Training Course

Climate Change and its Impact on Water Resources

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LECTURE - 7

ESTIMATION AND MODELLING OF MELT RUNOFF

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ESTIMATION AND MODELLING OF MELT RUNOFF

Snowmelt is a vital component of the streamflow for the Himalayan river system. The spring and summer runoff, comprising mostly snowmelt, is the main source of water for irrigation, hydroelectric power and drinking water supply. Therefore, estimation of snowmelt runoff is very essential for regulating the flow from the reservoirs, estimating design flood for the hydraulic structure and other water resources development activities in the Himalayan region. The development of suitable modelling approach of this valuable source of water supply is, therefore, of utmost important for management and utilization of water resources in the Himalayan region. In spite of the importance of snowmelt runoff in the Himalayan water resources, very limited efforts have been made for modelling of snowmelt runoff.

The majority of rivers originating from the Himalayas have their upper catchment in the snow covered areas. The solid precipitation results in temporary storage and the melt water reach the river in the melt season. The seasonal snow accumulation in Himalayas takes place during winters (November to March), while melt occurs from March/April to June. Thus, during March to June, snowmelt becomes the predominant source of runoff. 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. The snowmelt runoff modelling is of vital importance in forecasting of water yield. The contribution of the snow and glacier melt in annual flows of Himalayan rivers at potential project site is not available. Further, the extent of snow cover and its distribution with time is not available for the Himalayan region. Such information is necessary to solve the hydrologic problems of this region. There is great need to develop simple and systematic hydrological models considering rain and snowmelt inputs based on the limited data availability for this region.

Hydrologic simulation models that include snowmelt component are generally divided into three basic components namely the snow cover, a precipitation-runoff relationship and a runoff distribution, and routing procedure. Snowmelt runoff simulation models generally consist of a snowmelt model and a transformation model (WMO, 1996). The snowmelt model generates liquid water from the snowpack that is available for runoff. The transformation model converts the liquid output at the ground surface to runoff at the basin outlet. The snowmelt and transformation models can be lumped or distributed in nature. Lumped models consider whole catchment as a singe unit and use one set of parameter values to define the physical and hydrological characteristics. 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 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 processes.

The snowmelt component of snowmelt runoff simulation models generally takes the form of an energy balance or a temperature index to simulate the process of melting. The first approach is known as energy budget or the energy balance approach and the second is the temperature index or degree-day approach. These approaches are discussed below:

Energy balance approach

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).

$$Q_m = Q_n + Q_h + Q_e + Q_p + Q_g + Q_q \qquad (1)$$

where:

Q_m	=	heat used for melting
Q_n	=	net radiation (long and short wave)
Q_e	=	latent heat transfer
Q_h	=	sensible heat transfer
Q_p	=	the heat content of rain water
Q_g	=	the heat gained through conduction from under ground
Q_q	=	the change of internal energy storage of the snowpack

In the above energy balance 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.

Data required to evaluate Equation (1) are measurements of air temperature, albedo, wind speed, vapour pressure and incoming solar radiation. These data are difficult to obtain on a basin scale and extrapolation to areal values from point data is another problem, especially the spatial details are required for distributed models. This becomes further difficult when such data are 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.

Degree–day or Temperature index approach

As discussed above, the specific type of data that 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. This is the reason that 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.

SNOWMELT MODEL

Modelling 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.

When precipitation falls as snow it accumulates in the basin and gradually snowpack is developed during winters. Conceptually snowmelt runoff models are similar to 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 (Ferguson, 1999)

- 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 melt water.

Specific major considerations in the design of the model components are as follows:

(a) The model computes or simulates the snow melt and runoff processes on daily basis. The basin is divided into snow covered and snow free part and modelling of runoff is carried out separately for 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.

In order to execute the snowmelt 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

GUIDELINES FOR SNOWMELT MODEL SELECTION

The aim of the hydrologist in the choice of a particular mathematical modeling scheme depends on a clear definition of the problem to be solved and upon the database that is available to describe the physical system. The key points in the selection of the appropriate modeling methodology are as follows.

