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DEVELOPMENT OF A CONCEPTUAL MODEL FOR SNOW, GLACIER AND RAINFED CATCHMENTS

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Abstract

Streamflow in the rivers originating from the Himalayas comprises of the contribution from rain, snow and glaciers. A substantial contribution is derived from snow and glaciers into these rivers. Each component of streamflow plays important role in the management of water resources including reservoir operation and streamflow forecasting. There is a need to develop a hydrological model for the Himalayan basins. To understand the hydrological behaviour of the Himalayan basins, an understanding of rainfall-runoff, snowmelt and glacier melt processes is required. Topographical influence on precipitation distribution is another important problem in the Himalayan basins and further adds to the complexity of the hydrological modelling of these basins. It has been pointed out that energy balance approach cannot be adopted for the estimation of snow and glacier melt in the Himalayan basins because data required for application of such methods are not available. In the present work, keeping in view the sparse network, availability of data and topography of the Himalayan basins, a structure of a simple conceptual model is proposed. The model is based on the area-elevation characteristics of the basin and utilizes the relationship describing temperature lapse rate and orographic precipitation distribution. Because there is difference in the melt rate of snow and ice under the same environment, therefore, separate computation of snowmelt runoff and glacier melt runoff are suggested. The contribution from various sources is added together and acounting of losses is made. The routing of surface and sub-surface flow is proposed using concept of linear cascade reservoirs. The structure of the model is described and details of associated hydrological processes and parameters to be adopted for such a model are discussed.

1.0 Introduction

Snow is an important part of the hydrologic cycle and considered as a dominant source of streamflow in many parts of the World. The geographical distribution of snow indicates a general increase in both snowfall and snow cover with an increase in latitude and altitude (Bates and Bilello, 1966). The hydrological significance of the snow cover is dependent on the moisture provided by a thin layer to soil to generate runoff round the year runoff provided by the deep snowpacks in some mountain regions. In the context of India, Himalayas are the reservoir of snow and glaciated ice and regulate the annual water distribution. A substantial amount of melt water is received in the major river systems of India, namely the Indus, the Ganga and the Brahmaputra. Studies carried out in the western Himalayan region confirm a substantial contribution of snow and glacier melt runoff into annual streamflow of these rivers (Singh et al. (1994a, 1994b, 1996c). As such, Himalayas are considered as the life-line to Indian sub-continent. Accurate estimates of the volume of water stored in the basin in the form of snow in winter and its rate of release due to melting in summer, are needed for many purposes. These include streamflow and flood forecasting, reservoir operation, watershed management, water supply, and the design of hydraulic structures. The planning of new multi-purpose projects in the Himalayan region further emphasizes the need for reliable estimates from rain, snow and glacier runoff. During the monsoon season, there is good rain in the outer and middle Himalayan ranges and therefore, modelling of rainfall-runoff is also required when total streamflow is simulated/ forecasted (Singh et al. (1995), Singh and Kumar (1996b)). A thorough understanding of the relationships between meteorological variables and the snow and glacier melt processes is needed for seasonal and short-term water yield forecasting.

Worldwide the status of data collection, climatic and physiographic characteristics are not uniform. In some countries, the network in the mountainous regions is dense or reasonably good providing adequate hydrometeorological data, whereas in many countries including India it is very poor or sparse with very limited data. Therefore, development/ selection of model cannot be the same. Keeping in view the data availability, this report discusses the salient features of a hydrological model suitable to Himalayan basins. The basic formulation of the model together with background information on the philosophy of its design, is provided. This model can be used to provide mathematical hydrologic simulations as required for the planning, design and operation of water resources projects.

2.0 Model Types and Their Use for Hydrologic Applications

In general, snow melt models can be divided into two types of models, namely index models and energy balance models. Broadly, energy balance models require the information on radiant energy, sensible and latent heat, energy transferred through the rainfall over the snow and heat conduction from ground to the snowpack. Several meteorological parameters are to be monitored to obtain this information over the snowpack. A thorough understanding of the basic energy transfer processes and their role in melting of snowpack, helps in improving the performance of the operational snow melt models.

Index models use one or more variables in an empirical expression to estimate snow cover energy exchange. Air temperature is the most commonly used index, but other variables such as net radiation, wind speed, vapour pressure and solar radiation are also used. Zuzel and Cox (1975) studied the relative importance of meteorological variables in snowmelt and found that if only one meteorological variable is available for snowmelt prediction, average temperature is the best predictor. The degree-day method is more popular because temperature represents reasonably the energy flux and at the same time, it is relatively a easy parameter to measure, extrapolate and probably to forecast. However, snowmelt prediction can be significantly improved by using vapour pressure, net radiation and wind rather than the temperature variable alone.

Consideration of limited variables in an index model is preferred, otherwise it becomes difficult to correctly account for the interdependency between the variables when large number of variables are considered. If data for a number of parameter are available for use, it is probably much more logical to use a theoretically based energy balance model to ensure that the variables are combined in a reasonable manner. Techniques need to be devised to account for the effect of factors like slope, aspect, elevation, and forest cover on various input parameters.

