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INVESTIGATING THE APPLICABILITY OF WEB-DHM TO THE HIMALAYAN RIVER BASIN OF NEPAL

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A distributed biosphere hydrological model, WEB-DHM has been evaluated from point scale to basin scale at a sub-basin of Himalayan river (The Dudhkoshi river basin of Nepal). At point scale (Syangboche CEOP reference site), the model performance was carefully checked by the longterm hourly upward shortwave radiation (USR) and soil surface temperature (ST). In general, the model performed well in the point scale simulation but it was found that the USR was underestimated and the ST was overestimated during highly snow-covered days. The results were successfully improved by modifications of albedo and bulk soil heat capacity. For basin scale simulation, the model can reproduce the seasonal variation of the discharges at the basin outlet, but needs further improvements in snow accumulation for better representation of snowmelt runoff in the basin.

Key Words : *WEB-DHM, soil surface temperature, upward shortwave radiation, CEOP site, discharge, Dudhkoshi*

1. INTRODUCTION

The surface energy and water balance in high elevation and cold regions are controlled by functions of vegetation, seasonal snow cover, air temperature, surface moisture content, incoming shortwave and longwave radiation. Hence, physically based models should be used for the understanding of land surface hydrologic processes of such regions. Few studies have been carried out to estimate the surface energy and water balance of high elevation and cold regions using Distributed Hydrological Model (DHM) and Land Surface Models (LSM)1)2). Independent application of these DHM and LSM cannot represent the integrated energy and water budget and hence distributed biosphere hydrological model shall be used by coupling DHM and LSM for improved representation of hydrologic systems and estimates of water and energy fluxes.

Water and Energy Budget – Based Distributed Hydrological Model (WEB-DHM)3) is a distributed biosphere hydrological model, developed by coupling Simple Biosphere Model 2 (SiB2)4) into geomorphology based hydrological model (GBHM)5). WEB-DHM physically describes evapotranspiration with coupled water and energy budgets in the soil-vegetation-atmosphere transfer (SVAT) system. Although WEB-DHM has been successfully evaluated against several field experiments from point scale to basin scale6)7)8), it has not been applied to high Himalayan river basin yet.

In Nepalese Himalayan river basins, very few studies have been conducted using DHMs2)9). The water balance of the Koshi river basin of Nepal has been studied in lumped and distributed water balance approach in monthly time steps10). Research in high head watersheds is not well advanced due to extreme terrain, monsoon climate and lack of field observations limiting the transferability of hydrologic principles, techniques and models developed elsewhere. However since the assessment of hydrologic response of the Himalayan basin is affected by the high degree of uncertainties in meteorological data, it is essential to validate the field measurements prior to application of the model.

This study focuses on the applicability of WEB-DHM to the Himalayan river basin of Nepal, the Dudhkoshi basin and validation of the model performance at Coordinated Enhanced Observing Period (CEOP)[11) reference site “Syangboche” inside the basin against upward shortwave radiation and soil surface temperature.

2. STUDY AREA

The study area for the research is the Dudhkoshi river basin which is located in northeast of Nepal. It is one of the sub basins of the Koshi basin. The basin elevation ranges from 452 m to 8600 m mean above sea level. The catchment area lying upstream of Rabuwabazar discharge gauge is about 3700 km^2 in which about 1090 km^2 lie in Himalayan region. The detail of meteorological gauges are shown in **Fig. 1**. and **Table 1.**

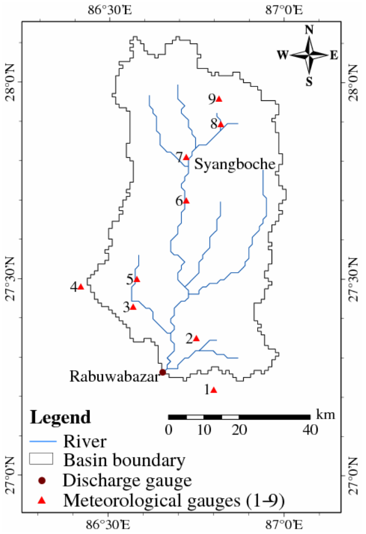


Fig. 1 The Dudhkoshi River Basin

Table 1 Detail of Meteorological Gauges.

