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Effectiveness of Four Water-Bearing Zones of the Glacierized Basin in Meltwater Runoff Modeling

Umesh K. Haritashya
University of Dayton, uharitashya1@udayton.edu

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UMESH K. HARITASHYA

Department of Geology, University of Dayton, Dayton, Ohio 45469-2364 USA

uharitashya1@udayton.edu

Abstract Meltwater runoff modelling from glacierized basins needs several input data, including total meltwater contributing area. This study utilizes optical remote sensing data to assess glacierized basins in the central Himalayas where snow and glaciers contribute substantially to the water resources. Result shows that there are four main water-bearing zones in the basin: (a) dry snow, (b) wet snow, (c) exposed glacial ice, and (d) debris-covered glacial ice, and it is possible to differentiate and map these zones and their spatio-temporal variations from satellite sensor data. These zones can then be incorporated in meltwater runoff modelling as separate entities because they behave differently and cannot be aggregated into a uniform body.

Key words glacier; dry snow; wet snow; meltwater runoff modelling; temperature index; Himalaya

BACKGROUND AND INTRODUCTION

Melting from glaciers is an important component in the hydrology of catchments. The hydrological response of the glacier is not the same throughout the ablation period. The magnitude of melt runoff and its pattern changes with time. The meltwater runoff from the glaciers have direct relationships with weather conditions, but still a comprehensive modelling approach taking into account the melt estimate and its transformation to melt runoff is limited. This is probably due to the fact that meltwater generation processes and drainage systems of the glaciers are not well understood. In the modelling studies, meltwater generation processes have been represented in several ways: degree-days (Hock, 2003; Singh *et al.*, 2008), surface energy balance (Hoffman *et al.*, 2008), statistical type (Hay & Clark, 2003), and conceptual/lumped type (Schaefli *et al.*, 2005).

Several studies have shown that temperature index or degree-day models are the most widely used models for runoff computation from a glacierized basin (Rango & Martinec, 1995; Hock, 2003; Singh *et al.*, 2008). Most of the popular and operational meltwater runoff models (e.g. HBV, SRM, UBC etc.) are also based on this approach. The wide use of temperature index-based models is due to readily available air temperature data, straightforward interpolation and forecasting possibilities of air temperature, good model performances despite their simplicity, and computational simplicity (Hock, 2003). Furthermore, high correlation of temperature with several energy balance components provides a strong basis to use air temperature as the sole index of melt energy.

For the Himalayan basins, the most important factor influencing the model and the approach to be adopted is the limited availability of data. There is very sparse network of measurement stations in the Himalayas. Data collected at most of the measurement stations consist of mostly temperature and precipitation. Therefore a conceptual model with temperature index approach for calculating melt is considered as a suitable choice for estimation of meltwater runoff in the snow- and glacier-fed Himalayan basins.

One of the prime inputs in temperature index models, or any model, is total melt contributing area. Broadly, two approaches are used for estimating this area: (a) field-based, (b) remote sensing. In the field-based approach, the area of glacierized basin is obtained from topographic sheets or field surveys. Using temperature at the base station and the environmental temperature lapse rate with height, the altitude corresponding to 0°C temperature is computed. Then the area of the glacierized basin below this 0°C temperature altitude is used as one homogeneous body that is contributing meltwater. In the second approach, remote sensing data are used to compute the total snow/ice cover area on which the temperature lapse rate method is applied, to determine the part of the snow cover area which lies at an altitude below 0°C. However, this method ignores the fact that there could be glacierized basins below the snow cover that may also be contributing to the

meltwater runoff. Again, most of these methods also use total melt contributing area as one homogeneous body.

Therefore, the present study utilizes optical remote sensing data to assess glacierized basins in the central Himalayas where snow and glaciers substantially contribute to the water resources, but little information is available, and incorporates various water bearing zones of glacierized basins as separate components to the temperature index model for better modelling results.

