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HYDROLOGIC MODELS FOR MOUNTAINOUS AREAS

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1987-88

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ABSTRACT

Estimation of runoff in Mountainous areas is required for the design, development and management of Water Resources Projects. Since the mountainous catchments have a complicated hydrological behaviour, the hydrological response would be controlled by a large number of climatic and physiographic factors which vary both in space and time. The complexity of the flood producing process in Mountainous regions makes the modelling difficult even by the most rigorous model. The limited availability of data makes it necessary to make adequate approximation and simplification to use them for mountainous catchments.

Several Watershed models are available and most of them were developed taking into account the component processes of the runoff formation as the basis of their development. These include the models for snow covered areas, non-snow covered areas and catchments with both types of areas. Some models have capabilities to make use of the remotely sensed data as well.

A general review of hydrologic models was carried out with empahsis on studying the capabilities of models, the data requirement for them, techniques of evaluating model parameters their application to mountainous areas and associated difficulties and limitations are discussed. Tabulated information of some of the above models are appended.

Most of the models have been developed and applied abroad under prevailing conditions and assumptions. It is

essential to test these models for Indian Mountainous catchments and modify where necessary to suit the hydrometeorological and physiographical conditions of Indian mountainous area.

Based on the review it is concluded that such of the models which are distributed in their approach and physically based are most suited for application to Indian mountainous catchments. SHE, UBC and Leavsley are some such models. Besides SRM and Sacramento could also be applied.

1.0 INTRODUCTION

Estimation of runoff in mountainous areas is required for the design, development and management of Water Resources Projects. The complexity of various component processes of hydrologic cycle and their interaction has necessiated the development of mathematical approaches such as simulation and synthesis to investigate the total project.

Runoff estimation in mountainous areas requires a thorough understanding of runoff process in these areas. The rain and snowmelt runoff processes in mountainous catchment is relatively a complex phenomena than that in plain areas, primarily because of the rapid variation of hydro-meteorological, geomorphological and other catchment characteristics in the mountainous areas.

The development of hydrological models for mountainous regions involves great difficulties due to the fact that the necessary data and information available are either sparse or not available. For the estimation of runoff in mountainous areas under such condition the regionai/empirical approaches were used which indirectly accounted for the geomorphology of the area. These appraoches, however, do not adequately represent the internal structure and response of the catchment. Besides they do not conceptualise the various component process of the hydrologic cycle.

Hydrologic models were developed to mathematically conceptualise the various component processes based on set of equations and algorithms which describe the behaviour of the hydrologic system. As such, they are capable of handling large quantity of data with the aid of computers and describes the component processes.

Many models have been developed for the simulation of runoff in mountainous areas so far. These include models for snow covered area, non snow covered area and catchment with both types of areas.

A general review of hydrologic models has been attempted with a view to examine the capabilities, the different techniques in evaluating the model parameters, the data requirement for them, their suitability for application and intercomparison in mountainous areas of India and abroad and associated difficulties, alongwith the discussion of results.

2.0 REVIEW

Rainfall-runoff process in a catchment is a complex and complicated phenomenon governed by large number of known and unknown meteorological, hydrological and physiographic factors which vary in space and time. Runoff in mountainous regions results from rainfall, snowmelt and glacier melt. The rain or snow falling on a catchment undergoes a number of transformations and abstractions through various component processes such as interception, detention, evapotranspiration, overlandflow, infiltration, interflow, percolation, subsurface flow, baseflow etc. and emerges as runoff at catchment outlet.

Each Watershed comprises of different types of soil cover, vegetation land use topography, drainage pattern and density, slopes etc. Runoff processes in mountainous areas differ from those in plain areas primarily because of differences in meteorological and physiographic factors in plain and mountainous areas. Meteorological parameters like rain, snow, temperature and physiographic factors like soil, rocks and their composition in a watershed are highly variable at different elevation levels in the waterhsed.

In mountainous regions, precipitation occurs more frequently and sometimes with hign intensities for longer durations. Interception losses are significant due to forest type of vegetation and density of vegetation. Interception losses are high at the beginning of rain spell and are reduced gradually to a constant value. Similarly infiltration rates depend on the nature of soil and slope of surface, initial soil moisture condition etc. The land surface is generally irregular and rough thereby increasing the resistance to surface runoff. Small surface depressions and well defined streams are more common in mountainous areas.

To simplify analysis of these complex processes different watershed models have adopted different laid out approaches and methods of approximation for each process so that the developed model as a whole would be capable of simulating observed runoff.

Watershed models can be classified as general models and special purpose models. A general model is one that is acceptable to watersheds of various types and sizes. a special purpose watershed model is one that is applicable to a particular type of watershed in terms of topography, geology and land use.

Most of these models have been developed by a particular user or agency to apply the model for particular applications. It is uncommon to find models widely applied by users not associated with their development and only few attempts of systematic comparison of models have been made. With vast array of different models currently available, it would seem obvious that these models should be objectively reviewed and tested.

WMO (1974) and WMO (1986) arranged to test 10 and 11 different models on six selected rivers respectively. Nordenson, T.J. (1969), Weeks, W.D. & etal (1980), and Ricardo, A., etal (1982) applied conceptual catchment models and made a comparative analysis of rainfall-runoff models. Peck, E.L. and etal (1981) reviewed hydrologic models for evaluating use of Remote Sensing capabilities.

Through this review, it is proposed to identify relevant hydrologic models having scope for application to mountainous catchments, in India, based on the capabilities of the respective hydrologic models to model the important hydrologic factors and the temporal and spatial variation of precipitation and snowmelt, the role of groundwater flow, the hydraulics of steep mountain streams, basic rainfall-runoff relationships and the effects of land use on runoff.

The decision about the best approach to a particular model application depends on available data, modelling principle and good knowledge of catchment vis-a-vis the model.

2.1 Lumped Parameter Models

Lumped parameter models can be also classified as implicit moisture accounting models. The temporal distribution function, that is, the unit hydrograph or some variations of it are to be calibrated for all events, both large and small, and hence cannot duplicate the nonlinearity of the physical process in space and time. In the absence of good quality data for model development and availability of sparse data for model application, the lumped parameter models may have a better capacity to cope with this deficiency and, therefore, may give better forecasting results than explicit moisture accounting models or physically distributed models.

The model such as STORM, HEC-1, HYDPAR, LAMBERT, USGS, NAM/SII, BMC, TANK and TR model may be considered in this group.

2.1.1. STORM Model

The storage, Treatment, overflow Runoff Model (STORM) is a continuous stimulation model intended for use in stimulation of the quantity and quality of storm water runoff.

The quantity portion of STORM was developed for the city of San Francisco by Water Resources Engineers, inc. (WRE) of Walnut Creck, California. The water quality computations were added in 1973 by WRE while under contract with HEC. Since then, the HEC has added other capabilities including snow melt and land surface erosion computations and prespecified hydrographs. The HEC added the U.S. Soil conservation service (SCS) curve number technique for runoff computation and the SCS trangular unit hydrograph technique for Runoff transformation (from rainfall excess to subbasin runoff hydrograph). A future version will include channel routing, and a planning level stream water quality module.

2.1.1.1 Model Capabilities

The programme computes runoff from rainfall or rainfall plus snowmelt and the associated pollutant wash off. Runoff quantity can be computed by one of the three. methods the coefficient method, the SCS curve number technique or a combination of the two.

The combination method uses the coefficient method on impervious areas and the SCS method on pervious areas of the watershed.

In the coefficient method, average annual runoff, runoff coefficients for the pervious and impervious areas of the watershed are specified, and subsequently, weighted according to the total fraction of impervious area in the watershed so as to obtain a single composite runoff coefficient. This coefficient is then used for each rainfall event in the precipitation record to calculate runoff excess above depression storage regardless of rainfall or soil characteristics. This method may not produce accurate or properly shaped hydrographs for individual rain events, but, when calibrated, may produce sufficiently accurate volume of runoff. Depression storage, Runoff coefficient for pervious areas, and runoff coefficient for impervious areas are input data requirements for this method.

The SCS curve number technique uses a simple curve to relate accumulated runoff to accumulated rainfall. The curve number is related to the soil type and anticedent moisture conditions. The procedure includes use of an initial abstraction (depression storage) variable which must be excluded before any runoff can occur for determination of runoff. The curve approaches a 45 degree slope; i.e. near zero incremental infiltration would occur at the end of a very large storm. Since STORM is a continuous simulation model, only initial curve numbers (for each land use) are required. The model computes the soil moisture storage capacity at the beginning of each storm in the record, based on recovery of soil moisture capacity, initial abstraction and percolation during dry periods. The curve number is expressed in terms of inches of soil moisture storage for input to the model and for computations.

2.1.1.2 Input Parameters

The following is a summary of input data and input parameters required by the SCS and snowmelt (degree-day method) options of programme.

SCS Method

Maximum initial abstraction capacity (IA) - DEPR
Starting value of initial abstraction capacity (IA) - ACTIA
Starting value of 'S' - SACT
Maximum soil moisture capacity (S) - S MAX
Maximum percolation rate - RATEIN
Maximum Deep percolation rate - PERCMX
Exponent in deep percolation equation - EPRC
Exponent in evapotranspiration equation - EERC

Snow Melt

Melt temperature threshold;
Starting snow pack water equivalent;
Melt rate coefficient;
Average daily or maximum and minimum;
daily temperature;

And in addition data like Hourly precipitation, Evaporation and area of Watershed are required.

2.1.1.3 Unit Hydrograph

Ratio of time of recession to time to peak (T_r / T_p) and subbasin time of concentration (T) are the two unit hydrograph parameters that must be provided by the user to STORM. Although the parameters define a Triangular unit hydrograph, STORM, working with a fixed 1- hour time period, computes the volume under the unit hydrograph in each time interval and does not deal with the actual ordinates of the unit-graph. The sequence of 1-hour unit hydrograph volume is then applied to the rainfall excess to determine the runoff volume hydrograph.

2.1.1.4 Limitations

Basic limitation is the one hour computation interval, which require hourly precipitation record. STORM may not produce properly shaped hydrographs for subbasins having times of concentrations less than one hour.

2.1.2 HEC-1 (Flood Hydrograph Package)

The HEC-1, flood hydrograph package, computer programme has originally developed in 1967 by Leo R. Beard and other members of the Hydrologic Engineering Centre staff of the U.S. Army Corps of Engineers of simulate flood hydrograph in complex river basins in meeting their water management responsibilities. In 1973, the programme underwent a Major revision. The present (HEC-1981) again represents a major revision of the 1973 version of the programme.

2.1.2.1 Capabilities of HEC-1

The HEC-1 model components are used to simulate the precipitation-runoff process as it occurs in an actual river basin. The computer programme consists of three major hydrologic components i.e. meteorologic, hydrologic and hydraulic processes which determine the average precipitation and snowmelt and the amount of effective precipitation contributing to direct runoff from a subbasin, compute the sub-basin runoff hydrograph, route and combine the subbasin runoff hydrographs. All components in HEC-1 empty lumped parameters for each sub-basin or routine reach. This means that the models input, parameters, and output are considered to be average values over the entire subbasin of interest.

Precipitation

Any of the model options used to specify precipitation will eventually result in a hyctograph. The hyctograph represent subbasin average precipitation depths over a computation interval. Precipitation data for an observed storm event can be supplied to the programme by either of two methods, subbasin average, or gages and weightings. There are three methods for generating synthetic storm distributions : standard project, probable maximum, and specific frequency storms. A synthetic storm of any duration from 5 minutes to 10 days can be generated based on given depth - duration data.

Loss rate functions

Precipitation losses to interception, depression storage and infiltration may be simulated by one of the four loss rate functions; initial loss followed by a constant loss rate, the SCS curve number technique, Holten loss rate, or the HEC exponential loss rate function. The latter computes precipitation losses as a function of antecedent soil moisture, precipitation intenstiy, and an infiltration rate that is a non-linear function of accumulated losses, as shown in Fig.1.

The programme contains a separate set of loss rate equations that are employed when the snowmelt capabilities of the programme are desired :

$$\mathrm{A\ LOSS} = \mathrm{AK}\ (\mathrm{RAIN} + \mathrm{SNWMT})^{\mathrm{ERAIN}}$$

$$\mathrm{AK} = (\mathrm{STRKS})/(\mathrm{RTIOK})^{0.1\ \mathrm{CUML}}$$

Where AlOSS is the loss rate in inches (Mm)/hr; AK is the basic loss coefficient; RAIN is the rainfall intensity in inches (Mm)/hr; STRKS is the basic loss coefficient for snowmelt in inches (Mm)/hr; RTIOK is loss coefficient recession constants; SNWMT is the snowmelt in inches (Mm)/hr; and CUML is the accumulated loss determined by summing the actual losses computed for each time interval.

The losses are substracted from rainfall and snowmelt in each zone, and the excesses are summed to yield the excess precipitation from the subbasin. In the loss rate and snowmelt equation the following parameters must be determined by calibration : STRDR, RTIOL, DLTKR, COEF, STRKS, RTIOK, and RRTP.

Unit Hydrograph Function

Unit hydrograph technique is used in the subbasin runoff component to transfer rainfall/snowmelt excess to sub-basin outflow. A unit hydrograph can be directly input to the programme or a synthetic unit hydrograph can be computed from user supplied parameters using synthetic techniques proposed by Clark (1945), Synder (1938) or the SCS (1972).

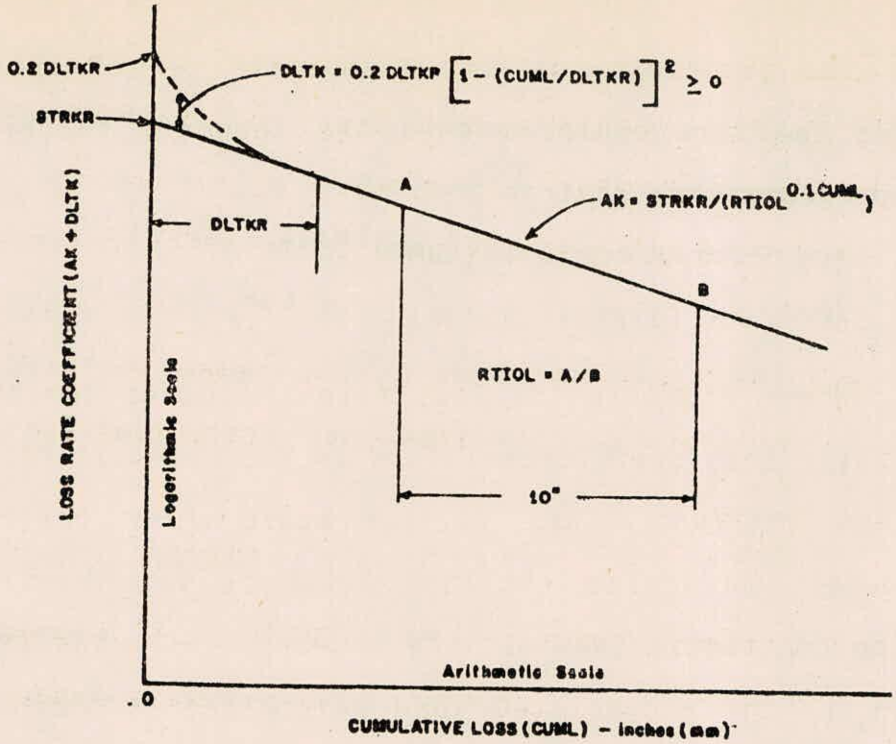


FIGURE 1 GENERAL HEC LOSS RATE FUNCTION FOR SNOW FREE GROUND.

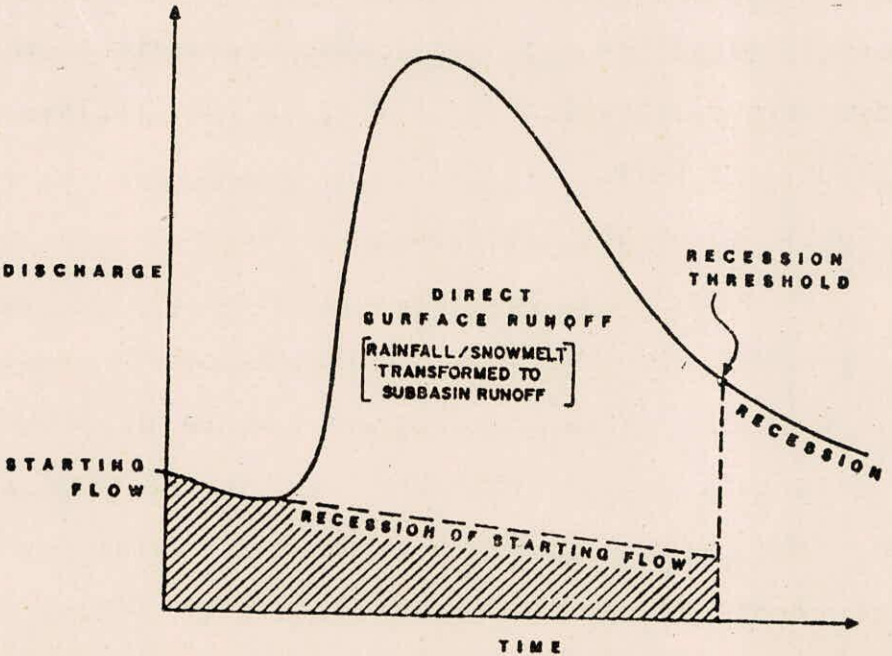


FIGURE 2 BASE FLOW DIAGRAM.

The Clark method requires three parameters to calculate a unit hydrograph; TC, the time of concentration for the basin, R, a storage coefficient, and a time-area curve. In the case that a time-area curve is not supplied, the programme utilizes a dimensionless time-area curve.

The snyder method determines the unit graph peak discharge, time to peak and widths of the unit graph at 50 & 75% of the peak discharge. The initial Clark parameters are estimated from the given snyders coefficients TP and CP, which define the peak of the unit hydrograph.

The SCS dimesnionless unit hydrograph technique, which uses a single lag parameter, TLAG, to define the shape of a triangular unit hydrograph, can also be used.

The unit hydrograph parameters required for calibration are TC and R or TP & CP, or TLAG.

Kinematic Wave

The kinematic wave technique transforms rainfall/snowmelt excess into subbasin outflow. In determining subbasin runoff by the kinematic wave method three conceptional elements are used, overland flow planes, collector channels, and a main channel. An overland flow element is described by four parameters : a typical overland flow length, L, slope and roughness factor which are used to compute 'a' (AIIa), and the percent of the subbasin area represented by this element. The HEC-1 model requires that atleast one overland flow plane and one main channel be used in kinematic wave applications.

Base flow

The HEC-1 model provides meas to include the effects of base flow on the stream flow hydrograph as a function of three input parameters : STRTQ-Starting flow, QRCSN-a recession threshold, and RTIOR- recession rate as shown in Fig.2.

The programme adjusts RTIOR to the time step of the particular simulation and computes the recession flow Q as :

$$Q = Q_0 \, (RTIOR)^n$$

Where Q_0 is STRTQ, and n is the number of time intervals since recession was initiated.

Streamflow Routing

Most of the subbasin runoff routing methods available in HEC-1 are based on the continuity equation and some relationship between flow and storage or stage. These methods are Muskingum, Kinematic wave, modified puls or multiple storage, working R&D, and level-pool reservoir routing. In all these methods, routing proceeds on an independent reach basis from upstream to downstream; backwater effects are not considered. These methods cannot simulate discontinuities in the water surface such as jumps or bores. These methods should, however, give good results for routing runoff through channels on moderate to steep slopes and through reservoirs. There are also two routing methods in HEC-1 (Tatum and Straddle-stagger) which are based on lagging averaged hydrograph ordinates. These models are not physically based, but have been used on several rivers with good results.

Parameters are automatically calibrated for Muskingum method, Working R&D method, straddle-stagger and Tatum method.

2.1.2.2 Snow-Melt Computaion

The amount of snowmelt is calculated separately in each elevation zone based on the air temperature which is calculated from a base temperature at the lowest elevation and user supplied adiabatic lapse rate. Instead of monthly, the components can be also used or computed for daily or hourly value. Snowmelt may be computed by the Degree-day or Energy-budget methods. The basic equations for snowmelt computations are from EM 1110-1-1406 (Corps. 1960)

The degree day method for computing snowmelt is :

SNWMT = COEF (TMPR- FRZTP)

Where SNWMT is the melt in inches (Mm) per day in the elevation zone, TMPR is the air temperature in ^{O}F or ^{O}C lapsed to the mid point of the elevation zones, FRZTP is the temperature ^{O}f or$_{O}^{O}$ c at which snow melts, and COEF is the melt coefficient in inches (Mm) per degree day (^{O}F or ^{O}C). Precipitation is assumed to fall as snow if the zone temperature (TMPR) is less than base temperature (FRZTP) plus e degrees.

Energy-budget equations for melt during rain or melt this progrmme K and K' in the basic equations are assumed to be 0.6 and 1.0, respectively.

The following equations for snowmelt are for English units of measurement. The programme has similar equations for the metric system which use the same variables with coefficients relevant to metric units. The programme computes forested melt during rain by equation, which is applicable to heavily forestea areas as noted in EM 1101-2-1406.

$$\mathrm{SNWMT} = \mathrm{COEF}\ (0.09 + (0.029 + 0\text{-}00504\ \mathrm{WIND} + 0.007\ \mathrm{RAIN})\ (\mathrm{TM\ PR}-\mathrm{FRZTP}))$$

Equation below, is for melt during rainfree periods in partly forested areas.

$$\mathrm{SNWMT} = \mathrm{COEF}\ (0.002\ \mathrm{SOL}\ (1-\mathrm{ALBDO}) + (0.0011\ \mathrm{WIND} + 0.0145 + (\mathrm{TMPR}-\mathrm{FRZTP}) + 0.0039\ \mathrm{WIND}\ (\mathrm{DEWPT}-\mathrm{FRZTP})$$

Where SNWMT is the melt in inches per day in the elevation zone, TMPR is the air temperature in °F lapsed at the rate TLAPS to midpoint of the elevation zone, DEWPT is the dewpoint temperature in °F lapsed at a rate 0.2 TLAPS to the midpoint of the elevation zone. FRZTP is the freezong temperature in °F, COEF is the dimensionless coefficient, RAIN is the rainfall in inches per day, SOL is the solar radiation in langleys per day, ALBDO is the albedo of snow, 0.75 ($D^{0.2}$), constrained above 0.4, D is the days since last snowfall, and WIND is the wind speed in miles per hour, 50 feet above the snow.

2.1.2.3 Computer Requirements & Support

HEC-1 requires a Fortran IV compiler and up to 16/ input/output scratch (tape, disk, etc.) files. The Computer memory required on the CDC 7600 is 15000 words. It requires approximately 7 seconds to compile on that machine. The users manual and programers suppliment describe detailed programme characteristics, variables & parameters list and modifications necessary to run the programme on different computer systems and to reduce memory necessary requirements. The programme and documentation may be obtained from the HEC for the cost of reproduction & handling.

2.1.2.4 Application

Abroad - At HEC the HEC-1 optimization scheme has been used in numorous studies for nearly 10 years. This model has been employed in studies of the shellpot & Naaman crecks, the schhylkill River, the Maurice River and the Lehigh River. An application was made on the pennypack creck as part of an expanded flood plain information report. It has been applied to develop reservoir inflow forecasts for W.kerr Scott Reservoir on the Yadking River of North Carolina.

India - HEC-1, Flood forecasting model is a single flood event model has been successfully modified, sengmented and transferred to HP-1000 F. Series computer at CWC for Yamuna catchment. However, lot of further work is required for evaluation.

At NIH, Roorkee this model has been tested thoroughly and used for rainfall-runoff simulation, PMF estimation and forecasting to Narmada Sagar and Sardar Sarover Projects. Currently effort is being made to test the HEC-1 snowmelt runoff option for a typical basin of Indian Himalayas.

2.1.3 Hydrological Parameters (HYDPAR)

Subbasin or water shed hydrologic parameters that might be used as input to rainfall runoff models or other analytical techniques can be determined from the HYDPAR(Hydrologic Parameters) program as developed by U.S. Army Corps of Engineers (1978) at HYdrologic Engineering Centre (HEC).

2.1.3.1 Capabilities of HYDPAR

The HYDPAR Programme computes and formate for subsequent use, hydrologic parameters that permit determination of precipitation loss rate functions and surface runoff response.

The parameters that can be generated are (1) SCS curve numbers, and (2) unit hydrograph parameters (basin lag) based on the SCS dimensionless unit hydrograph procedure. The programme has also the option to compute the percent of impervious surface within a watershed and calculate unit hydrograph parameters utilizing Synder's approach.

The functin defining the relatinship between the geographic data drawn from the grid cell data bank (landuse, subbasin boundaries, hydrologic soil group, surface slope, etc.) and the selected procedure are defined externally and input to HYDPAR. The HYDPAR programme performs the appropriate file manipulations computations and book keeping, prints the results and then if the user desires, writes a tape for further automated processing.

2.1.3.2 Computational Procedures

Soil conservation service (SCS) methods

The U.S. Soil Conservation Service (1972) developed a technique for determining direct runoff from rainfall based on land-use, antecedent moisture condition and soil type. The technique (curve number technique) is specially attractive to many hydrologic planning evaluations since it provides a systematic and consistent method of evaluating the effect of alternative land-use patterns on surface runoff within a watershed.

A relationship wherein accumulated runoff is a function of accumulated rainfall and physiographic characteristics, land-use, antecedent moisture and soil type is utilised in SCS method. Curve numbers are developed to represent various combined states of these particular physiographic parameters.

In HYDPAR programme, only land-use and soil type are utilised in determining a curve number (CN). The process involves accessing a grid cell data bank and determining the land use and soil type for each grid cell. Then based on an input relationship between CN and these two particular parameters, a value of CN is assigned to each cell. Based on number of cells in each sub-basin and their respective CN's, an average value of CN is then computed for each sub-basin in the study area.

SCS (1972) developed a simplified dimensionless unit hydrograph approach to transform excess rainfall to runoff. Hydrograph is based on a single parameter, basin time lag (time response of runoff to rainfall) which, in normal practice is estimated from one of several empirical equations, from travel time studies or from observed flood hydrograph reconstitutions. The HYDPAR programme computes from the following empirical equation.

$$\text{Lag (hours)} = \frac{(L)^{0.8} * (S + 1)^{0.7}}{(1900) * (Y)\ 0.5}$$

Where,

L = Hydraulic length of subbasin (that water course length from subbasin outlet to the upstream boundary which yields the longest time of travel) in feet

Y = Average subbasin land slope (determined from HYDPAR programme based on sloped data for each grid cell) in percent

S = (1000/CN) - 10, and

CN = Arithmetic average curve number

Fig. 3 conceptually displays the data that must be available in grid cell data bank and the computatinal procedures used to determine the hydrologic parameter, curve numbers and subbasin lag time.

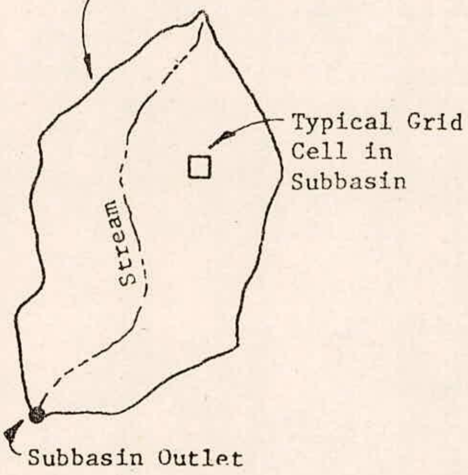
Composite Imperviousness and Snyder's Method

Estimation of the effect of changing land-use on runoff is performed by computing the proportion of imperviousness for an alternative land-use plan and adjusting the loss rate accordingly. The HYDPAR programme computationally implements this basic concept by assigning percent values of imperviousness to each grid cell based on input land-use and then computes an average per cent imperviousness for the subbasin under investigation.

Several investigators have attempted to study the rainfall-runoff process affected by land-use changes by performing regression analysis of unit hydrograph parameters. Typically regression expression were derived in which a parameter such as basin lag, was expressed as a function of subbasin area, imperviousness and perhaps other physiographic characteristics. The HYDPAR programme computes a Snyder's lag based on the following equation.

$$t_p = C\ (X^{CI})\ (10^{C2\ I})$$

2.1.3.3 DATA REQUIRED



/ 5 /	Grid representation of land use (exhaustive for study area).
/ 3 /	Grid representation of hydrologic soil group.
/12 /	Grid representation of subbasin.
/ 7 /	Grid representation of land surface slope.
DIRECT INPUT	
— —	Tabulation of land use-soil type curve number. (Not part of grid data bank).
1.30 miles	Subbasin hydraulic length. (Not part of grid data bank).

FIGURE 3 HYDROLOGIC PARAMETER COMPUTATION OF HYDPAR.

PROCEDURE

COMPUTATION OF SUBBASIN AVERAGE CURVE NUMBER (CN)

a. Determine cell land use from grid data bank.
b. Determine cell hydrologic soil group from grid data bank.
c. Determine cell curve number (CN) from input relationship.
d. Determine cell subbasin assignment.
e. Aggregate CN's for all cells within subbasin and compute average value.