No.	Name	Elev. (m)	Data Source	Resolution
1	Diktel	1623	DHMNepal	Daily
2	Aiselukhark	2143	DHMNepal	Daily
3	Pakarnas	1982	DHMNepal	Daily
4	Mane Bhanjyang	1576	DHMNepal	Daily
5	Salleri	2378	DHMNepal	Daily
6	Chaurikhark	2619	DHMNepal	Daily
7	Syangboche	3833	DHMNepal /NCAR-EOL	Hourly
8	Pheriche	4260	NCAR-EOL	Hourly
9	Lobuche	5035	NCAR-EOL	Hourly

The climate of the basin is represented by four seasons; winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post monsoon season (October–November). The source of runoff is monsoon rainfall and snow and icemelt. About 80 % of the precipitation falls in monsoon period. The summer monsoon precipitation occurs in solid form in higher altitudes.

3. METHODOLODY

WEB-DHM was applied to investigate its applicability to a high Himalayan river basin from point scale to basin scale. The details of the data, model structure and its evaluation criteria are described in this chapter.

(1) Data

The daily discharge data at Rabuwabazar gauge and daily precipitation data for 6 meteorological stations (1-6) were obtained from Department of Hydrology and Meteorology, Nepal (DHMNepal). Hourly surface meteorological datasets (downward and upward shortwave radiation, U and V components of wind speed, specific humidity, air temperature, atmospheric pressure and precipitation) for the three CEOP reference sites (stations 7, 8 and 9) were obtained from National Center for Atmospheric Research – The Earth Observing Laboratory (NCAR – EOL) for Earth Observation Period 3 (EOP-3). Syangboche station was selected for point scale simulation among 3 CEOP reference sites. Hourly soil temperature data at 0.5 cm depth (hereafter regarded as soil surface temperature) for Syangboche station was obtained from DHMNepal.

The topographic data was obtained from SRTM 90m DEM. Global Leaf Area Index (LAI) and the Fraction of Photosynthetically Active Radiation (FPAR) MOD15_BU_C5 0.25 degree datasets were used in this study, which were 8-daily composites of MOD15BU products. LAI and FPAR data were provided by EOS Data Gateway of NASA. FAO Soil and USGS land use data were used as vegetation parameters **(Fig. 2)**.

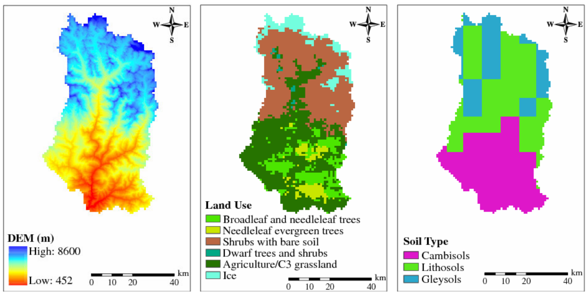


Fig. 2 DEM (left), land use (middle) and soil type (right) in the basin

Cambisols, lithosols and gleysols were the soil types inside the basin. The average soil texture of the study basin was classified as 28 % clay, 46% sand and 26% silt. Land use type was reclassified according to SiB2 type. Meteorological data sets (downward shortwave radiation, downward longwave radiation, air temperature, cloud fraction, specific humidity, U and V components of wind speed, surface atmospheric pressure) for the basin were processed from the Japanese 25 years Reanalysis (JRA-25) dataset. All the surface meteorological data including precipitation, LAI/FPAR, soil type, land use data were interpolated at a 1 km grid for model simulation.

