CHAPTER 3

SNOW/GLACIER MELT RUNOFF MODELING

3.1 General

Snow is of great importance as a key environmental parameter. It not only influences earth's radiation balance but also plays a significant role in river discharge. A major source of river discharge in middle and higher latitudes are contributed through snowmelt from seasonal snow covered areas of the Earth's mountain region. The Himalayan mountain system is the source of one of the world's largest suppliers of freshwater. From west to east the Himalayan glaciers can be divided into three segments according to their latitudes and topographic features: those on the Western Himalayas, the Central Himalayas and the Eastern Himalayas. Broadly rivers originating from the Himalayan region can be grouped in three main river systems; the Indus, the Ganges and the Brahmaputra. In India, 35% of the geographical area is mountainous and out of which 58% is covered under Himalaya. This area covers about 16% of India's total geographical area. The water flowing in the Himalayan Rivers is the combined drainage from rainfall, snowmelt and glacier-melt runoff. In Himalayan region, several water resources projects are under operation and many more are coming up to harness these resources. These projects are of considerable national and local importance in terms of hydropower generation, irrigation, flood control and subsequent socio-economic development of the region. Proper planning and management of these projects depends on correct assessment of stream flow generated from snow and glacier melt.

The Himalayan region, including the Tibetan Plateau, has shown consistent trends in overall warming during the past 100 years (Yao et al. 2007). Various studies suggest that warming in the Himalayas has been much greater than the global average of 0.74°C over the last 100 years (IPCC, 2007). Long-term trends in the maximum, minimum and mean temperatures over the north western Himalaya during the 20th century (Bhutiyani and others, 2007) suggest a significant rise in air temperature in the north western Himalaya, with winter warming occurring at a faster rate. Global warming has remitted in large-scale retreat of glaciers throughout the world. This has led to most glaciers in the mountainous regions such as the Himalayas to recede substantially during the last century and influence stream run-off of Himalayan Rivers. The widespread glacial retreat in the Himalayas has resulted in the formation of many glacial lakes. Glacier retreat and shrinking could form dangerous moraine lakes, which can produce sudden glacier lake outburst floods (GLOFs) damaging life and property downstream over a long distance. For water resources planning and management, it is therefore essential to study and monitor the Himalayan glaciers and glacial lakes including GLOF. There are very limited studies on the impact of climate change on the Himalayan River basins. However, NIH has conducted sensitivity analysis using the SNOWMOD on some of the Himalayan basins i.e. Sutlej, Spiti, Chenab, Beas and Dokriani basins.

3.2 Snow and Glacier Melt Runoff

Snow and glacier runoff play a vital role in making all these rivers perennial, whereas the rainfall contribution during the monsoon period is critical for storages in various reservoirs. Estimation of the snow and glacier contribution in the annual runoff of various

Himalayan rivers is necessary for the development and efficient management of water resources, which include flood forecasting, reservoir operation, design of hydraulic structures, etc. The planning of new multi-purpose projects on the Himalayan Rivers further emphasizes the need for reliable estimates of snow and glacier runoff. Despite their well-recognized importance and potential, not many attempts have been made to assess the snow and glacier contributions in these rivers, although a few hydrological studies have been carried out for glacierized river basins in the western Himalayan region (Singh *et al.*, 1994, 2005; Singh & Kumar, 1997; Singh & Jain, 2002). Singh *et al.* (1994) estimated about 28% as the average contribution of snow- and glacier-melt in the annual flow of the Ganga River at Devprayag. Singh *et al.* (1997) estimated about 49% as the snow and glacier contribution for the Chenab River at Akhnoor. In a similar study of the Satluj River at Bhakra Dam site, the snow- and glacier-melt contribution was estimated to be 60% (Singh & Jain, 2002) and 39% for Beas basin up to Pandoh dam (Jain et al., 2010).

The snowmelt model is designed to simulate daily streamflow in mountainous basin where snowmelt is major runoff component. The process of generation of streamflow from snow covered areas involves primarily the determination of the amount of basin input derived from snowmelt along with some contribution from glacier melt and rain. Most of the Himalayan basins experience runoff from the snowmelt as well as rain. The contribution of rain comes from the lower part of the basin having elevation less than 2000m, the middle part between 2000m to 4000m contributes runoff from the combination of rain and snowmelt while in the high altitude region having elevation more than 4000m, runoff computation comes from the glacier melt. The contribution from snow and glacier is controlled by the climatic conditions and therefore, varies from year to year. For the Himalayan basins, most important factor influencing the development of model and the approach to be adopted is the limited availability of data. There is very sparse network of measurement stations in the high altitude region of the Himalayas. Data collected at most of the measurement stations consist of mostly temperature and precipitation data. Most of the meteorological data required for the application of energy balance approach is hardly available. Therefore, development of a conceptual model with an index approach for calculating the snow and glacier melt runoff is the suitable choice for snowmelt runoff in the Himalayan basins. Keeping in view the limited data availability, the structure of the present model has been kept simple so that all suitable/available data is properly utilised.

3.3 Modeling Approach

Modeling of streamflow from a basin is based on transformation of incoming precipitation to outgoing streamflow by considering losses to the atmosphere, temporary storage, lag and attenuation. Hydrological models use for simulation or forecasting of streamflow are generally categorized as simple regression models, black-box models, conceptual models and physically based models. Black-box models are generally lumped in nature by treating a basin as a single spatial unit. Physically based models use appropriate physical equations contain equations for all the processes involved. These models are invariably distributed and involve desegregation of basin into zones or grid cells. Conceptual models may be either lumped or distributed with one or more storage represented by conceptual units and connected by incoming and outgoing fluxes representing different hydrological pathways.

