Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Assessing Snow Melt Contribution of SWAT Model with a Comparative Analysis of MODIS Snow Cover Area in Dudh Koshi River Basin

Sandip Dangi [a], Suraj Lamichhane [b]

[a, b] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
✉ [a] sandipdangi27@gmail.com, [b] klsuraj@gmail.com

Abstract

Managing water resources at watershed scales is crucial as it facilitates the examination of intricate hydrological processes and the interplay between terrain, climatic variables, and anthropogenic influences. This approach allows for a comprehensive understanding of these dynamic interactions.The escalating global climate change has led to accelerated ice melt and more frequent intense precipitation, resulting in prolonged social and economic impacts, and increased environmental challenges, causing widespread scarcity and disruptions worldwide. Combining high-resolution spatial and temporal data from the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover dataset with a semi-distributed hydrological model enables the simulation of streamflow, the impact of snowmelt on streamflow, and alterations in snow cover within a complex Himalayan river basin. This study tested the framework in the Dudh Koshi River basin. First, the model is calibrated (1986-2006) and validated (2007-2019) with initial three years as a warm-up period. Results revealed that about 28.2% (631.7) mm of precipitation falls as snowfall and about 27% (168.98mm) of this meltaway and contributes as snowmelt runoff. In contrast, remaining snow may get compacted and form ice/glaciers. Snow cover maps obtained from MODIS satellites were further compared with snow water equivalent obtained from SWAT simulations to assess model performance for simulating snow processes. The snowpack's water content in the sub-basin closely matched the snow cover maps derived from MODIS data. The findings indicate a significant increase in water runoff from snowmelt occurring in the period before the monsoon season, as the accumulated winter snow begins to thaw. The model can be used further for assessing snow process changes in the Dudh Koshi basin under future climate change scenarios. These results offer valuable insights for engineers, urban developers, and government officials in crafting strategies for the sustainable management of water resources.

Keywords
Water availability, Himalayan river basin, SWAT modeling, MODIS datasets, snowmelt contribution

1. Introduction

In terms of availability, Nepal is endowed with an abundance of water resources. Water bodies are critical vital natural resources that have the ability to act as a catalyst for the country's overall development and economic growth. Nepal has throughout 6000 rivers with a total catchment area of 194,471 Km^2. Out of this, 74% lies within the country, 33 of these rivers have a drainage area that exceeds 1000 Km^2 [1]. Thousands of rivers are more than 10 Km long; about 24 of them are over 100 Km long. The flow patterns are regulated mainly by the melting of snow and glaciers. As a consequence, flow is perennial in these rivers, and flows are maintained throughout the dry season [**?**]. Snow melt dynamics and its impact on water resources in river basins are of significant interest for hydrological studies and water resource management. The Dudh Koshi River Basin, located in the eastern part of Nepal, covering Solukhumbu, Khotang and Okhaldhunga districts, is an important watershed that experiences notable snow accumulation during the winter months. Snow melt in this basin plays a crucial role in the overall hydrological processes, affecting water availability and streamflow. The Soil and Water Assessment Tool (SWAT) model is widely used for simulating water flow and quality in watersheds, including snow melt estimation and has been successfully applied in various regions worldwide to evaluate snow melt dynamics and its contribution to stream flow[2]. Conversely, the Moderate Resolution Imaging Spectroradiometer (MODIS) offers a valuable source of satellite-based data concerning snow cover area, enabling a global-scale evaluation of snow distribution and extent. MODIS data have found extensive utility in snow monitoring research, facilitating the analysis of snow cover fluctuations, seasonal snow duration, and temporal trends[3]. However, the specific application of the SWAT model and its performance in estimating snowmelt dynamics in the Dudh Koshi River Basin have not been thoroughly investigated. Furthermore, the comparison of SWAT model outputs with MODIS snow cover area data in this basin remains unexplored. By conducting a comparative analysis, we seek to evaluate the accuracy and reliability of the SWAT model and understand its strengths and limitations in capturing the complex snowmelt processes in this particular basin.