3.0 Factors Influencing the Snowmelt and Model Selection

In hydrological modelling the level of complexity at which modelling can be carried out varies according to data availability, type of problem, scale of operation, required accuracy, computer facilities, and of course, economic considerations. Anderson (1976) described the impact of various factors in selecting a snow melt model for a given hydrologic application. Broadly these factors are related with climatic and physiographic characteristics, and availability of data for the specific mountain region. A brief description indicating how these factors influence the selection of a model, is given below.

3.1 Atmospheric conditions

Under less variable climatic conditions, especially during snowmelt period, index snow melt models tend to work best. When meteorological conditions vary widely during a melt season or from year to year, an energy balance model is considered more suitable for estimating snowmelt. As discussed above, Zuzel and Cox (1975) studied the relative importance of meteorological variables in snowmelt and found that if only one meteorological variable is available for snowmelt prediction, average temperature is the best predictor.

3.2 Physiographic factors

The most important physiographic factors affecting snow cover energy exchange are slope, aspect, elevation, and forest cover. A considerable variation in these factors over a watershed affects the areal and time distribution of melt. This could lead to the need to divide the basin into more homogeneous sub-basins/ elevation zones. However, the main effect of physiographic factors on the selection of an index or energy balance snow melt model is governed by the degree of influence of these factors on the variation in meteorological conditions.

The presence of forest cover in a basin restricts the penetration of solar radiation to the snow cover and restricts wind movement. Therefore, wind speed and solar radiation have a small effect on the energy balance. Net long-wave radiation would be the dominant method of energy transfer. Incoming long-wave radiation is closely related to the forest canopy temperature which in turn is related to the air temperature. Thus index models give good results for the heavily forested basins.

In open areas there is a much greater chance for variability in meteorological conditions during snowmelt and consequently, all terms in the energy balance are likely to be important. However, their relative importance can vary from day to day and probably even during the day.

3.3 Availability of data

An energy balance model obviously requires much more data than an index model. The basic question that needs to be answered is what amount and quality of data are needed to ensure that an energy balance model will give better results as compared to an index model? In many cases simulation models are used to predict behaviour under extreme situations. During extreme events, conditions are likely to be much more different from those used in model calibration. An energy balance model offers more reliable means of extrapolating to determine behaviour under extreme conditions. It might be possible to get improved results by using an energy balance model under extreme conditions even with a minimal amount of data. Whereas, under normal conditions a considerable amount of high quality data might be needed to improve results over those that could be obtained with an index model.

Keeping extreme events in view, Franz (1974) explored the predictive relationships for solar radiation, dew-point, and wind speed in which daily maximum and minimum air temperature served as the predictor variables. A strong relationship was found between dew-point and minimum air temperature, a weak relationship between solar radiation and the daily range in air temperature, and no relationship between wind and air temperature. This indicates that more than just air temperature data are needed to get improved results by using an energy balance model even under extreme conditions.

A logical minimum data requirement for using an energy balance model would be measurements of solar radiation, wind, and vapour pressure in addition to air temperature. A reasonable estimate of solar radiation based on cloud cover or percent of possible sunshine might suffice in place of solar radiation measurements. Whether measurements of these variables at a low elevation station would be adequate for use in a high elevation mountain watershed is uncertain. The extrapolation technique would have to account for the climatic variability between the two locations. If estimates of air temperature, vapour pressure, wind, and solar radiation are available, it is still necessary to estimate incoming long-wave radiation and albedo before using an energy balance model.

Another argument for using an energy balance model, even though only minimal data, such as air temperature, exist, is that as the additional data become available they could be substituted directly into the model without recalibration. This would require extreme care to insure that the relationship between air temperature and each of the other variables is unbiased. It would be especially difficult to establish unbiased relationships when working with areal estimates of the variables. For example, it would be most difficult during calibration to separate the relationship between the wind speed predictor and the mean areal wind speed from the determination of the wind function coefficient. It is very likely that such a procedure would require recalibration of the model whenever additional data become available.

3.4 Other considerations

The type of application is also an important consideration in model selection. For design applications where only extreme conditions are of interest, an energy balance model is probably needed. Even if the needed data are not available, likely extreme conditions could probably be generated with the aid of meteorological and statistical techniques. When all types of conditions are of interest, as in river and water supply forecasting, the selection of a snow melt model should be based on the other factors affecting model performance (climatic conditions, physiographic factors, and available data). Further, economic considerations should also influence the selection of a snow melt model. The question that needs to be asked is how much improvements in accuracy are worth? For a given application it needs to be determined if the benefits will exceed the costs of obtaining the improvements in accuracy.