(2) Model Structure

The model structure of the WEB-DHM[3)6)7)] can be summarized as follows:

(i) The basin is divided into sub-basins using Pfafstetter[12)] scheme. Each sub-basin is divided into a number of flow intervals considering flow distance to its outlet. Each flow interval comprises several model grids.

(ii) Turbulent fluxes between the atmosphere and the land surface are calculated by hydrologically improved SiB2 on each model grid using one combination of soil type and land use.

(iii) Each model grid is treated as geometrically similar hillslope unit which is the basic computing unit of WEB-DHM.

(iv) Hillslope module is used to simulate surface and sub surface runoff generated from hillslope units and kinematic wave approach is used to route the water flow in the river network.

(3) Model Performance Indicator

The model performance is evaluated by Mean Bias Error (MBE), Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE)[13)]. MBE, RMSE and NSE are defined as followings;

$$MBE = \sum_{i=1}^{n} (S_i - O_i) / n \qquad (1)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} (S_i - O_i)^2 / n} \qquad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n} (Q_{oi} - \overline{Q}_o)^2} \qquad (3)$$

where n is the total number of time series, S_i is the simulation result, O_i is the in-situ data, Q_{oi} is the observed discharge, Q_{si} is the simulated discharge, $\overline{Q}_o$ is the mean observed discharge over the simulation period.

4. RESULTS AND DISCUSSIONS

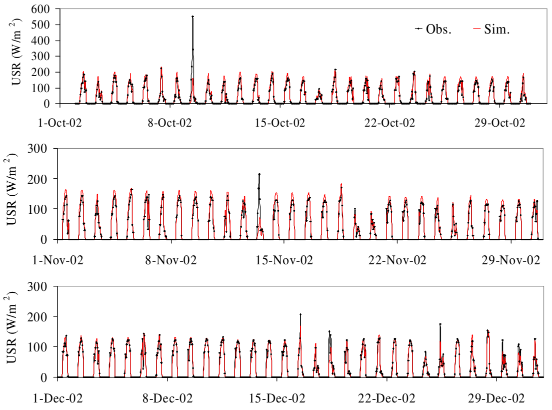
(1) Point Evaluation of the WEB-DHM at the CEOP Reference Site (Syangboche station).

Point scale model simulation at CEOP reference site, Syangboche station was driven by initial condition of observed soil surface temperature. Hourly field measurements of downward shortwave radiation (DSR), precipitation, pressure, specific humidity, air temperature, U and V components of wind speed and 6 hourly JRA-25 data of cloud and long-wave radiation were used as atmospheric forcing data for the model run. The model was run from 2 October 2002 to 24 June 2003. The model output was compared with measured hourly upward shortwave radiation (USR) and soil surface temperature (ST). The snow cover days are considered when ST is at a constant value below freezing temperature (273.15 K) and the albedo is above 50%[14)].

a) Upward shortwave radiation (USR)

Upward shortwave radiation (USR) is the critical parameter in the radiation budget of surface energy balance. It reflects the reflectivity power of the land surface, i.e. albedo of the surface can be calculated from the information of USR. Higher the USR with respect to DSR means the land surface absorbs less energy. Since radiation budget governs the whole energy budget in the higher elevations, USR should be correctly validated for the energy balance studies.

The comparison between observed and simulated hourly USR is shown in **Fig. 3**. The diurnal cycle of USR is well simulated by WEB-DHM with high accuracy for the months October–December and April–June. The simulation results showed that the USR is underestimated during snow cover days of the months January–March. This discrepancy is endorsed due to the high reflectivity of snow.