COMPUTATION OF SUBBASIN LAG TIME

a. Determine cell land surface slope from grid data bank.
b. Determine cell subbasin assignment from grid data bank.
c. Aggregate land surface slope for all cells within subbasin and compute mean value.
d. Retrieve average CN computed above.
e. Compute subbasin lag.

$$\text{Lag} = f\ (\text{curve number, hydraulic length, mean slope})$$

Where,

t_p = Snyder's lag in hours

C = Regression constant

$X = \frac{L * LCA}{S}$

L = Characteristics stream length in miles

LCA= Length from subbasin outlet along stream channel to point opposite the centroid of the subbasin area in miles

S = Characteristic stream slope in ft./miles

C_1 = Regression coefficient

C_2 = Regression coefficient, and

I = Imperviousness in percent

2.1.3.3 For data requirement refer fig.3

2.1.3.4 Application of HYDPAR

U.S. Army Corps of Engineers (1978) selected Trail Creck Watershed to illustrate both SCS curve number techniques and percent imperviousness and Snyder's method.

2.1.3.4 Lambert Model

The I.S.O. (Inflow-Storage-Outflow) rainfall-runoff model was first proposed by Lambert in 1969 and applied to the Ceiriog, a tributary of river Dee (N.Walas). Subsequently the model was defined in two forms (linear and non-linear) and applied to the Afon Dyfrdwy (a tributary to Llyn Tegid on the river Dee) as a sub-catchment model and as a routing model to Llyn Tegid itself (Lambert, 1972).

The water balance for a catchment was written as :

$$\frac{dS}{dt} = r - e - q$$

where ,

S = Catchment storage

r = Rainfall input

e = losses due to evaporation

q = outflow from the catchment

The loss term 'e' was ignored in the above equation. To solve the above equation, a second equation relating storage to outflow was required, two forms of which were proposed by Lambert.

1) ISO - function Type-I (non-linear)

$$S = K_1 \log_e q$$

2) ISO - function type II (linear)

$$S = K_2 q$$

The final equations of Lambert model was found as

Type I Model

(a) when $r \neq 0$

$$qn = q \quad * \left(\frac{1}{X + (1 - X) \frac{1}{Y}} \right)$$

where ,

q_n = Predicted flow at time T hours from now,

q_o = Present telemetered flow

S = $e^{\frac{rT}{K_1}}$

r = Total rainfall input to the model

T = basic time interval

K_1 = Storage parameter

Y = $\frac{r}{q_o}$

(b) when $r = 0$

$$q_n = \frac{q^{\;q_0}}{\left(1 + q_0 - \frac{T}{K_1}\right)}$$

Type II Model

$$q_n = q * (W - WY + Y)$$

where, $W = \frac{6}{e}^{\,T/K_2}$, and

$$Y = \frac{r}{q_0}$$

Equation given above equations form the basic equations. The second parameter, the catchment lag, L, is introduced into the model by delaying the effect of rainfall of L hours.

Application of Lambert Model to Dee catchment

Lambert model was applied to five gauged sub-catchments of river Dee (N. Wales). The five subcatchments were Dee at New Inn, Hirant, Ceiriog, Gelyn, and Alwen.

The dee at New Inn, in common with the other sub-catchments, is a mountainous catchment with steep valley sides covered with only a thin layer of soil on impermeable rock; there is a rapid response of runoff to rainfall. Rainfall and flow data were both at half hour intervals. In determining the best parameter values for the Dee at New Inn. an 11 month period from November 1972 to September 1973 was used.

From the New Inn results Green (1979) expressed that the Type-I (log-linear) model with separate rising and falling parameters (i.e. variable K_1) emerged as the most satisfactory model. The results from the Type-I model with separate rising and falling limb parameters showed significant improvement in hydrograph prediction over the fixed parameter version of the Lambert model.

2.1.5 U.S. Geological Survey Rainfall-Runoff Model

Carrigan (1973) calibrated the USGS model to be used in evaluating short streamflow records and calculating peak flow rates for natural drainage basins. The programme actually monitors the daily moisture content of the subbasin soil and can be used as a continuous streamflow simulation model. The model was classified as an event simulation model because its calibration was based on short-term records of rainfall, evaporation and discharge during a few documented floods.

Input to the model consists of initial estimates of 10 parameters which are modified by the model through an objective optimization fitting procedure that matches simulated and recorded flow rates. Other input includes daily rainfall and evaporation, close interval (5 to 6 min.) rainfall and discharge data, drainage areas, impervious areas and baseflow rates for each flood.

Philip's infiltration equation is used to determine rainfall excess hyctograph which is translated to subbasin outlet and then routed through a linear reservoir using time area watershed routing techniques.

The USGS rainfall-runoff model can be used to simulate streamflow for relatively short periods for small basins with approximately linear storage - outflow character-

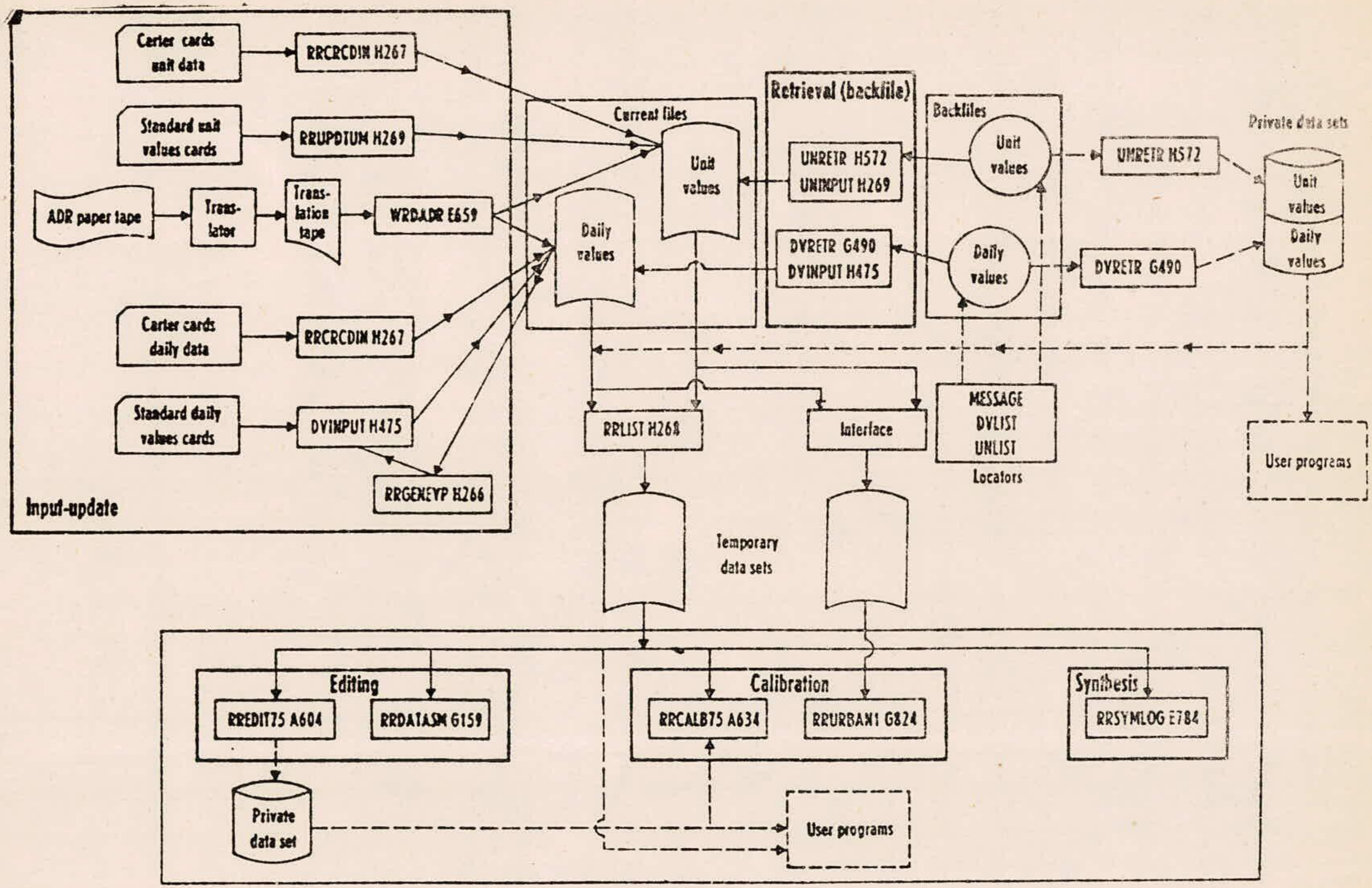


FIGURE 4 FLOW CHART FOR RAINFALL-RUNOFF MODELS PROGRAMS SYSTEMS

istics in regions where snowmelt or frozen ground is not significant. Output from the model includes a table showing peak discharge, storm runoff volumes, storm rainfall amounts and an iteration by iteration printout of magnitudes of parameters and residuals in fitting volumes and peak rates.

Carrigan-et al (1977) produced the User's Guide for USGS rainfall-runoff models which contained instruction for use of data files and computer programmes for various models. The organisation and general procedures for storing and retrieving data and abstracts of computer program cataloged procedures for storing retrieving and editing data and for model calibration and flood record analysis were also described. The function of procedure the cards needed to invoke or to use a procedure (input instructions), the output and diagnostic error messages of the program and an example of the utilisation of a procedure (including input cards and output prints and cards) were described sanctionwise. The flow chart for rainfall runoff models describing steps in entering, retrieving, editing and merging data and in utilizing the data is shown in Fig.4 and the functions of cataloged procedures is listed in Table 1.

Table 1 : List of cataloged procedures used with rainfall runoff model data processing and editing, model calibration and synthesis of flood peak discharges.

Cataloged procedure name	Function	Program number
WRDADR	Computation of unit rainfall and discharge	E659
DVINPUT	Input and update of data in daily values file	H475
UNINPUT	Input and update of data in unit values file	H269
UNOPER	Special file operations which change identifiers, parameters, dates, and record disposition	H568
RRCARDED	Editing of cards in carter formats	A556
RRCRCDIN	Input of data cards with carter format	H267, H475, H269
RRGENEVP	Synthesis of daily evaporation	H266, H475
DVRETR	Retrieval of daily values from current and historical files	G475, G490
UNRETR	Retrieval of unit values from current and historical files	G475, H572
RRLIST	Retrieval of unit and daily values from current disk files	H268
RREDIT75	Retrieval and editing of unit and daily values	H268, A604
RRDATASM	Summarization of unit and daily data to evaluate suitability for use in calibration and synthesis	H268. G159
RRIDSYN	Test for identical distribution of annual flood discharges	J503

RRIDTEST	Test for identical distribution of rainfall characteristics	J504
RRCALB75	Calibration of rainfall-runoff model for natural basins	H268, A604 A634
RRURBAN1	Calibration of rainfall-runoff model for urban basins	J149 G824
RRSIMLOG	Synthesis of peak discharges using a rainfall runoff models calibrated from procedure RRCALB75 or RRURBAN 1 and Pearson Type-III flood frequency computation	H268, E784, E675

2.1.6 NAM/SII-FF

The NAM models is a traditional lumped-conceptual model to describe rainfall-runoff process from a catchment. This model is specially well suited for simulation of the rainfall-runoff process when hydrological time service sufficiently long for a model calibration exist. Thus, typical fields of application are (1) Extension of streamflow records based on long rainfall records and (2) Real time rainfall-runoff simulation for e.g. flood forecasting.

The NAM/SII-FF mathematical modelling for R-T flood forecasting consists of four main elements : A hydrological rainfall-runoff model (NAM), a hydrodynamic model (S11) for river routing and reservoir simulation, and updating procedure (linear "Noise-model") for use in real time operation, and a data management package for data processing. This system was developed under a cooperation between Danish Hydraulic Institute (DHI) and Central Water Commission of India (CWC) by Refsgaard et al (1985) and

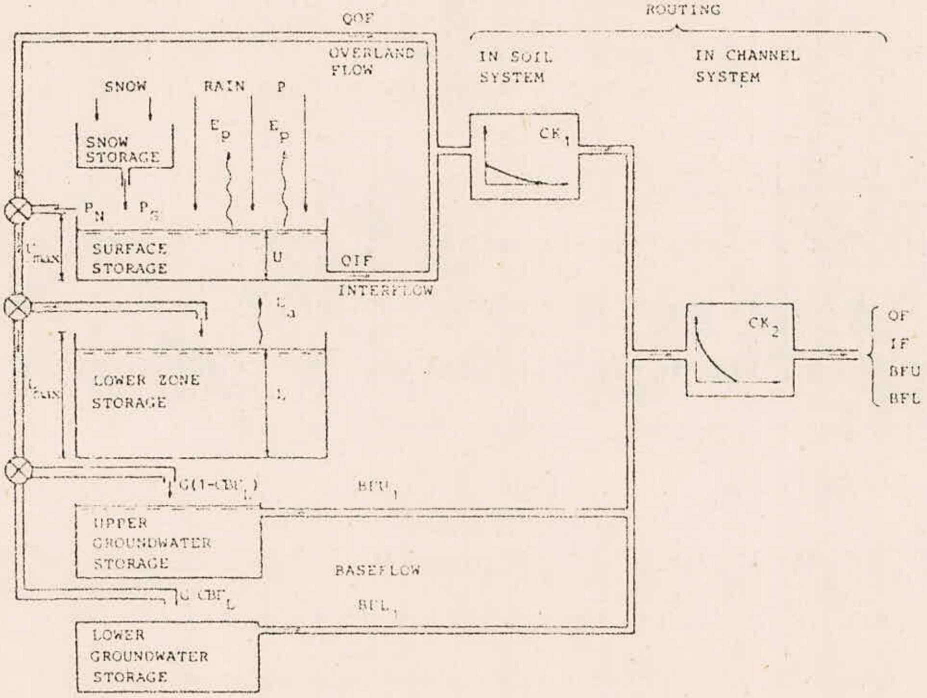


FIGURE 5 STRUCTURE OF THE 'NAM' RAINFALL-RUNOFF MODEL.

applied to Damodar River Catchment.

2.1.6.1 The Rainfall-Runoff Model, NAM

This model operates by accounting continuously for the moisture content in five different and mutually Inter-related storages representing physical elements in the catchment(Fig.5). The data input requirements are : Precipitation, potential evapotranspiration and (only of snow occurs) temperature data.

The sampling interval of the input data can be given arbitrarily.

2.1.6.2 The Hydrodynamic River Model, System 11.

System 11 is a general mathematical modelling system for the simulation of flows and water levels in rivers, reservoirs, estuaries and canal system. In its most advanced form, system 11 is based upon numerical solution of the general one-dimensional 'Saint Venant' equations (consideration of mas and momentum).

The system has options of using the diffusive wave or the Kinematic wave approximation if the fully dynamic wave equation is not required. Several types of hydraulic structures can be described by system 11, for example, reservoirs, dams, weirs, and other types of flow regulators.

2.1.6.3 The Updating procedure for RT forecasting

It is based on so-called "Noise-model", simulating the deviations between observed and simulated runoff thro' a linear autoregressive model. The simulated deviation (noise) is used to adjust the streamflows simulated by NAM prior to routing by system 11.

2.1.6.4 The Data Management Programmes

This package consists of a number of small programmes for redially checking and transforming the real-time data into formats directly applicable by the model.

2.1.6.5 Application of NAM/SII:- FF System

The NAM/SII-FF system has been applied to a 22000 Km^2 Upper Damodar River Basin by Refsgaard et al (1985) in North-eastern part of India.

The total catchment was divided into 13 sub catchments with separate rainfall and evaporation input in the rainfall-runoff (NAM) modelling system 11 was performed from Tilaiya, Konar and Tenughat reservoirs down to Durgaput Barrage using a total of 84 grid points to model 470 Km long river reach. The outflows from NAM model are taken as inflow to the system 11.

The system was calibrated on 1978-80 data and tested on data from 1971-77. The model performance in calibration period and in the test period was found to be of the same quality.

The flood of September 26-27, 1987 could not be simulated satisfactorily. It was felt that the poor fit was because of uncertainities in the rainfall input data and as such updating procedure was aplied to this event. Compared to initial simulation (without updating) the peak value has increased from 8200 m^3/s to 10800 m^3/s which can be compared to the recorded peak of 12,300 m^3/s.

2.1.7 Hydrometeorological Centre (HMC) Model

Rainfall-Runoff Model and Snowmelt runoff model of the Hydrometeorological Research Centre, USSR, were developed in 1971 for short term forecasting of rain floods and spring floods respectively.

2.1.7.1 Model Capabilities

This lumped parameter model, takes into account infiltration, evaporation, surface retention, sub-surface flow and wave profile transformation in the catchment area and in the channel. Snowmelt model takes into account snowmelt processes in the basin, basin water losses and channel water losses, separately. The water travel time and discharge transformation are considered upto the section in question. Snowmelt processes, basin water losses and snowmelt water travel time upto outlet are considered separately for field and forest parts of the basin.

The HMC ranfall-runoff model can be treated as explicit moisture accounting model where as HMC snowmelt-runoff model as implicit moisture accounting model.

2.1.7.2 Data Requirements

Rainfall-intensity, air humidity deficit, or ET potential, wind speeds for 1 to 2 months before and during flood for 6-9 floods, etc. are required for the operation of rainfall runoff models. For the snowmelt model the data such as, pre-melting snow-thickness, Mean daily temperature during snowmelt period, snow cover disappearance, maximum snow water equivalent and precipitation during flood, runoff volume during spring floods and basin wetness before snowfall etc. for 10-15 years for open and forested part of basin are required. For operation of snowmelt runoff model, the data or mean and ten daily temperature and precipitation during snowmelt period are required for simple model. But for complex model, data of 10 daily air temp. (mean daily, mean day time, mean night time, maximum and minimum), mean daily wind speed, total cloud amount, dialy precipitation during snowmelt period are required.

2.1.7.3 Parameters

Rainfall-Runoff model includes 11 empirical parameters optimised by information on input and output by combination of orography and related gradient methods.

The most sensitive rainfall-runoff model parameters are, the drainless area in the fractions of the whole area (Z), time parameter of the surface flow transformation, the maximum water capacity of soil in the zone of aeration (W_{max}) and the proportionality parameter in the infiltration formula (K_3).

Snowmelt runoff model includes following six parameters:- (1) Snow coefficient at which snow begins to yield water, (2) melting coefficient in mm/degrees for forested and open part of basin, (3) Variation coefficient of snow cover distribution, (4) a coefficient of basin storage capacity (soil and surface retention), (5) hydraulic & (6) morphometric characteristics of a basin.

2.1.7.4 Application

The rainfall-runoff model is applicable to basin area of 20-15000 Km^2 at interval of 1 hour to 1 day. This rainfall-runoff model was tested on the data set of Bird Creck and Bikin basin under WMO Project on intercomparison of conceptual models (WMO, 1975).

Snowmelt model is applicable to lowland basins of different extensions, having stable snow cover during Winter period. The large basins are divided into sub-basins, with areas from 1000 to 8000 Km^2 and time interval as one day. This model was tested on the Kestroma River data set.

2.1.8 Tank Model

Tank Model was developed by Sugwara (1967) in Japan. This is a conceptual runoff model for simulatin of flood events and daily runoff for humid as well as non humid basins. This model has been widely used successfully by Prof. Sugwara in Japan to runoff analysis of snowy & non-snowy Mountainous Regions.

Following data are necessary for operation and calibration of the Tank Model.

i) Daily precipitation (or hourly data in case of flood) at several points in or near the object basin).

ii) Daily maximum and minimum air temperatures, or daily mean air temperature or daily temperature data in the case of snowy basin;

iii) Evaporation data;

iv) Daily or hourly discharge data only required for the calibration of the model.

2.1.8.1 Model Structure

The catchment is represented by a number of tanks placed one below the other. Major input to the tank is precipitation. Rain water in all zones and snowmelt from all zones are summed up and the sum is transformed into runoff by the model which is shown in Fig.6 schematically.

The tanks have outlet at bottom and /or on side. These respectively represent the vertical and horizontal movement of the water. In general, the top tank corresponds to surface flow, the intermediate tanks represent the sub-surface flow whereas the bottom tank gives out base flow. Therefore, the bottom most tank has outlet only on sides and the upper tanks have outlets both on sides and at bottom. There may be two or more outlets on side of upper tanks. If there are many small outlets on the side, then the relation between runoff Y and storage X is represented by a smooth curve as shown in Fig. 7.

Constants and variables of the tank model are mostly shown in Fig. 8, QA, QB, QC & QD are the weighted sum of the outputs from subbasins. They are obtained by accummulating the output from the repsective tank of each subbasin. (Fig. 6, on page 39).

Non-Snowy Basins

For humid regions one series of Tanks can be assumed to represent the basin quite satisfactorily, since there is

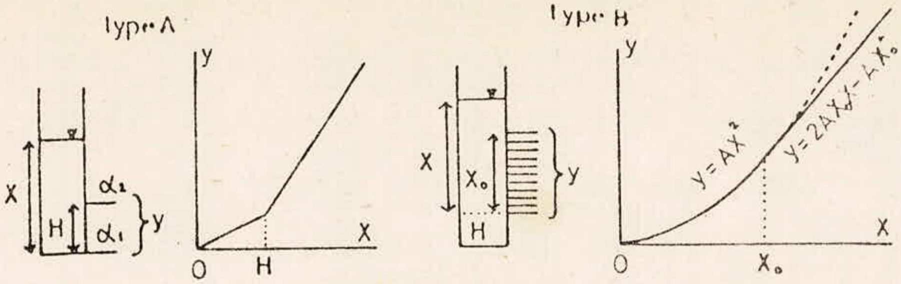


FIGURE 7 DEFORMATION MODELS IN RIVER CHANNEL.

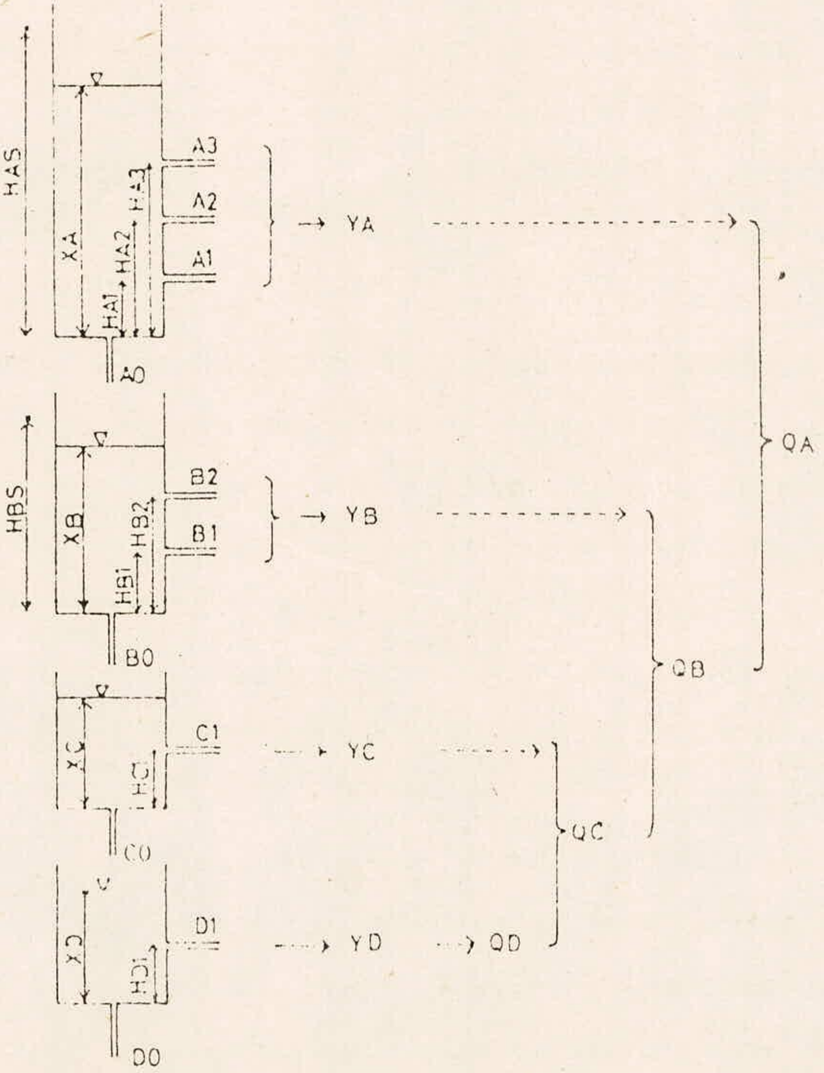


FIGURE 8 TANK MODEL STRUCTURE & ITS VARIABLES.

no major change in moisture over the catchment. However, for semi-humid or arid regions, there exists considerable change in moisture at different locations in the basin and also at different strata. For this purpose more such series, each representing a zone, have to be added.

In a non-humid basin, where some part is wet and the remaining part dry, the surface runoff occurs only in the wet are while in the dry area all the rainfall is observed as soil moisture. When the rainy season begins, the wet area grows larger, starting from a small area along the river. To approximate the continuous change of wet area, divide the basin into several zones, S_1, --- S_m as shown in fig. 9 where m=4.

In this model free water moves in two directions, horizontal & vertical. Each tank receives water from the upper tank of the same zone or from the mountain-side tank of the same zone stratum, and transfers water to the lower tank of the same zone or to the river side tank of the same stratum. Those is another important water transfer, that is the water transfer, that is the water supply to soil moisture from lower free water by capillary action.

2.1.8.2 Snowy Basins

Many basins are under the large effects of snow. When winter comes, snow deposits on mountain area at first and when spring comes, snowpack begins to melt on plain or low mountain area at first. To simulate such a state, the basin is divided into zones by elevation contours with an equal elevation interval. Air temperature decreases with

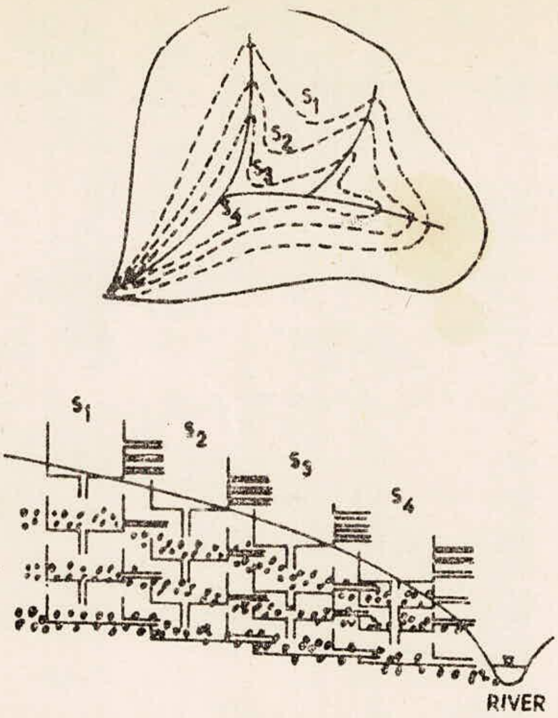


FIGURE 9 4X4 TANK MODEL ALONG A SLOPPING GROUND OF A BASIN.

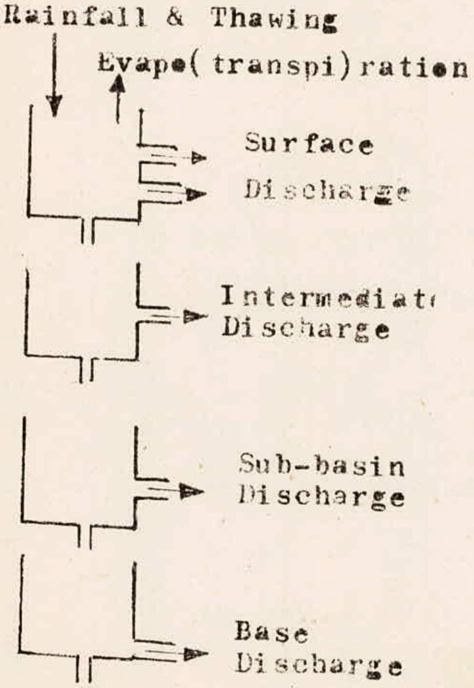


FIGURE 6. ARRANGEMENT OF TANKS

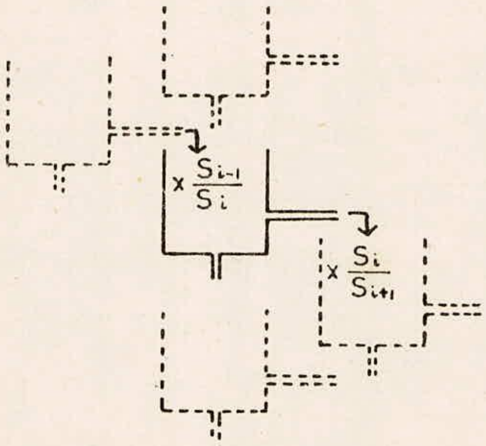


FIGURE 11 WATER TRANSFER BETWEEN ZONES.

elevation and precipitatin usually increases with elevation. Some parameters are necessary for such a structure.

From Daily precipitation data and daily air temperature data, mean precipitation and mean air temperature in each zone can be estimated.