INDEX MODEL FOR SNOWMELT AND GLACIERMELT RUNOFF (IMSGR)

This model has been developed based on the platform provided by the temperature index model "SNOWMOD" (Singh *et al.*, 2008). Due to the short length of this paper, details regarding the estimation and simulation of the individual component has not been included in this article but they can be found in Singh & Jain, 2003; Haritashya, 2005; Singh *et al.*, 2008. Even though the concept of both models is the same, the parameters have been significantly modified in this model to incorporate new information and accurately simulate the runoff. This new model, IMSGR, performs on the basis of the availability of four main water bearing zones in the basin: (a) dry snow, (b) wet snow, (c) exposed glacial ice, and (d) debris-covered glacial ice. Previous study has shown the possibility of differentiating and automatically mapping these zones and their spatio-temporal variations from optical satellite data (Gupta *et al.*, 2005). Incorporating these zones as separate entities is extremely important because they behave differently and cannot be aggregated into a uniform body. The dry snow cover area occurring at a relatively higher altitude is likely to experience negligible melting while wet snow fringe and exposed glacial ice are the main melting zones. The melting behaviour of debris-covered glacial ice depends upon the thickness of the debris, which in most Himalayan basins increases downward from the equilibrium line altitude. Gangotri Glacier in the central Himalayas (latitudes 30°43′–31°01′N and longitudes 79°0′–79°17′E) has been used as the test side for this model. Meteorological and discharge data used for the simulation of meltwater was collected near the terminus of the glacier.

ESTIMATION AND SIMULATION

The basin has been divided into nine elevation zones based upon the topographic relief. Precipitation was distributed to these zones using critical temperature, $T_c = 2°C$, which determines whether the measured precipitation is rain or snow. Similarly, temperature was distributed in various zones using empirical lapse rate of 0.6°C/100 m. Different weights of minimum, maximum and mean temperature were used to find the suitable temperature index for this model. By considering the matching of observed and computed streamflow, the appropriate weights for maximum and minimum temperatures were found to be 0.80 and 0.20, respectively. Thus, the following temperature index method was used:

$$T_i = (0.80T_{max} + 0.20T_{min}) \quad (1)$$

Furthermore, degree-day factor (D) is used to convert the degree-days into melt expressed in depth of water. A seasonally changing degree-day factor in the range of 2.5–9.0 mm $°C^{-1}$ d^{-1} was used. Minimum degree day factor was observed at the start of the melt season, and maximum during the peak melting season. Finally, melt contributing areas of all nine zones was divided into dry snow, wet snow, exposed glacial ice and debris-covered ice. Routing of runoff for all these zones was done independently because their hydrological responses are unique. Melt runoff generated from different parts of the basin can be classified as: melt due to prevailing air temperatures, under rainy conditions, melt due to heat transferred to the wet snow, dry snow, debris-covered ice, and exposed ice surface from rain.

Using these above parameters, runoff was computed for each elevation zone separately:

$$M_{g,i,j} = C_{g,i,j}\, D_{i,j}\, T_{i,j}\, G_{c,i,j}\, W_{c,i,j}\, R_{c,i,j}\, B_{c,i,j} \quad (2)$$

where $M_{g,i,j}$ represents melt in terms of depth of water (mm d^{-1}), $C_{g,i,j}$ is the runoff coefficient for melt, $D_{i,j}$ is the degree-day factor (mm °C^{-1} d^{-1}), $T_{i,j}$ is the index temperature (°C), $G_{c,i,j}$ is the ratio of exposed ice to the total area of the elevation band, $W_{c,i,j}$ is the ratio of wet snow to the total area of the elevation band, $R_{c,i,j}$ is the ratio of dry snow to the total area of the elevation band, and $B_{c,i,j}$ is the ratio of debris-covered ice to the total area of the elevation band. The suffixes i and j denote day and zone, respectively.

The daily total discharge, Q_{GWRB}, from these four water bearing zones is computed by adding contributions from each elevation zone:

$$Q_{GWRB} = \alpha \sum_{j=1}^{n} (M_{g,i,j} + M_{r,i,j} + R_{g,i,j})\, A_{G,i,j}\, A_{W,i,j}\, A_{R,i,j}\, A_{B,i,j} \tag{3}$$

where n represents total number of zones, α is a conversion factor (1000/86400 or 0.0116) used to convert runoff depth (mm d^{-1}) into discharge (m^3 s^{-1}), $M_{r,i,j}$ is the melt in terms of depth of water due to rain on glacier (mm d^{-1}), $R_{g,i,j}$ is runoff depth from rain falling over water bearing zones, $A_{G,i,j}$ is exposed ice area (km^2), $A_{W,i,j}$ is wet snow area (km^2), $A_{R,i,j}$ is dry snow area (km^2), and $A_{B,i,j}$ is debris-covered ice area (km^2). The zonewise area of all four water bearing zones corresponding to the satellite images have been extracted using area elevation curve. After this, they were plotted in all elevation bands against the time to construct the depletion curves for the various elevation bands in the basin.