4.0 Development of a Model for the Himalayan Basins

Most of the Himalayan basins experience runoff from the rain, snow and glacier. The contribution from the lower part of the basin (~ < 2000m) comes from the rain, from the middle part between 2000m to 4000m comes from the combination of rain and snowmelt and from the high altitude region >4000m arrives from the glacier melt. The contribution from snow and glacier is controlled by the climatic conditions and therefore, varies year to year. It shows that Himalayan basins are complex in nature in terms of input to the basin and contribution from all three sources to be estimated. For these type of basins, situation becomes more complex because contribution from each component is not known separately. The observed flow consists of the contribution from all these three sources in addition to the base flow/ground flow contribution. Keeping in view the Himalayan basins, the first and most important factor influencing the development of model and the approach to be adopted, is the availability of data. There is very sparse network in the high altitude region of the Himalayas. Data collected at those stations consist of mostly temperature and precipitation only. Data required for the application of energy balance approach are hardly available. Therefore, obviously development of a conceptual model with an index approach for calculating the snow and glacier melt runoff would be the right start in this direction for the Himalayan basins. The proposed model will include the simulation of snow accumulation, snowmelt and glacier melt runoff and rainfall-runoff. Algorithms for modelling of snowpack cold content is needed for the seasonal conditioning of the snowpack before generating the melt water. The provisions to handle the evapotranspiration, soil moisture deficit, base flow infiltration and routing of surface and sub-surface runoff should be incorporated in the model.

The successful application of the model is dependent upon derivations of the various parameters and relationships specific to a particular basin or river system. Some of the relationships are general and, therefore, are applicable to many sub-basins/zones within a major drainage basin. Others can be specifically derived for a particular watershed. Some are relationships which can be observed or derived, while others must be considered to be model parameters which only have qualitative physical significance. Watershed runoff characteristics are primarily determined by trial-and-error solutions with the computer program to obtain the best fit of historic streamflow data. This procedure is repeated until adequate verification of observed flow is obtained. The characteristics are then tested with independent data. The efficiency of adjustment procedures is dependent upon the judgement and skill of the user who must evaluate the interactions of the various parameters. The knowledge gained in verification studies can add significantly to the overall understanding of basin hydrologic characteristics.

As discussed above, the purpose of this report is to present the basic formulation of the model together with background information on the philosophy of its design (Figure 1). Therefore, details of the components to be considered and the manner in which they will be handled only are discussed.

5.0 Program design considerations and data requirement

Specific major considerations in the design of the model components will be:

(a) To use practical yet theoretically sound methods in evaluating the various physical and hydrologic processes relevant to snow melt and its appearing as streamflow at the outlet.

(b) To provide flexible methods of specifying functional relationships used in simulation.

(c) To provide a capability which allows the model to adjust itself to specified or observed conditions of streamflow from previously computed amounts, and maintain continuity of functions in further processessing.

The model would be developed around the requirements of relatively large drainage basins with a sparse network of data. However, it can be applied to a wide variety of large and small catchments, for both snowmelt and rain-only situations. To execute the model, the following input data will be needed:

1. Non-variable characteristics data describing the physical features of the basin. It will include drainage area, glacier covered area, elevation contours, altitude of meteorological stations, and other watershed characteristics affecting runoff.

2. Time variable data will include precipitation, air temperatures, snow covered area, streamflow data, and other parameters determining the distribution of temperature and precipitation.

3. Data specifying the initial conditions of the basin including the soil moisture status and snow accumulation, if any.

4. Miscellaneous job control and time control data which specify such items as total computation period, routing intervals, and special computer instructions to control printouts and other input-output alternatives.