The areal mean precipitation P(i,m,k) of the i-th zone in the m-th month at the k-th station is calculated as follows:

$$P(i,m,k) = (1+(PD)\ (i,k),\ C(m),\ C_p(k,m).P(k)$$

Where P(k) are the observed daily precipitations at the raingauge stations or the mean of daily precipitations at several stations, and C_p (k,m) correction factors for precipitation PD(i,k) precipitation increase coefficients with altitutde, c(m) coefficents for the seasonal change.

The temperature T(i) of the i-th zone is calculated as follows:

$$T(i) = T + To-(i-1),\ TD$$

Where 'T' is the daily temperature observed at a meterological point or the mean of daily temperatures at some points. 'To' the temperature correcting constant, and 'TD' the temperature decreasing constant.

When temperature T(i) of the i-th zone is positive (T(i)>0), precipitation P(i,m,k) ofthe i-th zone is assumed to be rain, and some part of the snow deposit will melt if it exists in the i-th zone. The volume of thawing U(i,k) consists of two parts as follows:-

$$U(i,k) = Mo.T(i) + \frac{1}{80} P(i,m,k)\ .T(i),$$

Where Mo (usually to 4 to 6) is the constant of thawing. U(i,k) is substracted from the snow deposit of i-th zone at the k-th station. When temperature T(i) of the i-th zone is not positive, precipitation P(i,m,k) in the i-th zone is assumed to be snow and it is added to snow deposit.

When the available temperature data are the daily maximum and minimum, the mean air temperature T is calculated as follows :-

$$T = \alpha T_{mx} + (1-\alpha)\ T_{min}$$

Where α is usually 0.5-0.6

Total ssnowmelt U(k) at the k-th station is accumulated as follows :-

$$U(k) = \sum ZA\ (i,k),\ U(i,k),$$

Where$\sum$ZA (i,k) are areas of zones.

Sum of rain water and snowmelt is input to the top tank of the tank model. The daily evapo(transpi)ration is substracted from the top tank. Water of each tank partly goes to the next tank through the outlet in the bottom and partly goes out through the outlet(s) in the side well. The sum of the outputs through the side outlet(s) of each of the tanks forms the river discharge QE(K) at the k-th station. Flow chart for daily calculation is shown in Fig.10.

The same tank model is used all the year, including snowy season and non-snowy season.

In some cases, the effect of water storage in

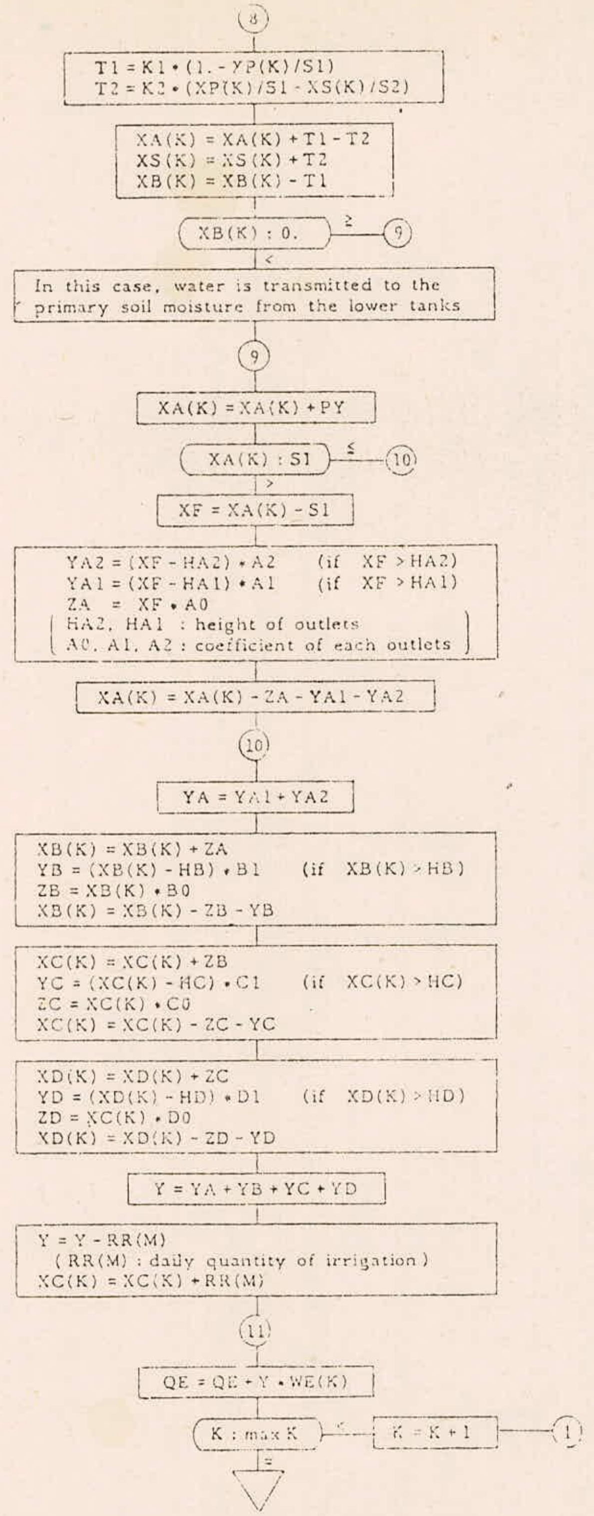
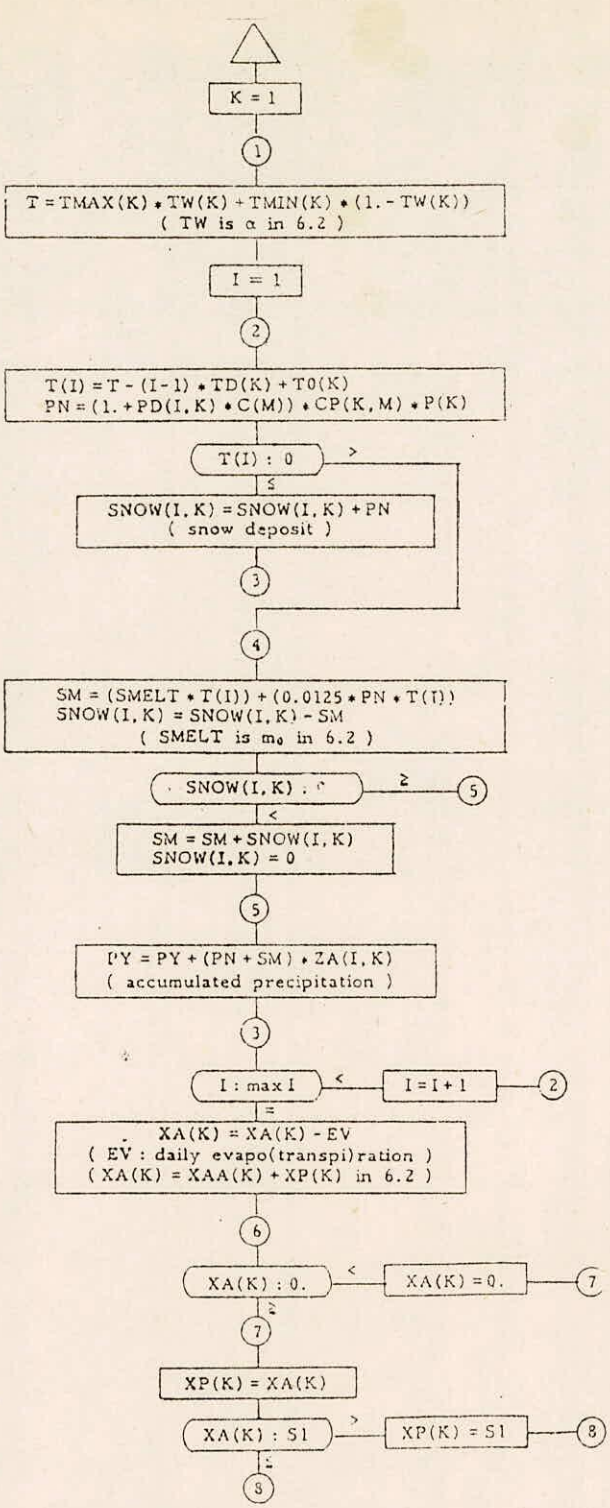


FIGURE 10 FLOW CHART FOR TANK MODEL.


K = 1
1
T = TMAX(K) * TW(K) + TMIN(K) * (1. - TW(K))
(TW is α in 6.2)
I = 1
2
T(I) = T - (I-1) * TD(K) + T0(K)
PN = (1. + PD(I,K) * C(M)) * CP(K,M) * P(K)
T(I) : 0
>
≤
SNOW(I,K) = SNOW(I,K) + PN
(snow deposit)
3
4
SM = (SMELT * T(I)) + (0.0125 * PN * T(I))
SNOW(I,K) = SNOW(I,K) - SM
(SMELT is m₀ in 6.2)
SNOW(I,K) : 0
≥
5
<
SM = SM + SNOW(I,K)
SNOW(I,K) = 0
5
PY = PY + (PN + SM) * ZA(I,K)
(accumulated precipitation)
3
I : max I
<
I = I + 1
2
=
XA(K) = XA(K) - EV
(EV : daily evapo(transpi)ration)
(XA(K) = XAA(K) + XP(K) in 6.2)
6
XA(K) : 0.
<
XA(K) = 0.
7
≥
7
XP(K) = XA(K)
XA(K) : S1
>
XP(K) = S1
8
≤
8

snowpack must be considered. In such a case, rain and snowmelt water is put into the snowpack tank which simulates the water storage in the snow-pack and the output is put into the tank model. In some cases, it is very cold in the highest zone and snow accumulation is larger than snowmelt and so snow storage continues to increase forever. This is the case of glacier. In such a case, flowing down of glacier must be considered. The simplest assumption for this problem is that some definite portion of the snow storage transfers to the nest . wer zone every day.

2.1.8.3 Water Transfer

Depending on the time of season, water may percolate donw or may rise due to capillary action and may have effect of evaporation. To represent this movement of water, soil moisture sturcture in the form of primary and secondary soil moisture are incorporated in tank model. Depending on the position of free water in the top tank the evaportranspiration coefficient is to be determined.

For water transfer between zones the output from the tank of the i-th zone must be multiplied by R_i ($R_i = \frac{S_i}{S_{i+1}}$ to consider it as input to the tank of the (i+1)-th zone. Where S_i and S_{i+1} are the area of i-th zone and i+1th zone respectively, as shown in Fig.11.

The output from the tank model goes into the river channel, where its hydrograph is deformed by storage effect of the channel. To consider such deformation in river channel, two type of models, type A and type B are

considered in the tank model.
of the model structure and methodology can be referred from the manual of Tank model, Sugawara, M., etal (1974, 1975, 1985)

2.1.8.4 Application

Tank model applied to many river basins in Japan, e.g., R.Yodo, R. Ishikari, R.Kitakami, R. Shinano, R. Tenryu, R. Kumano, R. Kuma, R. Bikin, R.Kitsu, R. Sanaga etc. Mae Nam Chao Phraya and R.Yuam in Thailand, R. Kerantan in Malaysia, R.Tjitaum in Indonesia, etc.

In India, at NIH, Roorkee, Tank model has been used, and flood analysis models have been developed for Jamatra (16, 575 Sq. Km) and Belkheri (4, 816 Sq Km) basins; where as daily runoff models have been developed for Jamtara and Ginnore (1,508 Sq Km) basins. All the three basins studied are part of Narmada Basin, Datta, B. and Seth, S.M., (1985).

Tank model developed for flood analysis as reported above for Jamtara basin has been applied to four floods during the years 1978 and 1979 using 6- hourly data and that developed for Belkheri basin has been applied to the floods during the years 1978 and 1980 using 3-hourly data. For successful application of Tank model for flood analysis for Indian basins, effect of evapotranspiration has been incorporated in the model by using average evaporation rate over the incremental time (used for the model calibration). Daily runoff model for Jamatara basin has been developed using daily data for the years 1978 and 1979 using the tank models for humid basins (4 tanks) and non-humid basins (4X4 tanks). Daily runoff model for Ginnore basin has only a 4X4 tank model structure and has developed using daily data for the 1972 and 1973 and was tested on the 1974 data. It is demonstrated that a 4X4 tank model structure is better suited for simulation of daily runoff for basins in India.

Ekbote & Bhave (1982) used 4X3 tank model for daily runoff analysis for venna catchment located in the western ghat area. They have used the 1975 monsoon data for calibration of the model and reported good comparison of the observed and simulated flows.

2.1.9 Tangborn - Rasmussen Model

Tangborn and Rasmussen (1976) suggested a forecast model based on the annual water balance of the basin considering runoff, precipitation, evapotranspiration and basin water storage. Since the basin primarily accumulates water from winter precipitation and a portion of this goes to Winter runoff, the differences of these two approximates the spring storage which eventually becomes the summer runoff. Further more, it is assumed that the winter and summer evapotranspiration, the contribution of summer precipitation to runoff and ground water and snow carry over effects are the same every year. With the above arguments, the summer runoff forecast Rs* is given by :

$$Rs^* = a_s (Pw+Pt) + bs-Rw-Rt$$

Where Pw, Pt = Winter and spring precipitation; Rw, Rt = Winter and spring runoff and 'As', 'bs' = model parameters obtained by linear regression.

2.1.9.1 Model properties

Due to seasonal variations in basin storage calculation the forecast errors resulting from above equation are rather large. To improve the forecast, Tangborn and Rasmussen introduced a test season (spring) forecast equation. They observed that the errors resulting from summer runoff forecast equations and the test season forecast equation are highly correlated. Thus, their improved summer runoff forecast model is :

$$Rs^{\wedge}* = a'Pw + b'Pt + c' (Rw+Pt) + d'$$

Where $a'=as - Cat$, $bZ=a_s$; $c'=c-1$;

$d' = b_s-cbt$; a_t; b_t = regression coefficients for the test season, and

c = Coefficient relating the spring and summer errors.

2.1.9.2 Application

The Tangborn and Rasmussen model and the runoff data of thunder creck, Washington, were used (Gwillermo, 1982) to assess the use of the Kalman filter. Only one precipitation gauging station was used. The available runoff and precipitation were accumulated into seasonal totals where the winter season is from October to March, the spring test season is April and the forecast season is May. The data consist of 44 water years (1930-1974) and both the Standard Kalman filter (SKF) and Adaptive limited memory filter (ALMF) were tried. Using improved summer runoff forecast equation the ALMF yields better forecast values in all cases.

2.1.10 Modelling of Daily snowmelt Runoff During Premonsoon months for Beas Basin upto Manali

The model has been developed by Dr. S M Seth (1983). The model considers attitudinal effect on temperature, orographic effect on precipitation, melt due to Rain, losses from melt water and effect of Rain falling on non-snow covered area. Simple routing relationship used for obtaining daily streamflow at catchment outlet. The eight parameters representing degree-day factor for two parts of the season, losses from snowmelt, rain on snow covered area and rain on non-snow covered area lapse rate, melt due to rain and routing (recession) factor are estimated for different alternative number of elevation zones, by pattern search optimisation technique, using least square objective criteria. The cross-correlation analysis and sensitivity analysis have also been used for examining seasons for good or bad reproduction of observed flow. Nine relevant assumptions were made for the mountainous catchment condition of India. It was concluded that the degree day method is quite appropriate method for computation of snowmelt-runoff when only temperature data is available.

2.2 Distributed Parameter Models

The distributed parameter models may be also classified as explicit moisture accounting models. Such models are simple as well as complex depending on the degree and nature of its parameter distribution with space and time. Complex models are capable to represent the non-linearity of physical process to an acceptable extent.

The difference in data requirements between the lumped and distributed parameter models is not that the distributed parameter model must have additional data types, but that it can use them if they are available, as the lumped parameter model cannot.

The model such as SRM, UBC, USBR, HSF, KWM, SACRAMENTO, NWSRFS, SSARR, LEAVSLEY, HBV, WATBAL, HIM, SHE and EGMO may be considered in this group.

2.2.1 The Snow-Melt-Runoff Model (SRM)

The snowmelt-runoff model (SRM : also referred to in the literature as the "Martinec Model" or "Martinec-Range Model") is designed to simulate and forecast daily streamflowin Mountain basins where snowmelt is a major runoff factor. With the advent of satellite snow-cover data in the 1970s, it became possible to test SRM in basins ranging from 2-65^2 Km to 4000^2 Km . As pointed out by Rango & Mertinec that the accuracy of simulation generally decreases as the basin size increases because of spare hydrometeorological data networks. SRM is to be used in a Mountain basin with significant snow accumulation.

In the simulation mode, SRM produces daily discharge values from the start until the end of the snowmelt period (usually 1-6 months) using the actual sequence of temperatures and the depletion curves of the snow coverage obtained from snow-cover monitoring.

The model requires good daily air-temperature and precipitation data and periodical monitoring of snow-covered area in the given basin by satellites, aircraft, or visual observations. Long term historical data sets are not necessary (but helpful, if available) because little or no optimization (calibration) of model parameters is necessary. Daily discharge data from the basin are required to determine the recession coefficient and, otherwise, only to evaluate, the accuracy of simulation. The discharge preceeding the start of the snowmelt season (winter baseflow) must be known or estimated for initializing the model.

2.2.1.1 Model Structure

Each day during the snowmelt season, the water produced from snowmelt and from rainfall is computed, superimposed on the calculated recession flow, and transformed into the daily discharge from the basin according to equation given as :

$$Q_{n+1} = C_n \left(a_n (T_n + \Delta T_n) S_n + P_n\right) \frac{A * 0.01}{86400} * (1 - K_{n+1}) + Q_n K_{n+1}$$

where Q = average daily discharge in $M^3 S^{-1}$

C = runoff coefficient expressing the losses as a ratio (runoff/precipitation) programme permits changes in 'C' every 15 days. The model can handle different 'C' for snow and for rain from zone to zone in a basin as determined by the user.

a = degree day factor (cm. $^oC^{-1}$ d^{-1}), indicating the snowmelt depth resulting from 1-degree day. In the absence of data the 'a' can be obtained from an emperical relation developed by Martinec (1980) :

$a = 1.1 \frac{P_S}{P_W}$ where P_S is density of snow and P_W is density of water.

SRM allow modifications of 'a' every 15 days for each zone if necessary.

T = number of degree-days (°C.d)

ΔT = the adjustment by temperature lapse rate (80/100m) necessary because of the altitude difference ($h_{ST} - h$) between the temperature station and the average hypsometric elevation ($\bar{h}$) of the basin or zone. Lapse rate changes can be instituted. Every 15 days, monthly or yearly.

S = ratio of the snow-covered area to the total or zonal area, obtained from a total or zonal depletion curve prepared based on ground (observation, aircraft, photographs or satellite imagery.

P = Precipitation contributing to runoff (C m). A preselected threshold temperature, TCRIT, determines whether this contribution is rainfall and immediate.

A = Area of the basin or zone in m^2.

$\frac{0.01}{86400}$ = conversion from $Cm.m^2.d^{-1}$ to $m^3.S^{-1}$

K = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall, $K = \frac{Qm+1}{Qm}$ or, $Kn+1 = XQY_n$. (m, m+1 are the sequence of days during a true recession flow period). The constant X and Y are determined for the given basin.

n = Sequence of days during the discharge computation period. Snowmelt equation is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. As a result, the number of degree-days measured on the 9th day corresponds to the discharge on the n+1 day. Different lag times will result in the proportioning of day 'n' snowmelt between discharges occuring on days n, n+1 and possibly n+2.

Data available in English units can be converted into the SI system and Vice Versa.

2.2.1.2 Variables and Parameters

T, S, and P are variables to be measured or determined each day, where as, C, a, k, and ΔT are parameters which are characteristics for a given basin or, more generally for a given climate. The parameters are evaluated before hand from actual data, observations, or prior knowledge, or they are estimated by analogy from other basins.

In addition, the area-elevation (hypsometric) curve of the basin is required in order to determine zonal area and the altitude difference for the exprapolation of temperature.

The ideal situation would have temperature measurements made at the $\bar{h}$ of each elevation zone. When only one station is used a lapse rate has to be assumed in order to extrapolate degree days from the base station to the appropriate mean hypsometric elevation. At stations where hourly reading are made, the number of degree days for each 24 hour period (0600 Hours to 0600 hours) is determined by summing the hourly temperatures and dividing by 24 and using 0° C as the base temperature. Where only maximum & minimum temperatures (Tmx, Tmn) are available, the number of degree days (in $^{\circ}$C) is determined as

$$T = \frac{Tmax + Tmin}{2}$$

value below 0 $^{\circ}$C indicating no degree-days. An effective minimum temperature approach also can be used. Whenever Tmin 0°C it becomes Tmin $< 0^{\circ}$c before being entered into equation.

Treating minimum temperatures below the freezing point as $0^{o}C$ can also be employed when using hourly temperatures to calculate the degree-days.

2.2.1.3 Programme Input Requirements

Data to be input to SRM will be handled through the FORTRAN NAME-LIST feature. The NAME-LISTs CLIM and BASE provide climatological and basin dependent parameters, respectively. Whereas the NAMELIST OPT provides programme control options to properly execute the SRM programme. Description of variables in NAMELIST CLIM is given in Table-2, and description of parameters in NAME LIST BASE and NAMELIST OPT are given in Table 3 & Table 4 of SRM Manual, Martinec, J.,etal (1983).

Assessemnt of simulation Accuracy

a) In first step the simulation accuracy can be determined by a compariosn plot of computed and measured hydrographs.

b) In order to quantity the comparison, several goodness-of-fit measures may be added to the hydrograph plot. The computer programme automatically calculates the percentage volume different (D_v)between the measured (Rom) and model-computed (Ro_c) seasonal runoff

When running the model in the simulation model, if a good agreement is not achieved initially, the following order of items to check in problem solving is recommended:-

1- Re-evaluate snow-cover depletion curves.

2- Re-consider lapse-rate in the basin

3- Adjustment requirement in runoff coefficient.

4- The degree day factor should be investigated after runoff coefficient.

5- Discrepancies in precipitation input, as peak flows may be missed.

6- Recession coefficient should be revised if hydrograph rises or falls two rapidly.

7- Discrepancies in the timing of flow peaks and valleys can be due to an incorrectly determined time lag.

2.2.1.4 Application

Using landsat data the model was successfully applied to various basins in the USA. The total basin relief (amplitude of elevation) encountered on watersheds tested so far has ranged between 350 and 4000m. In basins with less total relief problems may arise due to the fact that SRM may not be applicable to non-mountain basins. As pointed out in SRM user's manual that SRM has been used in mountain basins ranging in climate conditions from humid to semi-arid and ranging in basin area 2.65 Km^2 to 4000 Km^2 with the serious limitations. It seems however, that simulation tends to less accurate when there are significant amounts of rainfall during the snowmelt period and basin size increases.

It is understood that this model is suitable for Indian Mountainous catchment as snowmelt runoff model. Verdhan A. (1987) at SASE compailed the variables based on 5 years observations for upper Beas catchment and estimated the parameters and coefficients of the model. For predicting snowmelt runoff during spring season the model has been thoroughly calibrated and simulation found satisfactory. Special adjustment has been made for the extrapolation of precipitation data and application of lapse rate (being affected by precipitation) for each zonal strips of the basin.

Under Remote Sensing utilisation programme SASE and MRSA in collaboration with France sanctioned a project to test the model for Beas and channels catchments. NIH has implemented this model and model has been tested on the test example. Based on the availability of data the model will be tested and applied to the Indian Mountainous catchment.

2.2.2 UBC Watershed Model

The UBC watershed model was originally developed for daily streamflow forecasting on the Fraser River System in British Columbia (Quick, M.C., and A. Pines, 1972). The model has been tested and adopted by the Praiyie Provinces Water Board for mountain snowmelt forecasting in the Saskatchewar River system headwaters. The model has also been used in planning studies for the Peace River System (Quick, M.C. and A.Pines, 1977).

2.2.2.1 Model Capabilities

The model was originally designed for forecasting runoff from mountain catchments and for this reason the model is divided into area-elevation hands. Meteorological and streamflow data are scarce in the mountain areas and the model was therefore designed to operate on a sparce data input, although, if available, a more extensive data base can be utilised. The model estimates snowpack accommulation and depletion and operates entirely from meteorological inputs of daily maximum and minimum temperatures and precipitation. Soil moisture and groundwater characteristics are used to control the sub-division into fast, medium and slow components of runoff. These various components of runoff are routed to the stream system by using unit hydrograph and storage routing techniques. Additinal facilities are available in the model to describe lake storage and lake routing techniques.

In the case of temperature, the model normally uses a constant lapse rate for calculation of snowmelt, and at times this can give rise to errors, especially during periods of high melt when the lapse rates may be abnormal. This source of error can be avoided if data are available at staions high in the basin and at valley level. Under these conditions an option in the model permits calculation of lapse rates.

A number of parameters are fairly constant in the model and do not vary from basin to basin vary significantly. The remaining hydrological parameters such as runoff parameters during recession periods can be determined. Each part of the basin can be assessed independently and it can be seen whether soil moisture capacities and other hydrological coefficients are changing considerably with elevation.

The annual cycling capability of the UBC model, particularly its ability to accummulate snowpack from the winter precipitation and to assess soil moisture conditions at the beginning of each year's snowmelt, helps in operating the model around the year.

2.2.2.2 Model Structure

A schematic of the UBC Watershed Model is presented in fig. 12. Elevation is considered to be one of the most

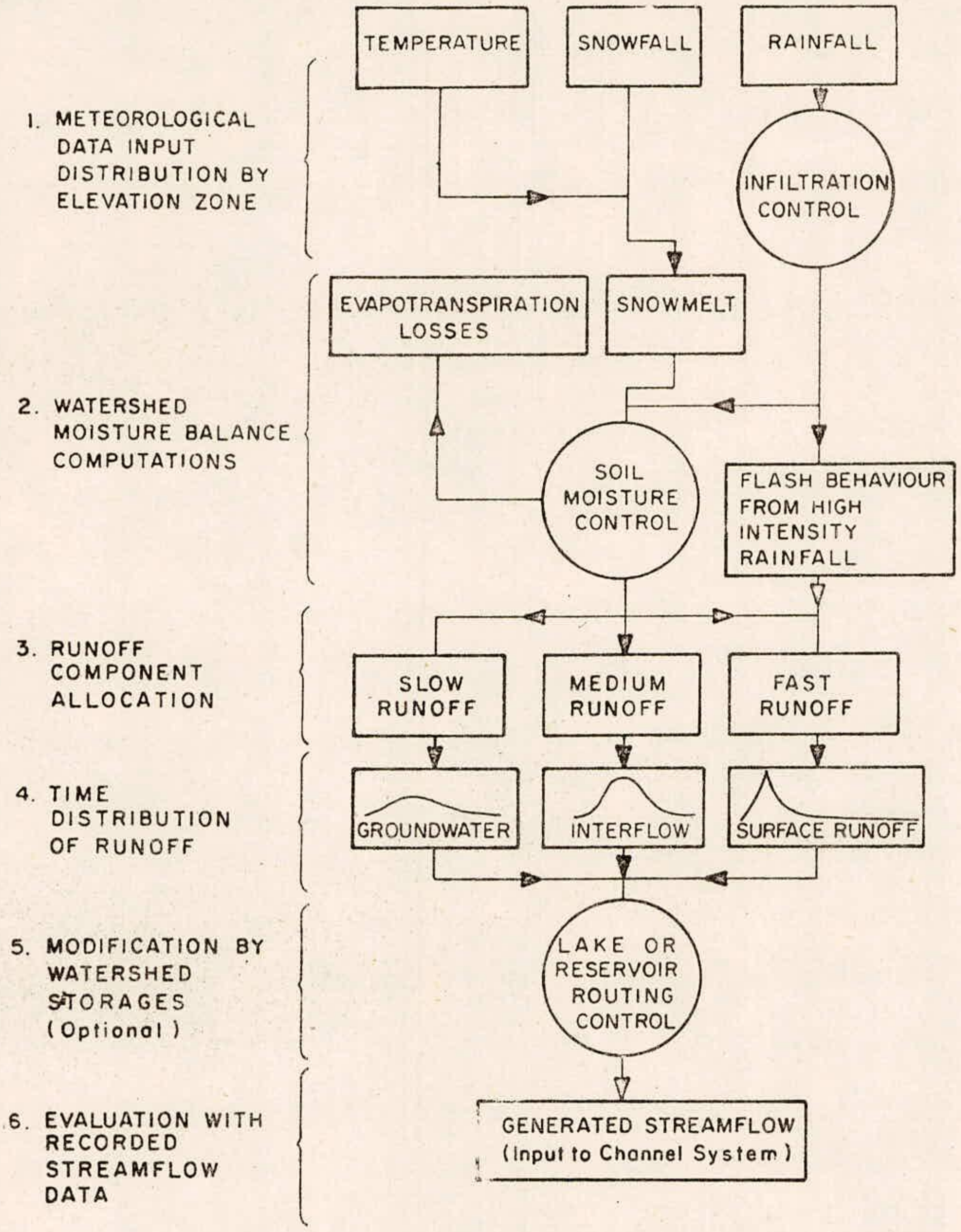


FIGURE 12 U.B.C. WATERSHED MODEL GENERELIZED FLOW CHART.

important variables in the description of mountain runoff. For this reason, the model is divided into area-elevation bands. Elevation relationships of temperatures and winter and summer precipitation are specified in the model and the basic meteorological data are distributed to these various elevation levels. Runoff characteristics also tend to be distributed by elevation.