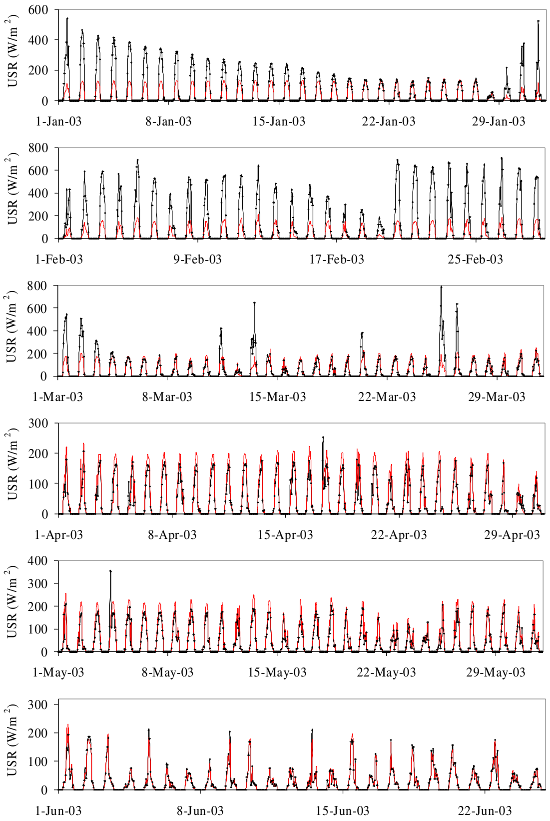


Fig. 3 Observed and simulated hourly upward shortwave radiation (USR) from 2 October 2002 to 24 June 2003 at Syangboche station.

b) Soil surface temperature (ST)

Soil surface temperature is another important parameter of the land surface energy balance. It directly affects the sensible and latent heat fluxes. The accurate estimation of temperature gradient between atmosphere and land surface is very important in high elevation area for the estimation of evapotranspiration. It is the key variable for the estimation of upward longwave radiation when the in-situ data are not available.

The comparison between observed and simulated hourly ST is shown in **Fig. 4**. The diurnal cycle of ST is well simulated for the months October–December and April–June. The simulation results show that the ST is overestimated during snow cover days of the months January–March.

Statistical analysis of the simulation results are shown in **Table 2**.

Table 2 Statistic analysis of model simulation for whole period.

	MBE	RMSE
Soil surface temperature (K)	1.10	6.65
Upward shortwave radiation (W/m^2)	- 11.21	63.56

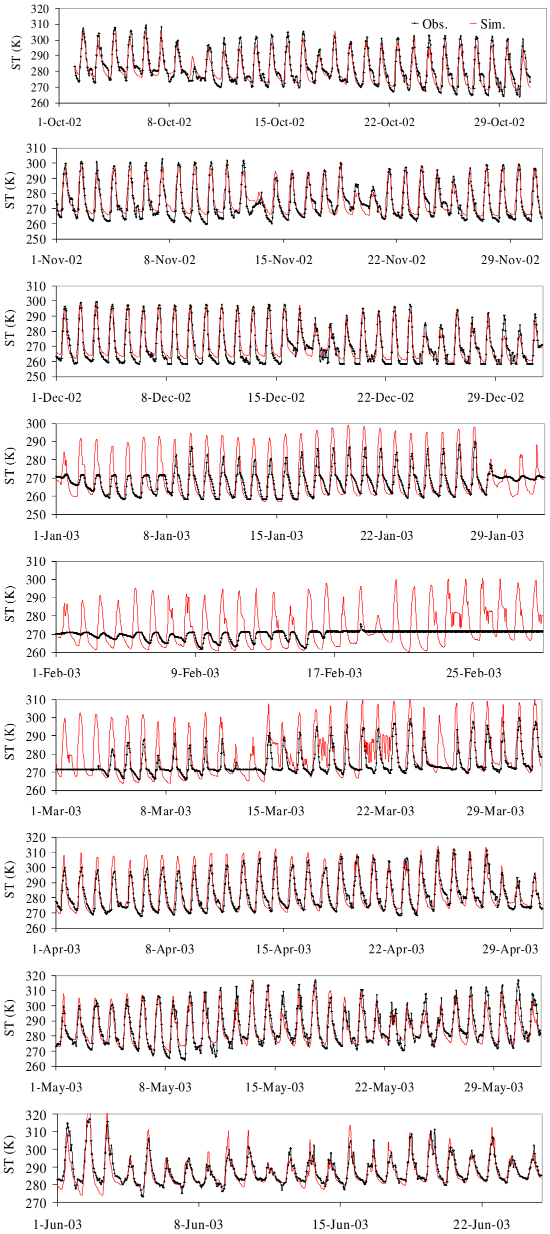


Fig. 4 Observed and simulated hourly soil surface temperature (ST) from 2 October 2002 to 24 June 2003 at Syangboche station.

