Glacio-Hydrological Simulation in Dudh Koshi River Basin, Nepal

Examining Glacier Melt Contribution to River Flow

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***Abstract*—The hydrological dynamics of the Dudh Koshi River examined through physically based semi-distributed model, SWAT – the Soil, Water Assessment Tool, with the aim of understanding the glaciers and snowmelt contribution in the River. The analysis suggests that the model can give a fair estimation of the water yield. The river discharge is mainly dependent on precipitation. The effects of glaciers and snow are largely dependent on the basin characteristics and the glaciated area. The melt water contribution from the glaciers and snow is nearly 30% in the Dudh Koshi River. The T-index method of glacier melt estimation is a simple approach requiring only the temperature and melt factor, however use of such model underestimated the melt while using mean daily temperature data. The energy-balance model further confirmed the melt underestimation by T-index approach. The finding shows that the melting of glaciers continue until 3 °C below the average mean temperature, indicating that the important role of solar radiation in such higher altitude.**

***Index Terms*—Glacier melt, River flow, Components, T-index, Energy Balance**

I. Introduction

Glaciers and snow play important roles in meltwater production and regulation of mountain hydrological processes ([1]-[4]). The observed accelerated glacier shrinkage in past decades and foreseen future of glaciers under climate change [5] has raised concerns about the role of the Himalayan glaciers ([6], [4], [7]) on water resources.

River runoffs from basins without the presence of glaciers represent the behaviour of precipitation, unless an anthropic activity interferes the process. In the glacierized basins, runoffs are subject to response with a combination of climatic factors, like temperature and precipitation [8]. Glaciers and snow provide meltwater to river runoff when air temperature is above melting point (> 0 °C). In glacierized basins, under the effect of increasing temperature, runoffs are expected to be increased initially due to glaciers melt, over time the decreasing of the glacier surface area offsets the increasing melting during warm period. A "deglaciation discharge dividend" is added to the basin runoff from depletion of the glacier surface over time [9], but this process cannot go on forever as glaciers disappear. On the other side, the changes in the precipitation form and amount can have a direct as well as an indirect influence (through glacier mass balance) on runoffs [4].

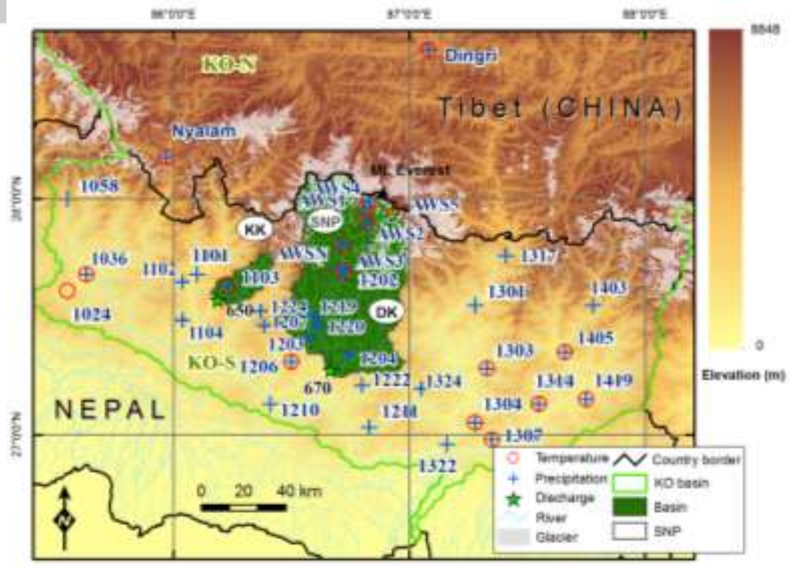

Figure 1. Location of Dudh Koshi (DK) and Khimti Khola (KK) in the Koshi (KO) basin. Further, the hydro-meteorological sations are also indicated

The estimations of the hydrological response in the mountain region are complicated by heterogeneity, lack of adequate ground station data, and the uncertainties remaining in glaciers and snow behaviour [1]. An increasing number of studies, attempting to understand the hydrological dynamics in the central Himalaya, have addressed the glaciers and snow components at the basin-scale using various models (e.g., [10]-[13]; [7]). Most of these studies did not use the higher elevation (where the glaciers are located) climate data and information on glacier change over time.