- Operation and calibration data availability.
- Expected physiographic and climatic conditions.
- Detail and type of results required.
- Probability of extreme events.

a. The availability of operation and calibration data is a key constraint to the choice of methodology. If an ungauged catchment is the area of interest, any model involving optimization procedures based on historical discharge record or a complex conceptual energy budget would be ruled out because of the absence of data. The accuracy, representativeness, and validity of the collected data are as important as their availability in model selection. Models based on physical parameters require physically meaningful data inputs to correctly characterize the snowmelt process. Even with simple empirically derived index methods, the issues related to data reliability are of major importance. The versatility of a model in characterizing varying physiographic and climatic conditions is an important factor. This is called model mobility and is critical to applying a model to a new site. Most calibrated snowmelt models tend to be site specific, and their applicability to differing conditions is a function of their deterministic quality. The purpose of the analysis is probably the most exact requirement of snowmelt analysis. Whether or not the model is used for real-time forecasting is also a consideration. The detail and type of results required, e.g., peak flow, event volume, event hydrograph, or a long-term sequence of flows, weigh greatly on the choice of the appropriate modeling scheme.

b. The probability of extreme events leads the hydrologist to consider a physically based approach versus empirically derived indexes. As mentioned previously, index methods are most accurate under normal conditions, whereas energy budget approaches, owing to their physical basis, are more accurate at forecasting extreme events.

c. For the operational hydrologist, the availability of resources and time to carry out a snowmelt forecasting analysis is of extreme importance. Some techniques, such as a complete energy budget approach to snowmelt analysis, require extensive commitments of personnel, computer resources, and expertise to become operational. These management applications or operational constraints need to be fully considered in selecting methodology. In general, two main issues emerge in model selection: the need for widely applicable models and the requirement for suitable databases to support the snowmelt modeling.

SYNTHESIS OF INDIAN CLIMATE CHANGE IMPACT ASSESSMENT STUDIES

Any climate change impact assessment on water resources study requires the down-scaling of the precipitation and other variables such as temperature, relative humidity, solar radiation, wind direction and wind speed from the global scale to the regional scale. Such down-scaling is done by using either analogue or statistical down-scaling procedures (Anandhi et al., 2007).

The future predictions are described in terms of SRES (Special Report on Emissions Scenarios) storyline scenarios (IPCC, 2007) which are labeled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century. Each scenario has made assumptions that are dependent on demographic, social, economic, technological, and environmental developments.

The predictions made on the future scenarios through the region level downscaling are used by researchers to quantify the impacts on water resources. At the national level the NATCOM (NATional COMmunication) (2004) project has been the first one in this direction. Around the same time there has been a study wherein general projection of the water resource demand for 2050 has been worked out by the Central Water Commission without considering any climate change impact (Thatte, 2000). He has shown that even without considering climate change impacts, the total water demand shall surpass the availability by 2050 even under a low consumption scenario. Similarly, Gupta and Deshpande, 2004 has predicted that the gross per capita water availability in India will decline from about 1,820 m3/yr in 2001 to as low as about 1,140 in 2050. The reduction in per capita availability of water is entirely due to population growth and can not attributed to climate change or any other factor.

There are very few other studies on climate change impact assessment. A case study by Roy et al (2003) deals with the impact assessment of climate change on river water availability in the Damodar basin. Hydrologic modelling for evaluation of the effect of climate change on the water scenario has been performed. The water availability in the basin under changed climate scenario was evaluated using the projected daily precipitation and mean monthly temperature data for 2041-2060. It was concluded that decreased peak flows would hinder natural flushing of stream channels leading to loss of carrying capacity and production of non-monsoonal crops will be severely affected.

Wilk and Hughes (2002) have used a monthly rainfall–runoff model for a large tropical catchment in southern India. Various land use and climatic change scenarios were tested to assess their effects on mean annual runoff and assured water yield at the Bhavanisagar Reservoir. Owing to the fact that the dynamics of the hydrological processes cannot be well represented by models used with temporal scales of more than a day, it is imperative that wherever possible (due to factors such as data availability) continuous hydrological models with daily time step are used.