The conversion of snow and ice into water is called snowmelt, which needs input of energy (heat). Hence snowmelt is linked with the flow and storage of energy into and through the snowpack (USACE, 1998). Snowmelt models have two basic approaches towards calculating the amount of snowmelt occurring from a snowpack: energy budget method and temperature index method. The energy budget approach attempts to make the process as physically based as possible. The goal is to simulate all energy fluxes occurring within the snowpack to give an accurate account of total snowmelt in response to each of these energy fluxes over time and space. This approach is extremely data intensive, requiring vast amounts of input data either to force an initial run of a model, or to calibrate it based on historical data before running a forecast. Too often, this approach suffers from inadequate data supply or simply that the level of data is unwarranted for the purpose at hand. In light of the intensive data requirements necessary for the energy budget approach, an alternative method known as the temperature index or degree day approach allows for snowmelt calculation with much less data input. The basis of the temperature index approach is that there is a high correlation between snowmelt and air temperature due to the high correlation of air temperature with the energy balance components which make up the energy budget equation.

When precipitation falls as snow it accumulates in the basin and snowpack is developed. The solid precipitation results in temporary storage and the melt water reach the river in the melt season. The snow accumulation in Himalayas is generally from November to March, while snowmelt is from April to June. During April to June, snowmelt is the predominant source of runoff and during July to September it forms a significant constituent of melt. The snowmelt runoff modeling is of vital importance in forecasting water yield. Snow and glacier melt runoff is very important particularly in the lean season and it plays a vital role in making perennial nearly all the rivers originating in Himalayas perennial. Conceptually snowmelt runoff models are rainfall-runoff models with additional component or routines added to store and subsequently melt precipitation that falls as snow. Some snowmelt runoff models are purpose built and are not intended for use in non snowy environments, though they have to make some allowance for precipitation which falls as rain during the melt season. In general, the part of the model which deals with snowmelt has to achieve three operations at each time step.

- Extrapolate available meteorological data to the snowpack at different altitude zones calculate rates of snowmelt at different points, and
- Integrate snowmelt over the concerned effective area of the basin and estimate the total volume of new melt water.

The energy balance or heat budget of a snowpack governs the production of meltwater. This method involves accounting of the incoming energy, outgoing energy, and the change in energy storage for a snowpack for a given period of time. The net energy is then expressed as equivalent of snowmelt. The energy balance equation can be written in the form (Anderson, 1973):

$$\Delta Q = Q_n + Q_e + Q_h + Q_g + Q_m \qquad (3.1)$$

where: Q_n=net radiation (long and short wave), Q_e = latent heat transfer, Q_h = sensible heat transfer, Q_g = ground snow interface heat transfer, Q_m = heat transfer by mass changes (advected heat), ΔQ = change in heat storage.

In the above equation, different components of energy are considered in the form of energy flux, which is defined as the amount of energy received on a horizontal snow surface of unit area over unit time. The positive value of Q_m will result in the melting of snow.

The relative importance of the various heat transfer processes involved in melting of a snowpack depends on time and local conditions. For example, radiation melting dominates the weather conditions when wind is calm. Melting due to sensible heat flux dominates under warm weather conditions. When all the components of energy balance equation are known, the melt rate due to energy flux can be expressed as,

$$M = Q_m/[\rho_w.L.\beta] \qquad (3.2)$$

where

M = depth of meltwater (m/day)

L= latent heat of fusion (333.5 kJ/kg)

ρ_w = density of water (1000 kg/m^3)

β = thermal quality of snow

The thermal quality of snow depends on the amount of free water content (generally 3 – 5 %) and temperature of the snowpack. For a snow that is thermally ripened for melting and contains about 3% of free water content, the value of β is 0.97. For such cases equation (3.2) reduces to,

$$M = Q_m/[1000*333.5*0.97] \qquad (3.3)$$

which leads to a simple relationship,

$$M = 0.0031 * Q_m \quad \text{(mm/day)} \qquad (3.4)$$

Data required to evaluate Equation (3.1) are measurements of air temperature, albedo, wind speed, vapour pressure and incoming solar radiation (Anderson, 1973).These data are difficult to obtain on a basin scale and extrapolation to areal values from point data is another problem, especially the spatial detail is required for distributed models. This becomes further difficult when such data is required for a highly rugged terrain, such as Himalayan terrain. As such application of the energy balance equation is usually limited to small, well-instrumented or experimental watersheds.

3.3.1 Degree-day approach or temperature index approach

The specific type of data required for the energy budget method is rarely available for carrying out the snowmelt studies. This is particularly true for the Himalayan basins where the network for data collection is poor. The commonly available data in the Himalayan basins are daily maximum and minimum temperatures, humidity measurements and surface wind speed. This is why the temperature indices are widely used in the snowmelt estimation. It is generally considered to be the best index of the heat transfer processes associated with the snowmelt. Air temperature expressed in degree-days is used in snowmelt computations as an index of the complex energy balance tending to snowmelt. A 'degree-day' in a broad sense is a unit expressing the amount of heat in terms of persistence of a temperature for 24-hour period of one-degree centigrade departure from a reference temperature. The simplest and the most common expression relating daily snowmelt to the temperature index is,

$$M = D\,(T_i - T_b) \tag{3.5}$$

where

M= melt produced in mm of water in a unit time
D= degree-day factor (mm $^{o}C^{-1}day^{-1}$)
T_i = index air temperature (^{o} C)
T_b = base temperature (usually 0 ^{o}C)

Daily mean temperature is the most commonly used index temperature for snowmelt. The mean temperature is computed by,

$$T_i = T_{mean} = (T_{max} + T_{min}) / 2 \tag{3.6}$$

There are several methods of dealing with the index temperatures used in calculating the degree-day value. When using the maximum-minimum approach, the most common way is to use the temperature as they are recorded and calculate the average daily temperature. The inclusion of minimum temperature at an equal weight with the maximum temperature gives undue emphasis to this effect. On the other hand, the use of maximum temperature only excludes this effect entirely. In order to counteract such problems, alternatives have been suggested in which unequal weight to the maximum and minimum temperatures are given. U.S. Army Corps of Engineers (1956), used the following index temperatures,

$$T_i = (2T_{max} + T_{min}) / 3 \tag{3.7}$$

Another approach is given by,

$$T_i = T_{max} + (T_{min} - T_{max})/b \tag{3.8}$$

where b is a coefficient less than 2.