In this study, the glacier and snowmelt contribution to river flow is estimated through coupling the Soil Water Assessment Tool (SWAT), a physically-based model with the Temperature index (T-index), and a physical energy balance method in the Dudh Koshi basin (area: 3717 km^2) located on the south slope of Mt. Everest region in Nepal (Fig. 1).

II. DATA AND METHODS

Hydro-meteorological data: The data from meteorological ground stations in the Koshi basin, discharge series from Dudh Koshi river (station 670) and Khimti Khola (station 650), and hourly radiation data from the AWS Pyramid station from 2002–2012 are used. The locations of these stations in the Koshi basin are presented in Figure 1.

Spatial data: The ASTER GDEM ver 2 (30 m), the Land Cover data of Himalayan Region (2009) developed by the Food and Agriculture Organization, and the Soil Map of Nepal (2008) prepared by the ICIMOD, are used in addition to hydro-meteorological data for hydrological simulation in the SWAT.

III. SEMI-DISTRIBUTED HYDROLOGICAL MODEL: SOIL WATER ASSESSMENT TOOL (SWAT)

The physically based semi-distributed hydrological model, the SWAT was applied for a glacierized Dudh Koshi basin, including both the snowmelt and glacier melt processes. The SWAT is well established and most commonly applied tool for watershed research and management. Some studies have already used this tool successfully on the glacierized mountain basins for hydrological simulation (e.g., [14], [11]).

The hydrologic balance in the SWAT [15] is represented by,

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

In this equation, SW_t = the final soil water content (mm H_2O); SW_0 = the initial soil water content (mm H_2O); t = the time (days); R_{day} = the amount of precipitation on day i (mm H_2O); Q_{surf} = the amount of surface runoff on day i (mm H_2O); E_a = the amount of evapotranspiration on day i (mm H_2O); w_{seep} = the amount of percolation and bypass flow exiting the soil profile bottom on day i (mm H_2O); Q_{gw} = the amount of return flow on day i (mm H_2O)

ArcSWAT 2012 was used for model set up and the simulation (Fig. 2). For delineating the basin, sub-basins, and Hydrological Response Units (HRUs) characteristics, the SWAT needs DEM, soil, and landuse data. The SWAT was applied both with and without glacier and snowmelt modules. The SWAT includes an inbuilt snowmelt module, but not the glacier melt module. For glacier, T-index method was used to compute the meltwater outside the SWAT and incorporated to the simulation output.

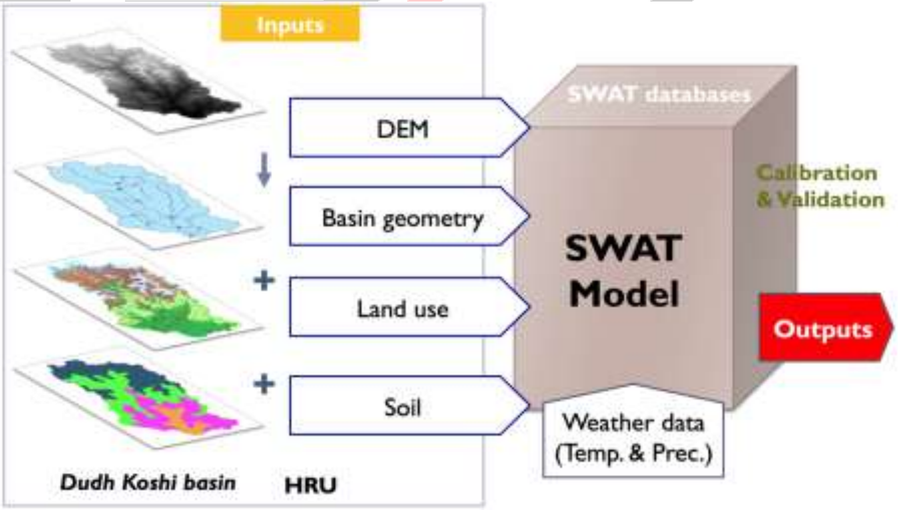

Figure 2. Schematic diagram of hydrological simulation in the SWAT

IV. SWAT CALIBRATION, VALIDATION, AND APPLICATION

The SWAT model is calibrated (through trial and error method) and validated [16] in the Khimti Khola basin (650), a basin without glacier and permanent snow cover, lying close to the Dudh Koshi basin (670) (Fig. 1). The model was calibrated in 1995–2001 and validated in 2002–2008 period at daily-scale. Then, the model is applied to our glaciarized Dudh Koshi basin (670) for understanding the glaciers and snowmelt in the basin. A total of 9 subbasins and 39 HRUs were created for the calibration and validation basin, while 23 subbasins and 168 HRUs was implemented in the Dudh Koshi basin.