c) Modification of surface albedo and bulk heat capacity of soil

We assume that the site is covered by continuous snow cover from 28 January to 3 March of year 2003 from the analysis of observed data of ST, DSR and USR. During this period, the model results seem inaccurate and USR seems inaccurate from 1 to 18 January too but the observed ST is found below the freezing point from 1 to 8 January only. Although the 8 days with ST below the freezing temperature can also be assumed as snow cover days, we ignored this short period for modification during simulation. In this study, we focused on the longterm period with ST below the freezing temperature for modification and hence the albedo and bulk soil heat capacity are modified for the period from 28 January to 3 March, 2003. The albedo is modified as a function of air temperature following Meteonorm[15)] as shown in equation 4. The original equations for albedo and bulk soil heat capacity can be found in Sellers et. al.[4)]. The linear regression equation for albedo and modified bulk soil heat capacity (C_{soil}) are as followings;

$$Albedo = 0.618 - 0.044 \times (T_a - 273.15) \quad (4)$$

$$C_{soil} = (1-\eta) \times C_s + w \times C_w \quad (5)$$

where T_a is the air temperature (K), η is the porosity of soil (from FAO soil data[16)]), C_s is the specific heat capacity of soil (0.8×10^6 J m^{-3}K^{-1}), w is the water content of soil (simulated by the model itself), C_w is the specific heat capacity of water(4.18×10^6 J m^{-3}K^{-1}). The simulation results with new scheme of albedo and bulk soil heat capacity show the good agreements with the observed ones as shown in **Fig. 5**. The scatterplots of USR and ST as shown in **Fig.6 (a,b)** shows that the performance of the model is remarkably improved after the modifications.

The statistic indicators for improvement of model performance are shown in **Table 3**. Although these statistics presents the increased performances of the model, the energy budget of the model should be physically improved further in the albedo distribution, physics of snow accumulation and snowmelt for the high performance in the Himalayan river basins.

Table 3 Statistic analysis of model simulation for 28 January 2003 to 3 March 2003.

	MBE	RMSE
a) Before modification		
Soil surface temperature (K)	3.20	10.58
Upward shortwave radiation (W/m^2)	- 74.00	149.43
b) After modification		
Soil surface temperature (K)	1.82	2.91
Upward short-wave radiation (W/m^2)	2.92	45.90

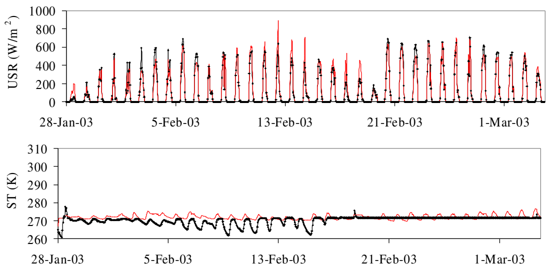


Fig. 5 Observed and simulated hourly USR and ST from 28 January to 3 March 2003 at Syangboche station.

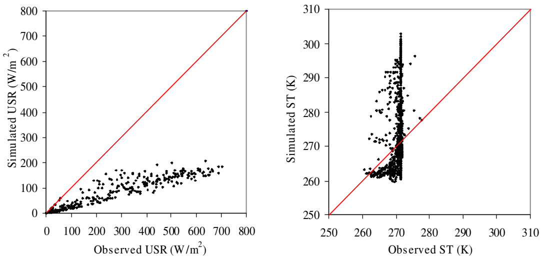


Fig. 6(a) Scatterplots of hourly observed and simulated USR and ST from 28 January to 3 March 2003 before modification.