When the basin is subdivided based on elevation zones, the degree-days are extrapolated to an elevation zone by using a suitable lapse rate i.e.,

$$T_{i,j} = \delta\,(h_{st} - h) \tag{3.9}$$

where

$T_{i,j}$= degree-day of the elevation zone
δ= temperature lapse rate in ^{o}C per 100 m
h =zonal hypsometricmean elevation in m.
h_{st}= altitude of the temperature station in m.

In a basin with little seasonal variation, a lapse rate of 0.65 ^{o}C /100 m has been found to be suitable.

3.4 Forecasting of Snowmelt Runoff

Streamflow forecasting is the process of estimating future stages of flow and their time sequence at selected places along a river. The best possible forecast is the one which completely and identically describes the process that is supposed to occur in the future. If the forecast is not available sufficiently before the event occurs, its value is nil. The entire forecasting has to be planned around a time factor. The lead time of a forecast often determines the value of the forecast. Since very precise forecasts are not possible, the forecast should be used with minimum variance forecast errors. In real-time forecasting, the time needed for data to reach from upstream catchment to the place of analysis is very important and it involves checking inconsistent and incomplete data and its validation before it is used for computing an accurate forecast.

Reliable long-term or seasonal forecasts are essential to various aspects of water resources planning and management. The short-term forecast, a few days in advance, is very helpful in operation of reservoirs or other flow controls. For short-term forecasting, only the present state of the watershed and streamflow are needed, while for long-term forecasts it is necessary to have a reliable prediction of various meteorological parameters in addition to the knowledge of initial conditions of the basin. When the temperature index method is used for snowmelt computation, the success of forecasting depends especially on the accuracy of forecasting temperature, precipitation, and snow covered area. In general, temperature can be forecasted with higher accuracy than precipitation. Known historic meteorological records can be used to forecast the input parameters of a model.

Depending on the snow cover and temperature conditions in the basin, the entire basin or a part thereof can contribute to melting. Therefore, forecasting of the snowline elevation is also very important. Snowline also decides the snow covered area and snow free or bare area of the catchment. If rainfall occurs during a snow-cover period, the contributions of rainfall from bare area and snow covered area will be different. The complete melting of seasonal snow cover occurs generally within a known period of time, but uncertainty in the upper position of snowline in glacier regions limits the accuracy of long-range forecasting. Therefore, seasonal forecasting is not much successful in the areas where glaciers exist. Reliable climatic forecasts may help improve the accuracy of short-range or long-range snowmelt runoff forecasts. The reliability of a method used for forecasting depends on the adequacy of available hydrological data used for calibration and capability of forecasting of input variables. As temperature can be predicted more accurately than other parameters used in the energy balance equation, the temperature index methods are mostly used in operational forecasting.

3.5 Data and Parameters

3.5.1 Snow Cover Area (SCA)

Conventional snow cover data, such as snow surveys, provide detailed information on such snow pack properties but their site specific nature and infrequent occurrence limit their potential for use in distributed models. In order to provide distributed information characterizing the snow cover of a watershed, snow survey measurements must be extended to regions where no snow survey data are available. Remote sensing offers a significant potential for collecting this data in cost effective manner. Because of difficult access and expensive operation of hydrological stations, radar or satellite data are particularly appropriate. However, ground truth data are indispensable in the calibration and verification of remotely sensed data. Aerial and satellite surveys are useful in mapping snow lines. The wealth of observational material obtained by remote sensing can be integrated into models, such as snowmelt runoff models, considerably improving the forecast accuracy. Snow was first observed by satellite in eastern Canada from the TIROS-1 satellite in April 1960. Since then, the potential for operational satellite based snow cover mapping has been improved by the development of higher temporal frequency satellites such as GOES (Geostationary

Operational Environmental Satellite), Landsat, SPOT and IRS series, and NOAA-AVHRR, NIMBUS-SMMR and DMSP SSM/I satellites.

Another possible source for snow cover information is microwave satellite imagery. The regular and frequent mapping of snow cover is possible using a sensor independent of time and weather. Depending on wavelength, microwave radiation will penetrate clouds and most precipitation, thus providing an all-weather observational capability, which is very significant in snow regions where clouds frequently obscure the surface (Schanda et al. 1983).There are two types of microwave sensors: active and passive. Passive radiometers include NIMBUS-7 Scanning Multi-channel Microwave Radiometer (SMMR) and the DMSP SS/I satellites and measure surface brightness temperatures. Active satellite sensors contain synthetic aperture radar (SAR) and emit microwave radiation at a specific frequency and polarization and measure the return backscatter in the form of the backscatter coefficient.