The model was applied using elevation bands and considering the temperature and precipitation lapse rates. Activating default snowmelt routing and applying elevation bands, improved the simulation results. Subbasins were divided into different elevation bands of 1000 m and fraction of surface area calculated for each elevation band. In that way, a maximum of four elevation bands used in subbasins of the Khimti-Khola basin, while it was up to eight elevation bands in the Dudh Koshi basin. The ArcSWAT interface, used for running SWAT, allows inserting single lapse rate for each temperature and precipitation. In order to incorporate two precipitation lapse rates, the SWAT source codes are modified in FORTRAN and compiled. A common temperature lapse rate (TLAPS) rate -5.9 °C km-1, and precipitation lapse rate (PLAPS) rate 1340 mm km^{-1} below 2800 m, and an additional PLAPS rate -204 mm km-1 above 2800 m elevation, were applied. The performance of SWAT with two lapse rates was better than one lapse rate.

Evaluation of Model Performance

The SWAT calibration and validation performance was evaluated using Nash-Sutcliffe (NS) efficiency coefficient, Absolute Error (AE), and Coefficient of Determination (R2) ([17],[18]).

V. Temperature Index (T-index)

In order to compute the glacier melt, currently existing methods are simple T-index, enhanced T-index, and energy balance model ([19],[20]). In this study, a simple T-index or degree-day melt method for estimating ablation from glaciers [19]. Other methods demand more data for their application. The T-index method uses the relationship between glacier melting (melt factor or degree-day factor) and air temperature and is given by,

$$M = \begin{cases} M_f(T_d - T_0), & T_d > T_0 \\ 0, & T_d \leq T_0 \end{cases} \qquad (2)$$

Where, M is daily-melt; T_d is daily mean temperature; T_0 is a threshold temperature beyond which ice melt is assumed to occur (0 °C), and M_f is a melt factor. T-index melt model was applied to each 100 m elevation band, using temperature data for each band separately, calculated by using varying monthly lapse rates [21] derived from the ground station data.

The M_f value 0.0087 m d^{-1} $°C^{-1}$, provided by [22] from the field measurement (Glacier AX010) in the Dudh Koshi basin, was used. Moreover, the glacier melts was also computed separately for the debris-covered and debris-free glacier area using the M_f values provided by [7].

VI. Surface Energy Balance (SEB)

The physical Surface Energy Balance (SEB) approach was also used for estimation of the glacier melt at the elevation of weather station location for evaluating the melts calculated by T-index method. The SEB method is usually considered the best one for accurate computation of ablation if sufficient data are available, but the availability of data normally limits its application. The ice and snow melt at the temperature 0 °C, but it is not necessary that at air temperature equal or greater than 0 °C. The melting depends on the energy available around the surface and various other weather and surface conditions.

The general surface energy balance [20] is expressed as,

$$Q_m = Q_N + Q_H + Q_L + Q_G + Q_R \qquad (3)$$

In this equation, Q_m = energy available for melting, Q_N = net radiation, Q_H = sensible heat flux, Q_L = latent heat flux, Q_G = ground heat flux, and Q_N = sensible heat flux supplied by rain incoming shortwave radiation. The SEB was used according to [23] neglecting the Q_G and Q_R as they are negligible compared to other heat fluxes [20].

When the positive energy is available, it is assumed that the available energy is used for melting and thus converted to meltwater as,

$$Meltwater = Q_m/L_m * \rho \qquad \text{[mm w.e.]} \qquad (4)$$

Here, L_m = latent heat of melting and ρ = density of water

The SEB was computed using hourly radiation data (2002–2012) from AWS station close to the ablation area at an altitude of 5050 m, above the average terminus elevation (~4800 m). The total meltwater for a 100 m elevation band estimated by generalizing the point SEB to make comparison with melting by T-index method.