Surface runoff was calculated from non-snow and non-glacier cover areas (called free zone 'F') from each of the nine elevation zones. The source of this runoff is mainly rainfall and was calculated using:

$$Q_F = \alpha \sum_{j=1}^{n} R_{f,i,j}\, A_{F,i,j} \tag{4}$$

where $R_{f,i,j}$ represents melt runoff computed for each zone, and $A_{F,i,j}$ is non-snow and non-glacier cover area in the jth zone on the ith day.

The subsurface flow or the baseflow represents the runoff from the saturated zone (subsurface) of the basin to the streamflow. It was computed by multiplying the depth with conversion factor α and area, and given as follows:

$$Q_b = \alpha \sum_{j=1}^{n} R_{b,i,j}\, A_{i,j} \tag{5}$$

where $A_{i,j}$ is total area of zone jth on ith day and represents sum of $A_{G,i,j}$, $A_{W,i,j}$, $A_{R,i,j}$, $A_{B,i,j}$, and $A_{F,i,j}$.

Finally, all components were routed separately for individual zones and output from all the zones was integrated to provide the total runoff from the basin for each day:

$$Q = Q_{GWRB} + Q_F + Q_b \tag{6}$$

For the meltwater runoff estimation on a daily basis, the daily coverage of all water-bearing zones for each elevation zones were computed from the depletion curves and used as input in the model for simulating runoff on the daily scale.

Finally, the simulation has been made for Gangotri Glacier meltwater for the melt season of 2000 (Fig. 1). The model overestimated the runoff in comparison to observed discharge with the difference in volume (D_v) being 2.3%. The value of RMSE was 0.22 while R^2 was found to be 0.95. As a whole, the model overestimated runoff throughout the melt period, but volume of high peaks was reproduced quite well. This overestimation or higher difference in the volume could be possible due to the reason that the model assumes equal depth of debris spread throughout the ablation zone, possibly contributing more melt than it should. Moreover, no cloud-free images were available for peak melt period, which is the most important part of the melt season, and that may have resulted in the imprecise interpolation and eventual overestimation of the meltwater.

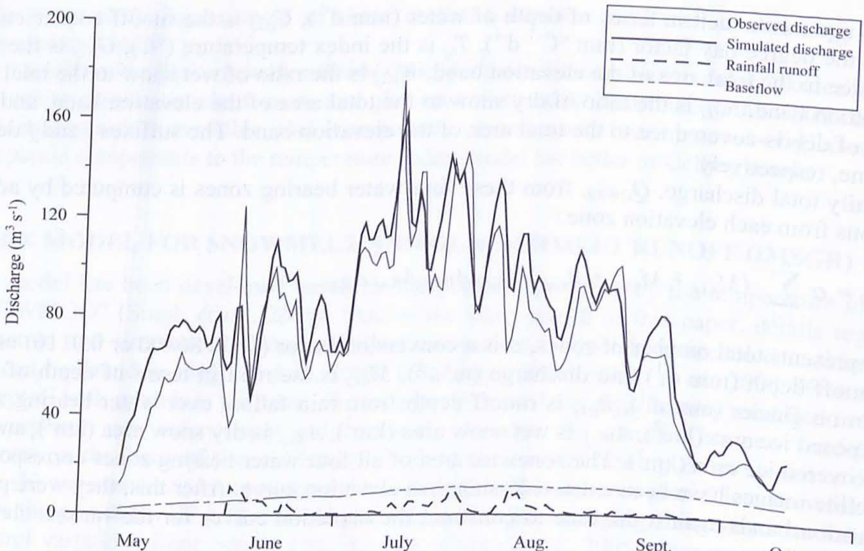

Fig. 1 Comparison of observed and simulated discharge of the Gangotri Glacier for the melt season 2000.

CONCLUDING REMARKS

This preliminary study has provided extremely encouraging results and has shown the importance of various zones of a debris-covered glacier in melt runoff modelling. This model will now be extended to other melt seasons by first using observed discharge data to calibrate the model for few years, and then simulate it for the next few years. Furthermore, it is also understood that in order to simulate meltwater accurately using this method, the following steps must be considered in future: (i) use of separate degree-days for snow and ice because of their different properties; (ii) use of precise, periodical and continuous snow cover information (the satellite coverage should be as repetitive as possible so that the interpolation will be minimum while preparing the depletion curve); and use of automated methods that utilize geomorphometric parameters to accurately map the debris cover zones.

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