Microwaves have unique capabilities for snow cover modeling:

1. They can penetrate cloud cover (Chang, 1986), providing reliable data;
2. They can penetrate through various snow depths depending on wavelength therefore potentially capable of determining internal snowpack properties such as snow depth and water equivalent (Rott, 1986);

Active microwave sensor on the First European Remote Sensing Satellite (ERS-1) and Canadian RADARSAT offer the possibility to observe seasonal snow cover characteristics in detail over the entire snow-cover season. In one simulation of RADARSAT data, snow-cover classification accuracy was 80%, comparable to aircraft Synthetic Aperture Radar (SAR). Comparing a classification of snow-covered area based on SAR with that done using TM suggests that a SAR-based classification is sufficiently accurate to substitute for visible-and-near-IR based estimates when such data are not available, e.g., due to cloudiness.

Passive microwave signals are also sensitive to the liquid-water content of snow, thus offering the potential to develop snow wetness estimates. The sensitivity of passive microwave signals to snow wetness aids in determining the onset of spring melt and the occurrence of multiple melt events during the winter.

3.5.2 Division of catchment into elevation bands

There are two approaches for defining a computer model of a watershed; a lumped model, which does not take into account spatial variability of processes, and a distributed model, which consider these. Lumped model is a simple approach and can be applied for basins that have a wide variety of physical features. However, the major limitation with this model is that it does not run beyond a single event (USACE, 1998). Distributed model on the other hand can be run for continuous simulation. In such models, the watershed is divided into subunits with variables being computed separately for each. This method of subdividing the basin is logical one, since in mountainous areas hydrological and meteorological conditions are typically related to elevation.

Distributed models attempt to account for the spatial variability by dividing the basin or catchment into sub-areas and computing snowmelt runoff for each sub area independently with a set of parameters corresponding to each of the sub-areas. Generally distributed models use one of the following general approaches to sub-divide a basin: (i) Elevation zone or band (ii) basin characteristics such as slope, aspect, soil, vegetation etc. and (iii) a fixed or variable length, two or three-dimensional grid. Lumped and distributed models are classified further by their use of energy balance approach or temperature index approach to simulate the snowmelt process.

3.5.3 Degree days

Degree-days are the departures of temperature above or below a particular threshold value. Generally, a threshold temperature of 0°C is used, with snowmelt considered to have occurred if the daily mean temperature is above 0°C. This follows from the idea that most snowmelt results directly from the transfer of heat from the air in excess of 0°C. The difference between the daily mean temperature and this threshold value is calculated as the degree-day. Snowmelt-runoff models, which incorporate a degree-day or temperature index, routine are the most commonly used in operational hydrology and have been successfully, verified world-wide over a range of catchment sizes, physical characteristics and climates. The basic form of the degree-day approach is:

$$M = D(T_{air} - T_{melt}) \tag{3.10}$$

Where M = daily snowmelt (mm/day); D = degree-day factor (mm ° C^{-1} day^{-1}); T_{air} = index air temperature (°C); and T_{melt} = threshold melt temperature (usually, 0°C).

Although air temperature and other hydrological variables vary continuously throughout the day, the daily mean air temperature is the most commonly used index temperature. When daily maximum (T_{max}) and minimum (T_{min}) air temperature is available, daily mean air temperature is calculated as

$$T_{air} = T_{mean} = \frac{(T_{max} + T_{min})}{2} \tag{3.11}$$

3.5.4 Degree day factor

The degree-day method is popular because temperature is a reasonably good measure of energy flux, and, at the same time, it is a reasonably easy variable to measure, extrapolate, and forecast (Martinec and Rango, 1986). The degree-day factor, D, is an important parameter for snowmelt computation and converts the degree-days to snow melt expressed in depth of water. D 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.

3.5.5 Rain on snow

Rain-on-snow event is hydrologically an important phenomenon as most of the floods in British Columbia, Washington, Oregon and California were reported to have occurred due to this event (Colbeck, 1975; Kattelmann 1987; Brunengo, 1990; Berg et al., 1991; Archer et al., 1994). Further, this event is one of the prime causes of avalanches as rain falling over snow weakens the bond between the snow packs thereby reducing the mechanical strength of the snowpack (Conway et. al, 1988; Heywood, 1988; Conway and Raymond, 1993).

3.6 Processes of Snow/Glacier Melt Runoff Modeling

3.6.1 Snow accumulation processes

A detailed understanding of the seasonal and spatial variations of snow accumulation within a basin is critical for the winter water budget and is a key issue to reduce uncertainties in modeling snowcover ablation and snowmelt runoff. Snow accumulation is what remains after falling snow has been modified by interception in vegetation canopies, sublimation, redistribution as a result of wind transport, and melt. Consequently, it is incorrect to assume that an increase of the snow on the ground is equivalent to snowfall (Pomeroy and Gray, 1995). Estimation of snowfall is particularly challenging. The properties and characteristics of fallen snow change as a function of energy fluxes, temperature, wind, moisture, water vapour, and pressure (Gray and Male, 1981). Sublimation reduces the snow available for accumulation. Compared with snow on the ground, snow sublimates more quickly in forest canopies because of greater absorption of short-wave radiation by the canopy and a higher exposure to turbulent-exchange forces (Lundberg et al., 2004). Forest canopy is important in controlling the interception-sublimation process (Pomeroy et al., 2002).

3.6.2 Snow ablation process

Snowmelt is the most significant hydrological event in arctic and subarctic environments, since the spring snowmelt freshet is usually the largest runoff event of the year. The snowmelt period is characterised by complex and dynamic processes resulting in rapid changes in albedo, turbulent fluxes, internal snow energy, and surface temperature as the snow cover is depleted. These changes have drastic effects on the surface-atmosphere exchanges (Pomeroy et al., 1998b).