2. Material and Methods

2.1 Study Area

The Dudh Koshi River Basin (DRB) is located in the eastern part of Nepal, covering Solukhumbu, Khotang, and Okhaldhunga districts. The catchment area of DRB is 3716. Km^2 and elevation varies from 8848 m to 444 m.The Sapta Koshi river system, which drains Eastern Nepal, includes the Dudhkoshi River. The Nepalese Himalayas are home to its

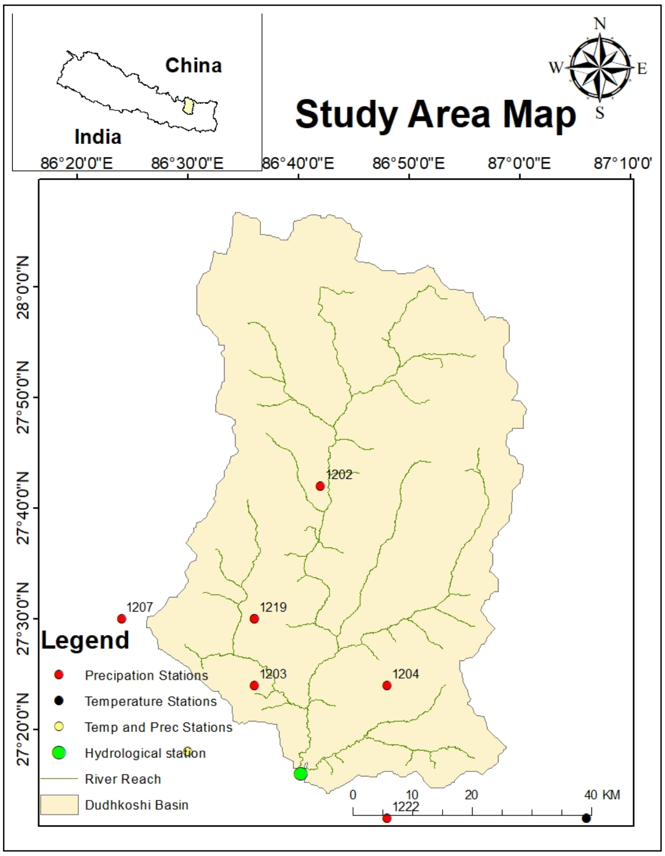

Figure 1: Location of the Dudh Koshi river basins

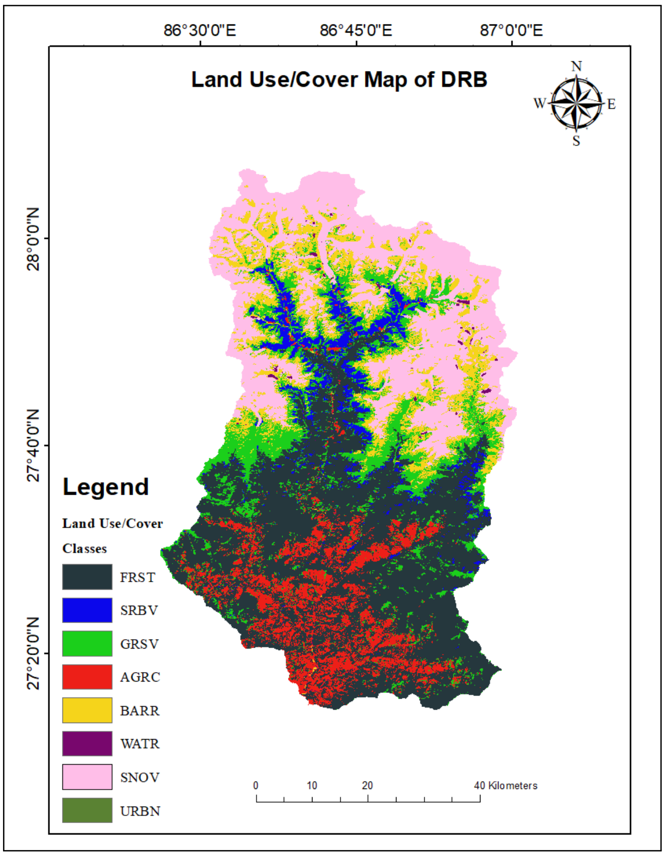

Figure 2: Detail and LULC map of the Dudh Koshi river basin

source, the Mount Everest massif, and its flowing waterways. Dudh Koshi stream closed at Rabuwa Bazar is 90 Km in length and has a catchment range of 3600 Km^2 (Source: Watershed area calculation in GIS). Based on the findings of in Dudh Koshi basin, the annual precipitation in the southern region of the basin is four times greater (1931 mm) compared to the northern region (536 mm). Likewise, the southern region exhibits significantly higher annual evapotranspiration (507 mm) in comparison to the northern region (178 mm). The majority of people living in this basin are indigenous ethnic communities who rely on farming and raising livestock to sustain their livelihoods.