Lakes can be represented in the certain portions of the basin. In fact two types of lake storage are specified, the first is an upland lake storage. A variable percentage of the basin can be specified for regulation by this upland storage, and only the runoff from the portion of the basin above the elevation specified for this upland lake storage will be regulated. A lake can also be incorporated at the bottom of the basin and this lake will regulate the total outflow.

The most important variable in the model is the soil moisture deficit. This soil moisture deficit is used to allocate snowmelt or rain in each band to the various zones of runoff, for example, if the soil moisture deficit is low then a sizeable portion of runoff will occur as fast runoff. Some runoff will be allocated to interflow and the remainder to slow baseflow groundwater runoff. This allocation procedure is quite automatic and is functionally dependent on the soil moisture deficits. For example, if the soil moisture deficit has not been satisfied, in this case, when further melt occurs or rain falls, only a certain percentage of the basin will contribute runoff this contribution will be fast runoff.

When the soil moisture deficit decreases, the amount of fast runoff increases until a maximum value is reached. When sufficent melt or precipitation has occured soil moisture deficit will be satisfied and at this point the next demand on the excess moisture is groundwater percolation. If the groundwater percolation is also dissatisfied the remaining melt or precipitation will go to an interflow system.

The total runoff results for the routing of these various fast, medium and slow runoff components, and the routing processes used are storage routing procedures. To be more specific, the fast and medium components of runoff are routed by unit hydrographs specified by Nash's series of reservoirs and the slow component of runoff utilizes recession coefficients.

2.2.2.3 The Model Parameters

Some parameters are obtained directly, Basin area-elevation characteristics are measured directly for suitable scale maps. Any elevation increment could be specified, although 150-m or 300-m intervals are generally used in mountinous areas. Upto 12 elevation bands or zones can be specified.

There are various meteorological parameters. The main one is laps rate for temperature. Lapse rates for the daily maximum temperature and minimum temperature are calculated separately. Under open sky conditions the maximum temperature laps rate tends to the dry adiabatic value while the minimum temperature laps rate tends to a low value. During rain and humid conditions, represented by a low daily temperature range, both lapse rates tend to the saturated adiabetic value. A further option does exist, namely, to determine the lapse rate directly for the measured temperature data. Other meteorological parameters are used to distribute snow and rain to the various elevations so that the precipitation increases logarithmically with elevation.

The next set of parameters describe the hydrological runoff characteristics of the basin. The most important parameter is the soil moisture deficit, BSD, and the soil moisture deficit decay function ASDK. These two parameters work in conjunction with temperatures to estimate potential evapotranspiration.

Two parameters, PMXIMP and ASDK specify the percentage of the basin which contributes to direct runoff, and this percentage is an exponential function of soil moisture deficit. Another constant describes the groundwater percolation rate and this determines the amount of flow going as deep percolation. Any excess soil moisture over and above the groundwater percolation rate is routed to the interflow component of runoff. The remaining parameters specify the rates at which these various component of runoff reach the channel. The fast runoff is routed by unit hydrograph the shape of which is controlled by two parameters NRESVO, the number of linear reservoirs and UZ, the reservoir storage constant. The groundwater and interflow components of runoff are routed using recession storage constants, although the interflow component also uses a unit hydrograph, much like the fast runoff, to distribute the daily release to the stream system.

2.2.2.4 Snow-Melt Calculation

Snowmelt rates depend on three major sources of thermal energy, namely (i) convective heat transfer from a warm air mass, (ii) net radiant heat transfer and (iii) latent heat changes associated with evaporation or condensation of water vapour. Temperature data are commonly available to estimate convective heat transfer. Radiation and vapour pressure measurements are not commonly available, especially from remote mountain areas. It has been found possible to describe the contribution of radiant energy input in terms of the daily temperature range. The latent heat changes associated with the humidity of the air mass is reasonably well characterized by the daily minimum temperatures which approximate to the dewpoint.

The total energy can be subdivided into energy for melting and energy for evaporation. This energy partition is controlled by the vapour pressure of the air mass compared with the snow surface vapour pressure. The equation which is used to describe snowmelt is (Quick, M.C, & A. Pipes, 1977) :

$$\mathrm{PM}\ (J,L) = \mathrm{PTM} * T(J,L)$$

$$T\ (J,L) = T(J,L) + \mathrm{TCEADJ}*(\mathrm{TDIURN}/\mathrm{XTDIUN} + \mathrm{TCEMLT})$$

$$0 < \mathrm{TCEADJ} < 1.5 = \mathrm{TCEMLT}/\mathrm{XTDEWP},\ \text{where } 0\quad \mathrm{TCEADJ}\quad 1.5$$

where

TCEMLT	minimum temperature above freezing;
XTDIUN	usual value 8;
XTDEWP	reference dewpoint, usual value $4.4^{\circ}C$;
TDIURN	daily temperature range;
PM(J,L)	snowmelt for day J and band L;
PTM	point snowmelt factor-usual value $3.0 mm/^{\circ}C$.

The extra terms in this melt formulation which re-present radiant heat and latent heat have little influence when the daily temperatures are low, but these terms become very important under extreme melt conditions and can nearly double the melt rates.

2.2.2.5 Application

The snowmelt formulation has been tested (Quick, M.C. and A. Pipes, 1977) using data from a number of high flow years on the Fraser and Columbia rivers. It has also been more directly tested against snowpillow data where there is an almost direct measurement of snowmelt.

The UBC watershed model has been used operationally for forecasting daily streamflows in 13 sub-basin of the Fraser River system which is subject to snowmelt floods from the mountain snowpacks of the coast, columbia and Rocky Mountains in British Columbia.

A 30-year sequence of missing streamflow data has been generated by the model from the measured meteorological data in planning studies for the Peace River System. Snowpacks were estimated by the model from measured valley precipitation. The model was tested using 12 year period of measured flows and correlation coefficients of 0.96 was obtained for monthly flows.

2.2.3 USBR Model

The USBR Model (Ford, 1959) forecasts total seasonal snowmelt runoff using multiple regression. The models is written as :

$$y = a_0+a_1x_1+a_2x_2+a_3x_3+ \ldots\ldots\ldots +a_nx_n$$

where y = total seasonal runoff say. Apr-July runoff;

x_1 = Snow Water equivalent averaged from various snow course stations, say Feb. Snow;

x_2 = seasonal precipitation, say, Oct-Jan. Precipitation,

$x_3 \ldots\ldots x_n$ = Other independent variables, and $a_0{}' a_1 \ldots\ldots a_n$ are regression coefficients.

The choice of the independent variables in the model is determined based on the highest correlation coefficient.

2.2.3.1 Model Capabilities

The $x_1{}'$s in above equation are arithmetic averages based on measurements made at the available gaging stations in the watershed. A station weighting procedure, called successive increment method, was later introduced in order to find weights for each gaging stations which gives the best multiple correlation coefficient. In the successive increment method, the initial solution is the average solution. Then starting with the first station of the first independence variable, its initial weight of 1.0 is decremented or incremented by some fraction say 0.01. Then, the correlation coefficient is computed and compared to the previous one. The process is repeated until the best correlation coefficient is obtained and all stations and variables are exhausted. The minimum station weight is limited to zero while there is no limit to the maximum. However, the maximum station weight is generally 4.0.

2.2.3.2 Deficiencies

The use of the successive increment method which is based on finding the best multiple correlation coefficient is computationally inefficient and arbitrary. First of all, different forecast model parameters and forecast reliability may be obtained when the order of the data input is changed. Secondly, the choice of the best model on the basis of the multiple correlation coefficient does not assure the best forecast which the model is intended for. This is because the correlation coefficient is only a good indicator as far as the historical data is concerned, but not for the future, lastly, depending on the number of stations available and variables considered, the multiple regression computations may be repeated a large number of times before the best weights are obtained.

2.2.3.3 Applications

The USBR model was used to demonstrate the advantages of the suggested areal averaging techniques to the Green Mountain Reservoir in Colorado (Guillermo, 1982). The April-July inflow was used as the forecast variable. Data of seasonal inflows, snow water - equivalent and precipitation for the period 1962-1078 were obtained from the USBR, loveland, colorado. The following independent variables were considered the Feb. 1 snow water equivalent, previous year Feb-June precipitation, Oct-Jan., precipitation and previous year Nov. inflow. Several forecast models were fitted using the first independent variable, then the first and the second, and the first and the third and so on.

The various models and areal averaging techniques (1-Average solution, 2-USBR weighted solution, 3-thiessen method, 4- multiguardic Interpolation, 5-optimal Interpolation, 6- Optimal Weighted Solution and various combinations of independent variables were made, i.e. A-Feb. 1 snow; B-Feb. 1 Snow & Feb-June precipitation; C-Feb. 1 snow & Oct.-Jan. precipitation; D-Feb. 1 snow with Feb-June & Oct.-Jan. precipitation.

For the set method 3 to 6 have smaller Root mean square error than 1 and 2 where the multiquardic technique has the lowest RMSE.

2.2.4 HYDRO COMP'S HSP

2.2.4.1 Model Capabilities

HSP attempts to simulate continuously the complete Hydrological cycle of a Water-shed. Based on given precipitation and potential evapo-transpiration, the lands module accounts for the followings (1) Storage; as interception, upper zone (surface or near surface), lower zone (sub-surface), and groundwater; and (2) flow; impervious runoff, interflow, overland flow, infiltration, percolation, base flow and actual evapotranspiration. Inflows to the channel system are routed downstream in

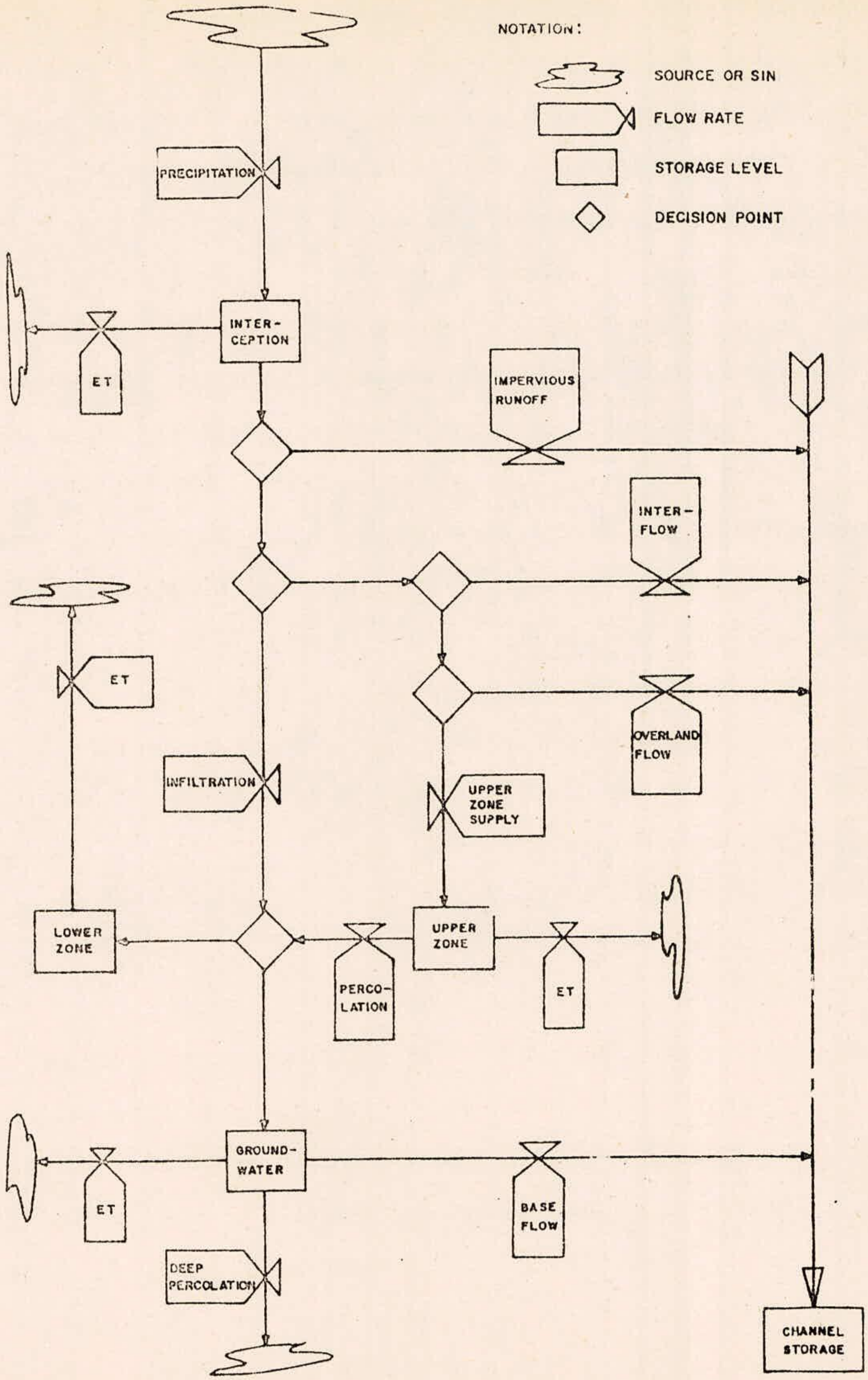


FIGURE 13 FLOW CHART FOR HYDRO CROMP'S HYDROLOGIC SIMULATION PROGRAM (HSP).

the channels module using Kinematic wave routing. Fig.13 is a schematic of HSP'S major components.

The model has the additional capability to simulate the complex snowfall-snowmelt process. Accumulation of precipitation in a snow pack and its eventual release as snowmelt is modeled using the equations published in the corps of Engineers "Snow Hydrology" Melt is the combined result of direct solar radiation, convection, condensation, rain or snow & groundmelt. Precipitation and temperature decide when snow is falling and, together with snow density, determine depth and equivalent water content of the pack.

2.2.4.2 Data Requirements

Twelve additional parameters are involved in the snowmelt routine. Mean elevation, elevation difference and forest cover can be measured from maps but the other nine variables are difficult to set without previous experience in modelling snowmelt for similar meteorological conditions. Meteorologic data pre-requisites for snowmelt include daily: Maximum and minimum air temperature, wind movement, dewpoint temperature, cloud cover, incident solar radiation and precipitation.

2.2.4.3 Parameter for Calibration

RAD CON	Radiation melt parameter
CONDS CONV	CONVECTION melt parameter
SCF	Snow correction factor to gage record
ELDIF	Elevation difference (gage to segment)

IDNS	Initial density of new snow
F	Forest cover
DGM	Daily ground melt (inches)
WC	Water content of Snow Pack maximum
MPACK	Snowpack at complete areal coverage
EVAP SNOW	Snow evaporation parameter
MELEV	Mean Watershed Segment elevation(ft)
T SNOW	Upper limit of temperature at which precipitation is Snow..

2.2.4.4 Application

Hydrologic Engineering Centre (Corps of Engg. US Army) applied (1978-79) Hydro Comp's HSP, a continuous hydrologic simulation computer programme, to model the West Branch Dupaga River above West Chicago, Ulinois. The HSP model was evaluated by how well it reproduced runoff volumes (annual, monthly and daily) and runoff peak discharges. Following are the adopted/calibrated parameters values for snowmelt routine.

1, 1, 1.6, 0.1, 0.45, 0.01, 0.05, 0.5, 0.1, 0.1, 800, & 33. Reported that March to April were generally low in simulated volume and July to September generally high. Spring runoff, either rain plus melting snow or rain on frozen ground was very difficult to stimulate due to the complex nature and data uncertainties of the snowmelt process. Also mentioned that if semi-daily temperature is not available, daily radiation, wind speed, and dew poit can be estimated but other meteorological, variables including evapcration can be difficult to obtain.

2.2.5 Kentucky Watershed Model

The Kentucky Watershed Model (KWM) is FORTRAN version of the Stanford Watershed Model (SWM). A schematic flow chart of KWM is given in Fig. 14 showing the Moisture movement through the runoff cycle as synthesised in the SWM.

2.2.5.1 Model Capabilities

The model continuously simulates the movement of the water over, into and through the soil, according to the best current knowledge of hydrological process. Output consists of synthetic streamflow, overland flow, interflow, baseflow, evapotranspiration (net and potential) and ground water storage. These hydrologic quantitites can be obtained daily, monthly or annually as needed.

Calculations start from known or assumed soil moisture conditions and proceed until the inputs are exhausted. After satisfying the interception and depression storage losses, the moisture enters the three storage zones-the upper, the lower and the groundwater zones. A certain amount of precipitation runoff from impervious layers is assumed to reach the streamflow directly. The upper zone simulates the initial responses to the rainfall and eventually water percolates to the lower zone. The lower zone controls watershed response to major storms controlling longer term infiltration rates. Groundwater storage supplies the baseflow to stream channels. Evapotranspiration is assumed to take place from the interception, upper zone, lower zone

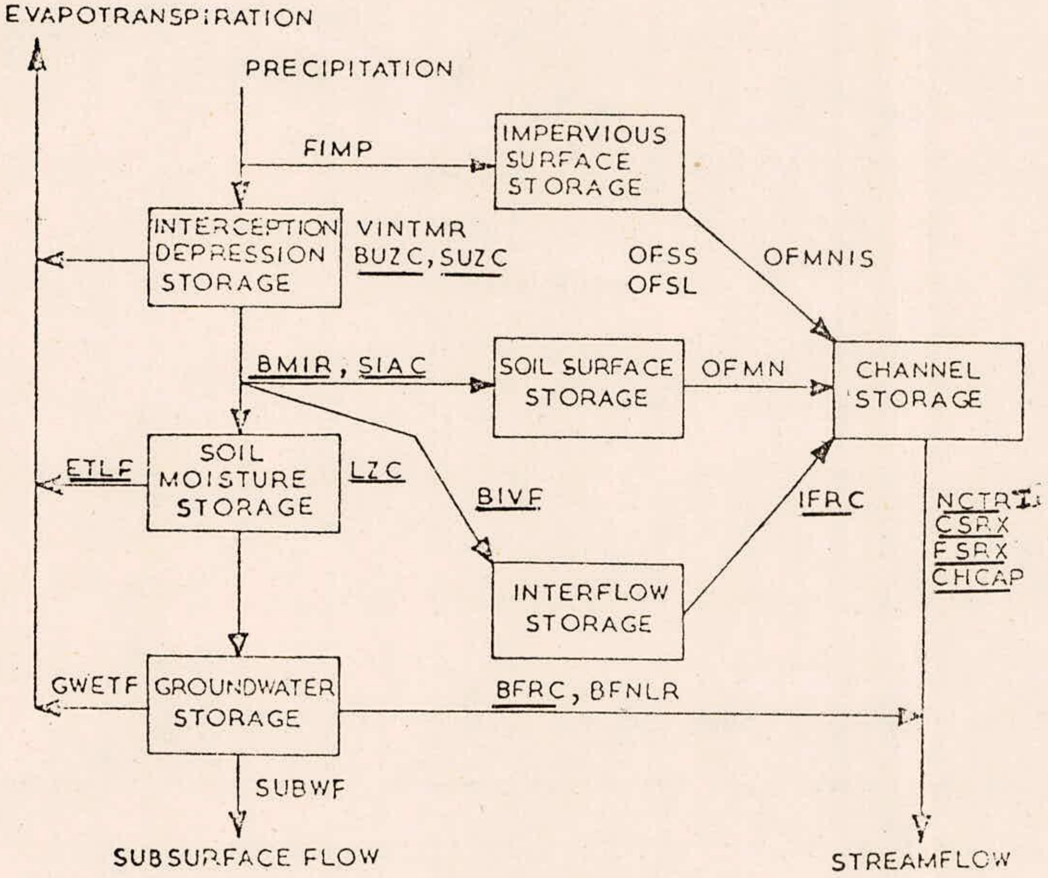


FIGURE 14 MOISTURE ACCOUNTING IN THE STANFORD WATERSHED MODEL.

and groundwater.

The total inflow from overland flow, interflow and groundwater enters the channel routing portion of the model and is routed to produce continuous hydrograph of outflow from watershed.

2.2.5.2 Input Data

The major input data are evapotranspiration and rainfall. If snow is a significant part of precipitation, then snowfall data should also be given as input data. In addition, several other input parameters and control arrays must be selected based on Watershed behaviour, characteristics and data availability. As example, the input parameters include AREA, the area of the basin, FIMP, the fraction that is impervious, FWTR, the fraction that is swampy, and several others shown in Fig.14 without underlining.

2.2.5.3 Parameters fro calibration

The model is said to be calibrated and the set of parameters optimised when the synthesised hydrograph (utilizing the following parameters) matches with the observed hydrograph in terms of volume, peak and time of occurrence of peak within limits of uncertainity.

Volume Parameters

LZC	- Lower zone storage capacity
BMIR	- Basic Maximum Infiltration Rate within Watershed
SUZC	- Seasonal Upper Zond Storage Capacity factor.
ETLF	- Evapotranspiration Loss Factor
SIAC	- Seasonal Infiltration Adjustment Constant

BIVF - Basic Interflow Volume Factor

Recession Parameters

IFRC - Interflow Recession Constant

BFRC - Base Flow Recession Constant

Routing Parameters

NCTRI - Number of Current Time Routing Increments

CSRX - Channel Storage Routing Index

FSRX - Flood Plain Storage Routing Index

CHCAP - Channel Capacity-indexed to Basin outlet.

Above parameters are estimated by OPSET. OPSET is a self calibrating version of the Kentucky Watershed Model.

2.2.5.4 Application

KWM has been implemented and used for simulation of small watershed in Punjab, Ramaseshan, S. etal (1976). Simulation made for one year period based on available evaporation, houly and daily precipitation and daily streamflows data. Water imported by Canals from outside the Watershed has not been taken into account even though there is provision for this in the model.

Results of above study indicate that the soil moisture storage volume in the Punjab basin varies from 8.40 cm to 19.60 cm consisting of 5.85 cm of lower zone storage and the rest of upper zone storage. It is reported that comparision of synthesized and observed runoff is satisfactory as shown in Fig.15 and improvements are possible by modifying the programme.

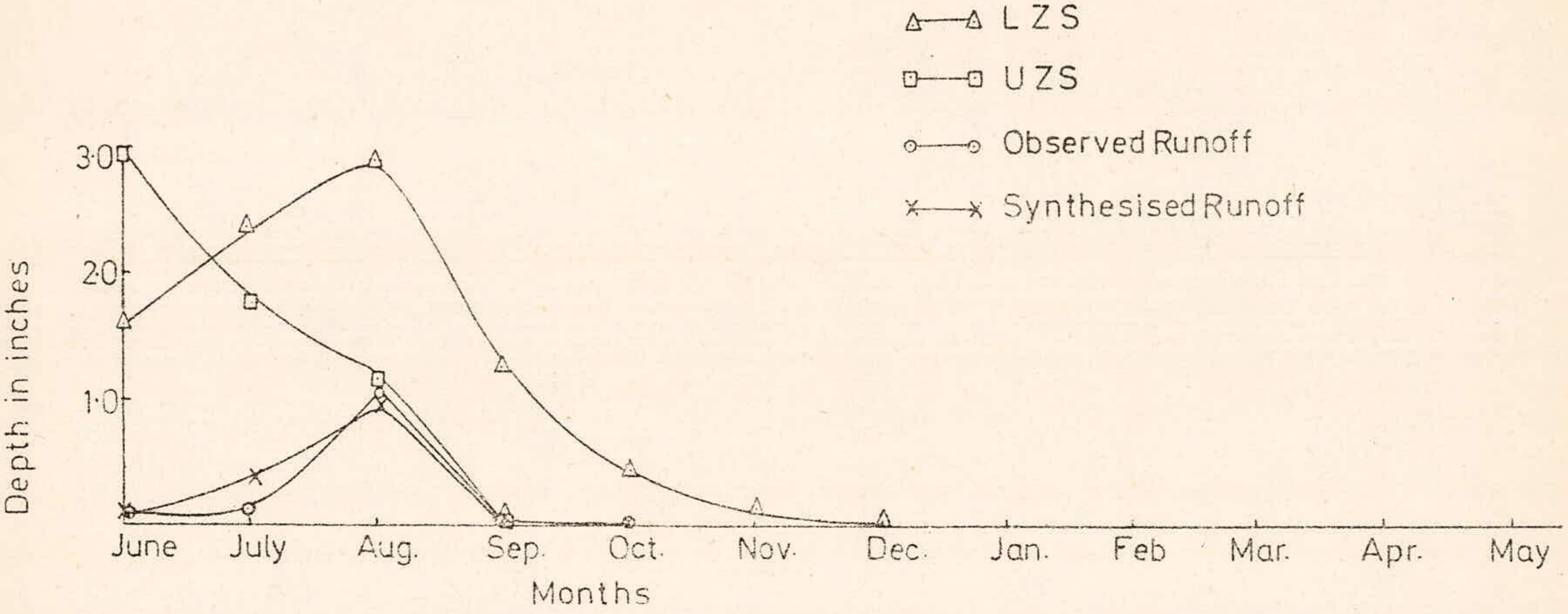


FIGURE 15 STORAGE AND RUNOFF CHARACTERISTICS OF THE WATERSHED AT PUNJAB.

The above study recommends the usefulness of KWM in estimation of soil moisture recharge due to precipitation, actual ET, irrigation needs and in deriving simulated or synthesised hydrographs from limited discharge data and extensive hydromet data, which is the case for a large number of small watersheds in India.

The CW&PRS have calibrated the Narmada basin using Kentucky Watershed model for pusposes of obtaining PMF estimates for both Narmada Sagar and Sardar Sarovar Reservoirs on the mainstream. For this purpose, the basin has been divided into twenty subbasins and each subbasin calibrated using historic data of several years. The KWM does not include a river channel routing routine so separate programme was applied for routing.

The time taken for a single run of KWM, on the HP system for all 20 subbasins put together for simulating a time duration of one week, is of the order of two minutes, Rajagopalan, K.S. and etal. The paper brings to focus the possibility of using calibrated KWM for forecasting purposes in the Narmada Basin.

2.2.6 SACRAMENTO Model

The Sacramento model was developed by the staff of the National Weather River Forecast Centre at Sacramento, California, U.S.A.

2.2.6.1 Model Capabilities

This model embodies a complex moisture accounting algorithm to derive volumes of several runoff components, while a rather simple and highly emperical method is used to convert there inputs to the outflow hydrograph. The soil mantle is treated in two parts, an Upper zone and a Lower zone, with each part having a capacity for tension water and free water. Tension water is that which is closely bound to the oil particles and is depleted only by evapotranspiration. Provision is made for free water to drain downward and horizontaly. The storage capacities for tension and free water in each zone are specified as model parameters. Water entering a zone is added to tension storage as long as the capacity is not exceeded and any excess is added to free water storage. A portion of any precipitation is derived immediately to the channel system as 'direct runoff'. This is the portion which falls on the channel system and on impervious areas adjacent thereto. The extent of this areas is time varient in the model.

All rainfall and snowmelt, other then that diverted to direct runoff, enters the upper zone. Free water in the upper zone is depleted either as interflow or as percolation to the lower zone.

If the rate of moisture supply to the upper zone is greater than the rate of depletion, the excess becomes "Surface runoff". Free water in the lower zone is divided between primary (slow drainage) storage and secondary storage. Percolation from the upper to the lower zone is defined as :

$$\mathrm{PRATE} = \mathrm{PBASE}\,(1+\mathrm{ZPERC}* \mathrm{RDC}^{\mathrm{REXP}})\,\frac{\mathrm{UZFWC}}{\mathrm{UZFWM}}$$

where

PRATE : is the percolation rate.

PBASE : is the rate at which percolation would take place if the lower zone were full and if there were an unlimited supply of water available in the upper zone. It is numerically equal to the maximum lower zone outflow rate and is computed as the sum cf the lower zone, primary and secondary free water capacities, each multiplied by its depletion coefficient.

RDC : is the ratio of lower zone deficiency to capacity that is RDC is zero when the lower zone is full, and unity when it is empty.

ZPERC : is a model parameter defining the range of percolation rate, Given an unlimited supply of upper zone water, the rate will vary form PBASE(1+ZPERC) when the lower zone is empty.

REXP : is a model parameter defining the shape of the curve between the minimum and maximum values described above .

UZFWC : is the upper zone free water content

UZFWM : is the upper zone free capacity. UZFWM represents the upper zone "Driving force", With the upper zone empty, their will be no percolation, With it full, the rate will be governed by the dificiency in the lower zone.

This equation is the Central mechanism cf the model. It interacts with other model components in such a way that it controls the movement of water in all parts of the soil profile, both above and below the percolation interface, and in turn is controlled by the movement in all parts of the profile.

Evapotranspiration rates are estimated from meteorological variables or from pan observations. Either day-by-day or long-term values can be used. The catchment "potential" in the product of the meteorological evapotranspiration and a multiplier which is a function of the calender date, thus reflecting the state of the vegetation. The moisture accounting within the model extracts the evapotranspiration loss, directly or indirectly, from the contents in the various storage elements and/or from the channel system. The loss is distributed according to a hierarchy of priorities and in limited by the availability of moisture as well as by the computed demand.