There has been one comprehensive study that has been carried out to quantify the climate change impact on majority of Indian river systems (Gosain et al, 2003). The SWAT model (Arnold et al, 1990), a distributed, continuous, daily hydrological model with a GIS interface has been used with daily weather generated by the HadRM2 control climate scenario (1981- 2000) and GHG (Green House Gas) climate scenarios (2041 – 2060). They concluded that although there is an increase in precipitation in some of the river systems for the GHG scenario, the corresponding runoff for these basins has not necessarily increased due to increases in evapotranspiration on account of corresponding increased temperatures. Two river systems which are predicted to be worst affected from floods are Mahanadi and Brahmani. The frequency as well as the magnitude of the floods is predicted to be enhanced under the GHG scenario. They further concluded that decrease in precipitation has been experienced in many other river basins. The two basins Sabarmati and Mahi show drastic decreases in precipitation and consequent decrease in total runoff to the tune of two thirds of prevailing runoff. This may lead to severe drought conditions in future in these basins.

There has been widespread retreat of glaciers worldwide during the current century (IPCC, 2007). If current warming rates are maintained, Himalayan glacier could decay at very rapid rates, shrinking from the present spread of 500,000 km2 to 100,000 km2 by the 2030s. Many rivers draining glaciated regions, particularly in the Hindu Kush-Himalayas and the South-American Andes, are sustained by glacier melt during the summer season (Singh and Kumar, 1997; Mark and Seltzer, 2003; Singh, 2003; Barnett et al., 2005). Higher temperatures generate increased glacier melt. Schneeberger et al. (2003) simulate reductions in the mass of a sample of Northern Hemisphere glaciers of up to 60% by 2050. The entire Hindu Kush-Himalaya ice mass has decreased in the last two decades. Hence, water supply in areas fed by glacial melt water from the Hindu Kush and Himalayas, on which hundreds of millions of people in China and India depend, will be negatively affected (Bernett et al., 2005).

Retreat of the Himalayan glaciers and its impact on the water availability is one of the issues which is debated from time to time. Indian Himalayas have nearly 9575 glaciers and it is estimated that these cover an area of about 38000 km^2 (GSI, 2007).

These glaciers provide the snow and the glacial-melt waters and make them perennial in nature throughout the year. The most useful facet of glacial runoff is the fact that glaciers release more water in a drought year and less water in a flood year and thus ensuring water supply even during the lean years. There is world wide retreat of glaciers and similar trend is reported for few Himalayan glaciers also. IPCC (2001 a,b, 2007) reported that majority of glaciers in the Himalayan region are retreating.

MODELLING IMPACT OF CLIMATE CHANGE ON SNOW AND GLACIAL MELT RUNOFF

The model can also be used to study the impact of climate change on river flows. The general procedure for estimating the impacts of hypothetical climate change on hydrological behaviour has the following steps: First, determine the parameters of hydrological models in the study catchment using current climatic inputs and observed river flows for model calibration. Second, perturb the historical time series of climatic data according to some climate change scenarios (typically, for temperature by adding ΔT = +1, +2, +3°C; and for precipitation by multiplying the values by $(1+\Delta P/100)$). Third, simulate the hydrological characteristics of the catchment under the perturbed climate using the calibrated hydrological model. Fourth, compare the model simulations of the current and possible future hydrological characteristics. Some of the impact studies are elucidated below:

Effect of climate change on runoff of a glacierized Himalayan basin. (Dokriani Glacier)

The impact of climate change on the monthly distribution of runoff and total summer runoff has been studied with respect to plausible scenarios of temperature and rainfall, both individually and in combined scenarios. The analysis included six temperature scenarios ranging between 0·5 and 3°C, and four rainfall scenarios (-10%, -5%, 5%, 10%). The combined scenarios were generated using temperature and rainfall scenarios. The combined scenarios represented a combination of warmer and drier and a combination of warmer and wetter conditions in the study area. The results indicate that, for the study basin, runoff increased linearly with increase in temperature and rainfall. For a temperature rise of 2°C, the increase in summer streamflow is computed to be about 28%. Changes in rainfall by ±1O% resulted in corresponding changes in streamflow by ±3·5%. For the range of climatic scenarios considered, the changes in runoff are more sensitive to changes in temperature, compared with rainfall, which is likely due to the major contribution of melt water in runoff.