2.2 Data Collection

2.2.1 Topographic Data

A 30m resolution Digital Elevation Model (DEM) based on Shuttle Radar Topography Mission data was used for topographical analysis (SRTM).DEM data is required to use in GIS and hydrological model (SWAT)[4].The DEM data was used to delineate the watershed and to obtain river network and drainage pattern. Also, the slope length and gradient along with other terrain information can be obtained from it. The elevation range of DRB varies from 444 m to 8848 m.

2.2.2 Land Use/Cover Data

The model uses a land use/cover map for 2010 that was produced by the International Center for Integrated Mountain Development (ICIMOD, 2010) and was accessible at a resolution of 30 meters. Eight terrain classifications make up the land cover map, with forests making up the majority of the basin overall.

2.2.3 Soil Data

A soil map of Nepal at a scale of one million was supplied by the Soil and Terrain Database Programme (SOTER). To develop soil map of the Dudh Koshi River Basin, different soil maps were used. Gelic LEPTOSOLS soil was discovered to predominate in the basin out of the six distinct soil types that were identified for it.

2.2.4 Hydro-meteorological Data

The Hydro-meteorological parameter is important to know the climatic condition of the study area and to derive the hydrological parameter. Precipitations(P), maximum and minimum temperatures(T), relative humidity (RH), wind speed (WS), and solar radiation (SR) were obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal. The average annual precipitation of Dudh koshi Basin is about 2160 mm and average annual discharge is about 204 m^3 . 19 metrological station data are used for input metrological data. The gauging station (Index no. 670) is used for the hydrological analysis of the model, which is located in the outlet of DRB at Dolakha district.

2.2.5 Moderate resolution image spectroradiometer (MODIS) snow cover

The snow product from the Moderate Resolution Imaging Spectroradiometer (MODIS) is used to determine the study area's percentage of snow cover.Several researchers utilize the

MODIS snow cover products as input for the Karnali Basin, West Seti basin of Nepal, snowmelt runoff model. The MODIS/Terra Snow Cover 8-Day L3 Global 500 m Grid, used for this study, contains data fields for maximum snow cover extent over an 8-day repeated period and has a resolution of approximately 500 m completely covering the Dudh Koshi River basin. The MODIS snow cover data has been used in snow cover monitoring, snowmelt runoff modeling, glacier mass balance estimation, drought monitoring [5]. The propose of using MODIS snow cover data in this project is to compare the snow cover data with snow water equivalent in the subbasin of Dudh Koshi River basin.