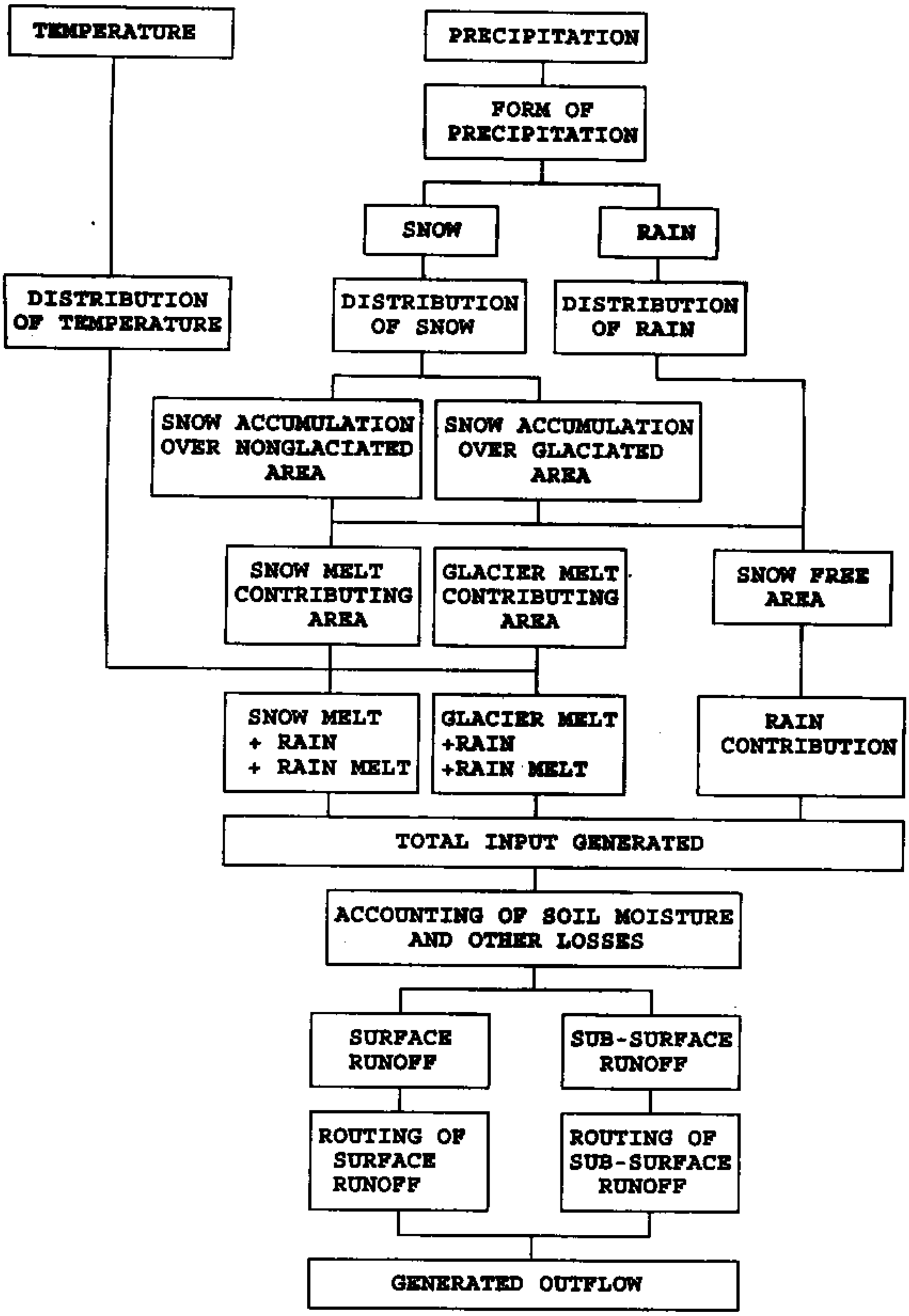

Figure 1: Flow chart showing the proposed structure of conceptual model

6.0 Division of Watershed into Elevation Bands

In the mountainous watersheds where temperature and snow depth vary with elevation, the drainage area is divided into some convenient number of the bands (usually elevation-contour bands) and each elevation band is treated as a separate watershed with its own characteristics and initial snow water equivalent. The areas can be derived planimetrically from topographic map. An inventory of snow accumulation and melt is maintained for each elevation band. This approach allows a more quantitative appraisal of the evolution and depletion of snowpack in the mountainous basins. The number of bands in a basin will depend upon the topographic relief of the basin. However, there is no specified range of altitude for slicing the basin in the bands, but an altitude difference of about 500 m or so is considered appropriate for dividing the basin into elevation bands. Moisture input for each band is the sum of snowmelt and rainfall. Runoff for each band is computed from watershed runoff characteristics developed for that particular band. Streamflow for the whole basin is found by summing the runoff synthesized for all bands. The program will store for every elevation band a value for each component of flow and each routing increment. The program maintains an inventory of soil moisture, snow accumulation, and all other values required to make the computation for the next period.

7.0 Handling of Meteorological Data

7.1 Distribution of temperature with altitude

Temperature data are available as point values at different elevations in a basin. These point values are extrapolated or interpolated to the mid elevation of each elevation zone using a predefined temperature lapse rate in the model. Lapse rates are known to be quite variable, ranging from high values of about the dry adiabatic lapse rate to low values representing inversion conditions. For example, during continuous rainstorm conditions the lapse rate will approximate the saturated adiabatic rate, whereas under clear sky, dry weather conditions, the lapse rate during the warm part of the day will tend to the dry adiabatic rate. During the night, under clear sky conditions, radiation cooling will cause the temperatures to fall to the dew point temperature, and this is particularly true for a moist air mass. As a result, night time lapse rates under clear skies will tend to be quite low, and at times even zero lapse rates will occur. The trends of variation of temperature show that a complete and detailed representation of the variability of temperature lapse rate is not possible, but in case temperature data are available at least at two stations, one at the bottom of the basin and one near the top, an actual temperature lapse rate could be computed and used for extrapolation/interpolation in the various zones. When one station is used, a lapse rate has to be assumed in order to extrapolate temperature from base station to the appropriate mean hypsometric elevation.

Generally temperature is lapsed, at either 6.5 °C/km or at a specified rate, from mean elevation of the index stations to the median elevation of the melt area of each band. The temperature at which snowmelt begins is the base temperature specified in the model. Temperature for each time period is lapsed from the index station to the rain-freeze and base temperature elevations. In fact in order to minimize the errors in extrapolation / interpolation of meteorological variables, at least one station for each elevation band is required. This will minimize the vertical distance for generating the information on meteorological variables.

7.2 Distribution of precipitation with altitude

A common problem with rainfall is the correct evaluation of point rainfall/precipitation in terms of areal distribution. Distribution of precipitation with altitude is much more difficult than the distribution of temperature. Charbonneau et al. (1981) mentioned that determination of the spatial distribution of precipitation is more important than the selection of a modelling approach. The distribution of precipitation is very much influenced by the topography of the basin in which height of the mountain barrier and direction of the air currents are the dominant factors.