The movement of moisture through the soil mantle is a continuous process, the rate of flow at any point varying with the rate of moisture supply and with the contents of relevant storage elements. This process is simulated by a quasi-linear computation. A single time step computation, the drainage and percolation process involves the implicit assumptions that the movement of moisture during the time step is defined by the conditions existing at the beginning of the step. This approximation is acceptable only if the time step is relatively short. In the model, the length of the step is volume dependent. The step is selected in such a way that no more than five milimeters of water may be involved in any single execution of the computational loop.

2.2.6.2 Routing

Five components of runoff are derived in the model. The three upper components (direct, surface and interflow) are summed and transformed by a unit hydrograph using method similar to time-area curve method. The two components from the lower zone, primary and secondary base flow, are added directly to the outflow hydrogrpah derived from the other three components. Provision is also made for routing the resultant hydrograph with variable routing coefficients.

2.2.7 National Weather Service River Forecast System(NWSRFS)

National Weather Service River Forecast System(NWSRFS) (NOAA,1972) as developed by United States National Weather Service was a comprehensive collection of the hydrologic techniques and included the basic hydrologic techniques to perform their operational function. The system was begun in 1971, along the lines described as follows and published in 1972. Originally the system included a modification of Stanford Watershed Model IV. The hydrologic techniques included the follows:

i) Catchment model which, through the use of soil moisture accounting formulations and mathematical modelling of flow through and above the soil mantle and within the channel, covert moisture input (rainfall or snowmelt) to a hydrograph of channel discharge at the outlet of the catchment.

ii) A mathematical model of the accumulation and ablation of snow.

iii) Channel routing models which model the translation and attenuation of a flood wave as it moves between two points in a channel.

iv) Techniques for modelling the areal distribution of precipitation to be used for computing the moisture input to a catchment on the basis of point values measured at raingauges.

In addition to the hydrologic techniques, the system included three other categories of material.

i) Procedure for archiving, retrieving and processing the type of data needed to apply the system

ii) Methods needed to calibrate the various hydrologic techniques, that is, to evaluate parameters to apply a hydrologic or hydraulic model to a specific location.

iii) Computer programmes necessary to execute the hydrologic techniques and support procedures described above in both the development and operational models.

However, since the system was originally published in 1972, the operational system had been expanded and revised frequently. A major revision was made in 1976 (NOAA,1976) in the soil moisture accounting for the catchment model. The components for soil moisture accounting of Sacramento Model replaced those of modified Stanford Model as used in the original system.

NWSRFS(Sacramento) Model Relating Remotely Sensed variables

The standard NWSRFS model do not land themselves to direct use of remotely sensed variables. This National Weather Service River Forecast System is continuously being updated and expanded. Study & Reports were made on creating a bridge between Remote Sensing and Hydrologic Models in 1983 by E.L. Peck, etal of Hydex Corporation.

2.2.7.1 Capabilities of the Model

The NWSRFS (Sacramento) model is a conceptual model, since the model characteristics (storage of moistures, percolation, evapotranspiration, etc.) are intended to represent actual hydrologic processes in a natural manner. However, even if the model perfectly represents what occurs in nature, the moisture stages in the model would not necessarily correspond directly with remotely sensed measurements because of measurement error.

The remotely sensed measurements that are to be used primarily with the hydrologic models are those of soil moisture for the rainfall/runoff model, and the areal extent and water equivalent of the snow cover for the snowmelt model. Therefore, the NWS rainfall/runoff (Soil moisture and accounting) and snowmelt (snow accumulation and ablation) models were modified. The structure of the NWSRFS rainfall/runoff model is illustrated in Fig.(16) and the NWSRFS Snowmelt model in fig.(17).

Rainfall/Runoff Model

The upper zone of the NWSRFS rainfall/runoff model represents the upper soil moisture layer and interception storage. The depth of the soil layer is not fixed by the model. The maximum amount of moisture that can be stored in the upper zone of the impervious area of the basin is a combination of the maximum tension water (UZTWM) and of the maximum free water (UZFWM). The actual water stored at any moment is the sum of the two model states representing upper zone tension water (UZTWC) and upper zone free water (UZFWC).

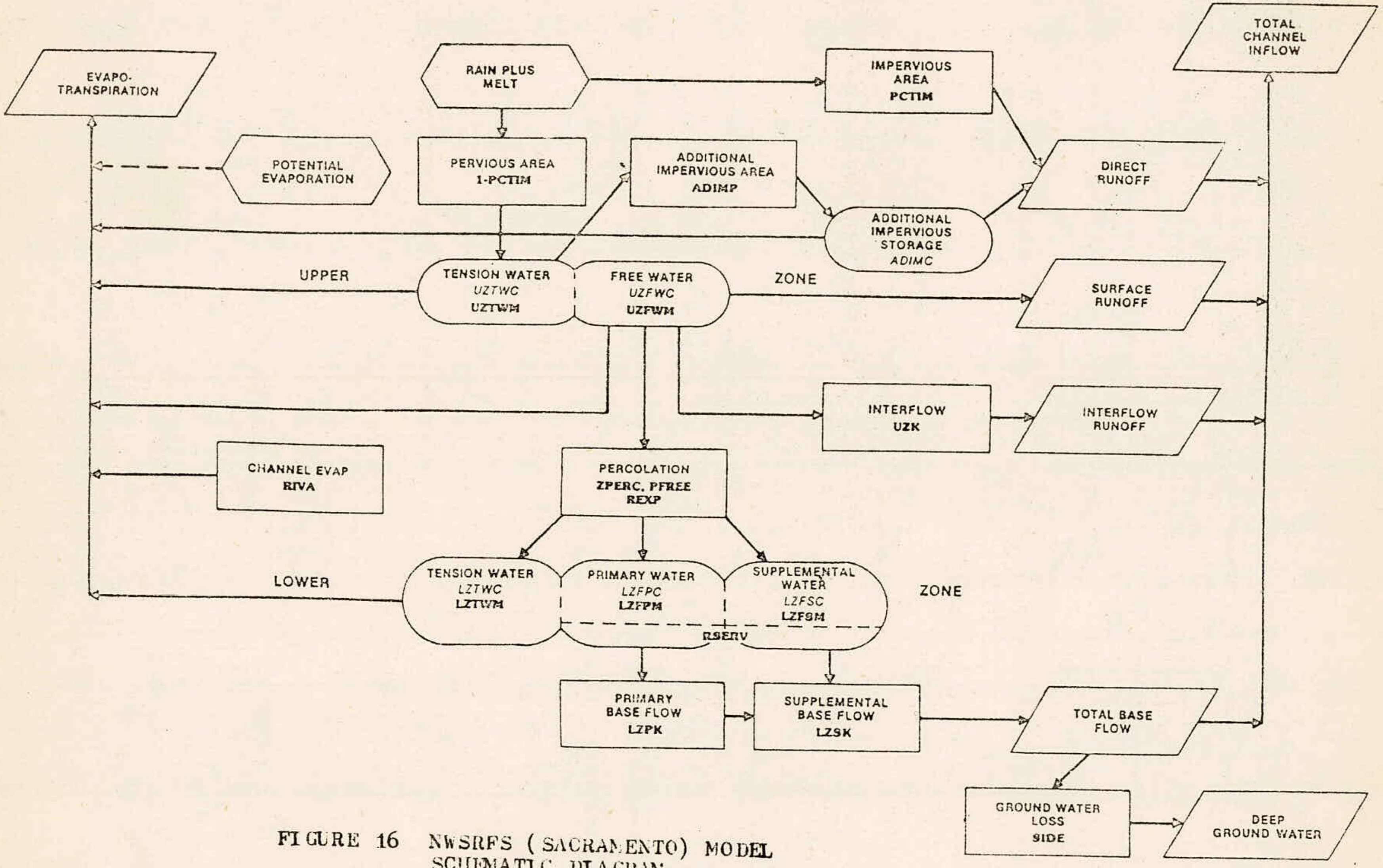


FIGURE 16 NWSRFS (SACRAMENTO) MODEL SCHEMATIC DIAGRAM.

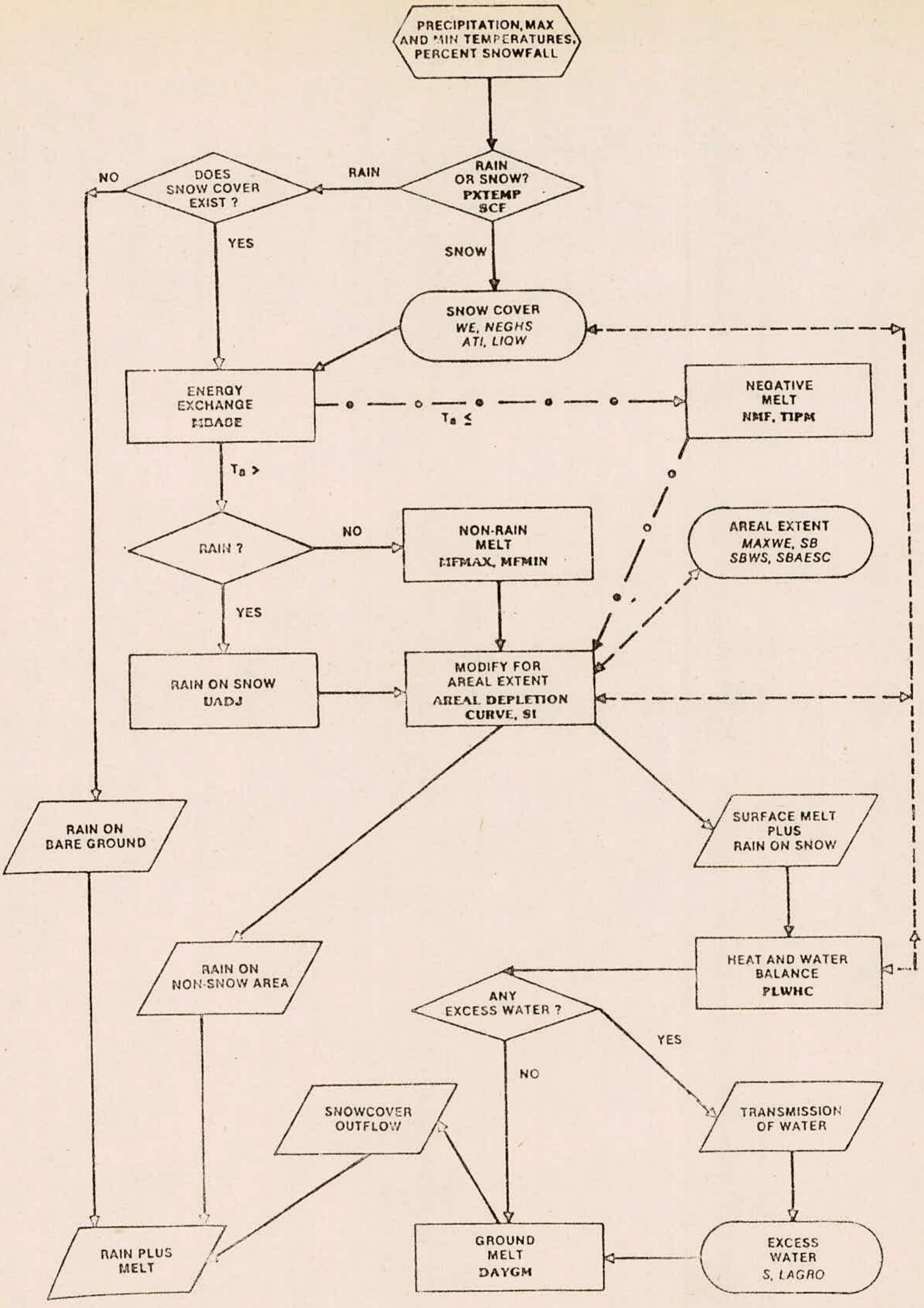


FIGURE 17 NWSRFS (ANDERSON) SNOW-MELT
MODEL SCHEMATIC DIAGRAM.

A remotely sensed measurement of soil moisture may be considered to represent only the total water in the top 10 cm of the soil. Thus, such a measurement for 10 cm cannot directly relate to the total soil moisture represented by the combined soil moisture states of the upper zone of the hydrologic model which often covers more than the top 10 cm. The depth for the upper zone varies with each particular basin characteristics. The relative depth can be at least an order of magnitude greater than the 10 cm representing a soil moisture measurement.

Snow-Melt Model

In the development of the NWSRFS snowmelt model the possible availability of remotely sensed data was considered. It can be subjectively updated using the areal extent of the snow cover and to a lesser degree using measurements of the water equivalent of the snowcover.

Badically, field measurements of the water equivalent of the snow cover represent the entire mass of water (ice layers, snow and liquid water) above the surface. In the model this total water mass is represented b, a combination of sotrage states. These includes the solid portin of the snowpack(WE), the liquid water held against gravity (LIQW) and the excess liquid water in transit in the snowpack (LARGO and S).

For the simpler case (no temporary snow cover) the areal extent of snow cover is a function of three state variables in the form (WE+LIQW)/AI. Where AI is the maximum value of WE+LIQW which has occured (AI does have an upper bound of SI, a parameter value). The areal extent of snow cover is found from the ADC (areal depletion curve). In temporary snow cover case it is function of new state variable SB, SBAESC and SBWS. SBAESC is simply the areal extent of snow cover at the start of snowfall on partially bare ground and SB is the associated value of (WE+LIQW). SBWS is the value of WE+LIQW) above which 100% snow cover temporarily exists. SBWS is increased by 75% of any snowfall during the temporary snow covered conditins.

2.2.7.2 Hydrological Process & Components

All rainfall and snowmelt, other than that diverted to direct runoff, enters the upper zone. Free water in the upper zone is depleted either as interflow or as percolation to the lower zone.

Evapotranspiration rates are estimated from meteorological variables or from pan observations. Either day-by-day or long-term values can be used. The catchment "Potential" is the product of the meteorological evapotranspiration and a multiplier which is a function of the calender data, thus reflecting the state of the vegetation. The moisture accounting within the model extracts the evapotranspiration loss, directly or indirectly, from the contents in the various storage elements and/or from the channel system. The loss is distributed according to hierarchy of priorities and limited by the availability of moisture as well as by the computed demand.

Five components of runoff are derived in the model. The three upper components (direct, surface and interflow) are summed and transformed by a unit hydrograph using method similar to time area-curve method. The two components from the lower zone, primary and secondary base flow, are added firectly to the outflow hydrograph derived from the other three components.

Routing

Provision is also made for routing the resultant hydrograph with variable routing coefficients.

If the catchment or subcatchment has upstream inflow contributions from outside, the area being modelled, then the variable K and lag river routing procedure is adopted to route the upstream inflow and the routed inflow is added to the runoff from the run area to give the forecasts at the watershed outflow point.

2.2.7.3 States & Parameters

States and Parameters definitions of NWSRFS Snowmelt model are listed below:

1. STATES(DEFINITIONS) NWSRFS SNOWMELT MODEL

ATI - Antecedent temperature Index; represents the temperature within the snow cover.

LAGRO - LAGRO and S together define the amount of excess liquid water in transit in the snowpack.

LIQW - The amount of liquid-water held against gravity drainage.

MAXWE - The maximum water-equivalent that has occured over the area since snow began to accumulate.

NEGHS - Heat deficit; the amount of heat that must be added to return the snow cover to an isothermal state at 0^{o}C with the same liquid water content as when the heat deficit was previously zero.

S - S and LAGRO together define the amount of excess liquid water in transit in the snowpack.

SB* - The areal Water equivalent just prior to the New Snowfall.

SBAESC* - The areal extent of snow cover from the areal depletion curve just prior to the new snowfall.

SBWS* - The amount of water equivalent above which 100 percent areal snow cover temporarily exists.

WE - Water equivalent of the solid portion of the snowpack.

* - These states are only used when there is a new snowfall on a basin with a partial snow-cover.

2. PARAMETERS (DEFINITIONS) NWSRFS SNOWMELT MODEL

AREAL DEPLETION CURVE - Curve that define the areal extent of the snow cover as a function of how much of the original snow cover remains. It also implicitly accounts for the reduction in the melt rate that occurs with a decrease in the areal extent of the snow cover.

DAYGM Constant amount of melt that occurs at the snow soil interface whenever snow is present.

MBASE - Base temperature for snowmelt computations during nonrain periods.

MFMAS - Max melt factor during nonrain periods; assumed to occur on June 21.

MFMIN - Minimum melt factor during nonrain periods; assumed to occur on December 21.

NMF - The maxim negative melt factor.

PLWHC - Percent (decimal) liquid water holding capacity indicates the maxim amount of liquid water that can be held against gravity drainage in the snow cover.

PXTEMP - The temperature that delineates rain from snow.

SCF - A multiplying factor that adjusts precipitation data for gauge catch deficiencies during periods of snowmelt and implicitly accounts for net vapour transfer and interception losses. At a point, it also implicitly accounts for gains or losses from drifting.

SI - The mean areal water-equivalent above which there is always 100 percent areal snow cover.

TIPM - Antecedent temperature index parameter (range in 0.1 TIPM 1.0)

UADJ - The average wind function during rain-or snow periods.

2.2.7.4 Applications

The South Yamhill river near Whiteson, Oregon, U.S.A. was selected for use to illustrate application of

NWSRFS. The initial values of soil moisture parameters as determined by NOAA (1976) has been listed in Table 2.

Table 2 : Initial value of soil moisture parameters for South Yamhill River near Whiteson, Oregon, U.S.A.

(Reproduced from NOAA, 1976)

Sl. No.	Parameter Description	Parameter notation	Initial values
1.	Lateral drainage rate of lower zone primary free water expressed as a fraction of contents per day.	LZPK	0.003
2.	Maximum capacity of lower zone	LZFPM	33 mm
3.	Lateral drainage rate of lower zone supplemental free water expressed as a fraction of content per day.	LZSK	0.054
4.	Maximum capacity of lower zone supplental free water storage in mm.	LZFSM	180 mm
5.	Fraction of Impervious basin contiguous with stream channels.	PCTIM	0.01
6.	Maximum capacity of lower zone tension water in mm.	LZTWM	140 mm
7.	Maximum capacity upper zone tension water in (mm).	UZTWM	35 mm
8.	Upper zone free water drainage rate.	UZK	0.3
9.	Upper zone free water maximum (mm).	UZFWM	25 mm
10.	The percentage of percolation water which directly enters the lower zone zone free water without a prior claim by lower zone tension water.	PFREE	0.3
11.	Percentage of basin covered by streams, etc.	SARVA	0.01
12.	Loss along stream channel	SSOUT	0.00
13.	Ratio of unobserved to observed baseflow.	SIDE	0.00

14. Fraction of the basin which becomes impervious as all tension water requirement is met.	ADIMP	0.01
15. Fraction of lower zone free water not available for transpiration purpose.	RSERV	0.30
16. Percolation parameter	ZPERC	8.0
17. An exponent determining the rate of change of percolation (percolation parameter).	REXP	1.80

NOAA (1976) also described the way of estimating initial values of the parameters.

Gosain, A.K., & S. Chander (1985) applied NWSRFS model for realtime flood forecasting on River Jamuna at Kalanaur. The model was loaded on ICL 2960, the main frame system at the IIT Delhi. The initial estimate of the set of model parameters and their final values achieved after the end of a manual optimisation are given in Table 3, out of four years of available data, two years of data was used for the calibration.

The evaluation with respect to the numerical criteria shows that at Kalanaur, six hours ahead forecasts can be issued with adequate accuracy. For twelve hours forecast lead time, the forecasts start deteriorating. This deterioration is understandable as the basin lag which is the index of available forecast lead time (varies between nine to twelve hours for the catchment upto Kalanaur).

Table 3 : INITIAL ESTIMATE OF PARAMETERS AND THE FINAL ESTIMATES AFTER MANUAL OPTIMISATION (AFTER, Gosain, A.K. & CS. Chander, 1985).

PARAMETERS	INITIAL ESTIMATE	FINAL ESTIMATE
LZFPM	98.0 mm	98.0 mm
LZPK	0.0197	0.019
LZFSM	91.5 mm	90.0 mm
LZSK	0.12	0.119
PCTIM	0.009	0.009
LZTWM	60.0 mm	100.0 mm
UZTWM	40.0 mm	60.0 mm
UZFWM	30.0 mm	48.0 mm
UZK	0.50	0.30
PFREE	0.30	0.30
SSOUT	0.0	0.0
SARVA	0.10	0.10
ZPERC	12.0	15.0
REXP	1.8	2.00
SIDE	0.0	0.0
ADIMP	0.1	0.1
RSERV	0.30	0.30

2.2.8 Streamflow Synthesis and Reservoir Regulation Model (SSARR)

The Streamflow Synthesis and Reservoir Regulation (SSARR) model was developed initially to provide mathematical hydrological simulation for system analysis as required for planning, design and operation of water control works. The

The SSARR model was further developed for operatinal river forecasting and river management activities. Numerous river systerms in various countries have been modelled with SSARR.

2.2.8.1 Conceptual Design of SSARR Model

The SSARR model synthesizes the streamflow by evaluating snowmelt and rainfall. The model is comprised of three basic components.

a) A generalised watershed model for synthesizing runoff from snowmelt, rainfall, or a combination of the two, by seperating Watershed into relatively homogeneous hydrologic units.

b) A river system model for routing streamflows from upstream to downstream points through channel and lake storage.

c) A reservoir regulation model whereby reservoir outflow and contents may be analysed in accordance with predetermined or synthesized inflow and free flow or any of several modes of operation.

Rainfall data can be input at any number of stations in the basin. The part that runoff is divided into is the baseflow, subsurface or interflow and surface runoff. The division is based on indices and on the intensity of direct runoff. Each component is simply delayed according to different processes and all are then combined to produce the final subbasin in outflow hydrograph. This sub area runoff is then routed through stream channels and reservoirs to be combined with other sub-area hydrograph, all of which become part of output.

Routing through channels and reservoirs are accomplished by the same technique. This requires an assumption of short stream reaches and occasional allowances for backwater effects are necessary in the channel routing process. Streamflow are synthesized on the basis of rainfall and snowmelt runoff.

Rainfall-Runoff Relationships

The SSARR watershed model incorporates rainfall-runoff relationships and other factors in the hydrologic cycle to synthesize streamflow. The U.S. Army Engineer Division(1975) listed the following basic hydrologic elements which are evaluated individually for analysis of each relatively homogeneous watershed.

a. Net Basin Precipitation, determined as the time variables weighted mean period precipitation from observed point values for a watershed.

b. Soil Moisture, determined as a time variable index of runoff effectiveness to represent the variable conditions of soil moisture which determine, in part, the amount of precipitation which contributes to runoff.

c. Evapotranspiration loss, determined from potential evapotranspiration, expressed either as watershed mean monthly values of determined from daily evapotranspiration, expressed either as watershed mean monthly values or determined from daily evapotranspiration data.

d. Runoff excess, determined from net basin precipitation minus losses to evapotranspiration, deep percolation and soil-moisture replenishment. The residual provides water input to each of three zones of temporary storage delay to runoff.

e. Surface storage, representing the storage effect of the upper zones of soil mantle. This storage provides a time dealy of the surface component of runoff.

f. Subsurface storage, representing the storage effect of the middle aquifers, thus providing a time delay of the subsurface component of runoff.

g. Ground water storage, representing the storage effect of flow that reaches the underlying aquifers.

h. Flow seperation relationship, for computing that portion of the water excess which enters each storage zone.

A scnematic representation of the basin elements of the SSARR watershed model is presented in figure 18.

Soil Moisture Runoff Relationship

The rainfall input is divided into: (1) Runoff, (2) Soil Moisture increase, and (3) Evapotranspiration losses.

1) Runoff: The percent of total rainfall input available for runoff is found from empirically derived relationships if soil moisture index (SMI) versus runoff per cent (ROP). If desired, rainfall intensity may be included as a third variable in SMI-ROP relationship.

The total generated runoff for period (RGP) is computed as follows:

$$RGP = ROP * (WP_n \text{ or } WP_d)$$

Where,

RGP = Generated runoff for period, in inches

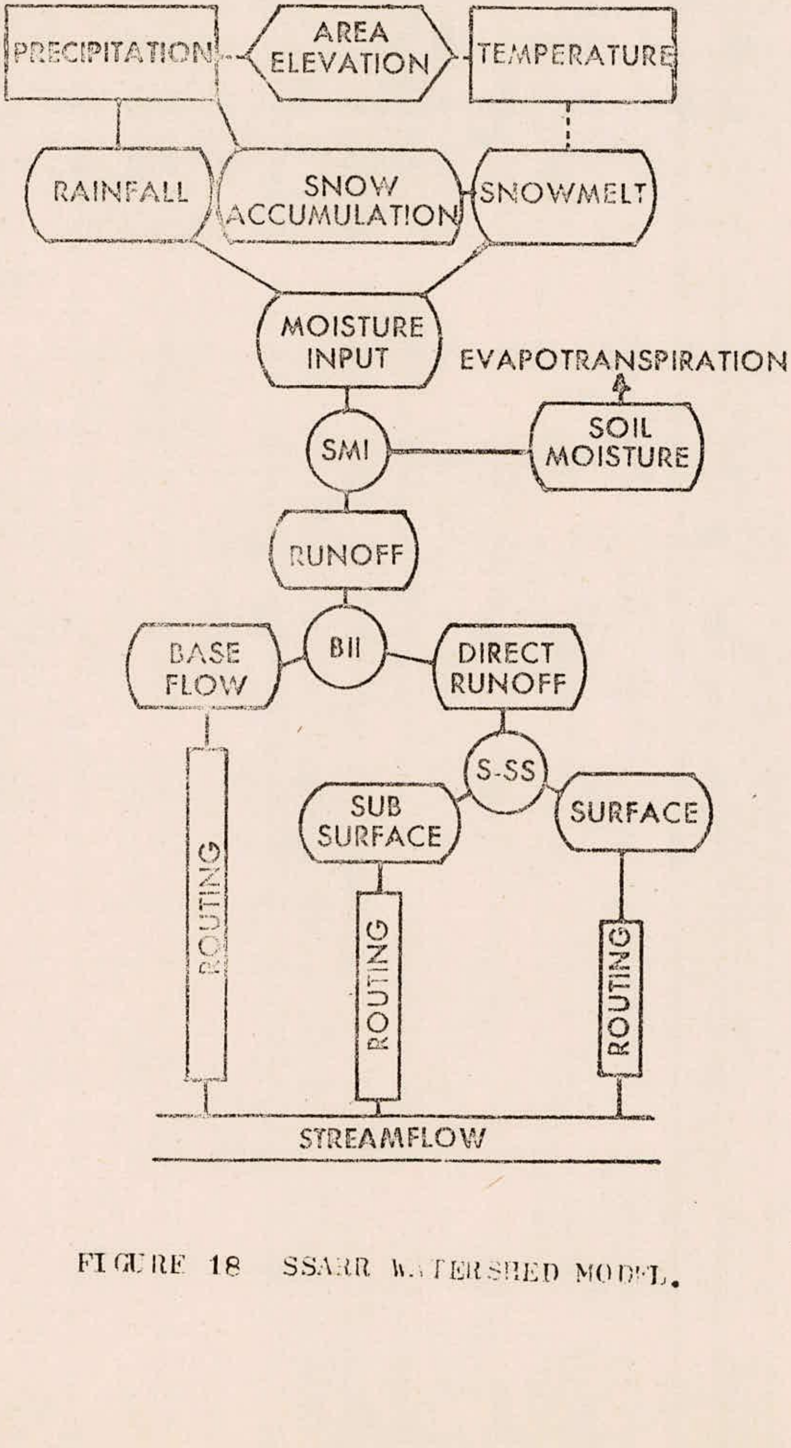


FIGURE 18 SSARR WATERSHED MODEL.

ROP = Runoff percent (from SMI table)

WP or WP = Weighted net precipitation or distributed net precipitation for the period respectively in inches.

2. Soil Moisture Evapotranspiration Relationships: The soil moisture index (SMI) is an indicator of relative soil wetness and is used to determine runoff. After every time period, SMI value is upgraded using the following equation:

$$SMI_2 = SMI_1 + (WP - RGP) - (\frac{PH}{24} * KE * ETI)$$

Where,

SMI_1 = Soil moisture index (in inches) at the beginning of period

SMI_2 = Soil moisture index (in inches) at the end of period

PH = Period length in hours

ETI = Evapotranspiration Index(in inches/day)

KE = A factor for reducing ETI on rainly day, specified to the computer in a table of KE vs. Precipitation rate in inches per day.

Daily estimates of ETI are desirable over monthly indices in arid and semi-arid basins where evapotranspiration losses are high in relation to precipitation input. Daily ETI are calculated from pan evaporation data as follows:

$$ETI_d = \frac{(ETI_1 * Et_1 + \ldots + ETI_n * Wt_n)}{n}$$

Where,

ETI_d = Weighted daily evapotranspiration index(inches)

ETI_1 .. ETI_n = Pan evaporation amounts (inches per day) for each station

$t_1 \ldots Wt_n$ = Weighting percentages for respective pan evaporation stations to approximate actual evapotranspiration

ETI_d can be distributed over eight periods per day as described for precipitation. The effect of rainfall on ETI are inherent to daily pan evaporation data. Therefore, SMI calculations used with daily ETI input is:

$$SMI_2 = SMI_1 + (WP - RGP) - DKE * ETI_d)$$

Where,

DKE = A factor for reducing daily ETI when soil moisture becomes depleted

In the present version of SSARR, daily ETI cannot be used with snowmelt calculations. Therefore, when snowmelt calculation are required. ETI input needs to be entered in table form as month versus ETI (inches per day).