2.3 Methodological framework

The overall methodology adopted in this study in Fig.3

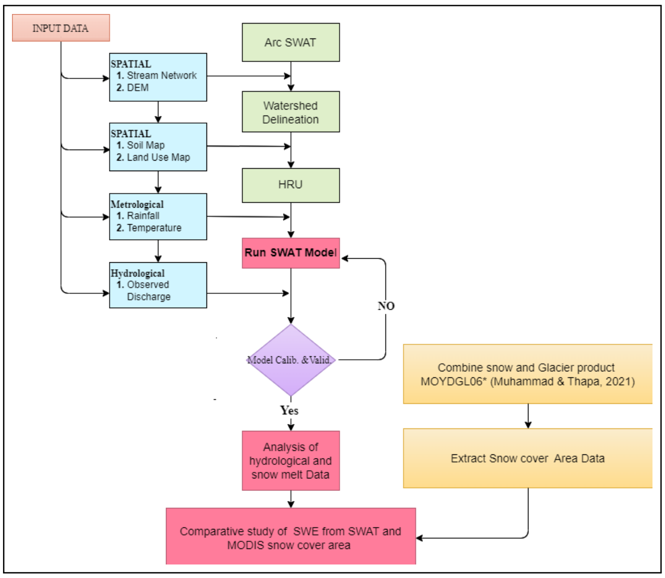

Figure 3: Methodological Framework

2.3.1 Hydrological modeling using SWAT

The SWAT is a powerful, comprehensive, semi-distributed, physically based model. Unlike empirical and conceptual models, a physically based SWAT model incorporates spatial and temporal variability in finer scale[6]. SWAT model first discretizes the water basin into the number of subbasins, connected through a stream network. The subbasin further divided into Hydrological Response Unit (HRU) that comprised of the distinct combination of land use, topography and soil characteristics in a watershed[7]. Runoffs generated from each HRUs with in sub-baisn are aggregated and routed to the main outlet of the watershed. 42 subbasin were delineated with 432 HRUs by defining the threshold area of 8000 units.The minimum and maximum temperatures obtained from metrological stations, as well as precipitation station data, were supplied on a daily basis.SWAT simulates hydrology at each computation-based water balance principle from Equation 1.

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{see}) - Q\check{n}_{gw} \quad (1)$$

Where, SW_t and SW_0 are the final and initial stage of soil water content respectively, R_{day} is the daily precipitation, Qsurf is the daily surface runoff, W_{seep} is the daily percolation, E_a is the daily evapotranspiration and Q_{gw} is the daily return flow, all units are in mm.

2.3.2 Model Calibration and Validation

Once the model is built and run, calibration and validation were performed, using independent observed dataset, to check the reliability of the model output. In this study, calibration and validation were performed, following the protocol suggested by Abbaspour et al.,(2015;2017)[8]. The most critical variables for the watershed are identified by SWAT-CUP utilizing the SUFI2 algorithm as the beginning phase in the model calibration and validation process[9]. A global analysis has been carried out in this study to rank the watershed's sensitive parameters. The model was calibrated and validated at Rabuwabazar hydrological station.

2.3.3 Performance Statistics Parameter

Calibration and validation were evaluated through qualitative and quantitative measures, involving both graphical comparisons and statistical tests between observed and model prediction. The graphical performance consists of plotting and comparison of observed and simulated hydrographs where as statistical tests uses simple tests such are absolute error and relative error to advances test like correlation as well as statistical test namely Nash Sutcliff Efficiency (NSE), coefficient of determination (R^2) and percentage bias were used for the model performance evaluation.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - \bar{Y})^2} \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^{n}(X_i - \bar{X}) - \sum_{i=1}^{n}(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad (3)$$

$$PBAIS = \frac{(\sum_{i=1}^{n}(X_i - Y_i))}{(\sum_{i=1}^{n}(X_i))} \quad (4)$$

Where, X = Observed discharge Y = Simulated discharge n = Number of values $\bar{X}$ = Average observed discharge $\bar{Y}$ = Average Simulated discharge

2.4 MODIS Snow cover Area

The final product, which covers the years 2002 to 2018, combines snow and glaciers from the final snow product MOYDGL06* used by Muhammad and Thapa [10] with the Ran-dolph Glacier Inventory version 6.0 (RGI 6.0), separated as debris-covered and debris-free .The snow cover area of (2015-2018) are taken for comparison with SWE of SWAT. A data set of 188 processed MOYDGL06* images available from 2015 to 2018 was extracted From `https://doi.pangaea.de/10.1594/PANGAEA.918198` First the raw data of MOYDGL06* is clipped with respected basin area. Reclassification, spatial analysis and raster calculation is done for binary classification of image with ArcMap. Then frequency analysis is done with the zonal histogram by Qgis software. The final result is frequency analysis is done with zonal histogram by Qgis software. The final result is compared with snow water equivalent (SWE) of SWAT on the snow fed subbasin to find the required relation.

3. Result and Discussion

3.1 Performance Evaluation of SWAT Model

The calibrated and validated period considered are 1986-2006 and 2007-2019, respectively. The result obtained from sensitivity analysis was used to perform auto-calibration in SWAT-CUP. Parameter PLAPS, TLAPS, REVAPMN are seen to be most sensitive whereas GW_REVAP, TIMP, CANMX seen to be least sensitive parameter. Model results are "very good" in terms of NSE, R^2 and PBIAS for both calibration as well as validation as shown in Table 2 and for daily time steps based on criteria defined by Moriasi [11].