The algorithms which describe the variation of precipitation with elevation can be described through the basic enhancement of precipitation with elevation barrier height. Because snow and rain indicate different patterns of variation with altitude, therefore, separate relationships should be provided. Previous studies conducted to understand the trends of precipitation variation with altitude in the study basin or in the nearby basin are very helpful to generate the precipitation at the different elevations bands of the basin, otherwise user's knowledge of the study area is to be used. Studies on precipitation distribution for few Himalayan basins has been carried out by Singh et al.(1995), and Singh and Kumar (1996b).

8.0 E: timation of Variables Associated with Hydrc :ogical Processes

8.1 Cc.nputation of degree-days

Air temperature expressed as degree-days is used in snow melt computations as an index of complex energy balance tending to snow melt. A degree-day, in its broad sense, is a unit expressing the amount of heat in terms of the persistence of temperature for 24 hour perio l of 1°C departure from a reference temperature. The simplest and most common expr ssion relating snow melt to temperature index is,

$$M = D_f (T_i - T_b) \qquad (1)$$

wh:re,

M = depth of melt water (mm) produced in a unit time

D_f = degree-day factor (mm °C^{-1} day^{-1})

T_i = index air temperature (°C)

T_b = base temperature (usually, 0°C)

Although temperature and other hydrologic conditions vary continuously throughout the day, daily mean temperature is the most commonly used index of temperature for snow melt. Where only maximum (T_{max}) and minimum temperatures (T_{min}) are available, the number of degree-days is computed as

$$T_i = T_{mean} = (T_{max}+T_{min})/2 \qquad (2)$$

At stations where hourly readings are made, the number of degree-days for each 24 hour period is determined by summing the hourly temperatures and dividing by 24. Further 0°C base temperature is generally used in computation of degree-days. This follows from the idea that most snowmelt results directly from the transfer of heat from the air in excess of 0°C. Some investigators have also used only T_{max} for computing the degree-days. In that case a lower value of D_f is used along with a lower value of base temperature.

8.2 Degree-day factor

The degree-day factor (D_f) is an important parameter and converts the degree-days to snow melt expressed in depth of water. D_f is influenced by the physical properties of snowpack and because these properties change with time, therefore, this factor also changes with time. The seasonal variation in melt factor is well illustrated by the results obtained from the study reported by Anderson (1973). The lower value being in the beginning of melt season and higher towards the end melt season. A wide range of a values has been reported in the literature with a generally increase as the snowpack ripens. For example, Garstaka (1964) reported extreme values of D_f as low as 0.7 mm °C^{-1} day^{-1} and as high as 9.2 mm °C^{-1} day^{-1}. Yoshida (1962) reported the values of D_f to be between 4.0-8.0 mm °C^{-1} day^{-1}, depending on the location, time of year and meteorological conditions. Singh and Kumar (1996) determined the D_f factor by monitoring a known snow surface area of the snow block within the snowpack at an altitude of about 4000m in the western Himalayan region in the summer. The mean daily value of the D_f was computed to be 5.94 mm °C^{-1} day^{-1}, while for a dusted block it increased to 6.62 mm °C^{-1} day^{-1}. In glacierized basins, the degree-day factor usually exceeds 6 mm °C^{-1} day^{-1} towards the end of summer when ice becomes exposed (Kotlyakov and Krenke, 1992). Details of degree-day factor determined under different conditions are given by Singh and Kumar (1996) and presented in table 1(a) and (b). As discussed above that D_f changes with season, therefore, when using degree-day approach changes in D_f with season should be taken into account. For rain periods, D_f can be adjusted as follows:

$$D_{f,rain} = D_f + 0.0126 * P_r \qquad (3)$$

where P_r is rainfall in mm. It is to be noted that this adjustment is required only when melt caused by rain is not computed separately. If this effect is taken into account with additional calculations, then unadjusted D_f is to be used throughout the snow melt calculations.

From the energy balance estimate of energy exchange the appropriate melt-factor for the day could be computed for each location. Then the melt-factors for each watershed could be determined by an interpolation scheme. The results should be nearly the same as if an energy balance model were used for each watershed. However, the computer requirements would be much less demanding.

Table 1(a): Mean daily snow melt factors for normal and dusted snow blocks. Daily average temperature used in the derivation of these values is computed as a mean of hourly (0800-0700 hours) temperature data (Singh and Kumar, 1996).

Date	Normal snow block (mm/(°C.day)	Dusted snow block (mm/(°C.day)
4.6.1995	6.03	6.75
5.6.1995	5.85	6.50
6.6.1995	5.95	6.62
Average	5.94	6.62

Table 1(b): Mean daily snow melt factors for normal and dusted snow blocks. Daily average temperature used in the derivation of these values is used as a mean of daily maximum and minimum temperatures (Singh and Kumar, 1996).