Baseflow

From the generated runoff (RGP) the baseflow is seperated using a relationship of baseflow infiltration index (ETI) versus Base Flow Percent (BFP). This relationship is supplied to the computer in a tabular form. The baseflow infiltration index is computed for each period as follows:

$$ETI_2 = BTI_2 + (24 * RG - BTI_2) \left(\frac{PH}{TSBII * PH/2}\right)$$

Where,

BII_1 = Baseflow Infiltration Index (inches per 24 hours) at the beginning of period

BII_2 = Baseflow Infiltration Index (in inches per 24 hours) at the end or period

RG = RGP/PH = Runoff rate in inches per hour

TSBII = Time delay or time of a storage

The input to surface and subsurface runoff (RGS) is computed as follows:

$$RGS = RG (1.0 - BFP)$$

Surface-Sub-surface Flow Separation

A table of surface runoff input (RS) versus total input to subsurface runoff (RGS) is specified to the model. Separation commonly used is based on the following assumption:

a. The minimum surface component (RS) is 10% of total generated runoff(RGS)

b. The subsurface flow component reaches a maximum(KSS) and remains constant for input dates (RGS) above 200% of KSS

c. Values commonly used are determined from following equations:

$$RS = (0.1 + 0.2 (RGS/KSS) * RGS$$

and if,

$$RS > KSS, RSS = KSS$$

Where,

RS = Surface component rate input (in/hr.)

RSS = Sub-surface component input rate (in/hr.)

RGS = Total input rate to surface and sub-surface component (in/hr.)

KSS = Maximum sub-surface input rate (in/hr.)

2.2.8.2 Runoff from Snowmelt

Snowmelt is determined on the basis of precipitation depth, elevation, air and dew point temperatures, albedo, radiation and wind speed. SSARR model offers the user either (i) the temperature indix method, or (ii) the generalised snow-melt equation to compute snowmelt from the basin snowpack. The basin snowpack in turn can be defined by either: (1)the elevation band, or (2) the snow cover depletion curve and its three option. Data availability, watershed characteristics are user requirements should govern which options are used.

Temperature Index approach is more widely used because of lack of energy budget data on a real time basis. Precipitation aire temperature and melt rate specifications are essentially the only data input required.

The temperature index method is commonly used for daily forecast operations whereas the more detailed energy budget approach of the generalised snowmelt equation is more appropriate for design flood derivations.

Water shed snowmelt option

In addition to two methods of calculating snowmelt, two options of evaluating the snowpack characteristics in a watershed are also available with SSARR. The basic snowpack can be defined by (1) snow cover depletion curve, and (2) snow bank option.

(1) Snow Cover depletion:

This option describes the snowpack covered area-runoff relationships of a watershed utilising a snow cover depletion function. Studies indicated that in mountainous areas, snow-cover depletion during the active snowmelt period can be expressed as a function of accumulated generated runoff in percent of seasonal total. The general shape of curve relating to snow cover to generated runoff are fairly uniform for different watersheds and from year to year. The model computes the snow cover depletion in accordance with the specified relationship. A general shape as described by U.S. Army Corps of Engineers (1960) can be expressed as:

$$\frac{SCA}{100} = 1.0 - \left(\frac{Q_{gen}}{1000}\right)^{n}$$

where,

SCA = Snow covered area in per cent of total watershed area

Q_{gen} = Accumulated generated runoff from snowmelt in percent of seasonal total

n = Parameter expressing characteristics of snow cover depletion for a watershed.

In mountainous watersheds, snow covered and snow free areas are differentiated by a 'snow line' which usually follows an elevation contour. Snowmelt occurs on that portion of the basin lying above the snow line and below the melting level.

Two programme options namely signal watershed and split watershed are available within the snow cover depletion option for analysis of runoff from rainfall as related to snow cover. In single watershed option, a single index of all watershed parameters (SMI, BII, etc.) is mained for both snow covered and snow free areas, whereas, in split watershed the snow covered and snowfree areas are treated as two separate watersheds, each with its own characteristics and parameters.

(2) Snow and Option: This option provides the capability to subdivide a watershed into elevation bands each of which are treated seperately with respect to snow accumulation and melt.

The basic difference between snow bank and snow cover depletion (SOD) options is that the band option maintains an inventory of snow water equivalent on each elevation band, whereas, the SCD only deplets the snow covered areas a function of percent seasonal accumulated runoff. Thus the band option is more quantitative.

2.2.8.3 Data Requirement

Input data needed for operation of the model include:

a. Non variable characteristics data, which describe physical features such as area, reservoir storage capacity, and watershed characteristics that affect runoff.

b. Initial condition data, for specifying current conditions of all watershed runoff indexes, flow in each increment of each channel reach and initial reservoir of lake elevations and outflows.

c. Time variable data, which inclue physical data expressed as time series, for example, precipitation data, air temperatures, and thermal budget data used for snowmelt determinations. Streamflow data, reservoir regulation data and other hydrometeorological elements.

d. Miscellaneous job control and time control data, which specify such items as computation period routing intervals, and special computer instructions to control plots, prints and other input-output alternations.

2.2.8.4 Application of SSARR Model

U.S. Army Engineer Division (1975) applied the model to watersheds, namely South Yamhill Basin and Bird Creek Basin, with different climatic and hydrologic characteristics. Snow accumulation and melt were negligible on these two watersheds. South Yamhill River Basin and a mild humid climate whereas Bird Creak Basin had Semi-arid climate.

High intensity rainfall is infrequent over South Yamhill Basin, so that a single soil Moisture Index (SMI) Runoff Percent (ROP) relationship was used. However, for Bird Creak Basic, the three variable SMI relationship was used to accounht for rainfall intensity effects on runoff.

In case of South Yamhill Basin, initially 'high effect' parameters such as precipitation weighting factors and SMI-ROP relationships were adjusted until computed volumes approximated those observed. The remaining parameters, BII, surface-sub-surface relationships, basin routing phases and time of storage per phase, and TSBII were then adjusted to to improve the hydrolograph shape and timing response.

The willamette Basin Snow Laboratory (WBSL) was selected by U.S. Army Engineer Division (1975) to illustrate the use of the snow cover depletion option and temperature index method on a single watershed (1.1.5 sq. miles).

The SSARR model was also applied to Tanana river basin to derive probable miximum and standard project floods for the fair banks areas. The generalised snowmelt equation was used to determine snowmelt under maximised conditions which could reasonably be expected to occur. The entire Tanana basin was assumed to be 100 per cent snow covered, with snow water equivalent increasing with elevation. Because of its size (over 25,000 sq. miles) and diversity, the basin was sub-divided and the individual watersheds were modelled where adequate data existed.

Chisana watershed (3280 sq. miles) which was a part of Tanana river basin was suited for the use of snow band option since during the spring runoff season the lower elevation had little or no snow, whereas, higher elevation had considerable snow depth. The watershed was subdivided into five elevation bands, which, when connected to summing points, represented outlflow from entire watershed.

Each band was treated as a separate basin with its own characteristics, area-elevation relationship and initial condition specifications.Each band was 100% snow covered with higher water equivalents designed for the high elevation bands. Snowmelt coefficients that were required for generalised snowmelt equation were maximised for standard project floods (SPF) and Probable Maximum Floods (PMF). These coefficients and their respective values for each snow band are listed in table 4.

TABLE : 4

SNOWMELT COEFFICIENTS USED FOR THE CHISANA BASIN

(REINTRODUCED FROM U.S. ARMY ENGINEER DIVISION, 1975)

Elevation band	Percent of total area	Short wave melt coeff. 'K'	Convection condensation melt factor K	Average forest canoopy cover F
4694(Glacier)	10	0.9	0.6	0.01
4695	15	0.9	0.6	0.20
4696	25	0.9	0.6	0.30
4697	25	0.9	0.6	0.40
4698	25	0.9	0.6	0.50

SSARR model was applied for the first time in India (Rajagopalan,. K.S., 1985) for obtaining the design hydrograph at Navagam where a high dam was proposed to be constructed. The study was completed through the following four stages.

Stage 1: Watershed calibration by dividing the basin into 20 sub-basins and determining the parameter utilising several years of observed watershed hydrometeorological data on the sub-basins.

Stage 2: Channel calibration by estimating the routing parameters using discharge observations at gauging stations on the main-stream of Narmada.

Stage 3: Inputting design storms on the calibrated model to obtain outflows from the sub-basins, and

Stage 4: Combining and routing the flows down the mainstream to obtain hydrographs at any desired point on the mainstream.

Because of paucity of continuous data from all sub-basins and for several years, the calibration was restricted to the number of years for which data were available. SMI-RCF, EII-BEP, SS-S, SMI-DKE relations, and number of phases and time of storage in each phase was calibrated and tabulated for several sub-basins.

Typical observed and synthesized hydrographs at selected locations of the river, viz. Jamatara, Sher, and Chota Tawa were plotted which were found closer to one another in terms of the volume of water under the curves, peak values, and time of occurence of the peaks.

Calibration of routing parameters was carried out and the calibrated parameters alongwith the number of sub-reaches were tabulated. Three day storm of 28,29 and 30 August, 1973, followed by a 2 day storm of 6 and 7 Sept. 1970 were tried. Storm maximisation factor of 1.35 was recommended.

These storms as were used as an input to the model assuming the calibrated parameters for the sub-basins and channel routing parameters to be valied. the sub-basins and channel routing parameters to be valied. The sub-basin outflows were routed down the mainstream of Narmada to obtain the peak flow hydrograph at Sardar Sarovar dam site. The PMF hydrograph was reproduced. The hydrograph showed a peak of 129000 cumec.

Mukhopadhyay (1984) applied the SSARR model on Yamuna catchment above Delhi. Daily rainfall data and gauge data for 1976 and 1977 were utilized for initial calibration of the model parameters by trial and error method. CDS-Cyber Computer was utilised for this purpose. A three variable relationship of rainfall intensity-Soil moisture Index (SMI)-Runoff percent (ROP) was used to simulate catchment and routing characteristics curve.

Mukhopadhyay (1984) stated that even after loading successfully the the programme could not run completely. There were still some errors in the programme. ENCODE, DECODE statements and DICTG/DICTP subroutines were being debugged to get the test results.

2.2.9 LEAVSLEY Model

Leavesley (1973) developed a mountain watershed model at Colorade State University for the prediction of water yield from forested wild and watersheds of Rocky mountain region. Snowpack accumulation and melt process alongwith the snowmelt runoff process have been the areas of major consideration in model formulation. Climatic; physiography and vegetation factors affect these processes, and the model has been developed to account for local and regional variation of these processes.

2.2.9.1 Model Structure

The model is a deterministic physical process hydrological model and uses daily climatic variables of temperatures, precipitation and solar radiation. A watershed needs to be subdivided into sub-units on the basis of measurable climatic physiographic, vegetative and soil features. Slope, aspect, vegetation type, soil type and snow distribution are the five primary features used in the sub-division process. The resulting sub-units within the watershed are each considered homegeneous with respect to its hydrologic response, and, thus termed as 'hydrologic response units' or 'HRUs' for short. A daily water balance is considered for each HRU and sum of response of all HRUs weighted on a contributing area basis, produce the overall response or water yield of the entire watershed.

There are as many 74 initialization and HRU variables, 9 Daily input variables, 12 optimization variables and 10 model parameters. The 10 model parameters are associated with physical watershed characteristics but are less easily measured.

The watershed system developed in this model can be visualised as a series of linear and non-linear reservoir whose outputs combine to produce total system response in terms of mean daily stream flow. The upper soil zone rfeservoirs are linear one. Each HRU has its own upper soil zone reservoir, however, the sub-surface and ground water reservoirs may be associated with one or several HRUs. The flow chart of the model operation is shown in fig. 19.

The model structure can be divided into three general areas of emphasis with regard to hydrologic cycle. These are climatic components, the land phase component and the snow component.

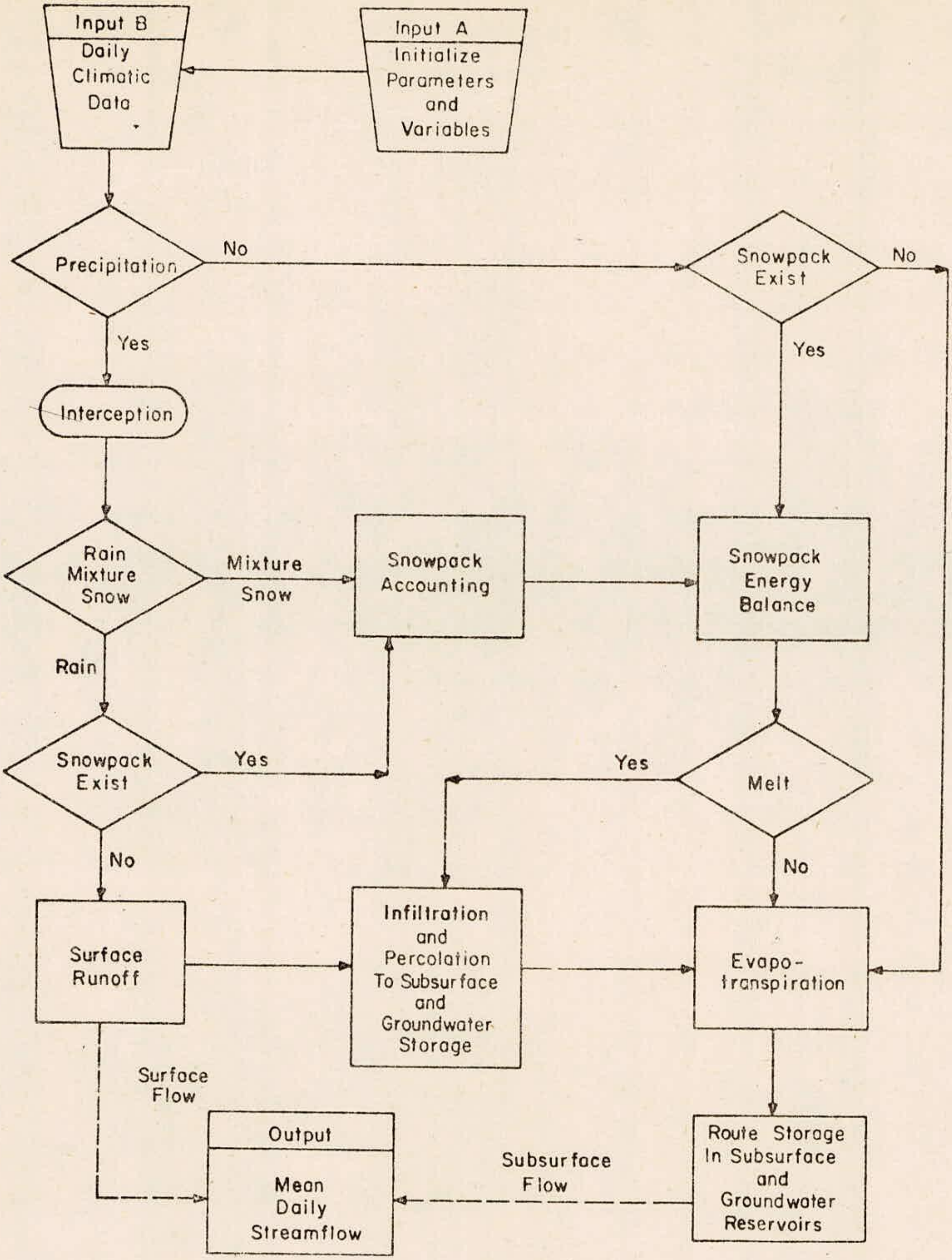


Figure 19 Flowchart of the model operation.

Climatic Component

These are the functions and sub-routine which handle and adjust the input climatic data to better define the daily climate of each HRU.

The variation of precipitation with season, storm type, elevation and inclination of land slope is accounted using a correction factor for rain and for snow as input for each HRU. The form of precipitation viz. rain, snow, or a maxture of rain and snow is determined for each HRU as a function of its maximum and minimum temperatures and the base temperature parameter(BST). BST is that air temperature on an HRU which differentiates the precipitation forms of snow and rain.

Land Phase Component

These components are those function and sub-routines which simulate the effects and response of the vegetation soil and geology of an HRU and their associated interactions.

Interception is computed using vegetation type, canopy density with precipitation type and form. For infiltration and surface runoff, contributing area concept is used to calculate the volume of surface runoff from rainfall events which occur on snowfree HRUs. For snowmelt events, the assumption is made that infiltration is not limiting and thus no surface runoff occurs when soil water stored in upper soil zone (SMAV) is less than maximum available water storage capacity in upper soil zone (SMAX). When SMAV equals SMAX, all snowmelt in excess of SMAX and less than the maximum daily infiltration parameter (SRX) is added to the sub-surface reservoir storage (RES) for routing as sub-surface flow.

The time of the year in which transpiration occurs are specified as a period; months between ITST and itnd which are input variables specifying the starting and ending months respectively of the transpiration period. Leavesley (1973) used April and November as ITST and ITND values respectively. Transpiration begins on the first day of ITST for all snow free HRUs but may be delayed to some later data for snow covered HRUs, by using temperature index parameter (ITST).

The upper soil zone of each HRU is classified according to its texture as either a sand, loam or clay for the purpose of soil water accounting. Based on soil texture type (Sand, Loam or Clay); and ratio of SMAV and SMAx, ratio of actual ET (AET) and potential ET (PET) have been fixed which are used to calculate AET of various HRUs.

Snow Components

Snow components are those functions which simulate the initiation, accumulation and depletion of snowpack on each HRU. An energy balance is computed daily and the resulting gain or loss of heat energy is used to modify snowpack condition.

The general energy balance equation for a snowpack in this model is expressed as:

$$Q_q = Q_{swn} + Q_{ewn} + Q_p$$

where all variables are expressed in calories of heat and:

Q_q = Change in heat storage of snowpack

Q_{swn} = net shorftwave solar radiation absorbed by the snowpack.

Q_{ewn} = net longwave radiation exchange between the snowpack and its environment.

Q_p = heat content of precipitation

The model computes Q_{swn}, Q_{ewn} and Q_p using values of solar radiation, albedo, transmission coefficients, emissivity, Temperature etc. which in turn are computed/ modified based non various factors affecting these parameters e.g. cover density, stage of snowpack (whether accumulation or melting) area of snow-surface etc.

2.2.10 HBV Model

A hydrological forecasting system was developed at the Swedish Mateorological and Hydrological Institute (SMHI) Norrkoping, Sweden. The system was based on HBV-model which was developed at SMHI by Bergstorm (1976).

2.2.10.1 Model Capabilities

The HBV model is a conceptual model for continuous calculation of runoff. Input data are observations of precipitation, air temperature and estimate of potential evapotranspiration. The time scale is one day. Monthly averages of evaporation values may be used. Air temperature data is needed for snow accumulation and ablation calculations only and can be omitted in snowfree areas.

The model consists of sub-routines for snow accumulation and melt, a soil moisture accounting procedure, routines for runoff generation and finally a sample routine procedure.

The basin need to be subdivided into elevation zones if it is of considerable elevation zones. The subdivision is made for the snow and soil moisture routines. Each elevation zone again need to be divided into different vegetation zones (forested and unforested areas). A schematic sketch of the HBV model is shown in figure 20.

It is also possible to run the model separately for several subbasins and then add the contribution from all sub-basins.

2.2.10.2 Snow Routine

A simple degree day relation is the basis for snow routine. A threshold temperature (TT) which is close to (°C) is used in this routine to define the temperature above which snowmelt is occuring:

$$\text{Snowmelt} = (T - TT) * \text{CFMAX}$$

Where,

T = temperature in the elevation zone

CFMAX = the melting factor, and

TT = threshold temperature

Threshold temperature is also used as a basis to identify whether precipitation is rain or snow. a liquid water holding capacity of snow, normally in the

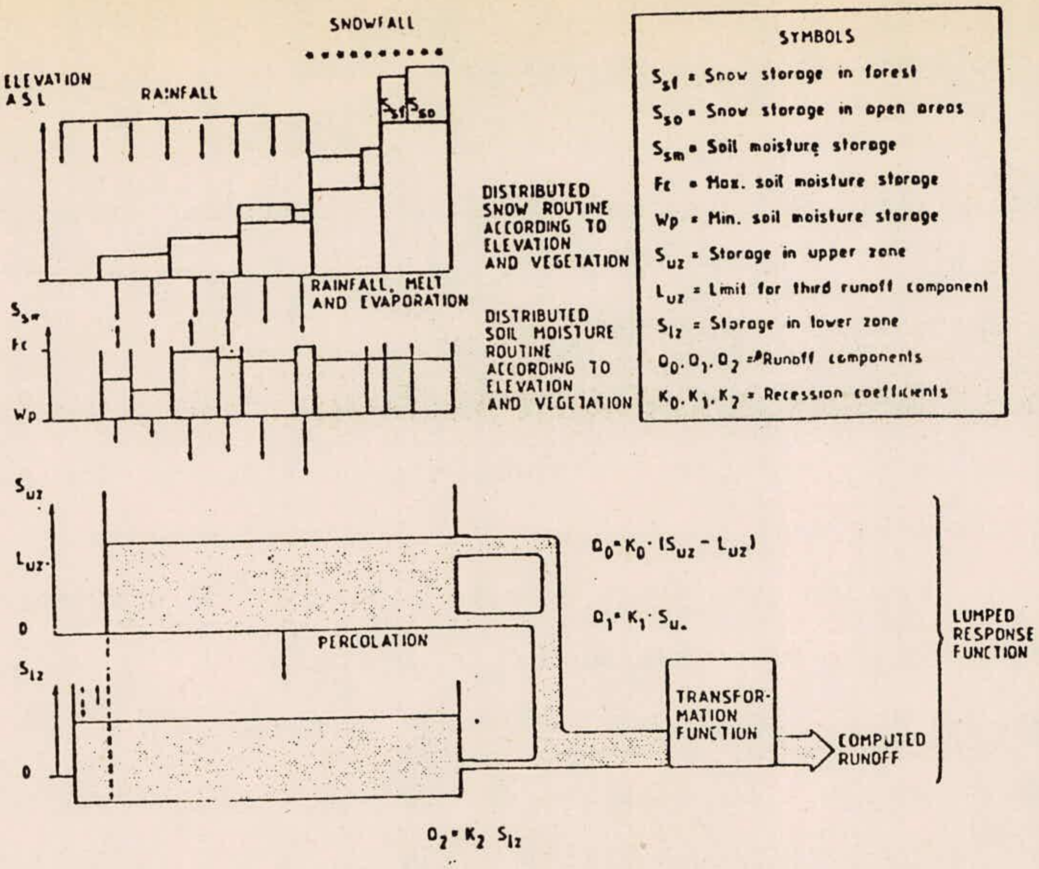


FIGURE 20 SCHEMATIC PRESENTATION OF THE HBV CONCEPTUAL RUNOFF MODEL (AFTER, BERGSTROM, ETAL, 1985).

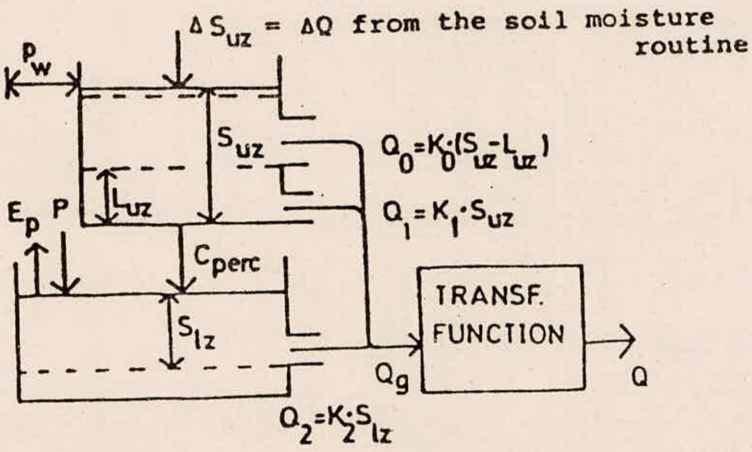


FIGURE 21 THE RESPONSE FUNCTION OF THE HBV-6 SUB MODEL.

order of 10% of the computed snowwater equivalent needs to be exceeded before drainage from the snowpack starts.

2.2.10.3 Soil Moisture Accounting Routine

This routine is the main part of controlling runoff formation. The routine is based on three parameters, L_p and R_c. β controls the contribution to the response function ($\Delta Q/\Delta P$) or increase in soil moisture storage $(1- Q/\Delta P)$ from each millimeter of rainfall or snowmelt, L_p is a soil moisture values above which evapotranspiration reaches its potential value, and F_c is the maximum soil moisture storage in the model. In order to avoid the problems with non-linearity the soil moisture routine is fed by snowmelt and rainfall.

2.2.10.4 Runoff Generation Routine

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part (Pw) which represents lakes, rivers, and other wet areas. The function consists of one upper and one lower quasi-linear reservoir as shown in fig. 21. These are the origin of quick and slow runoff components of the hydrograph.

The upper zone as interpreted by Bergstorm et al (1985) is as follow : If the yield from the soil exceeds a certain percolation capacity (operc), the winter will start to drain through more superficial channels and thus reach the river and streams with a higher drainage coefficient (K_1). At a storage in the upper zone exceeding Luz, even more rapid drainage according to K_o will start. The lower zone on the other hand represents the total groundwater storage of the catchment contributing to the baseflow.

The system has two ways to make forecasts. The first method is to enter data from a meteorological forecast. Such a forecast as a rule only cover a few days. the other type of forecast is a long range forecase wherein meteorological data from the corresponding dates during the preceeding years are used as input.

As expressed by Bergstrom et al (1985), even after completion of calibration work for a basin, some discrepancies may appear while running the model upto the data of forecast. So, the corrections need to be considered in some cases.

2.2.10.5 Application of HBV-6 Model to Upper Narmada Basin

Bergstorm (1985) applied the HBV-6 model to Upper Narmada Basin (Area = 16576 Km^2). The basin was subdivided into five subbasins. The division of the basin into subbasin helps this version of the model to account for variation of rainfall cover the basin. The HBV-6 model was subdivided into sub-models to make it possible to calibrate the submodel as well as the total model, if the data base is appropriate. Due to lacking runoff data this was not possible in the application of the model to Upper Narmada catchment.

In phase-II of the project, the number of precipitation stations was increased from 5 to 13, out of 9 years data available, it was decided to use 5 for calibration of the model (1963-1967) and the last 4 for the idemendent test of the model performance (1973-76).

The model was calibrated by a manual trial and error procedure, combined with mapping of the topography of the response surface of error function. Three main criteria viz (i) visual inspection of computed and observed hydrographs, (2) A continuous plot of the accumulated difference between the computed and observed hydrographs, and (3) of the explained variance around the mean, was used as the criteria of fit to finalise the model.

The calibration of the model was finalised within some 15 computer runs. The final values of the explained variance around the mean (R^2) was 0.79 which was a compromise between a high R^2-value and a low volume error.

The model was applied on the idenpendent data sequence period (1973-76) after excluding the year 1973. The year 1973 was excluded because the double mass plotting showed that the independent period contined more missing data than calibration period. The value of R^2 results from the test period (1974-76) was found to be 0.81.

In order to verify whether the distributed approach or merely the better data base are the cause of the increased performance of the model from Phase-I to Phase-II of the project, a lumped model structure was finally run. The parameter values were taken as averages of those found during calibration of the distributed model. The results were found in a very much close agreement with the distributed model as shown in table 5.

TABLE 5

Comparison expressed as R^2 values between the distributed & lumped model approach (re-produced from Bergstrom, 1985).

Model type	Calibrated period	Verification period
Distributed model	0.79	0.81
Lumped model	0.74	0.83

Bergstrom (1985) concluded that there was no significant improvement when distributed approach was used in Narmada catchment.

An attempt was also made by Bergstrem (1985) to transform the model into a set of nomograms for day-to-day simulation of runoff. The set of nomograms was constructed on the basis of synthetic rainfall records, which were run through the lumped version of the model with variable initial conditions. Bergstrem (1985) presented the set of nomograms and also the procedures of calculating runoff.

2.2.11 WATBAL

Knudsen et al (1986) described a semi-distributed, physically based hydrological modelling system, WATBAL, which accounted for the entire land phase of the hydrological cycle. As compared to two alternative hydrological model types, i.e. the traditional lumped conceptual rainfall-runoff models (STANDARD model type) and the complex, fully distributed, physically based model (SHE model type), WATBAL represented an intermediate approach.

2.2.11.1 Model Capabilities

The model allows full utilization of data on the spatial and temporal variations for rainfall, evaporation, topography, vegetation and soil types. The principal structure of WATBAL as shown in Fig. 22 illustrates the distrubuted approach for representing soil moisture storage. Figure shows that the model allows the catchment to be divided into various topographic zones. For a catchment encompassing different topographic features WATBAL recognizes that rain falling on upland areas is routed through hilslope zones before entering the stream as overland flow, inter flow or as base flow. Overland flows generated on upland areas may infiltrate in down slope areas if a sufficient capacity exists and be stored or percolate to a sub-surface storage. From here the water may contribute to the ground water recharge or move laterally as interflow towards the stream.