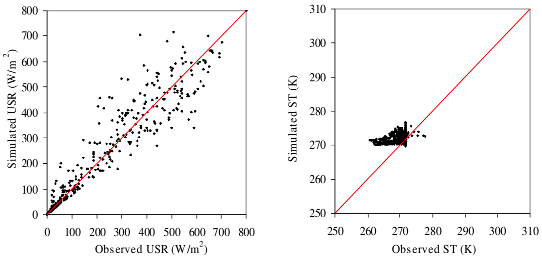


Fig. 6(b) Scatterplots of hourly observed and simulated USR and ST from 28 January to 3 March 2003 after the modification of albedo and bulk soil heat capacity.

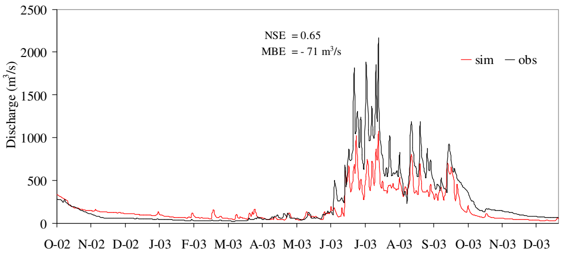


Fig. 7 Observed and simulated discharge at Rabuwabazar gauge from 2 October 2002 to 31 December 2003.

(2) Basin scale Evaluation of the WEB-DHM

Daily discharge at Rabuwabazar gauge of the Dudhkoshi basin is simulated from 2 October 2002 to 31 December 2003. The simulated discharge represents the seasonal variation as compared to the observed discharge but the volume error seems too high for the monsoon season as shown in **Fig. 7**. NSE and MBE for the simulation is 0.65 and -71 m^3/s respectively. The simulated discharge is not able to show the considerable amount of snowmelt in the monsoon and post monsoon season.

We simulated the discharge with new scheme of albedo and bulk soil heat capacity. The results are not improved because the snowmelt in the pre monsoon season depends upon the snow accumulation pattern in the winter season and current WEB-DHM is unable to simulate the snow accumulation patterns. Another reason for the high discrepancy of discharge during monsoon and post monsoon season may be due to the characteristics of the river basin itself. High elevation regions of the basin are covered by glaciers and glacier melt is ignored in current simulation. Generally snow accumulation pattern in high elevation of snow fed river basins are of two types: summer accumulation and winter accumulation type. The summer accumulation type has more snow accumulation in summer than in winter. Snow accumulation and snowmelt occur simultaneously in summer and the increased summer air temperature reduces the proportion of snow to rain causing reduction in the snow accumulation. This will result in a decrease in the surface albedo which ultimately increases snowmelt, i.e. snowmelt is strongly affected by accumulation variations. But for the winter accumulation type, snowmelt variations are almost independent of snow accumulation variations. The snow accumulation pattern in Dudhkoshi river basin is of summer accumulation type for which snowmelt is strongly affected by accumulation condition since both occur simultaneously. The current model can not simulate such simultaneous accumulation and melting process well. The refinements on the snow physics (both snow accumulation and snowmelt) in WEB-DHM are expected to improve the model performance in the basins with similar characteristics to Dudhkoshi.

6. CONCLUSIONS

In this study, WEB-DHM was evaluated in point scale at Syangboche CEOP reference site against the hourly soil surface temperature and upward shortwave radiation. Although the performance of the model was improved by new scheme of albedo and bulk soil heat capacity, the model needs further improvement in the spatiotemporal distribution of albedo, snow accumulation and snowmelt algorithms for the basin scale simulation. Hence, the research in improvement of snow physics of this model for accurate simulation in the Himalayan river basin is highly encouraged.

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