Date	Normal snow block (mm/(°C.day)	Dusted snow block (mm/(°C.day)
4.6.1995	5.70	6.39
5.6.1995	5.47	6.07
6.6.1995	5.52	6.14
Average	5.56	6.20

8.3 Form of precipitation

The distinction between rain and snow for each elevation band is very important for all the snow melt models because precipitation falling in the form of rain and snow behaves differently in terms of contribution to the streamflow. The contribution of rain to the streamflow is faster than that of snow because snow is stored in the basin until melted whereas rain is immediately processed. Precipitation in each period is assumed to fall as snow above the freezing elevation and rain below that elevation. On any one of the bands, precipitation might fall as rain, as snow, or a combination of the two. Rain on a band or part of a band is added directly to moisture input. Snow is added to the previous accumulation, if any. Accumulated snow is assumed to cover the entire band. Each band must be either snowfree or 100% snow covered. Further, the response of snow fallen over the accumulated snow or snow-free area, are different. The new snow that falls over the previously snow-covered area becomes the part of the previous seasonal snowpack and its effect on runoff depends on the condition of the snowpack. For example, rain falling over the cold snowpack, like in the early melt season, will be frozen in the snowpack and it is not immediately available for runoff. It melts when favourable atmospheric and snowpack conditions are available. But rain falling over the ripe snowpack is transferred through the snow layer and becomes available to contribute to runoff. The new snow falling over the snow-free area is considered as precipitation to be added to snowmelt, with delayed effect until the next warm day.

For this purpose a critical temperature is specified in the model to determine whether measured precipitation is rain or snow. This is of particular importance for models which simulate the build-up of snow cover from precipitation data. From direct observations, T_{crit} is generally higher than 0 °C as found by Charbonneau et al. (1981). Therefore, value of T_{crit} is usually selected slightly above the freezing point and may vary from basin to basin. A temperature 2 °C is proposed to be considered in this model. It indicates that

if $T_m \geq 2°C$, all precipitation is rain

if $T_m \leq 0°C$, all precipitation is snow

if $T_m \leq 2°C$ and $\geq 0°C$, precipitation will be considered as a mixture of rain and snow and their proportion will be worked out in the following way:

$$\text{Rain} = (T_m / T_{crit}) * P \quad (4)$$

$$\text{Snow} = P - \text{Rain} \quad (5)$$

where P is the total observed precipitation.

8.4 Precipitation representative factors

The precipitation measured at a point is not always representative of the areal distribution of precipitation. For example, a meteorological station may be in a rain shadow situation, or it may be in a narrow valley where it is receiving precipitation which is more representative of the mountain side some hundred meter higher than the station. These representation factors can be determined by comparing long term volumes of runoff with computed values. Therefore, each meteorological station has separate precipitation representative factor for rain and snow. These factors are introduced because, in general, snow measurements are more likely to be distorted by local exposure and orography.

8.5 Snow coverage and melt contributing area

Because snow accumulation and depletion is handled by the model, zonewise distribution of snow cover is computed by the model itself. In other words, extension and depletion of snow cover area is given by the model. However, if possible, it is recommended to update the computed snow covered area by the observed snow covered area for the dates at which observed snow covered area is available. For this purpose, data available through remote sensing technique can be used. The satellite (imagery or digital data) data on good resolution may be preferred and standard methods can be adopted for the analysis. Snowfall which occurs during the snowmelt period might modify the depletion of snowpack by increasing the snow covered area for some time. This temporary increase in snow covered area depends on the magnitude of the fresh snowfall and melting conditions. In general, fresh snowfall occurring during the melting period does not stay for longer periods because of the high temperatures generally prevailing around that time. Further, to obtain an insight into the pattern of depletion of snowpack, it is suggested that the depletion curves that normally relate the areal extent of the snow cover to elapsed time, may also be correlated with accumulated degree-days.

The melt contributing area can be estimated using altitude of base temperature and status of basin covered with snow. The base temperature altitude can be determined by extrapolating/ interpolating the temperature data. However, there may be two ways to obtain the area of snow covered basin. First, direct information on snow covered area from the satellite data and second compution of the snow covered area from the model itself.

8.6 Rain Melt

Rain-on-snow is a common feature in various alpine parts of the world and plays a significant role in generating high streamflows in some cases. Rain-on-snow events, in which snowmelt may be limited, are also hydrologically important (Colbeck, 1975; Berg et al. (1991). Most of the largest floods in British Columbia, Washington, Oregon and California have been associated with rain-on-snow (Kattelmann 1987; Brunengo, 1990). Archer et al. (1994) reported that in Britain more frequently flooding results from combination of melting snow and rainfall. A good rainfall occurs in the high altitude regions of Himalayas during the active melting period (Singh et al., 1995; Singh and Kumar, 1996). Further, rain-on-snow events are also considered a major cause in the release of avalanches. Introduction of liquid water into snow weakens the bond between grains and alters the snow texture which results in reduced mechanical strength of the snowpack. Various studies have been carried out to understand the role of rain in triggering avalanches in maritime climates (Conway et. al, 1988, Heywood, 1988; Conway and Raymond, 1993).