The albedo of glacier ice is assumed to be 0.2 based on the field observed data on Asian glaciers ([24],[25]). All other standard coefficients were used as provided by [23].

VII. Hydrological Dynamics of the Dudh Koshi River

The SWAT Simulation Outputs

The calibration and validation of the hydrological simulation in the SWAT was performed at daily time scale (Fig. 4). The model was calibrated (1995–2001; NS = 0.68, *AE* = 0.37, R^2 = 0.69) and validated (2002–2008; NS = 0.69, *AE* = 0.38, R^2 = 0.71) in the Khimti-Khola basin (650) close to the Dudh Koshi basin (Fig. 1), having no glaciers and permanent snow cover.

The SWAT simulation was able to capture the variations in the river discharge, providing a reasonable estimation of the runoff in the catchment in the 650 basin. Then, the model applied to the glacierized Dudh Koshi basin (Fig. 5). The application of the

model in the Dudh Koshi is able to capture the seasonality, due to strong monsoon domination, but unable to capture the high discharges. Figure 6 reports water balance computed from the application of the model in the Dudh Koshi basin.
Percentage bias was less < 1 for both calibration and validation periods. Without glacier and snowmelt, about 28.6 % deficit in water balance was found in compared to observed annual discharge in the Dudh Koshi basin. While applying the snowmelt module and glacier melt by the T-index method, about 2.3 % and 12.8 % water yield observed from snow and glacier melt, respectively. But still there was 13.5 % of water deficit in water balance. This could be associated with the uncertainties to the glacier and snow melt.

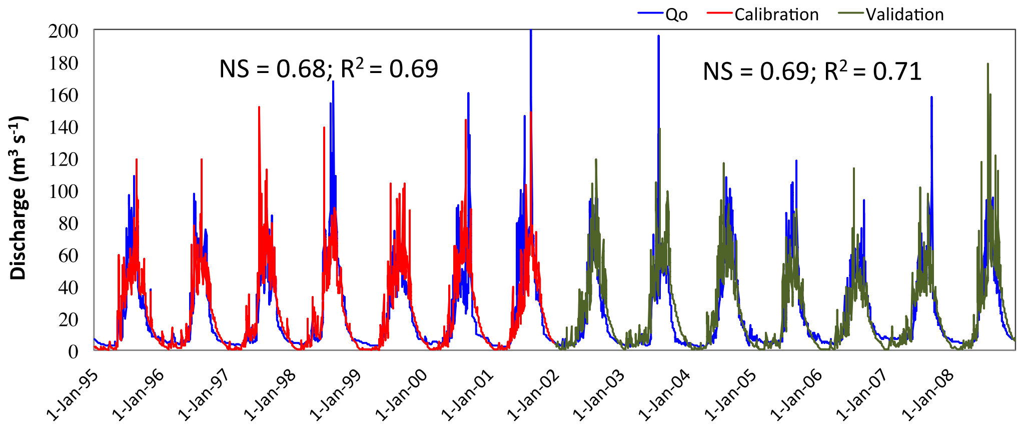

Figure 4. Calibration (1995-2001) and validation (2002-2008) of the SWAT model in the Khimti-Khola basin (650)