3.6.3 Precipitation data and distribution

The most challenging object of hydrological simulation of a mountain basin is the measurement of meteorological variables. The major problems posed in high mountain areas are the accessibility to the mountains on a continuous basis, the accuracy of measured meteorological variables, and the areal representativeness of measurements (Panagoulia, 1992). It has been observed that the most important factor in accurate estimation of snowmelt runoff is the assumptions of the spatial distribution and form of precipitation. In a distributed model, it is very essential to distinguish between rain and snow in each elevation band because these two form of precipitation behaves very differently in terms of contribution to the streamflow. Rainfall is contributed faster to the streamflow whereas snowfall is stored in the basin until it melts. The form of precipitation is influenced by two factors; meteorological and topographical. Meteorological factor includes air temperature, lapse rate, wind etc and topographical factors include elevation, slope, aspect, vegetation cover etc. Snow falling through warmer atmosphere or melting level air temperature melts and falls as rain. Similarly, snow falls at elevation above melting level and rain falls at elevation below melting level. Fig. 3.1 shows schematically how topographic and meteorological factors influence the form of precipitation. Similarly, the figure explains the mechanism adopted by the distributed hydrological model to determine the form of precipitation, considering topographic and meteorological factors, as below:

If $T_m \geq T_c$, all precipitation is considered as rain;

If $T_m \leq 0°C$, all precipitation is considered as snow

where T_m is mean air temperature.

In the cases, if $T_m \geq 0°C$ and $T_m \leq T_c$, the precipitation is considered as a mixture of rain and snow and their proportion is determined as follows:

$$Rain = \frac{T_m}{T_c} \times P \quad (3.12)$$

$$Snow = P - Rain \quad (3.13)$$

Where P is the total observed precipitation

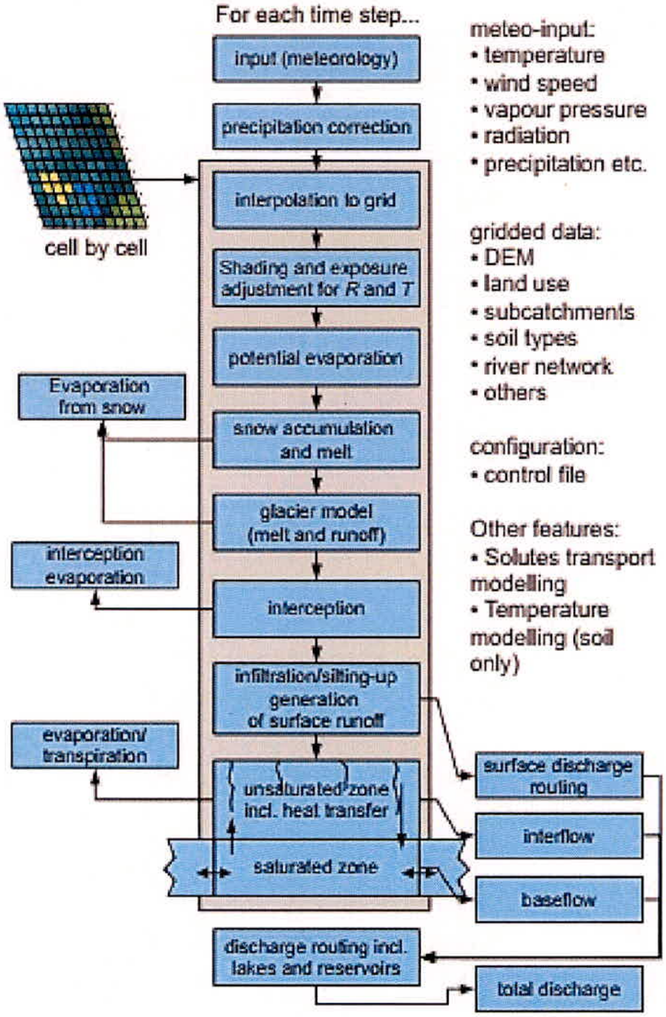

Figure 3.1: Schematic flow chart of model input parameters in a distributed hydrological model

3.6.4 Temperature data – Space and time distribution and Lapse Rate

Air temperature has a logical connection with many of the energy exchanges involved in snowmelt. Also it is the meteorological variable which is readily available to hydrologists in historical and near real time. Hence air temperature is the most widely used index in snowmelt (Sorman, 2005). Daily mean temperature is the most commonly used parameter in snowmelt computation. For the present study daily mean air temperature was calculated by using the equation given below:

$$T_{air} = T_{mean} = \frac{(T_{\max} + T_{\min})}{2} \quad (3.14)$$

Temperature shows an inverse relation with elevation. The rate with which the temperature changes with increase in elevation is called as lapse rate. Lapse rate is not a constant value but changes with season and region. 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 temperature 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 (Jain, 2001). Hence to define the spatial coverage of air temperature by extrapolation in a more representative manner, we need to input seasonally varying lapse rate value in the model (Jain et al., 2007c).

The daily temperature in the various elevation bands can be calculated by using the temperature lapse rate approach by extending data from the base station using the equation,

$$T_{i,j} = T_{i,base} - \delta(\mathrm{h}_{\mathrm{j}} - \mathrm{h}_{\mathrm{base}}) \quad (3.15)$$

Where $T_{i,j}$ = daily mean temperature on i^{th} day in j^{th} zone (°C), $T_{i,base}$= daily mean temperature (°C) on i^{th} day at the base station, h_j= zonal hypsometric mean elevation (m), h_{base}= elevation of base station (m), and δ= Temperature lapse rate in °C per 100 m.