When rain falls on the snowpack it is cooled to the temperature of snow. The heat transferred to the snow by rain water is the difference between its energy content before falling on the snow and its energy content on reaching thermal equilibrium within the snowpack. For snowpacks isothermal at 0°C, the release of heat results in snowmelt, while for the colder snowpack this heat tends to raise the snowpack temperature to 0°C. In case the snowpack is isothermal at 0°C, the melt occurring due to rain is computed by

$$Q_p = \rho_w C_p(T_r\text{-}T_s)P_r /1000 \tag{6}$$

where,

Q_p = energy supplied to the pack by rain (kJ/(m^2.day))

ρ_w = density of water (1000 kg/m^3)

C_p = specific heat of water (4.20 kJ/(kg.°C))

T_r = temperature of rain (°C)

T_s = temperature of snow pack (0°C)

P_r = depth of rain (mm/day)

Substituting the values of various parameters in the above equation, it reduces to

$$Q_p = 4.2\ T_r\ P_r \tag{7}$$

Usually, rain temperature is considered equal to the air temperature on that day.

The melt caused by this energy is computed as

$$m_r = Q_p/(\rho h_f B) \tag{8}$$

Here,

m_r = melt caused by the energy supplied by rain (mm/day)

h_f = latent heat of fusion of water (~335 kJ/kg)

B = Thermal quality of snow (0.95-0.97)

In the other case, when snowpack is at sub-zero temperature, the freezing of the rain water exerts a considerable impact on the thermal regime of the snowpack. The latent heat of fusion of water plays an important role in increasing the temperature of the snowpack under such conditions. Increase in temperature (°C) is computed as

$$\Delta T = \rho_w P_r h_f / (1000.\rho_s d_s C_s) \tag{9}$$

ρ_s = density of snow (kg/m^3)

C_s = specific heat of snow (2.09 kJ/(kg.°C))

d_s = depth of snow (m)

8.7 Evaporation

Evaporation at various elevation bands can be estimated using temperature and soil moisture status of the respective band. As in the case for estimation of melting of snow, radiation, vapour pressure and wind data are also required for the estimation of evaporation. However, for the Himalayan basins such data are generally not available. Therefore, it is proposed to estimate evaporation using temperature and other relevant information. For this purpose, it is proposed to develop a relationship between temperature and potential evapotranspiration (PET) considering a monthly factor. Potential evapotranspiration is that which occurs when the supply of water to the plant/soil system is unlimited. Actual evapotranspiration should have the potential rate as an upper limit and otherwise be reduced by restriction in supply of water from the soil to the roots. Such relationships can be established for a station consisting of required data or for any other station existing in the nearby region with similar topographical features. The station may be in the basin or in the nearby region. PET can be distributed to each elevation band assuming a potential evaporation lapse rate. Actual evapotranspiration (AET) may be calculated using PET in conjunction with computed soil moisture status potential. For each band separate calculations are made for evaporation losses. The evaporation losses from the snow covered area of the basin can be considered negligible because Bengtsson (1980) reported that evapotranspiration losses from the snow covered area are very less.

9.0 Accounting of Soil Moisture and Runoff Generation

Accounting of soil moisture and runoff is carried out for each elevation band separately. The water resulting from rainfall, snowmelt and glacier melt will be used for

(a) increase in soil moisture and contribution to ground water storage

(b) evaporation losses

(c) runoff generation

Sub-division of the available runoff for a period into various components of streamflow, namely surface flow and sub-surface flow is done by the model. The moisture partition factors (R_s and R_r) determine the amount of moisture input contributing to surface runoff and sub-surface runoff. These factors depend on the infiltration rate of the moisture into the soil which is governed by the land use, type and texture of the soil and the soil condition including moisture content. In some models straight runoff coefficient is used for this purpose, but this factor is different than the runoff coefficient. The selection of these coefficients requires first hand knowledge of the basin and its hydrologic behaviour under different hydrometeorlogical conditions. After partitioning of runoff, routing is done for different components separately. Runoff from the total moisture input can be derived in the following way:

$$\text{Snowmelt runoff} = R_s * \text{melt} \tag{10}$$

$$\text{Rainfall runoff} = R_r * \text{rain} \tag{11}$$

$$\text{Total runoff} = R_s * \text{melt} + R_r * \text{rain} \tag{12}$$

where, R_s and R_r are the moisture partitioning factors for the snowmelt and rainfall, respectively. The value of moisture partitioning factor for the glacier can be considered equal to snow melt. For the events when snowmelt and rainfall occur simultenoulsy, rain is added to snow melt and a combined input behaves as melt water in terms of its transmission through the snowpack and response to the streamflow. Thus R_r equals R_s and the total runoff will be determined as

$$\text{Total runoff} = R_s * (\text{melt} + \text{rain}) \quad (13)$$

The remaining water is retained in the soil which contributes to soil moisture storage. The wetness of the soil is represented by a soil moisture index (SMI). The moisture input and evapotranspiration losses from the soil are the prime variables to control the soil moisture index. In other words, moisture input recharges the soil, whereas evapotranspiration depletes the soil moisture. Further, the water stored in the soil is responsible for contributing to the deep ground water zone after satisfying the soil moisture deficit, if any. The soil moisture deficit for an elevation band is the difference between the current soil moisture content of the band and the soil moisture field capacity deficit for the corresponding band. Water in excess to the field capacity will percolate further down and will increase the deep ground water storage. This component gives the model the capability of reproducing the post monsoon and winter streamflow more effectively. For this purpose, the soil moisture field capacity (SMFC) and initial soil moisture conditions are to be defined in the beginning. The soil moisture index for a particular band for a period is written as,