Table 1: Daily calibration and validation statistical parameters

Timestep	Period	NSE	PBAIS	R^2
Daily	Calibration	0.75	-1.4	0.76
Daily	Validation	0.73	1.6	0.73

Table 2: Average annual basin values from SWAT model

Precipitation	2071.3 mm
Snow Fall	631.7 mm
Snow Melt	168.98 mm

Table 3: Percentage average monthly rainfall and snow melt contribution in Dudh Koshi River

Months	Rainfall (mm)	Snowmelt (mm)	Net rainfall input	Water Yield	Snow Melt contri -bution (mm)	Monthly snow melt contribution in streamflow (%)
Jan	17.72	0.60	18.32	7.86	0.26	3.27
Feb	28.91	1.63	30.54	11.11	0.59	5.34
Mar	34.74	4.84	39.58	13.90	1.70	12.22
Apr	52.27	13.90	66.17	20.78	4.37	21.01
May	118.05	7.41	125.46	54.48	3.22	5.91
Jun	333.04	42.05	375.09	216.25	24.24	11.21
Jul	544.67	52.49	597.16	425.63	37.41	8.79
Aug	551.95	38.99	590.94	459.07	30.29	6.60
Sep	295.95	5.70	301.65	251.60	4.75	1.89
Oct	57.26	1.16	58.42	32.80	0.65	1.99
Nov	15.26	0.17	15.43	9.80	0.11	1.09
Dec	21.27	0.05	21.32	14.54	0.03	0.23
Total	2071.09	168.99	2240.08	1517.82		

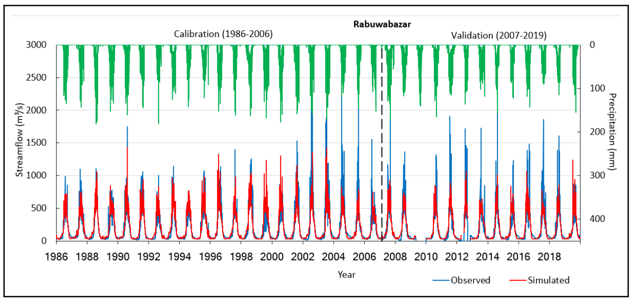

Figure 4: Observed and simulated hydrograph for daily discharge.

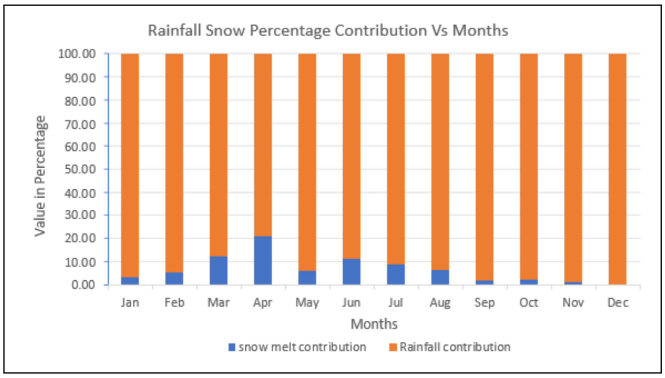

Figure 5: Average monthly rainfall and snowmelt contribution in Dudh Koshi River

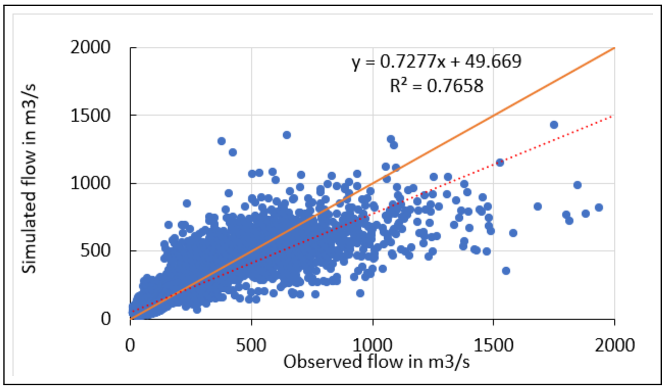

Figure 6: Observed and simulated flow scatter plot for calibrated daily discharge.