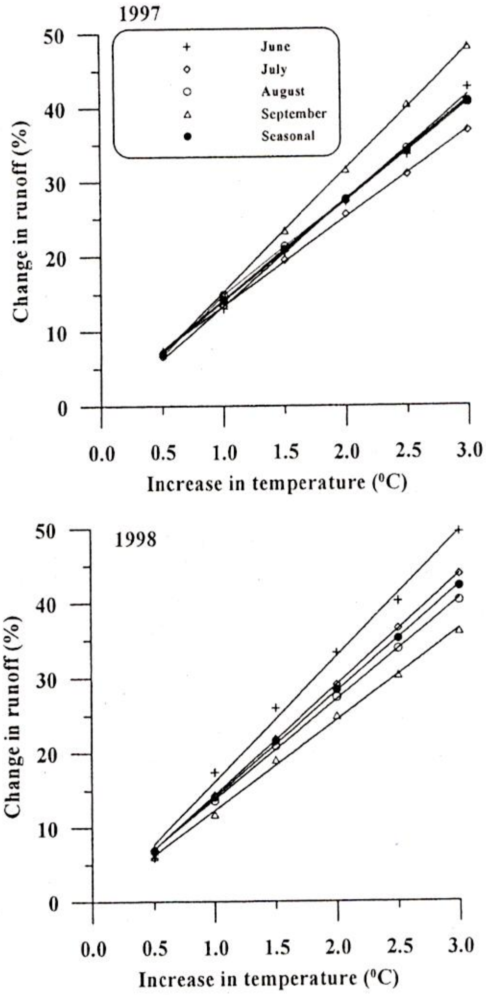

Figure : Change in monthly and seasonal runoff from the Dokriani Glacier with increase in temperature

Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river (Spiti River)

The total streamflow of this river has a significant contribution from snow and glacier melt runoff. Plausible hypothetical scenarios of temperature and precipitation change based on the simulation of climate change over the Indian subcontinent by the Hamburg climate model are adopted in the present study. The UBC watershed model was used to simulate the hydrological response of the basin under changed climatic scenarios. The adopted changes in temperature and precipitation covered a range from 1 to 3^0C and from -10 to +10%, respectively. Snow water equivalent reduces with an increase in air temperature. However, no significant change is found in the snow water equivalent of the

Spiti basin by the projected increase in air temperature (T + to T + 3^0C). An increase of 2^0C in air temperature reduced annual snow water equivalent in the range of 1 to 7%. Changes in precipitation caused proportional changes in snow water equivalent. It is found that annual snowmelt runoff, glacier melt runoff and total streamflow increase linearly with changes in temperature (1-3^0C), but the most prominent effect of increase in temperature has been noticed on glacier melt runoff for this high altitude. For example, an increase of 2^0C in air temperature has enhanced annual snowmelt runoff, glacier melt runoff and total streamflow in the range of 4-18%, 33-38% and 6-12% respectively. The effect of change in precipitation (P-10 to P+10%) suggests a linear increase in snowmelt runoff and total streamflow, while in general, glacier melt runoff is inversely related to changes is precipitation. Snowmelt runoff is found more sensitive than glacier melt runoff to changes in precipitation (P-10 to P+10%). Under a warmer climate scenario, snowmelt runoff and glacier melt runoff cause an earlier response of the total streamflow and a change in flow and a change in flow distribution. The seasonal analysis of total streamflow indicates that an air temperature produces an increase in the pre-monsoon season followed by an increase in the monsoon season.