The individual processes included in WATBAL for representing the land phase of hydrologic cycle is shown in fig. 23. The model operates with five inter related storages, i.e. interception, surface detension, soil moisture sub-surface and ground water storage. Individual interception and soil moisture storages are operated for each hydrological unit, whereas, seperate surface and sub-surface storages rages only are used for each topographic zone as defined by the user.

Interception storages:

WATBAL uses a time varying leaf area index for each type of vegetation to account for 'interception storage', whereby precipitation is retained on leaves, branches, and stems of vegetation. From this storage, water is assumed to be subjected to evapotranspiration at the potential rate while excess input is transferred to surface storage.

Infiltration process:

For the representation of 'infiltration' process WATBAL uses a Green Ampt model with its later modifications introduced by Mein and Larson (1971, 1973) to describe the prepending and postponding stages of the infiltration as follows:

$$f = I, \quad F = It \quad F_p \quad \text{(Preponding)}$$

$$f = I, \quad F = F_p \frac{S}{(I/K_s)-1} \quad \text{(at ponding)}$$

$$f = K_s\left(1 + \frac{S}{F}\right), \quad F = f \; dt \quad F_p \text{(post ponding)}$$

where,

I = Rainfall intensity (mm/h)

f = Infiltration rate (mm/h)

F = Infiltrated volume (mm)

F_p = Infiltrated vol. at time of surface ponding

Ω = Soil moisture deficit (Vol./Vol.)

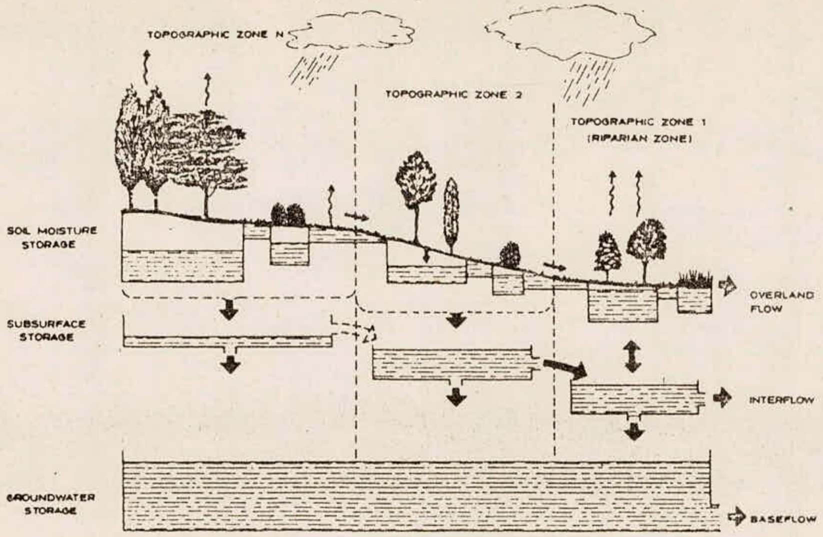
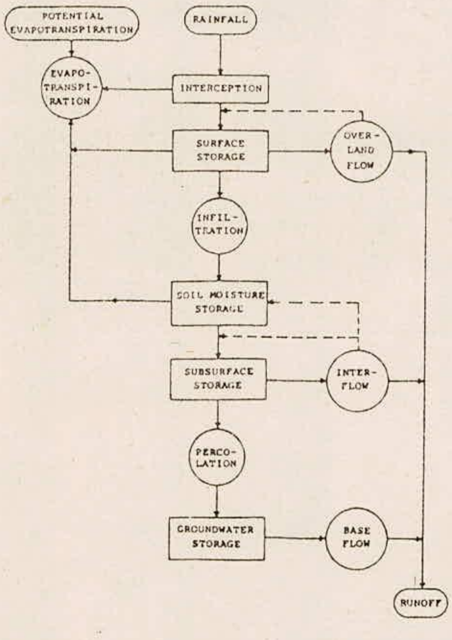


FIGURE 22 PRINCIPAL STRUCTURE OF WATBAL.



GURE 23 FLOW CHART OF HYDROLOGICAL SUB PROCESSES IN WATBAL.

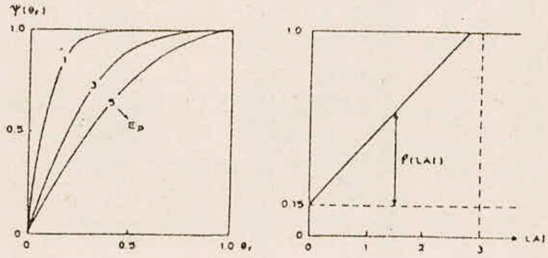


FIGURE 24 FUNCTION USED FOR DETERMINING THE TRANSPIRATION COMPONENT.

S = Suction at wetting front (mm)

K_s = Hydraulic conductivity at field saturation (mm/hr.)

The approach for overland flow component, similar to that of well know stanford watershed model has been used in WATBAL.

Soil Moisture Storage:

Soil moisture is represented by a two box approach in which case the depth of upper box currently follows the root depth. soil moisture is calculated currently taking calculated infiltration, actual evapotranspiration, and percolation into account.

Evapotranspiration :

Water held in interception, surface detension and soil moisture storages are currently subjected to 'evapotranspiration'. It is assumed that water is removed at the potential rate from the upper two storages while a limited leaf area and/or limited availability of moisture in general well restrict evapotranspiration from the root zone. The transpiration component is derived as follows:

$$E_t = E_p \phi (Lai) \psi (Q_r)$$

where,

E_t = Actual evapotranspiration

E_p = Potential evapotranspiration

L_{ai} = Leaf area index

Q_r = Relative moisture content (Q-Qwp)/(QFc-Qwp)

Q = Actual moisture content

Q_{wp}= Moisture content at wilting point

Q_{Fc}= Moisture content at field capacity

and $\emptyset$, ψ , and two functions as illustrated in fig. 24.

Sub-surface and Ground Water storage:

Usually very limited information is available for the saturated zone. As such a traditional conceptual approach was used for representing the storage and routing of water below root zone. both,. the 'sub-surface' and 'ground water' storages were represented by a linear reservoir, the ground water reservoir was a simple one with one outlet, while two outlets were included in every sub-surface storage to allow a diversion of flow into lateral interflow and ground water recharge.

2.2.11.2 Data Requirement

The requirement for parametric and exogenous data for an application of WATBAL depend on the particular model of operation chosen by the user. With respect of exogenous data, time series of rainfall on at least a daily basis and monthly potential evapotranspiration DATA is required. If a detailed representation of infiltration and overland flow processes is selected, more frequent observations of rainfall are required or some estimate on the storm duration in case the model is used for flood prediction.

With respect to model parameters, Table 6, provides a list of the necessary data to operate the model in its most advanced form.

TABLE 6

MODEL PARAMETERS FOR MOST ADVANCED MODE OF OPERATION OF WATBAL (REPRODUCED FROM KNUDSEN, ET AL 1986)

TOPOGRAPHY	Within each Topographic Zone
	* length of flow plane
	* Slope
	* Manning number
	* depression storage
VEGETATION	For each type of vegetation
	* leaf area index (time varying)
	* root depth (time varying)
SOIL TYPES	For each texture class
	* Wilting point
	* field capacity
	* total porosity
	* saturated conductivity
	* average suction
SUB-SURFACE REGIME	For each topographic zone
	* threshold value
	* two time constraint (interflow/percolation outlets)
	Ground Water storage
	* Ground Water area relative to catchment area

* time constant of baseflow outlets

2.2.12 Physically-based IH, Distributed Models

Two physically based, distributed models are being developed at IH, Danish, namely the Institute of Hydrology Distributed Model (IHDM) and System Hydrologique European (SHE). Although the models are based on the same process equations, the methods of simplification of the geometry of a Catchment used for each model are different.

2.2.12.1 Institute of Hydrology Distributed Model (IHDM)

The IHDM is based on a division of the catchment into hill-slope and channel elements. A subsurface hillslope component based on a two dimensional finite difference solution of the equation for flow in porous media has been implemented, with a component to allow for evapotranspiration losses distributed over the root zone. Procedures have been incorporated to allow the area contributing to surface flow to extent and contract dynamically on the hillside. The hillslope flow process components have also been coupled to routine that allow distributed predictions of precipitation, snowmelt and evapotranspiration rates by linking each point in the catchment to a zone of different topography and vegetation. The zones may well vary in elevation range, slope angle, aspect, and vegetation type and each zone may represent points on a number of spatially disjointed hillslopes of similar characteristics.

2.2.12.2 Applications

In 1982-83 this model has been run on data from the plynlimon catchments and work has begun on the cam catchment.

2.2.13 System Hydrologique European (SHE)

The SHE model has been developed as a joint collaboration effort of the Danish Hydraulic Institute (DHI), SOGREAH and Institute of Hydrology, Wallingford, UK. SHE is a deterministic distributed physically based modelling system. Based on numerical simulation of the equations of flow and mass conservation, SHE overcomes the basic weakness of many existing catchment models and provides a reliable physical approach for predicting effect of land use changes on the hydrologic regime.

The model has been developed from partial differential equations describing the processes of overland and channel flow, unsaturated and saturated subsurface flow solved by finite difference methods. The model is completed by the process of snowmelt, interception and evapotranspiration. In SHE the one-dimensional unsaturated flow columns of variable depth link a two dimensional groundwater flow component. The catchment is represented in the horizontal plane by rectangular grid squares, and the river system is supposed to run along the boundaries of grid squares.

The model structure is shown in figure 25. The deterministic distributed description of the hydrologic processes in SHE is based on the equation of flow for water moving over surfaces through porous media. The partial differential equations are solved by finite difference methods.

The individual submodels can be used independently or degenerate to simpler versions, depending on the data availability and requirements of a given application.

The SHE Computer Program is structural in five separate process oriented components. The five processes include

- Interception/evapotranspiration
- Overland and channel flow
- Unsaturated flow
- Snow Melt

The FRAME organises the modular structure to ensure flexibility in the description of individual physical processes. Data flow between various components is shown in figure 26.

The Interception-Evapotranspiration Model

The model determines the total evapotranspiration and net rainfall from meteorological input data. The interception description is based on an accounting procedure for canopy storage, potential and actual evapotranspiration rates are computed by the penman Morteith equation.

$$Ea = \frac{\Delta Rn + p \frac{C_p \; \delta_e}{\delta ra}}{\lambda/D + r(1+rs/ra)}$$

where

Ea is the actual evapotranspiration on rate (mm/a)

Rn is the net radiation minus the energy flux into the ground (W/m^2)

Δ is the shape of the specific humidity/temperature ($Mb/^{o}C$)

ρ is the density of air (Kg/m^3)

C_p is the specific heat of air at constant air pressure ($J/Kg/^{o}C$)

δe is vapour procure deficit of the air (mb) ra is the aerodynamic resistance to water vapour transport (s/m)

λ is the latent heat of vaporisation of water (J/Kg)

rs is the canopy resistance to water transport (S/m)

γr is the psychrometic constant ($mb/^{o}C$)

The parameter r_s can be interpreted as a bulk stomatel resistance of vapour flow. The evapotranspiration component interacts with the root zone (fig. 27) which is the upper portion of the unsaturated flow component. Net rainfall, transpiration and soil evaporation rates are required by unsaturated flow component which in turn provides information for the evapotranspiration component on soil moisture conditions in the root zone. The total actual evapotranspiration calculated for each grid square

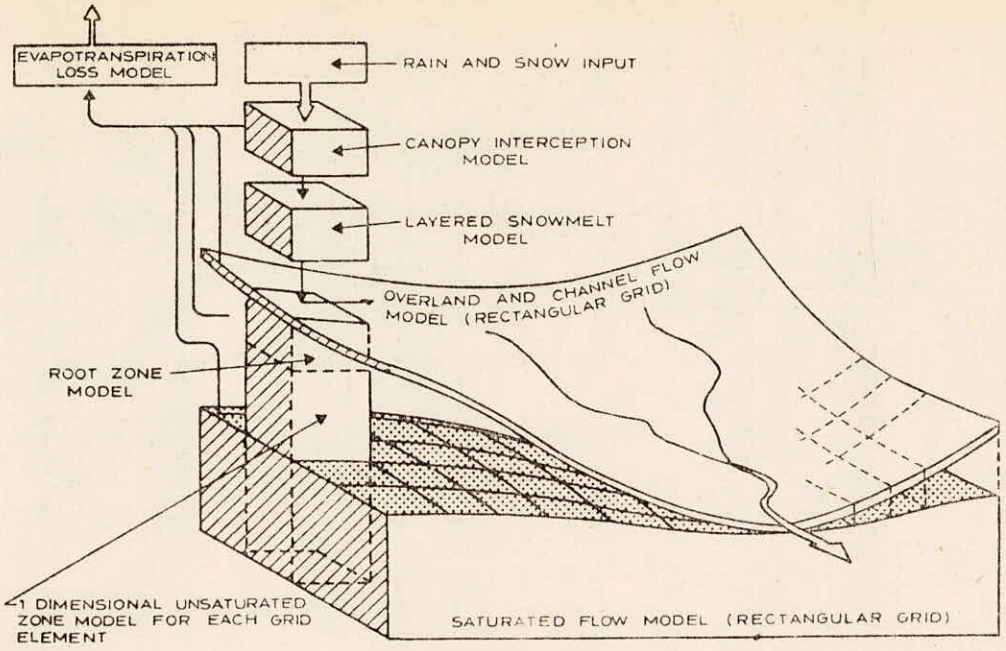


FIGURE 25 STRUCTURE OF THE EUROPEAN HYDROLOGIC SYSTEM.

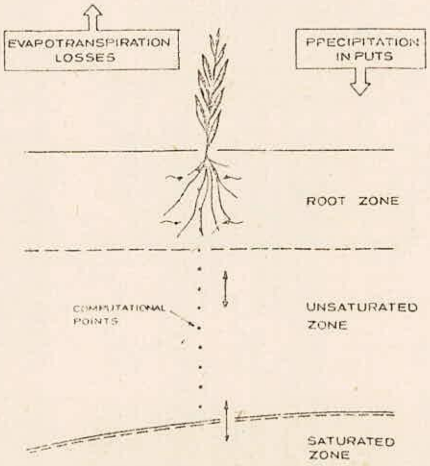


FIGURE 27 THE UNSATURATED ZONE FLOW.

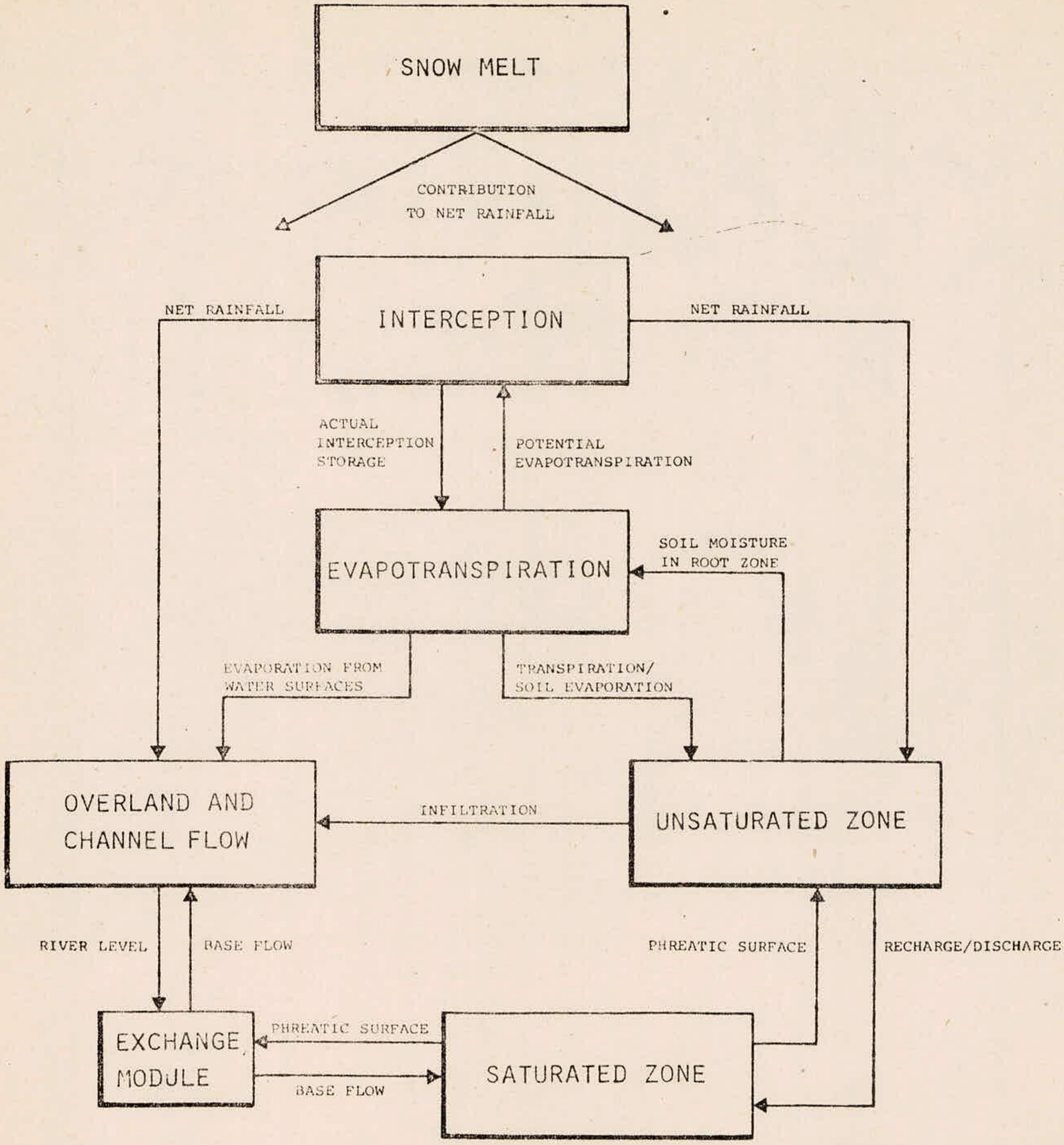


FIGURE 26 DATA FLOW BETWEEN COMPONENTS.

depends on wetness of the canopy and the degree of ground coverage by canopy.

Unsaturated Flow

This component of the model describes the processes of flow in the root zone and underlying unsaturated zone (fig.) which includes the processes of infiltration, root extraction and percolation to ground water recharge. The flow through several layers of the unsaturated zone is modelled in the SHE by Richard 's equation.

$$C \frac{\partial v}{\partial t} = \frac{\partial}{\partial z} \left(\frac{K \partial \psi}{\partial z} \right) + \frac{\partial k}{\partial z} - S$$

where,

ψ is the pressure head
t is the time variable
z is the vertical space corrdinate
C is soil water capacity
Q is volumetric moisture content
K is hydraulic conductivity
S is a source/sink term

Richard 's equation is solved numerically by an implicity finits difference scheme. The infiltration rate into the soil is determined by the upper boundary condition. The lower boundary is usually the phreatic surface level.

Overland flow and Channel flow

The overland flow and channel flow wer described by equations of unsteady, free surface flow based on physical principles of conservation of mass and momentum.

The overland flow process was described by the hydro-dynamic equations of continuity and momentum to a flow element in the dimensions.

$$\frac{\partial h}{\partial t} = \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q$$

$$\frac{\partial h}{\partial x} = S_{ox} - S_{fx}$$

$$\frac{\partial h}{\partial y} = S_{oy} - S_{fy}$$

where

h	is the local water depth
t	is a time variable
x,y	are horizontal cahtesian coordinates
u,v	are flow velocities in two directions
q	is net precipitation after accounting for infiltration.

S_{ox}, S_{oy} are bed slope in x and y directions.

S_{fx}, S_{fy} are frictional slope in x and y directions.

The above equations are solved in a finit difference scheme using an explicit procedure.

The channel flow is calculated by an equivalent set of equations for one dimensional flow.

$$\frac{\partial A}{\partial t} = \frac{\partial (Au)}{\partial x} = Q$$

and

$$\frac{\partial h}{\partial x} = S_{ox} - S_{fy}$$

where

a is cross sectional area of the channel

Q is a source/sink term

u is flow velocity

Ground Water (Saturated flow)

In SHE the description of the groundwater zone is restricted to a single-layer unconfined aquifer. This component of the model describes the processes of nearly horizontal saturated flow and stream-aquifer interaction through a numerical solution on a rectangular grid of the non-linear cuss = nesq equation

$$S\frac{\delta h}{\partial t} = \frac{\delta}{\delta x}(Kx \; \frac{H\partial h}{\delta x}) + \frac{\partial}{\partial y}(K_y \; \frac{H\delta h}{\partial y}) + R$$

where	S	is the specific yield
	h	is the phreatic surface level
	Kx, Ky	are the saturated hydraulic conductivities in the x and y directions respectively
	H	is the saturated thickness
	t	is the time variable
	x,y	is the horizontal space coordinates
	R	is an instantaneous source/sink term.

The above equation combines Darey's law and conservation of mass of two-dimensional laminar flow in an anisotropic heterogeneous aquifer.

The recharge/discharge term R is given by

$$R = \sum q - \frac{\delta}{\partial t} gs \int e(z,t) \, dz$$

where Q is soil moisture content of unsaturated zone and $\sum Q = Q_R + Q_1 + Q_o + Q_e$

including loss due to transpiration, evaporation, infiltration, stream/aquifer exhange and external boundary flows).

Snow Melt

On the basis of meteorological input data this model describes processes of snow accumulation and snowmelt, modelled by the simulataneous numerical solution of heat and water flow equations. Simpler snowmelt models based on degree-day or energy budget approach.

Application

The range of application of SHE is almost unlimited. As part of the model development and field testing, SHE was applied to the River Wye catchment on England. The River Wye catchment is an upland catchment of 10 Km^2 in Mid-Wales. It is characterised by rather steep slopes and shallow soils.

The soild water flow model in SHE can be used for studying the hydrologic effects of irrigation. In a joint effort between DRI and the Hydrology Centre, Christ Church, Ministry of Works and Development, New Zealand, SHE was applied to several IHD representative basins in New Zealand. The SHE model has also been applied to a ....Km^2 catchment in Thailand by DHI.

The general impression from the simulation has been that SHE is capable to simulate short storm event very accurately.

2.2.14 The Integrated Hydrological Catchment Model (EGMO)

The Integrated Hydrological Catchment Model (EGMO) was developed at Berlin, GDR (Becker, A; 1977). The intention of development of the integrated catchment model EGMO (for the mountainous areas of GDR) was to get a model as complex as necessary, as simple as possible, and usable for the solution of different taskes of operational hydrology (especially forecasting and water resources control planning) containing submodels and model parameters of physical significance.

2.2.14.1 Model Structure

A schematic representation of the general structure of the resulting model of flow formation is given in fig. 28. Additional information, especially on the structure and principles of the applied subsystem models are given in fig. 29. The symbols used in the model are defined in fig. 30.

The model consideres three runoff components, (a quick response component, a delayed response direct runoff component and a gradually varying component) and three levels of runoff. A quick response component is considered as overland flow AC, occuring only during intense rainfall or snowmelt. A delayed response direct runoff component is considered as direct lateral subsurface flow (interflow) or hypodermic flow AH, representing the main component of direct runoff in Central Europe. A gradually varying component is considered as baseflow QG mainly fed by the groundwater systems of the basin and representing the stable component of river flow.

At the surface runoff level model considers overflow as well as channel flow system. There are two additional surface flow components firstly the runoff AU from impervious areas (streets, urban areas etc.) and secondly the saturated

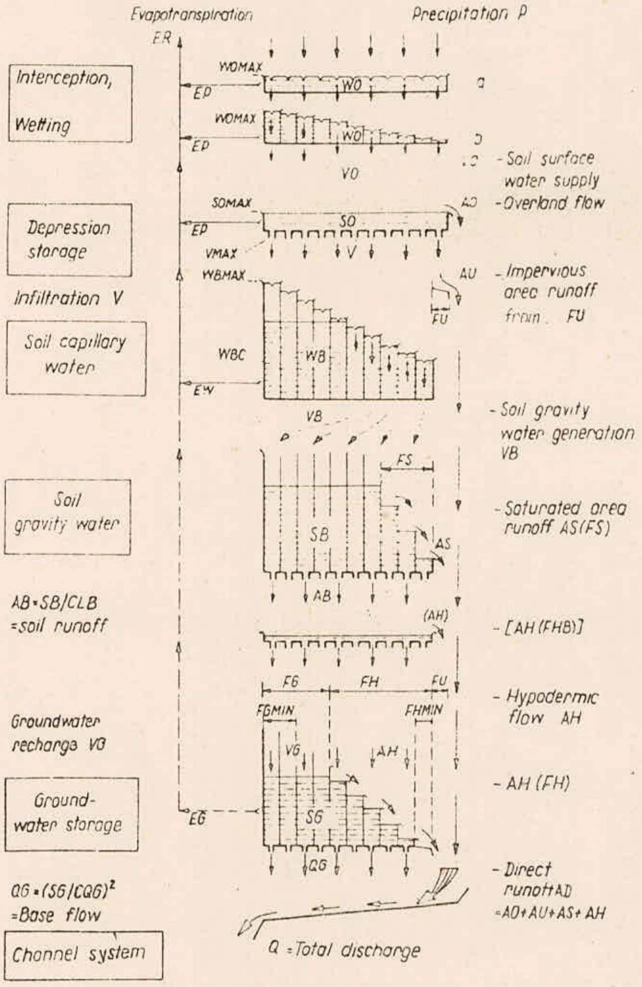


FIGURE 28 SCHEMATIC REPRESENTATION OF THE CATCHMENT MODEL EGMO.

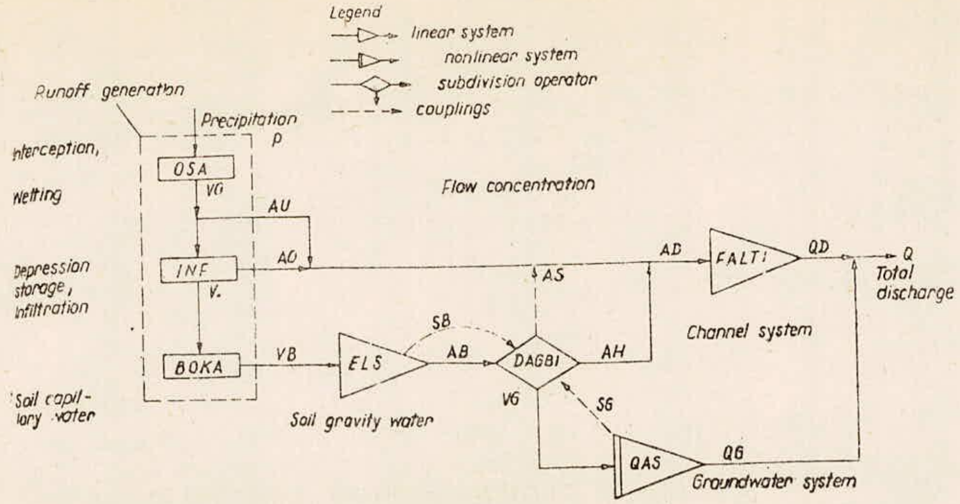


FIGURE 29 SCHEME OF SUBSYSTEM SEQUENCES IN THE INTEGRATED CATCHMENT MODEL EGMO.

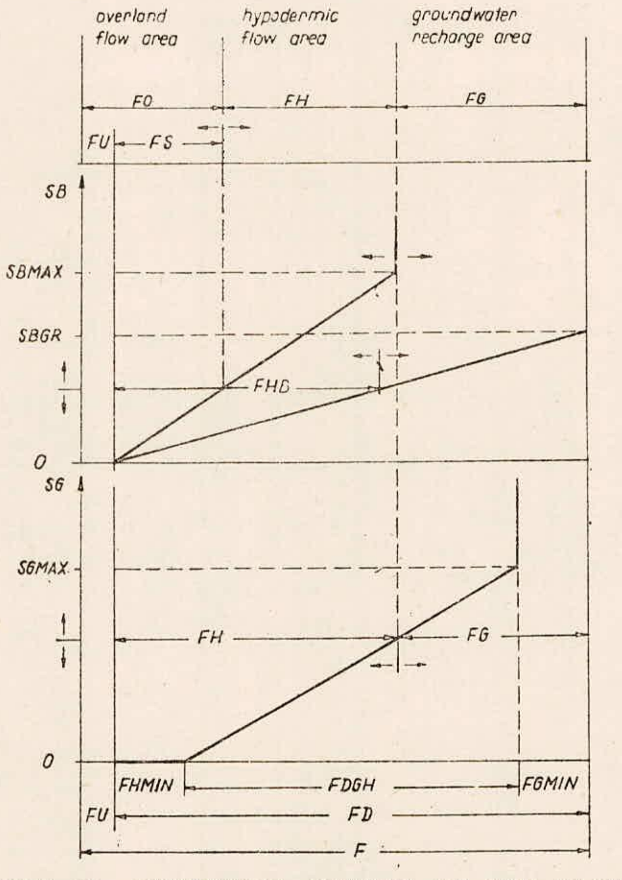


FIGURE 30 PRINCIPAL SCHEME OF THE VARIABILITY OF DIFFERENT RUNOFF GENERATING AREAS.

area runoff 'AS', generated in certain parts of the basin where, during rainfall or snowmelt periods, water saturation at the surface can be observed (depending on the soil gravity water storage SE). Other two runoff levels are the soil (horizones of higher hydraulic conductivity) and aquifers (groundwater system).