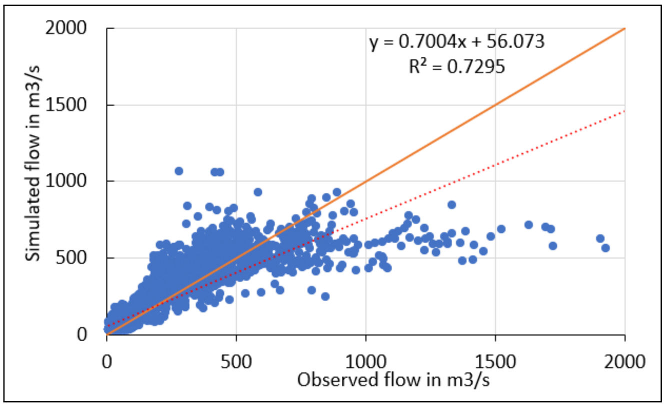

Figure 7: Observed and simulated flow scatter plot for validated daily discharge.

Figures 6 and 7 illustrate the scattering of observed versus simulated points from daily discharge over the calibrated and validated period. This allows hydrological simulations to be evaluated for fit at daily scales. Both figure shows that the model can capture extremes (both low and high flows) on a regular. The result shows that the model performance is less at very high flows than medium and low flows as similar to the result obtained by west Rapti basin [12].According to the SWAT simulation results, 107.62 mm of the total 1517.82 mm of yearly runoff—or around 7.5% of the runoff—comes from snowmelt runoff. In addition, the results demonstrate that a significant amount of the runoff from snowfall contributes to the flow throughout the dry season (March through une). For instance, approximately 21.02% of the river flow in April comes from snowmelt runoff.This suggests that rainfall leads the hydrology of the Dudh Koshi basin, accounting for about 90% of the annual river flow.There could be a lot of inherent uncertainty in the simulation of the melting of glaciers and snow.

3.2 Evaluation of MODIES Snow cover Area

The snow cover area of (2015-2018) are taken for overall basin with binary classification and frequency analysis is done by ArcMap and QGIS. The percentage of time snow cover is plotted on the basis of month in Figure 8 and Figure 9 shows that snow cover area decreases from April to September and snow cover area starts to increase gradually from October to December than increases insignificantly in January to March. Images of different months are merged together to look overall percentage time snow cover that also signifies permanent snow cover area on the basin and that can act as the reservoir for snow water equivalent (SWE) in Dudh Koshi River basin.

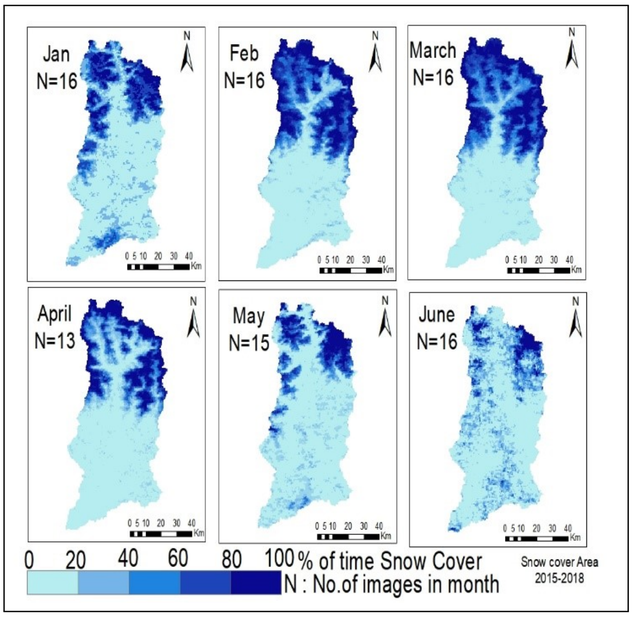

Figure 8: Spatial distributions of snow cover areas across Dudh Koshi River(Jan-June).