$$SMI_i = SMI_{i-1} + (1-R_s)*melt_{i-1} - AET_{i-1} \quad (14)$$

For the band which experiences only rainfall, the soil moisture accounting will take place in the following manner;

$$SMI_i = SMI_{i-1} + (1-R_r)*rain_{i-1} - AET_{i-1} \quad (15)$$

As discussed above, when rainfall occurs over the ripe snowpack and melting also taking place, then $R_s = R_r$, and accounting of soil moisture can be represented in the following form:

$$SMI_i = SMI_{i-1} + [(1-R_s)*(melt+rain]_{i-1} - AET_{i-1} \quad (16)$$

Water in excess of SMFC is accounted for ground water contribution, which in turn appears as base flow. It can be represented in the following way

$$GWC = SMI - SMFC \qquad (17)$$

A negative value of GWC indicates the soil moisture deficit. It is stored in the model and taken into account in the next event of moisture input from rainfall, snowmelt or glacier melt.

$$\text{If } GWC \leq 0, \text{ then } GWC = 0$$

This equation can also be used to account for the soil moisture deficit and would be able to provide the accumulated deficit for a particular period.

The combined runoff is obtained from rainfall, snow melt and glacier melt on daily basis. The continuity of runoff is maintained individually on each band or sub-basin area when watersheds are divided into elevation bands or snow covered and snow free areas. This provides the capability to evaluate differences in soil moisture and runoff conditions on a zonal basis.

10.0 Routing of Surface and Sub-surface Runoff

On large mountainous basins, the routing time for water travelling from the source (snowpack) to the basin outlet is often more than one day. Therefore, of the water produced by snowmelt on day n, some portion can be expected to appear as runoff on day n, while the remaining water will appear as runoff on subsequent days. As discussed above, moisture input is divided into surface flow (fast runoff) and sub-surface flow (slow runoff) and water allocated to each components of runoff is routed to produce the time distribution of runoff. The routing will be done using the concept of cascade linear storage reservoirs with equal storage coefficient. According to this concept, the resulting outflow from the nth reservoir at time t from a unit instantaneous inflow can be written as

$$u(t) = \frac{1}{k\sqrt{n}}\left(\frac{t}{k}\right)^{n-1} e^{-\frac{t}{k}} \qquad (18)$$

where,

k is the linear storage constant for each of reservoirs in the cascade,

n is the number of linear reservoirs in the cascade

t is the time after occurrence of input

For the routing of surface runoff (fast runoff) a cascade of linear reservoirs ($n > 1$) will be considered. The sub-surface flow is assumed to accumulate in a linear storage reservoir ($n=1$) and released slowly as long-term base flow. To produce the total runoff at a particular time, the routed flow from each components will be added. Consideration of flow into two components (surface and sub-surface) will result is less number of parameters to be optimized. The minimization of parameters is an important aspect of the model which should be addressed and is important if the model is not to become too cumbersome.

It has been shown by the environmental isotope tracer studies (Martinec, 1985) that overland flow is not a major part of the snowmelt runoff as previously believed. There is increasing evidence (Kobayashi, 1985) that a major part of the melt water infiltrates and quickly appears as corresponding outflow from the ground water reservoir.

The calibration may be accomplished by any of three methods: analytical, numerical, or subjective optimization. With subjective optimization, initial values of model parameters are selected using modeller's knowledge of the system and then trial- and-error is used to adjust the initial values in order to test by the goodness-of-fit statistics. Analytical method is more precise and reproducible method of calibration. The criterion function is defined to be the sum of squares of the prediction error. To obtain the accurate estimate of the parameters, the model should be calibrated by operating the model continuously with a number of years of data at a time.

11.0 Conclusions

Inspite of substantial contribution from the Himalayan rivers, at present no hydrological model is developed in India which can be applied for simulating/ forecasting runoff for the Himalayan rivers which consists of the contribution from rain, snow and glaciers melt. A conceptual model is proposed and described for calculation of streamflow runoff arising from rainfall, snowmelt, and glacier melt for the Himalayan basins. The simple structure of the model is designed keeping in view the sparse network, availability of data and topography of the Himalayan basins. The model is based on the area-elevation characteristics of the watershed and utilizes the relationships describing the temperature lapse rates and orographic precipitation distribution. The elevation-based structure of the snowmelt model was accomplished by subdividing the catchment into elevation bands. Each band was assumed to be either completely snow covered or else snow free and homogeneous with respect to snow cover. The method is so designed that a complete water balance is maintained between input, outflow and evapotranspiration, as well as accounting for soil moisture and groundwater. Because there is difference in the melt rate of snow and ice under the same environment, therefore, separate computation of snowmelt runoff and glacier melt runoff are suggested. The contribution from various sources is added together and acounting of losses is made. The routing of surface and sub-surface flow is proposed using concept of linear cascade reservoirs. Various parameters associated with melting processes are described and discussed in detail.

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