3.7 Snowmelt Runoff Models

3.7.1 Snowmelt runoff model (SRM)

The snowmelt runoff model (SRM) of is widely used. The Snowmelt-Runoff Model is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of climate change simulation. It can be written as:

$$Q_{n+1} = [C_{Sn} \cdot a_n (T_n + \Delta T_n) S_n + C_{Rn} P_n] \frac{A.10000}{86400} (1 - K_{n+1}) + Q_n K_{n+1} \quad (3.16)$$

where

Q = average daily discharge [m^3s^{-1}];

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation), with cS referring to snowmelt and c_R to rain;

a = degree-day factor [cm °C^{-1}d^{-1}] indicating the snowmelt depth resulting from 1 degree-day;

T = number of degree-days [°C d];

Δ T = the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [°C d];

S = ratio of the snow covered area to the total area; and

P = precipitation contributing to runoff [cm].

A preselected threshold temperature, T_{CRIT}, determines whether this contribution is rainfall and immediate. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

A = area of the basin or zone [km^2];
k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall;
k = Q_{m+1}/Q_m (where m and m + 1 are the sequence of days during a true recession flow period).
n = sequence of days during the discharge computation period. Equation (3.16) is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n + 1 day. Various lag times can be introduced by a subroutine. 10000/86400 = conversion from $cm^{-1}km^2d^{-1}$ to $m^3\ s^{-1}$

It is clear from equation (3.16) that the application of the SRM requires both the area of snow cover, which can be obtained from remotely sensed imagery and ancillary data such as temperature, precipitation, and runoff, which cannot be obtained in this way. The SRM is essentially a form of geographic information system in which data from different sources are fused. The ability to distinguish between frozen and melting snow cover can enhance the performance of the model.

3.7.2 Snowmelt Model (SNOWMOD)

The snowmelt model (SNOWMOD) is a temperature index model, which is designed to simulate daily streamflow for mountainous basins having contribution from both snowmelt and rainfall. The generation of streamflow from such basins involves with the determination of the input derived from snowmelt and rain, and its transformation into runoff. It is a distributed model and for simulating the streamflow, the basin is divided into a number of elevation zones and various hydrological processes relevant to snowmelt and rainfall runoff are evaluated for each zone. The model achieves three operations at each time steps. At first the available meteorological data are extrapolated at different altitude zones. Than the rates of snowmelt are calculated at each time step. Finally, the snowmelt runoff from SCA and rainfall runoff from SFA (snow-free area) are integrated, and these components are routed separately with proper accounting of baseflow to the outlet of the basin. The model optimizes the parameters used in routing of the snowmelt runoff and rainfall runoff. Fig.3.1 schematically shows the different steps involved with in the model. Details of computation of melt runoff and generation of streamflow.

3.7.2.1 Model structure

The flow chart of the model structure is shown in Fig.3.1. Specific major considerations in the design of the model components are as follows:

(a) The model computes or simulates the snow melting and runoff processes on a daily basis. The basin is divided into snow covered and snow free part and modeling of runoff is carried out separately from these two parts.

(b) Use of practical yet theoretically sound methods for subdividing the basin in evaluating the various physical and hydrologic processes relevant to snow melt and its appearance as streamflow at the outlet.

(c) The model has ability to perform simulation computations over any specified time interval according to the availability of input data

(d) Capability of the model to adjust itself to specified or observed conditions of streamflow from the previously computed amounts, and maintaining continuity of functions in further processing.

(e) Optimisation of parameters used in routing of the rainfall-runoff and snowmelt runoff.

To execute this model, the following input data are required:

1. Physical features of the basin which include snow covered area, elevation bands and their areas, altitude of meteorological stations, and other watershed characteristics affecting runoff.
2. Time variable data include precipitation, air temperatures, snow-covered area, streamflow data and other parameters determining the distribution of temperature and precipitation.
3. Information on the initial soil moisture status of the basin
4. Miscellaneous job controls and time control data which specify such items as total computation period, routing intervals etc.

3.7.3 Water flow and balance simulation model (WaSiM)

Water Flow and Balance **Si**mulation **M**odel (WaSiM) is a grid-basedtool for investigating the spatial and temporal variability of hydrological processes in complex river basins. It is a distributed, deterministic, physically based hydrologic model. The model can be used in various spatial and temporal scales ranging from the sizes of <1 km^2up to more than 100,000 km^2 with temporal resolution ranges from minutes to several days. WaSiM also equipped tobe used for both short-term (floods) and long-term simulations (long-term water balance simulations). For each time step, the sub models are processed one by one for the entire model grid thus taking most advantage of parallelized algorithms as offered by the OpenMP standard. Depending on the general availability of data and the hydrological problem to be solved, WaSiM allows a selection from several algorithms for the simulation of a specific process. The minimum data requirements for the model are time series of precipitation and temperature, as well as raster data for topography, land use and soil properties.

3.7.4 GEOtop hydrological model

GEOtop is a distributed model of the mass and energy balance of the hydrological cycle. GEOtop is applicable to simulations in continuum in small or relatively large mountain catchments. GEOtop deals with the effects of topography on the interaction between energy balance (evapotranspiration, heat transfer) and hydrological cycle (water, glacier and snow).

3.7.4.1 Availability

The source code of GEOtop 2.0 with detailed documentation is available at the following link: https://github.com/geotopmodel
Stefano Endrizzi, is maintaining his own source code at: https://github.com/se27xx/GEOtop/

3.7.4.2 Use and license of GEOtop

GEOtop 2.0 is provided with a GNU General Public License, version 3 (GPL-3.0). The source code, a first version of the manual (Dall'Amico et al., 2011b), and some template simulations are available through GitHub at the address: https: //github.com/se27xx/GEOtop/. Gubler et al. (2013) provide a good starting point for the selection of many parameter values; however, optimal choices and sensitivities may differ from application to application.