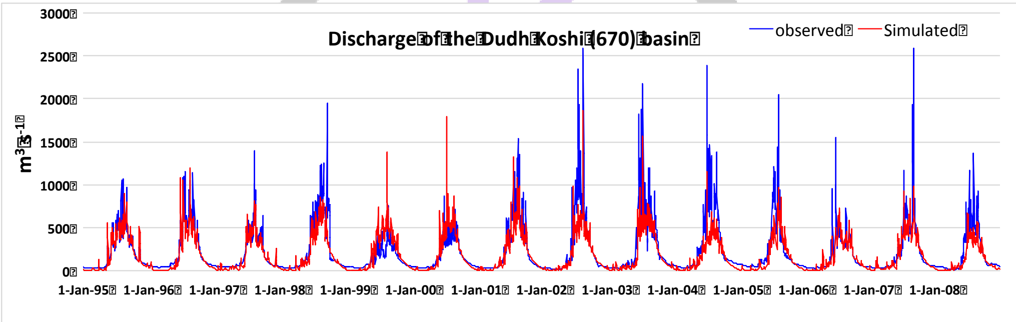

Figure 5. Application of SWAT to Dudh Koshi basin without glacier melts

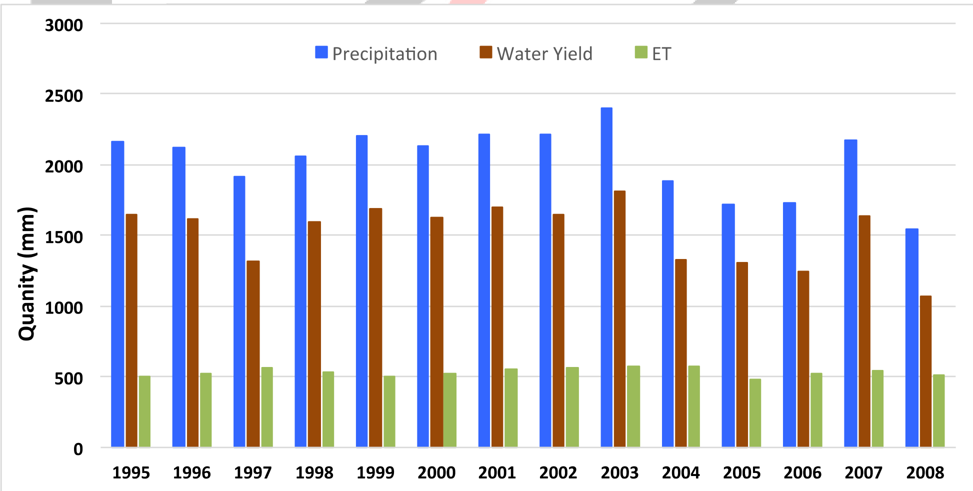

Figure 6. Annual water balance for the Dudh Koshi basin

The estimated annual quantity of glacier meltwater considering a constant glacier surface area (2013) over all years was less by an average 3.8 % compared to estimated meltwater by using changes of glacier surface over time, indicating that melt water has decreased with decreasing glacier surface area. For this computation, the glacier surface area change information from our glaciers analysis was used. A single melt factor M_f of 0.0087 m d^{-1} °C^{-1} reduced the negative bias, compared to using two melt factors. The estimation of glacier melts using two melt factors (for debris-covered and debris-free part) indicated that 40.5 % and 59.5 % share in the total melt from the debris-covered area and debris-free area, but produced significantly less (56 %) melt compared to single melt factor over the glaciers. This suggests that the choice of melt factor is very essential for reliable estimation of the glacier and snow melt.

T-index is a simple approach requiring only the temperature and melt factor; however, while using mean daily temperature data for calculations, such model underestimated the glacier melt. The diurnal ranges of temperature in the study site are large. Even though the mean daily temperature is below the melting point (0 °C), temperatures in certain hours of the day are positive. The simulated melting by the T-index method using the maximum temperature was much better than using mean daily data compared to the observed station discharge (produced meltwater nearly 100 % more and significantly reduced the bias). Further, first result from an experiment using SEB indicated much higher rate of glacier melt, confirming that T-index method significantly underestimated the glacier melt (Fig. 7). Results indicated that the melting of glaciers continues until 3 °C below the average mean temperature, suggesting that in such high altitude, the solar radiation can play vital role in the melting of glaciers and snow.

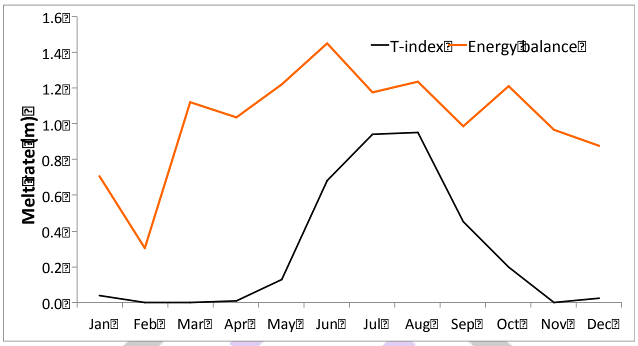

Figure 7. Comparison of the melt from T-index and surface energy balance (SEB) for the location of weather station