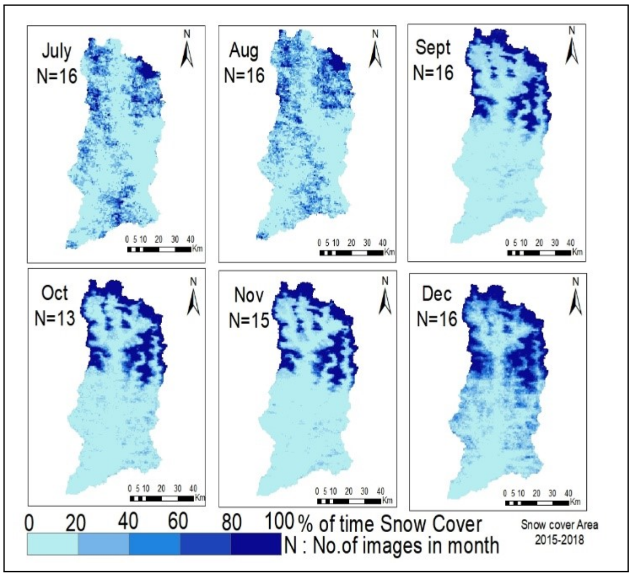

Figure 9: Spatial distributions of snow cover areas across Dudh Koshi River(July-Dec).

3.3 Comparative Study of Snowmelt and Snow Cover Area

A time-series comparison of the MODIS snow cover percentage and the SWAT snow water equivalent over the course of a four-year period is compared which shows that most years and subbasins, SWAT and MODIS snow season begins simultaneously, even if an early is noticeable for SWAT in subbasin 1 in starting of 2016, 2017. And some delay snow melt is noticeable in subbasin 2 in early of 2016 and 2017. While SWAT maintains that there is less snow than what is shown by MODIS data at the end of the snowmelt season, as in Figure10 there is less agreement. For SWAT as well as MODIS, the snowpack reaches its peak later or earlier.

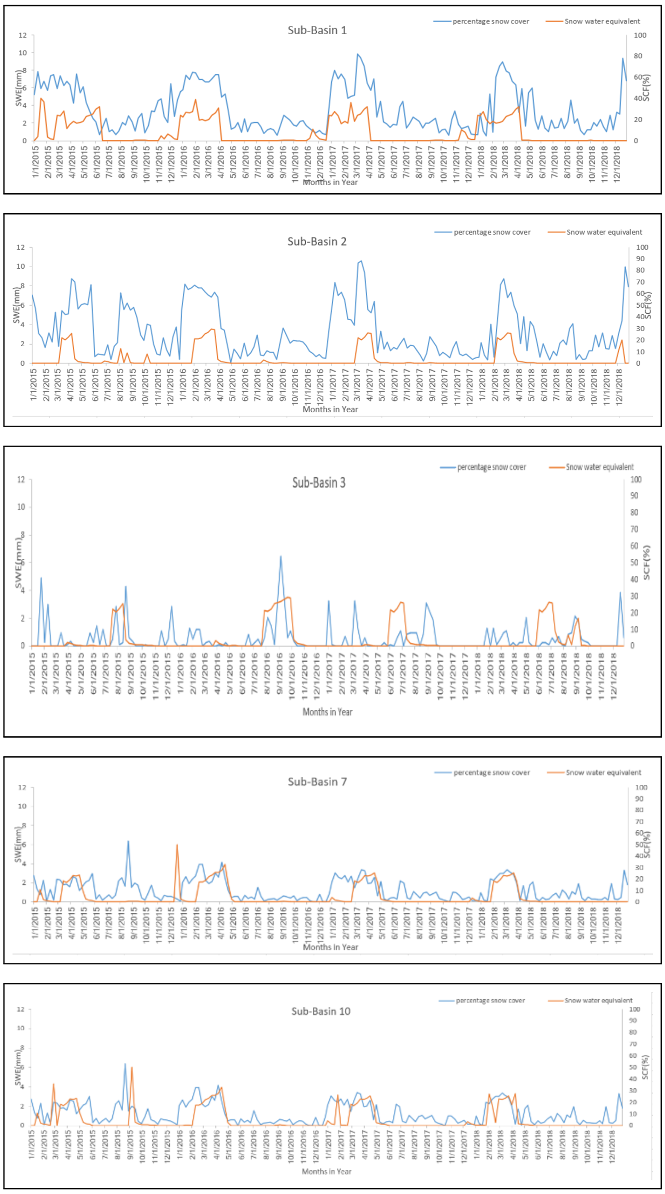

Figure 10: Comparison of SWE and percentage snow cover along different sub basins