3.7.4.3 Brief Description

The GEOtop 2.0, an improved version of the open-source software GEOtop, which simulates the energy and water balance at and below the land surface, soil freezing, snow cover dynamics, and terrain effects are included. It is a research tool for studying, for example, the hydrological and thermal phenomena at locations that differ in soil types and topography to specific climatic forcings. Output consists of variables such as temperature, water and ice contents, or of integrated variables such as stream discharge. The software operates in point-wise and distributed modes and can be flexibly controlled, because all relevant parameters that govern e.g. discretisation, input/output or numerics can be set via keywords.

GEOtop describes the evolution in time of temperature and water content in the soil and snow cover and is driven by meteorological forcings. This is accomplished by solving the heat and water flow equations with boundary conditions accounting for the interactions with the atmosphere at the surface in terms of energy and water fluxes. The solution of the equations is obtained numerically in the soil domain and snow cover.

GEOtop 2.0 is significantly different from GEOtop 0.75. It includes a fully three-dimensional description of the Richards equation, whereas in the previous version the equation was only solved in the vertical direction and the lateral flow was parameterised, in a similar way as in large-scale land surface models. In the new version, a multilayer snow cover and the surface energy balance are fully integrated in the heat equation for the soil, which is solved with a rigorous numerical method based on Kelley (2003), while in the previous version, snow cover was described with a bulk method (Zanotti et al., 2004) and the surface energy balance, though complete in its components and accommodating complex terrain, was not numerically coupled to the soil heat equation.

In GEOtop 2.0 (hereafter GEOtop), soil freezing and thawing are represented, meteorological forcings are distributed, and channel routing is described as overland flow with the shallow water equation neglecting the inertia. The description of vegetation with a double-layer surface scheme in order to more accurately represent the heat and vapour exchanges of vegetation with the soil surface and the atmosphere has also been included in GEOtop and is described in Endrizzi and Marsh (2010).

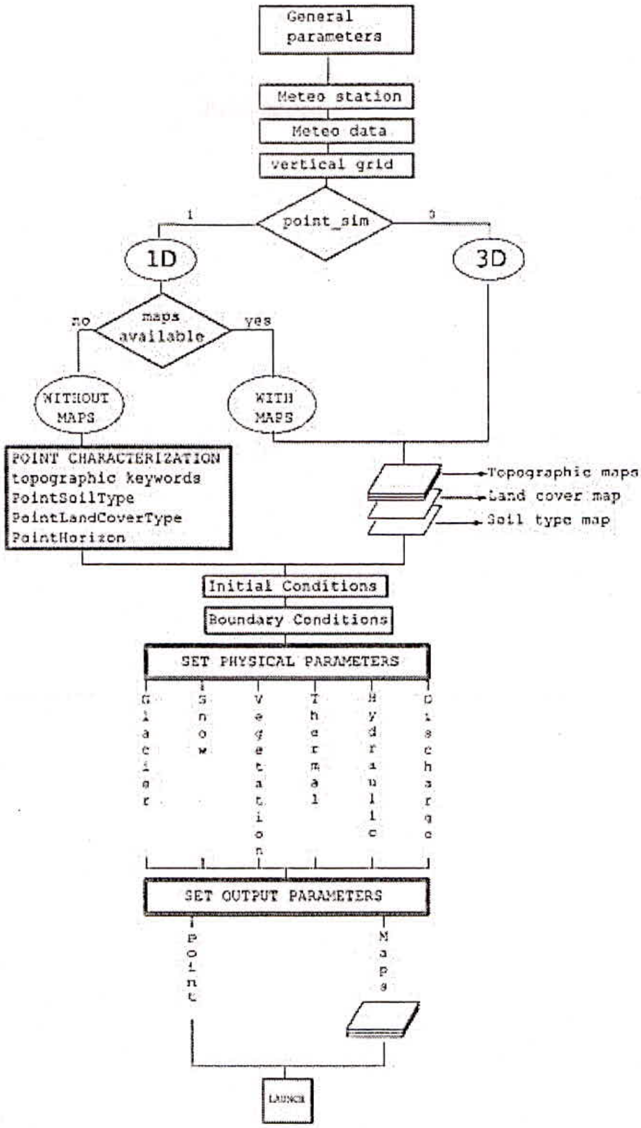

Figure 3.2: GEOtop flow chart: user point of view for preparing a simulation

GEOtop is known to run under the following Operating Systems:

- Mac OS X 10.8 or later
- Cent OS 6.5 or later
- Debian 7

GEOtop has NOT been tested on Microsoft Windows either with Cygwin or MinGW compiler. This configuration therefore is NOT supported

3.7.5 HBV Light

HBV light is a model that simulates daily discharge using daily rainfall, temperature and potential evaporation as input. Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature. In the snow routine snow accumulation and snowmelt are computed by a degree-day method. In the soil routine groundwater recharge and actual evaporation are simulated as functions of actual water storage. In the response (or groundwater) routine, runoff is computed as a function of water storage. Finally, in the routing routine a triangular weighting function is used to simulate the routing of the runoff to the catchment outlet.

3.7.5.1 Advantage & Shortcomings

This model is a good compromise between black-box models, which do not allow processes to be readily transparent, and physically-based models, which are usually too complex to be easily applied. The model is freely available to download. HBV-ETH does not distinguish the different glacier surface conditions for melt water simulation as TAC D does.

3.7.6 TAC D

The model TAC D (Tracer Aided Catchment Model, Distributed) is a fully distributed, modular catchment model, which at its core has a process-based runoff generation routine based on dominant process conceptualizations. A temperature-index method is used for the calculation of snow and ice melt as in TAC D, whereas the computation of melt of debris-covered glaciers is treated the same way as of debris-free glaciers.