Within the surface and the soil system, model distinguishes the capillary water storage (WO, WB), which is not freely movable and can be reduced only by evapotranspiration, and the gravity water storage (SO, SB) which is only temporarily in storage, i.e. this water will become runoff, either as direct hypodermic flow 'AH' into the channel system or groundwater recharge 'VG'.

2.2.14.2 Runoff Generating Sub-models

Though the hydrological processes taking place in a basin are coupled in a complex manner, it is possible to simulate the different component processes by separate submodels. The runoff generating submodels determine (a) that part of precipitation falling during an interval which will recharge the catchment (the losses), and (b) the runoff as a residual. All submodels are listed under the name of the corresponding sub-routines of the programme according to Fig. 29.

OSA (EOS)	Surface reservoir for capillary water (interception, wetting of the soil surface layer), Modelled by a cascade of two impermeable reservoirs, the first lumped, the second with a linear distribution of storage capacity WOMAX. Filled by rainfall or snowmelt, exhaused only by evaporation, overflow represents water

	supply VO from surface to soil.
INF	Depression storage and infiltration model Lumped system, reservoir with infiltration capacity index VMAX and storage capacity SOMAX. Filled by surface water supply VO, outflow by infiltration V (less or equal to VMAX), overflow represents overland flow AO.
BOKA (EBOG)	Soil capillary water storage. The filling dwB/dt (+) which is possible during infiltration periods is assumed to be proportional to the actual soil capillary water storage deficit (WBMAX-WB), i.e. to the difference between storage capacity WBMAX and actual soil capillary water storage WB. (Similarly the exhaustion dWB/dt (-), which is only possible by evapotranspiration, is assumed to be proportional to WB). This relation can be interpreted as a statistical distribution of this storage capacity throughout the basin. That part of infiltration V, which will not become capillary water storage WB, will become soil gravity water VB. VB can be stored temporarily (SB), and later on become either hypodermic flow AH or groundwater recharge VG.

The subroutines EOS and EBOG, which represent the counterpart of OSA and BOKA, calculate the real evapotranspiration ER (less or equal to potential evapotranspiration EP) during exhaustion periods.

2.2.14.3 The flow concentration Submodels

These submodels simulate only temporary storage and time delay or flow generated by the runoff generation models (losses are only possible by direct evapotranspiration).

During flow generation periods, free moving water occurs on the above-mentioned runoff levels (surface, soil horizons, groundwater). This water is temporarily stored, whereby areal variations of water supply are equalized.

ELS	Soil gravity water storage Single linear reservoir, containing temporary storages SB, resulting from excess water VB (as output of BOKA). The outflow AB of ELS is proportional to SB (AB=SB/CLB) with CLB a storage constant). AB is subdivided into hypodermic flow AH (direct soil runoff into the channel system) and groundwater recharge VG.

This submodel subdivides the soil gravity water outflow AB into the two runoff components AH (hypodermic flow) and VG (groundwater recharge).

To model the variability of different runoff generating areas the relations presented in Fig. 30 have been introduced.

A linear relation between the area producing hypodermic flow FH and groundwater storage SG (FH=FHMIN + FDGH. SG/SGMAX, as indicated by the lower line.

A linear relation between FHB and gravity soil water SB (FHB = F-FU) SB/SBGR, as indicated by the middle line in Fig. 30. At each time step of the calculation the greater value (FH or FHB) is taken to calculate the hypodermic flow

AH = AB. FH/F

The remaining area FG=F-FH-FU produces the groundwater recharge

VG = AB. FG/F

Besides this, the submodel DAGBI calculates the saturatated areas FS depending on the soil gravity water storage SB (upper line in Fig. 30)

FS = FH. SB/SBMAX

K_{d_I} with the response function H_k

$$QD_I = = \sum AD_{I-K} H_k$$

Finally the baseflow QG is added, to get the total catchment outflow

$$Q_1 = QG_I + QD_I$$

2.2.14.5 Model Parameters

F	Total catchment area,
FU	impervious area, producing surface runoff AU,
FHMIN	established minimum area producing hypodermic flow FH,
FGMIN	established minimum groundwater recharge area EG,
SGMAX	a parameter.

3.0 COMPARATIVE STUDY OF MODELLING DIFFERENT COMPONENTS

Different types of watershed models have been developed depending on the purpose such as flood forecasting, simulation of hourly or daily runoff or estimation of water yield. To simply representation of the various component processes and their complex interplay, different watershed models have adopted different lay out approaches, methods of approximations for the components so that the model could be capable of simulating the runoff as accurately as possible. A bried comparison of the different component processes as considered in the different models reviewed is presented below in the height of the requirements for mountainous watersheds.

3.1 Interception

The amount of interception is a function of the type of precipitation (i.e rain or snow), the leaf area, density of vegetation and season of the year. The interception loss is related to the precipitation amount as an exponential decay function (Fig. 31). The loss would be more at the beginning of a rainspell and reduces to a constant value during part of the spell.

Most of the models treat the loss as a total amount and subtract it entirely from the initial rainfall. Only a few models account for the variation of interception from species to species and variation from season to season and within season.

The factors like vegetation type, canopy density and precipitation type have been considered in the Leavesley model to compute interception for each hydrologic response unit of watershed. A canopy storage for rain (in inches) and a canopy storage for snow water equivalent (in inches) are used as input for each unit.

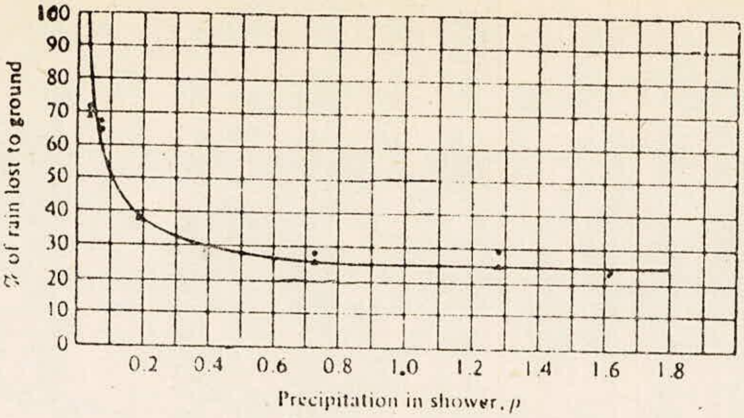


FIGURE 31 MEAN CURVE SHOWING TOTAL PERCENT OF PRECIPITATION IN SHOWER INTERCEPTED BY VARIOUS TREES (ADOPTED FROM VIESSMAN ET AL' ENGG.. HYDROLOGY').

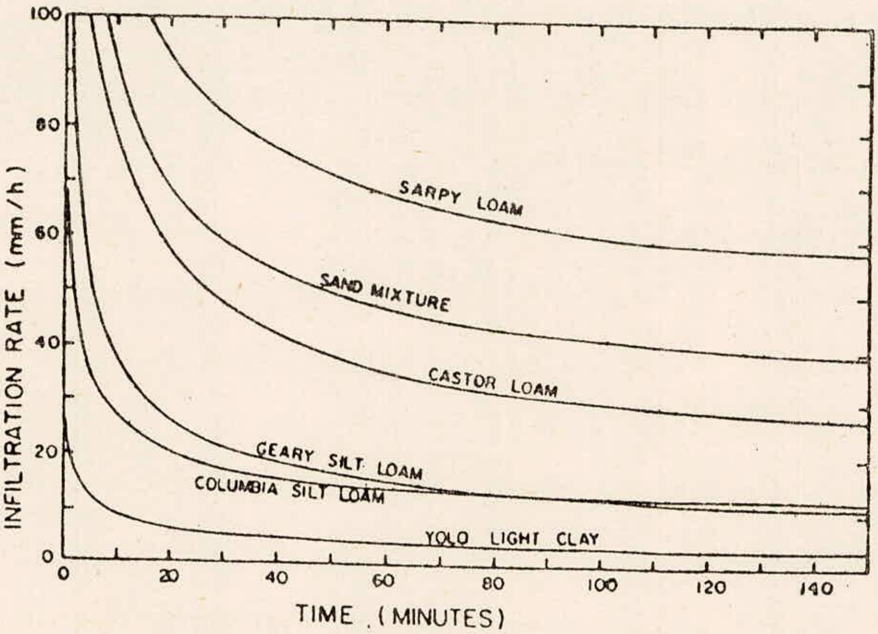


FIGURE 32 INFILTRATION RATE CURVE OF SOME SOILS (ADOPTED FROM HANN' SMALL CATCHMENT HYDROLOGY')

In SHE the interception process is represented by a variant of the Rutter Model. This includes canopy storage and drainage parameters that can be estimated by experiments. The model is essentially an accounting procedure for the amount of water stored in the caopy. The interception component is limited to include only one vegetation type within each grid square.

3.2 Evapotranspiration (ET)

Besides the variation in time, the loss due to evapotranspiration varies from place to place within a watershed as a result of variation in climate crop and soils. Elevation and crographic effects also largely determine the variation.

In the Stanford Watershed Model, evapotranspiration is considered to take place from interception storage, upper zone storage lower zone storage, streams and lake surface and groundwater storage. The potential ET is assumed to vary linearly over a watershed.

In the SSARR mode ET loss is determined from potential ET which is expressed as a watershed mean.

The UBC model treats the evapotranspiration process in three stages. In the first stage, PET is estimated for the lowest meteorological station in the Watershed. The value is then distributed to each elevation band mid level. The PET values thus arrived at are used in conjunction with the calculated soil moisture deficit to yield actual evapotranspiration.

In the Sacramento model evapotranspiration is considered to take place from two zones of soil water and two parts of catchment rea; one covered by river vegetation and other by streams and lakes. he SHE uses a modified Pemnan-Monheth equation with additional parameter for canopy resistance.

3.3 Infiltration

Infiltration is an important component of any watershed model. Infiltration rate is high initially and is diminished during continous rainfall and reaches a constant low rate (Fig. 32). Infiltration can be considered as a three space sequence (i) surface entry, (2) transmission through soil, (3) depletion of storage capacity in soil. Rainfall rate or intensity will determine as to how much rain will infiltrate and how much will runoff.

Various factors combine to result in seasonal variation in the infiltration capacity. Infiltration rates are higher in summer months in comparison to that during winter months.

Several empirical and semi-empirical relationships were developed by different workers for variation of Infiltration capacity with time. Some of the well known relationships were due to Hortan (1939), Kostiakov (1932), Philip (1957) and Holtan (1961). Different watershed models have adopted different approaches and approximation in considering infiltration. Some models like HEC-1 also have option for SOS curve.

In the Stanford watershed model infiltration is accounted for by considering (i) infiltration directly into soil profile and (ii) by delayed infiltration from temporary storages (e.g. depression storage). In SSARR model, infiltration is computed by considering soil moisture index and baseflow infiltration index separately.

In the Sacramento model, the basin is considered to comprise of two types of areas (i) a permeable portion of soil and (ii) a portion of soil covered by stream, lakes and marshes. HEC-1 also has provision for providing information on impervious area of catchment. The model has several options of loss including Holten loss rate and SCS curve number.

Infiltration in the SHE model is treated as part of unsaturated zone process and uses the Richards equation. The equation is solved numerically by an implicit finite difference scheme.

3.4 Overland flow

Overland flow is known to occur as a thin sheet flow before surface irregularities cause a gathering of runoff into discrete stream channels. Overland flow from a mountainous watershed is recognised as a non-linear process. In general, there are two non-linear approaches which are used in analysing watershed response; system approach and hydrodynamic approach. The hydrodynamic approach has been used by several investigators for modelling overland flow. Non-linear behaviour of overland flow in mountainous areas poses difficulty in solving hydrodynamic equations. Two simplified approaches namely Horton-Izzard approach and kinematic wave approximation are used for the solution of hydrodynamic equations.

A review carried out by National Institute of Hydrology (1986-87) indicated that the kinematic wave approximation to hydraulics of overland flow is better for rough and steep slopes. Various investigators developed both analytical and numerical solutions to kinematic wave equation. Wooding (1965) dealt with the problem of overland flow under a constant uniformaly distributed rainfall of finite duration with an analytical solution. However, in reality rainfall intensity is not uniform in space and time. Besides, interaction between overland flow and infiltration need also to be considered. The variation in rates of infiltration allow overland flow in areas with low infiltration while preventing overland flow in other areas.

In the SHE model the hydrodynamic equations of continuity and momentum are solved in a finite difference scheme using an explicit procedure due to Preissman and Zaoui (1979). In the Tank model the surface discharge corresponding to over flow takes place from the upper most tank.

3.5 Saturated Zone

The ground water reservoir is a significant part of the hydrological system and its quantification in various regions is a difficult task because the flows are governed by the percolation rates and the arrangement of rocks and soils in the region. The saturated zone receives water from net infiltration and percolation. The flow from the unsaturated zone to the lower saturated zone is conceptualised in an almost identical way in all the models (Stanford, Sacramento, Tank, SHE, etc.), however, with minor modifications. In the SHE model the description of the flow in this zone is restricted to a single-layer unconfined aquifer. In the Sacromanto and UGC models, the zone is conceived of as comprising an upper zone of groundwater and deep zone of ground water.

3.6 Channel Routing

Channel routing though relatively unimportant in small mountainous watersheds, is an important process in watershed modelling. The methods of routing vary from model to model. The HEC-1 has option of Muskingum, modified puls method and kinematic wave routing procedure. In the SSARR model each of the flows (surface, subsurface and base flow) are routed through a certain pre-specified number of increments of time. The routing is carried out by the solution of storage equation through a finite number of increments.

In the SHE model, the flow is routed as zone dimensional flow using a set of equations which are solved by implicit finite difference scheme. In the UBC model, the flow is treated as four components namely fast, medium, slow and very slow. Each runoff component is subjected to a routing procedure which produces a time distribution of runoff. The routing is done considering the channel as a linear storage reservoir.

3.7 Snow-Melt

Snowmelt is one of the important components of streamflow simulation in mountainous areas. Excepting a few, almost all the models reviewed have snowmelt component, however, with different methods of converting snow depth to melt water. The methods generally used were, (i) The degree day method and (2) The overgy budget method.

The HEC-1 model has both the degree day and energy budget method options. In the SSARR model snowmelt is determined by either (i) the temperature index (degree day) method or (ii) by a generalised snowmelt equation governed by elevation band and snowmelt depletion curve.

In the SHE model, the snowmelt component represents an attempt to model both energy and mass flux within a snow-pack and is intended for use when changes in the temperature and structure of snowpack have a significant effect on the flow of water within it. Equations for flow of heat and water within the snowpack are solved simultaneously linked by their internal source terms. Two-empirical equations are used to complete the set of relations required to define temperature and water content distribution. The snowmelt model is described in detail by Morris and Godfrey (1978).

The UBC model estimates snowpack accumulation and depletion and operates entirely from meteorological inputs of daily maximum and minimum temperatures and precipitation. The model uses a constant lapse rate for calculation of snowmelt. A linear temperature switch is used in the model to determine the amount of energy available due to variant heat and latent heat which give rise in melting.

4.0 REMARKS

There are two important problems associated with the application of any hydrological model; first the choice of the model and the second, the choice of criteria by which the success of the model could be judged. The rainfall-runoff processes being inherently spatial, non-linear and time variant the choice of the models is very limited considering most of the models are lumped, linear and time-invariant.

While it is neither easy nor wise to identify apparticular model, the ideal requirements of the model as laid down by Crawford and Linsley (1966) might have to be kept in view and could be helpful. These were what a model is expected to:-

1. represent the hydrological regime on a wide variety of catchments with a high order of accuracy.
2. be easily applied to any catchment for which hydrological data was available.
3. be physically realistic so that in addition to streamflow, estimates of other variables, such as soil moisture and groundwater recharge could be determined.

The detailed mathematical treatment of hydrological processes is based on hyman concepts and on understanding of the basic hydrological principles. Since overland flow rather than channel flow is important in the mountainous catchments, the accent has to be more on the modelling of the land surface process involving infiltration, surface and sub-surface flow and depression storage. There is, therefore, need for a distributed hydrological model which is capble of treating each of the processes snowmelt, interception, evaporation and evapotranspiration, infiltration, overland flow, soil water, subsurface and base flow in a modular form.

Though in actual field application, it may not be possible to feed the models with data for all the relevant parameters, the improvement in the physical understanding and analytical ability of the hydrologist has made it possible to develop a physically based model like SHE. Unlike traditional models, SHE has the ability to predict the change in the hydrological regime due to natural and man made changes which include afferestration, deforestation, cultivation, rural development, construction of projects etc. This suits the changing Indian Scenario aptly. The National Institute of Hydrology in cooperation with the organisations who have developed the model is in the process of applying the SHE model to Indian mountainous catchments.

4.1 Watershed Models Applicable for Indian Mountainous Catchments

In the Indian context, many of the mountainous areas have forest growth and interception shall be an important parameter to be considered. In the case of Himalayan catchments, snowmelt is an important contributing factor of stream flow and the models should, therefore, have the capability to estimate snowmelt and incorporate in the system. In many areas, sufficient data is not available for calibrating a model. The parameters need to be either physically measured or regional parameter values are to be adopted.

Some of the models reviewed in the report have been implemented and tested in India by CWC, NIH, CWPRS & IITS. These are the HEC-1, SSARR, Kentucky and OPSET (modified versions of Standford), Sacramento, NAM, TANK and HBV. While some of these models have been applied as academic and research studies, only few of them have been applied to field problems.

The CWC has been experimenting with HEC-1F (Forecasting version of KEC1), SYSTEM-11, SSARR and NAM for the catchment of Yamuna upto Delhi. National Institute of Hydrology and Gujarat NPDDC have used HEC-1 model for the estimation of design flood for Narmada Sagar and Sardar Sarovar in Narmada. The OPSET and SSARR models have been used by CWPRS for the same purpose.

The Rango-Martinec model has been used by Sharma and Divetia (1985) for the estimation of design flood of a Hydroelectric project on river Dhauliganga, a tributary of Sarda river.

The application of Watershed models to mountainous catchments, especially those with snow covered areas is thus so far limited in India.

Based on the comparison of the modelling of different component process carried out in the earlier section, it may be concluded that such of the models which are distributed in their approach and physically based are most suited for Indian mountainous catchments. SHE, UBC and Leavsley are thus the best models in this respect as they are not only distributed in approach but also have appropriate snowmelt modelling options suited to mountainous catchments. Other models like STORM, SRM, NWSRFS and Sacramento are useful models in this regard. However, all the models may not be suitable from the flood forecasting point of view. It is, therefore, necessary that the models are applied by clearly defining the objective that the models are applied by clearly defining the objective and fixing suitable criteria for judging the applicability of one model or the other.

Parameters most commonly used in the models which include snowmelt options are summariesed below. This, however, does not include some of the important models like SHE, UBC and Leavsley.

- Degree-day factor by which the snowmelt is calculated, DF
- Temperature lapse rate for temperature extrapolation, LR
- Critical temperature to decide between snow and rainfal, CT
- Runoff coefficient expressing the losses, RC
- Time lag between the snowmelt or rainfall and runoff, TL
- Recession coefficient characterizing the recession flow,CR

The total range of values used by the models (WMO, 1986) (calibrated or determined in the different basins is listed in table 7.

TABLE 7

TOTAL RANGE OF PARAMETER VALUES FOR THE RESPECTIVE MODELS
(Source, Martinec, WMO 1986)

Model	DF		LR		CT		RC		TL		CR	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
SRM	0.2	0.6		0.65	+0.75	+3	0.18	1.0	6	18	0.513	1.0
TANK	0.20	0.42	0.46	1.12	$0^{2)}$				0	15.6	0.1	0.876
NWSRFS	$0.15^{1)}$	$0.45^{1)}$	$0.1^{3)}$	$1.0^{3)}$	+1						$0.88^{4)}$	$0.92^{4)}$
NAM-II	0.19	0.63	0.5	0.6	+0.2	+0.8						
HBV	0.15	0.35	0.5	0.65	-1.5	+0.8						
SSARR	0.026	0.4	0	0.65	-1.8	+2						
IHDM			0.65		0^{0}							

Notes :

1) During main snowmelt periods
2) The real value varies according to the evaluation of a representative temperature for each elevation zone
3) Lapse rates determined from observed data prior to calibration
4) This is an intermediate baseflow recession. Primary baseflow recession was 0.995 for all basins.

4.2 Scope for future work

Many of the models require data of a number of parameters which are usually not available for Indian mountainous areas. Even precipitation and temperature data from higher elevations (above 2000 m) are generally lacking. Intensive data collection for mountainous catchments through representative basin studies over a given period of time would provide necessary data base to work with the models and assess their applicability to Indian mountanous catchments.

In recent years, information obtained through remote sensing techniques has increasingly been used in watershed models for providing information on areal snow cover from relatively inaccessible areas. Remote sensed data in visible, theremal and microwave region can play an important role in monitoring snowfield and glaciated region, which may be helpful in snowmelt studies. Models such as SRM, Kentucky, STORM and SSARR do have the capability to utilise remotely sensed data of snow cover.

Estimation of snowcover by conducting snow courses and through aerial photography or nuclear techniques need to be carried out for a proper assessment of the depth of seasonal snow available for melt during the melt season.

Most of the models developed have been applied abroad under conditions and catchment characteristics which are quite different from those obtained in Indian mountainous catchments and as such pose certain problems while using them. The model may work well in catchments for which they are developed under some assumption but the same assumption may not hold to Indian conditions. This requires the testing of the models for Indian mountainous catchments.

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APPENDIX I

Classification and Parameters of Reviewed Models
(Abstracted from WMO, 1986)

Name of Model	Model developed at	Classsification of Model		Number of Parameters			Computor Language	Hardware Recommended
		Snowmelt model	Transformation model	Basin	Externally derived	Calibrated		
2.	3.	4.	5.	6.	7.	8.	9.	10.
SSARR	USA (1958)	Distributed elevation zones Index	Water bal. distributed time distr. lumped	1	6	8	FORTRAN 77	Developed on virtual storages software. Direct acess disk work files used.
TANK	Japan(1967)	lumped index distributed elevation zones Index	Water balance lumped and distributed	3	4		FORTRAN	Any middle or large computer.
NAM II	Denmark	Distributed (both index &energy bal. versions)	Water bal. lumped & distributed Time distr. lumped	10	2	2	FORTRAN IV	Medium size computeri.e Univac 1108 56 K bytes
NWSRFS	USA	lumped index distributed elevation zones other index	Water bal. lumped & distributed time distr. lumped & distributed	1	6	6	FORTRAN	Any large or moderate size computer

2.	3.	4.	5.	6.	7.	8.	9.	10.
SRM	Switzerland USA	Distributed elevation zones Index	Water bal. lumped time distr. lumped	6			FORTMAN	13 3081 or any large mini or micro computer
HBV	Sweden	Distributed elevation zones Index	Water bal. lumped & distributed time distr. & lumped	2	4	4	ALGOL	Used on Univac 1100-21 computer Disk Calculation cambo used
STORM	USA	Lumped index	Water balance index	2	7	4	FORTRAN	
HSP	USA	Distributed energy budget index	Water balance lumped distributed	3	12	22	FORTRAN	
KWM	USA		Water balance distributed	3	6	12	FORTRAN	The program contains about 20 subroutines. It has been made operative even on HP-1000 in part.
HEC-1	USA	Partly distributed levation zones, index, energy budget	Water balance lumped and time distributed	3	9	18	FORTRAN	The computer memory required pm tje CDC 7600 is 15000 words. It has 16 input/output scratch (tape,disk files)

2.	3.	4.	5.	6.	7.	8.	9.	10.
NWSRFS (ANDERSON)	USA	Distributed elevation zones energy budget	Heat and Water balance distributed	1	10	11	FORTRAN	
HMC	USSR	Lumped, index energy budget	water balance lumped	2	9	17	FORTRAN	
UBC	British of Columbia	Distributed elevation, energy and index	Water balance lumped and distributed to to elevation	3	3	15	FORTRAN	
LEAVESLEY	Colorado (1973)	Energy Balance equation	Water balance lumped and distributed	5	5	4	FORTRAN IV	Used on a CDC 6400 computer system
SHE	DHI	Energy and mass flux within snow pack.						

APPENDIX II

Data Requirements and application range of different models
(Abstracted from WMO, 1986)

Sl. No.	Name of Model	Development Data Requirements			Operational data requirement	Output data	Application range.
		Physiographic data	Meteorological data	Hydrological data			
1.	2.	3.	4.	5.	6.	7.	8.
1.	SSARR	DA, elevation information, TM, glacier area Forested area	T,P,E Upper air data	Q snow covered area (optional)	T,P,Q	Q,M, Elevation of snow line, U,base flow, runoff percent	Size of basin : a few to several thousand Km^2
2.	Tank	AE,	T(D), ET (potential or actual) WE of snow (optional) P(D)	Q(D)	T(D),P(D), ET (potential or actual, daily or monthly)	WE of snow,SM U, (components of discharge according to needs), Q (D,H) TB and GP.	No limitations on size of drainage area.
3	NAM-II		Degree day T&P Every balance T,C,w,R&P	Q(D)	(same as development data requirements)	Q(D), SM&IM Actual E, Components of Q TB and SP	
4.	NWSRFS	DA,TM and vegitation map (optional)	T(Point or areal),P, ET(optional)	Q, WE of snow (optional)	T,P (at the basic interval WE of snow (optional)RS	Areal %age of A	No limitation

1.	2.	3.	4.	5.	6.	7.	8.
5.	SRM	AE curves	T(D), P(D) A for each elevation zone	Q(D)	T(D), P(D), A for each elevation zone	Q(D)	Suitable for Mountainous basins upto 4000 Km^2
6.	HBV	AE curves, %age of lakes, SWC (OPTIONAL)	T(D) P(D) E_T(M)	Q(D)	-do- -do-	Q(D), E, SMI, AP and SM	Limitations on drainage area: 1 Km^2 to several thousand Km^2
7.	STORM	Basin area, percentage of previous and impervious area	T(H), P(H), E(H), WE	Q(H)percolation and initial abstraction time of peak and time of concentration	T(H), WE P (H), E(H)	Q(H) and SM	Larger basin area with low range of elevation
8.	HSP	Basin area, impervious area, Forest cover and elevation	T,P,ET, W,C,S,R, Snow cover	Q, Water equivalent	(Same as development)	SM, Runoff Peak and volumes (H,M & yearly)	No restriction on basin area
9.	KWM	Basin area, Impervious area, Swampy area	P,ST,SM	Q,OFSS, OFSL	DA,E, F	Soil moisture storage volume, simulated or synthesised streamflow and Base flow	Applicable to even small watershed having ltd. discharge data and extensive hydromet data.

1.	2.	3.	4.	5.	6.	7.	8.
10.	HEC-1	Basin area, TM, Elevation information area impervious	T,W,S, Dew point t, P,WE,T-base, melt coeff., lapse,rate, freezing level-T	Q(t), base flow water transfer model input parameters	T,P,S Dew point WE	SM,Loss Excess, Q(T),Peak volume, summary	Applicable to larger basin, individual storm, smaller basin if the variables information area at smaller time interval in mountainous area
11.	NWSRFS (ANDERSON)	Basin area Areal depletion curve	P,T,%age of Snow, W,Et,Snow cover,WE.	Water transformation model	T,P,A, AE,ET, S	Rain, SM	Suitable if remotely sensed and ground truth informations are available.
12.	HMC	Basin area, Snow covered open and forested area	P,ET,T (Mean/Min, Max.)W,C, snow thickness,WE	Q, Wettness	P,T,A,DA,WE,ET,C	Q(daily, 10 daily average)	For low land basins and stable snow cover during winter. Large basins to be divided in subbasins.
13.	UBC	Basin area, Elevation, lake area	Tmax, Tmin, P, Lapse rate (optional)	Q	Tmax, Tmin,P	SM, snowpack simulated and generated runoff	For the mountainous area with snow & rain having lake and less nos. of measured variables.
14.	LEAVESLEY	DA, elevation information TM, Forested Area vegetation cover density	T,P,E, WE of snowpack	Q		Mean daily streamflow	Suitable for small mountainous watersheds fed with rain or snow or both components

1.	2.	3.	4.	5.	6.	7.	8.
15.	SHE	DA, Cover Density, Cover type details Soil related information	P, T,	Q	-	Water yield	suitable for small watershed fed with rain or snow or combination of both

A = Snow Cover
AE = Area Elevation Curve
AP = Snow pack
C = Cloud cover
D = Daily
DA = Drainage
E = Evaporation
ET = Evapotranspiration
F = Snowfall
GP = Graphs
H = Hourly
IM = Ice melt
M = Monthly

P = Precipitation
Q = Streamflow (observed/computed)
R = Relative Humadity
RS = River stage
S = Solar Radiation
SM = Snowmelt
SMI = Sint Moisture Index
SWC = Soil Water Capacity
T = Temperature
TB = Tables
TM = Topographical maps
W = Wind speed
WE = Water Equivalent