Hydrological sensitivity of a large Himalayan basin to climate change (Satluj basin)

About 65% of the basin area is covered with snow during winter, which reduces to about 11% after the ablation period. After having calibrated a conceptual hydrological model to provide accurate simulations of observed stream flow, the hydrological response of the basin was simulated using different climatic scenarios over a period of 9 years. Adopted plausible climate scenarios included three temperature scenarios (T + I, T + 2, T + 3°C) and four rainfall scenarios (P - 10, P - 5, P + 5 and P + 10%). The effect of climate change was studied on snowmelt and rainfall contribution runoff, and total stream flow. Under warmer climate, a typical feature of the study basin was found to be reduction in melt from the lower part of the basin owing to a reduction in snow covered area and shortening of the summer melting season and, in contrast, an increase in the melt from the glacierized part owing to larger melt and an extended ablation period. Thus, on the basin scale, reduction in melt from the lower part was counteracted by: the increase from melt from upper part of the basin, resulting in a decrease in the magnitude of change in annual melt runoff. The impact of climate change was found to be more prominent on seasonal rather than annual water availability.

REFERENCES

Anandhi, A, Srinivas VV, Nanjundiah RS, Kumar DN. 2007. Downscaling Precipitation to River Basin in India for IPCC SRES Scenarios using Support Vector Machine, International Journal of Climatology

Arnold, J.G., Williams, J. R., Nicks, A. D. and Sammons, N.B., 1990. *SWRRB-A basin scale simulation model for soil and water resources management*. TexasA&M Press. College Station, TX. 255 pp.

Barnett, T.P., J.C. Adam and D.P. Lettenmmaier, 2005: Potential impacts of a warming climate on water availability in snow-dominated region. Nature 438, 303-309.

Gosain, A.K., Rao, S., Basuray, D. 2003. *Assessment of Vulnerability and Adaptation for Water Sector*. Proceedings of the Workshop on Vulnerability Assessment and Adaptation Due to Climeate Change on Indian Water Resources, Coastal Zones and Human Health, Ministry of Environment and Forests, New Delhi, pp 17-24

Gupta, S.K. and R.D. Deshpande, 2004: Water for India in 2050: first-order assessment of available options. Curr. Sci. India, 86, 1216-1224

IPCC (Intergovernmental Panel for Climate Change), 2001. Climate Change 2000, The science of climate change, Assessment report of the IPCC Working Group I [Houghton, J. T. Et al. (eds.)] and WMO/UNEP, Cambridge University Press, Cambridge

IPCC (Intergovernmental Panel for Climate Change), 2007. Fourth Assessment Report, WMO/UNEP

Mark, B.G. and G.O. Seltzer, 2003: Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru.J.Glaciol., 49, 271-281.

NATCOM. 2004. *India's National Communication to UNFCCC*. Ministry of Environment and Forests, Government of India.

Roy, P. K., Debasri Roy, Asis Mazumdar and Balaram Bose, 2003. Vulnerability Assessment of the Lower Ganga-Brahmaputra-Meghna Basins. NATCOM - V&A Workshop on Water Resources, Coastal Zones and Human Health, IIT Delhi.

Schneeberger, C., H. Blatter, A. Abe-Ouchi and M. Wild, 2003: Modelling Changes in the mass balance of glaciers of the northern hemisphere for a transient 2xCO2 scenario. J. Hydrol. 282, 145-163.

Singh, P. and N. Kumar, 1997: Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan River. J. Hydrol., 1993, 316-350.

Singh, P., 2003: Effect of warmer climate on the depletion of snow covered area in the Satluj basin in the western Himalayan region. Hydrol. Sci.J., 48, 413-425.

Thatte C.D. 2000. *Green to Evergreen Revolution through a Blue Revolution*, J. Indian Water Resources Society, 20(2); 63-75.

Wilk, J., and Hughes, D.A., 2002. Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment, J. Hydrological Sciences, 47(1); 19–30.

Pratap Singh, Manohar Arora and N.K. Goal: (2006) Effect of climate change on runoff of a glacierized Himalayan basin. Hydrological Process, 20, 1979-1992.

Pratap Singh and Lars Bengtsson: (June 2003) Effect of warmer climate on the depletion of snow covered area in the Satluj basin in the western Himalayan region. Hydrological Sciences 48(3).

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