3.7.6.1 Advantages & Shortcomings

Certain periods, e.g. short-term runoff fluctuations during snow melt periods, could not be simulated well even when different model modifications were executed. This indicates model shortcomings because of incomplete process understanding and the necessity for further experimental research as well as for new concepts of model structure.

3.7.7 SWAT model

The Soil and Water Assessment Tool or SWAT is a river basin or watershed scale model developed by the USDA Agricultural Research Service (Arnold et al., 1998). SWAT is a semi-distributed, continuous watershed modeling system, which simulates different hydrologic responses using process- based equations. Spatial variabilities of the various types in a catchment are represented by dividing the catchment area into sub-watersheds which are further subdivided into hydrologic response units (HRUs). This subdivision is based on soil, land cover and slope characteristics. The model computes the water balance from a range of hydrologic processes such as evapotranspiration, snow accumulation, snowmelt, infiltration and generation of surface and subsurface flow components.

To estimate snow accumulation and melt, SWAT uses a temperature-index approach. Snowmelt is calculated as a linear function of the difference between average snowpack maximum temperature and threshold temperature for snowmelt. Snowmelt is included with rainfall in the calculation of infiltration and runoff. Although the SWAT model does not include an explicit module to handle snow melt processes in the frozen soil, it has a provision for adjusting infiltration and estimating runoff when the soil is frozen (Neitsch et al., 2005). However, this is not considered a major limitation and SWAT is one of the most appropriate integrated models currently available for application in cold regions environment.

3.7.8 University of british columbia watershed model (UBC)

The UBC watershed model has been developed by Quick and Pipes (1977) at the University of British Columbia, Canada. The model has been designed primarily for mountainous watersheds and calculates the total contribution from both snowmelt and rainfall runoff. A separate calculation can also be made for runoff occurring from glacier covered areas. The model has been designed to use sparse data networks which are, generally, found in mountainous regions. The basic structure of the model depends on a division of the watershed into a number of elevation bands. The elevation increment for each band is the same and an area for each band is specified. The UBC watershed model was also included in the WMO project on intercomparison of snow melt models (WMO, 1986).This model was revisited by Quick et.al. (1995).

3.8 Way Forward

The mountain snow and glaciers are huge storage and very important source of fresh water. In mid and high latitude mountain ranges, for example, seasonal snow cover exerts a strong influence on runoff variability, where as glaciers are the dominant source of water during the dry season at low latitudes. During summer period, substantial runoff is generated from the glaciers in all the Mountain River. Snow and glacier melt runoff studies will improve management of available water resources in the region.

Snowmelt runoff models developed so far have been categorised in two categories i.e. temperature index or degree day model and energy balance model. As per the literature survey most of the models falls under degree day approach. Some modeling studies have been carried out using energy balance approach. The degree approach involves computing the daily snowmelt depth by multiplying the number of degree days by the degree day factor. This approach can be used over large areas with limited data input requirements. However, the degree day method can be easily predicted by the temperature. Although degree day approach is simple for runoff estimation but there is problem in determination of melt rate. It is possible to estimate melt rate with the help of components of energy balance equation, therefore Energy balance approach is more physically based, enabling it to account directly for many of the physical processes that effect snowmelt. Incorporating the physical process involved in snowmelt increases the data input requirements needed to run these models. Due to scarcity of input data to run energy balance models, which has prevented them from gaining dominance over the Degree day approach. The intensive input data for energy balance approach include incoming thermal radiation, net radiation, cloudiness, wind speed and humidity etc. And process involved in data preparation is not only time consuming but also subject to errors due to the extensive manual editing and manipulation that may be difficult to automate. In other words, theoretical superiority of energy balance model is outweighed by its excessive data requirements. Therefore, degree day approach retains its prominence for snowmelt runoff.

In the Himalayan region long term series of temperature and precipitation are available at low altitude ranges. Also stream flow data and snowfall distribution availability is very limited. The lack of data availability in Himalayan region is one of the major constraints in projecting changes in runoff due to melt water and making a viable management programme for Himalayan rivers. A number of advances in snowmelt runoff simulation have been made during the past few decades. These advances resulted from an improved understanding of the physical processes of snowmelt and basin runoff, and the development of new technologies in the areas of data collection and computer technology.

Research needs can be categorized into five general areas of emphasis. These are: (a) Improvement of data measurement and extrapolation techniques. Use of new technologies and the combined application of point and areal measurement technologies need to be investigated. Procedures to expedite the processing and distribution of remotely sensed data for near real time applications need to be developed. (b) Development of a more physically based understanding of the hydrological processes and process interactions involved in snow accumulation and melt, and in basin runoff response. (c) Development of parameter measurement and estimation techniques those are applicable over a range of space and time scales. In conjunction with the development of physically based parameters, the variability and applicability of these parameters at different spatial and temporal scales needs to be determined. (d) Improvement of forecasting techniques to include objective procedures for updating components of the modeled system and the forecast itself. Improvements in data quality and availability and in hydrological process simulations will improve forecast capabilities. However, there always will be uncertainty in these forecast elements, and techniques to minimize this uncertainty need to be developed. (e) Development of modular modeling system and data management shells for developing, analysing, testing, and applying model components and for facilitating the incorporation of advances made in (a), (b), (c) and (d) above.

Maximum use of current and future advances in the fields of expert systems, geographical information systems, remote sensing, information management, and computer science needs to be done. Presently due to lack of data available Temperature Index models are popularly used. The indigenous model SNOWMOD can be transformed into operational environment and towards an ensemble approach. The other development could be propagating uncertainty through model inputs and parameterization.

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