Glacier Melt Contribution to River Flow

In Figure 8, different components of discharge are presented based on the application of the model. For the Dudh Koshi basin, using daily mean temperature in T-index method provided 12.8 % of glacier meltwater, and 2.3% snowmelt outside the glacier area, accounting for a total of 15.1 %. But considering the water deficit in annual water balance and observed much higher quantity of meltwater by T-index using maximum temperature and by the SEB, it is expected that the percentage of meltwater contribution to river flow could be much higher (15.1 to 28.7 %). The observed bias could be mainly related to the uncertainty in meltwater quantity. Previous studies have values ranging from 7.4 to 34.0 % contribution from glacier and snowmelt to the Dudh Koshi using different models. A paper [10], using the ice ablation model, indicated that glacier melt provides 7.4 % water to the Dudh Koshi river. [13], using J2000 model, reported 17 % glacier and 17 % snowmelt, in total 34 % contributing to river runoff. [7] estimated 18.8 % of contribution from glacier and 4.8 % from snowmelt in the Dudh Koshi river. [3] estimated about 10% of snow and glacier melt to the river runoff in the Ganges river basin. However, it is necessary to keep in mind that with increasing distance from the glacier downstream, the melt contribution decreases [6].

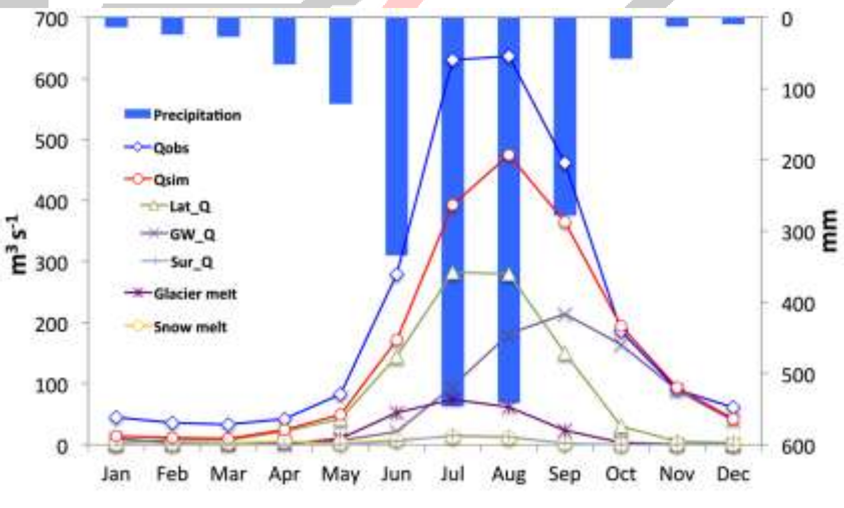

Figure 8. Annual hydrograph for the 1995–2008 period at Dudh Koshi River. The observed station discharge and the SWAT simulated discharge including three components (lateral, ground, and surface) and glacier melt using T-index are indicated

VIII. Conclusion

This paper demonstrated that the use of SWAT model can give a fair estimation of the water yield. The river discharge is mainly dependent on precipitation. The effects of glaciers and snow are largely dependent on the basin characteristics and the glaciated area. For the Dudh Koshi basin, the melt water contribution from the glaciers and snow is nearly 30%. The T-index method of glacier melt estimation is a simple approach requiring only temperature and melt factor, however use of such model underestimated the melt while using mean daily temperature data. The finding shows that the melting of glaciers can continue until 3 °C below the average mean temperature, indicating that the important role of solar radiation in such higher altitude. The radiative energy dominates energy exchanges at the glacier-atmosphere interface, due to the variation in the net shortwave radiation. In fact, [26] indicated that the threshold temperature for ablation of snow can be a minimum daily air temperature of -4.6 °C. The potential climatic impacts on hydrology under the climate change in the Himalayan basins needs better assessment for management of water resources. In case of catchments hosting several glaciers, the hydrological response is a function of the combined effect of different glacier volume changes, and is therefore more variable in space and time.

IX. Acknowledgment

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