4. Conclusions

In this study, hydrological model (SWAT) was setup, calibrated and validated using available input parameters and observed data in the Dudh Koshi River Basin which show well integration of observed hydrographs with simulated flow and with rainfall patterns. NSE value of calibrated daily discharge is 0.75 and NSE value for validation daily discharge is 0.73 which seems very good. According to observed results, the Dudh Koshi basin receives an average of 2240.08 mm of precipitation annually. Of this, approximately 28.2% (631.70 mm) falls as snowfall, and approximately 27% (168.98 mm) of this melts away and contributes to runoff from snowmelt. The remaining snow may be compacted and form the basin's ice or glaciers. Snowmelt runoff is significant during dry season. The Snow water equivalent from SWAT of different sub basin is significant on the wet season in which snow cover area percentage is maximum which contributes in snow melts. The snowmelt during January, February, March, April, May is captured in subbasins. Although some of the snow fall can be seen at November and December months, snow doesn't melt acts as storage. The findings of this research provide guidance for designers, planners, and policymakers in developing different approaches to sustainably manage water resources.

Acknowledgments

The authors would like to thank Centre for Disaster Studies, Nepal for providing technical support and also like to thank DHM, Nepal for providing climatic data.

References

[1] WECS. *Water resources of Nepal in the context of climate change. 68*. WECS, 2013.

[2] Susan L Neitsch, Jeffrey G Arnold, Jim R Kiniry, and Jimmy R Williams. Soil and water assessment tool theoretical documentation version 2009. Technical report, Texas Water Resources Institute, 2011.

[3] George A Riggs, Dorothy K Hall, Miguel O Román, et al. Modis snow products collection 6 user guide. *National Snow and Ice Data Center: Boulder, CO, USA*, 66, 2015.

[4] Sunil Bista, Umesh Singh, Nagendra Kayastha, Bhola Ghimire, and Rocky Talchabhadel. Effects of source digital elevation models in the assessment of gross run-off-river hydropower potential: A case study of west rapti basin, nepal. 04 2021.

[5] Flavia Burger, Alvaro Ayala, David Farias, Thomas E Shaw, Shelley MacDonell, Ben Brock, James McPhee, and Francesca Pellicciotti. Interannual variability in glacier contribution to runoff from a high-elevation andean catchment: understanding the role of debris cover in glacier hydrology. *Hydrological Processes*, 33(2):214–229, 2019.

[6] Elias G Bekele and John W Nicklow. Multi-objective automatic calibration of swat using nsga-ii. *Journal of Hydrology*, 341(3-4):165–176, 2007.

[7] Birsingh Dhami, Sushil Kumar Himanshu, Ashish Pandey, and Amar Kant Gautam. Evaluation of the swat model for water balance study of a mountainous snowfed river basin of nepal. *Environmental Earth Sciences*, 77:1–20, 2018.

[8] Karim C Abbaspour, Saeid Ashraf Vaghefi, and Raghvan Srinivasan. A guideline for successful calibration and uncertainty analysis for soil and water assessment: a review of papers from the 2016 international swat conference. *Water*, 10(1):6, 2017.

[9] Sushant Mehan, Ram P Neupane, and Sandeep Kumar. Coupling of sufi 2 and swat for improving the simulation of streamflow in an agricultural watershed of south dakota. *Hydrol. Curr. Res*, 8(3):10–4172, 2017.

[10] Sher Muhammad and Amrit Thapa. An improved terra–aqua modis snow cover and randolph glacier inventory 6.0 combined product (moydgl06*) for high-mountain asia between 2002 and 2018. *Earth System Science Data*, 12(1):345–356, 2020.

[11] Daniel N Moriasi, Jeffrey G Arnold, Michael W Van Liew, Ronald L Bingner, R Daren Harmel, and Tamie L Veith. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3):885–900, 2007.

[12] Rocky Talchabhadel, Hajime Nakagawa, Kenji Kawaike, Kazuki Yamanoi, Anil Aryal, Binod Bhatta, and Saroj Karki. Swat modeling for assessing future scenarios of soil erosion in west rapti river basin of nepal. In *EGU General Assembly Conference Abstracts*, page 1853, 2020.