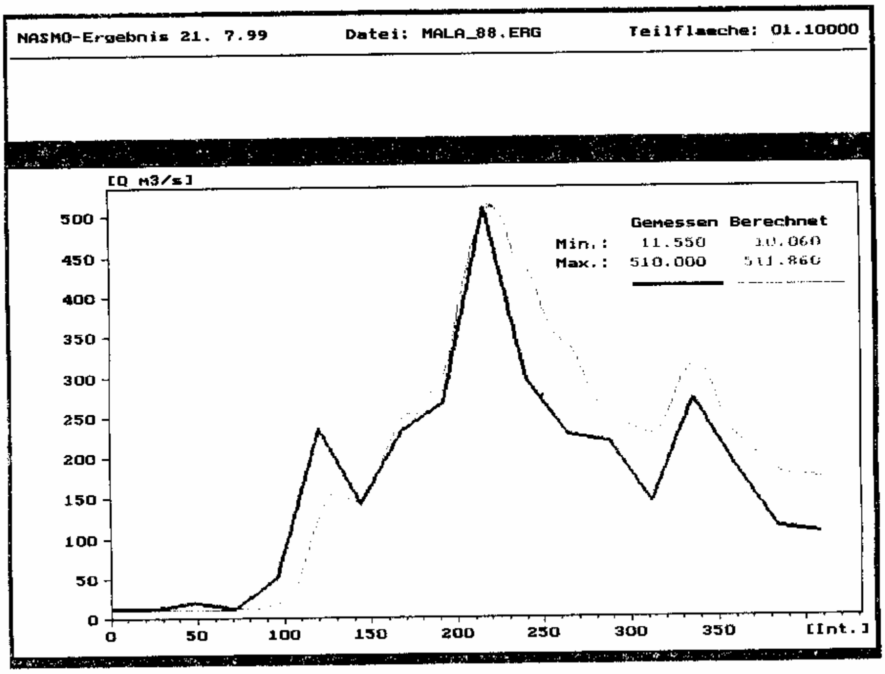

Fig 10 Observed and calculated hydrograph for the year 1988

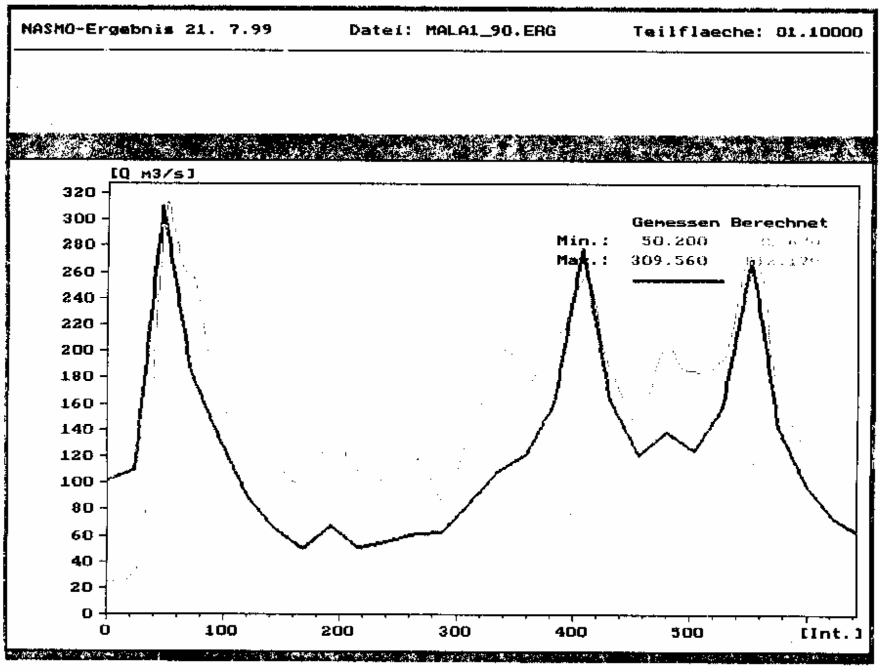

Fig 11 Observed and calculated hydrograph for the year 1990

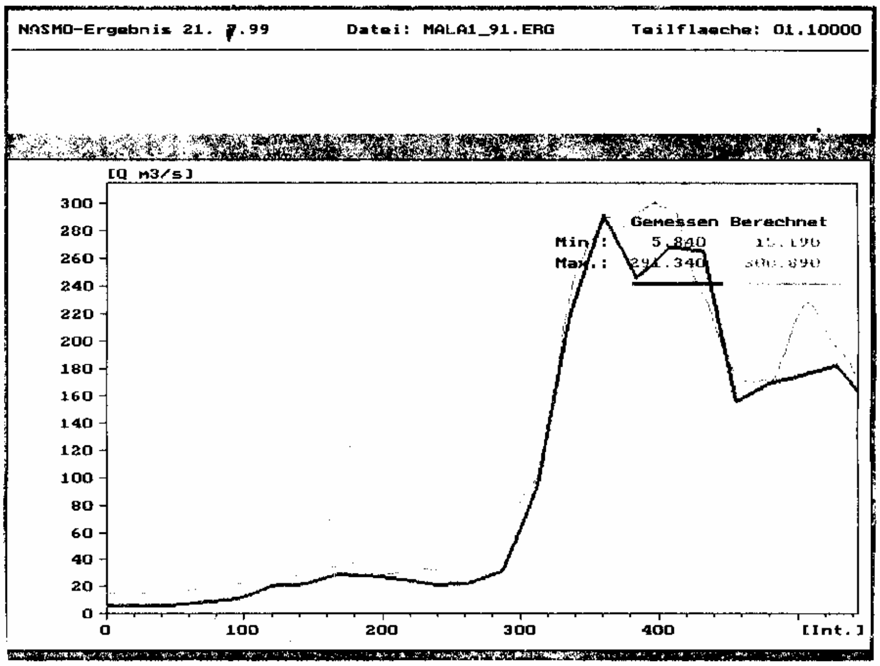

Fig 12 Observed and calculated hydrograph for the year 1991

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