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

Impact Assessment of Future Snow Cover Variation on Hydrology of Marsyangdi River Basin, Nepal

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Abstract

In the water cycle, snow cover is a crucial hydrological reservoir, especially when the watershed contains a mountainous region. Numerous studies have indicated that the Himalayan snow cover line is generally receding as a result of climate change. Marsyangdi River Basin, a snow fed basin of Hindu Kush Himalayas, lying of the north central part of Nepal has more than 20% snow coverage but the status of variation of snow cover area in future in the MRB, however is rare. The observed annual snow cover area of 2010 is reduced by 0.7% per year in Marsyangdi River Basin. Studying snow cover, its changes over time and its influence on basin hydrology is crucial for effective water resource management. We used the DynaCLUE model, which utilized spatial rules and constraints, land use conversions, land use needs, and geographical features, as inputs to forecast future snow cover. Thus generated future snow cover maps from the year 2010 to year 2100 were evaluated through statistical analysis, specifically Kappa analysis, which showed good agreement with the validation map. The projected snow cover maps shows decrease in snow cover area by 2.03%, 4.03%, and 14.20% for 2030, 2050, and 2090 with respect to baseline map of 2010. A physical based semi distributed hydrological model termed the Soil and Water Assessment Tool (SWAT) model was used to examine the effects of future variations in snow cover on the hydrology of the Marsyangdi River Basin. The most sensitive hydrological parameters were identified and calibrated using the SWAT-CUP tool following Sequential Uncertainty Fitting (SUFI-2) technique over the 1988-2017 period using hydrological station 439.7 (Bimalnagar station) at outlet of the watershed. The future hydrology of the watershed is simulated using the projected snow cover maps and the baseline climate data as input to the calibrated SWAT model. Then, the simulation of future stream flow and water balance of the basin were conducted and compared with the baseline hydrology. According to the findings, there will be an increase in average annual stream flow relative to the baseline of 4.1% (near future), 4% (mid future), and 3.5% (far future). This study also demonstrates the variation in the components of the water balance. Therefore, it offers crucial information that project planners and decision-makers need to make well-informed decisions on upcoming developments.

Keywords

DynaCLUE model, Future snow cover map, SWAT model

1. Introduction

A significant portion of the yearly stream flow in the Himalayan region may originate from the snow cover and glaciers [1]. Snow fall and snow melt are the two of the more dominant hydrological process of snow fed basin [2]. During dry periods in snow-fed basins,when water supply is most critical, melting snow and glaciers contribute significant quantities of water [1]. However, the region is facing the substantial challenge regarding climate change, which is causing both fast melting of the snow and glacier and snow accumulation reduction due to precipitation shift [3]. Global warming is expected to raise the temperature by 1.7°C to 6.3°C in the Hindu Kush Himalaya region by the 21st century's end [4]. The consequences of climate change on the hydrological cycle and water resources are expected to exacerbate ecosystem degradation, water quality disturbances, and the loss of snow cover, glaciers, and sea ice in the future [5]. The snow cover and glaciers of the Hindu Kush Himalaya (HKH) are some of the fastest-thinning in the entire world [6]. The Snow and ice melt waters of Hindu Kush Himalaya region play a significant role to provide water for downstream farming, generating hydropower, and domestic use [7]. As a result, snow cover in locations with high-altitude stream sources, such those in the Hindu Kush Mountains, is likely to alter the water supply in mountain basins and, over time, negatively impact people's quality of life, especially in areas downstream [1]. The more rapidly melting of snow cover and glacier increased incidence of natural hazards [3].

The Marsyangdi River basin (MRB), a critical water source in the HKH region, is already experiencing a decline in its snow cover area, decreasing at a rate of 0.7% each year based on a previous snow cover map of the research region from 2000 to 2010. Given the anticipated changes in snow dynamics in the future, it is imperative to gain a comprehensive understanding of current snow cover dynamics and their implications for basin hydrology. While studies on glaciers in the Himalayas are relatively more abundant, research specifically focused on snow cover is rare [1]. There is still a clear knowledge gap when it comes to understanding how changes in snow cover could affect basin hydrology, despite the fact that several studies have been conducted on the impact of Land Use and Land Cover (LULC) changes on watershed hydrology. This paper aims to bridge that knowledge gap by employing, Dyna CLUE model to project the future snow cover in the Marsyangdi River Basin based on logistic regression. For hydrological simulation of the snow fed basin, various research have employed the Soil and Water Assessment Tool (SWAT) model (eg: Marahatta et al. [8], Bhatta et al. 2019 [9], Adhikari, Baniya, and Raj 2022 [10]). Dhami et al. 2018 [11] implemented an analysis to assess the SWAT model for the water balance research of snow-fed river basin in Nepal and the outcomes showed that SWAT models could be successfully used for planning and managing water resources in Nepal’s Himalaya river basins. This study used the semi-distributed, physically-based soil and water assessment tool (SWAT) [12] over a snow-covered watershed to analyze the potential effects of future changes in snow cover on the hydrology of the basin. This study’s specific goals are to: (i) predict the Marsyangdi River Basin’s future snow cover map using the Dyna-CLUE model, and (ii) evaluate the effects of that change on the basin’s stream flow and water balance components. This research addresses the critical need to comprehend how shifts in snow cover could influence basin hydrology, which has implications for water resource planning, development, and management strategies in the region. Establishing a robust knowledge base on the relationship between snow cover fluctuations and hydrology is crucial for adapting to the challenges posed by climate change in the Himalayas.

2. Materials and Methods

2.1 Study Area

The study has been conducted in Marsyangdhi river basin of Nepal as shown in Figure 1. It is a snow fed basin with the catchment area of 4039.524 Km2. The elevation of this basin ranges from 349m to 7698m above sea level. The basin lies within longitude 83^{o}47’24” E to 84^{o}48’04” E and latitude 27^{o}50’42” N to 28^{o}54’11” N. Hydrological station no. 439.7 is the outlet of this watershed lies at Bimalnagar. The basin physically stretches from the Greater Himalaya in the north to the Lesser Himalaya in the south. Four administrative districts comprise the research area: Manang, Lamjung, Gorkha, and Tanahu. The majority of the Marsyangdi River basin is on the southern sides of the Central Himalayas, with the northern section situated on the leeward side of the Annapurna mountain.This basin’s Marsyangdi River is a tributary of the Narayani River System, which eventually merges with the Ganges River. The Marsyangdhi River is a 150 km long alpine river in Nepal. Before flowing south through the Lamjung region, the Marsyangdi River passes through the Manang district to the east. The river’s tributaries include the Paundi Khola, Chundi Khola on the right, and the Nagdhi Khola, Dordi Khola, Chepe Khola, and Daraundi River on the left. The Marshyangdi River offers considerable potential for both hydropower generation and recreational activities like rafting and kayaking. In this region, there are presently numerous prominent hydroelectric projects in operation, such as Middle Marsyangdi (70 MW), Lower Marsyangdi (69 MW), and Upper Marsyangdi (50 MW). Other hydroelectric projects in the tributaries, including Nyadi, Midim, Chepe, Dordi, and Daraudi, are also included in the operating phase. Study and development are under ongoing for several more major hydropower projects, such as Manang Marsyangdi (135 MW), Lower Manang Marsyangdi (140 MW), Upper Marsyangdi 1 (138 MW), and others. The basin is one of Nepal’s primary hydroelectricity producing sources [10].

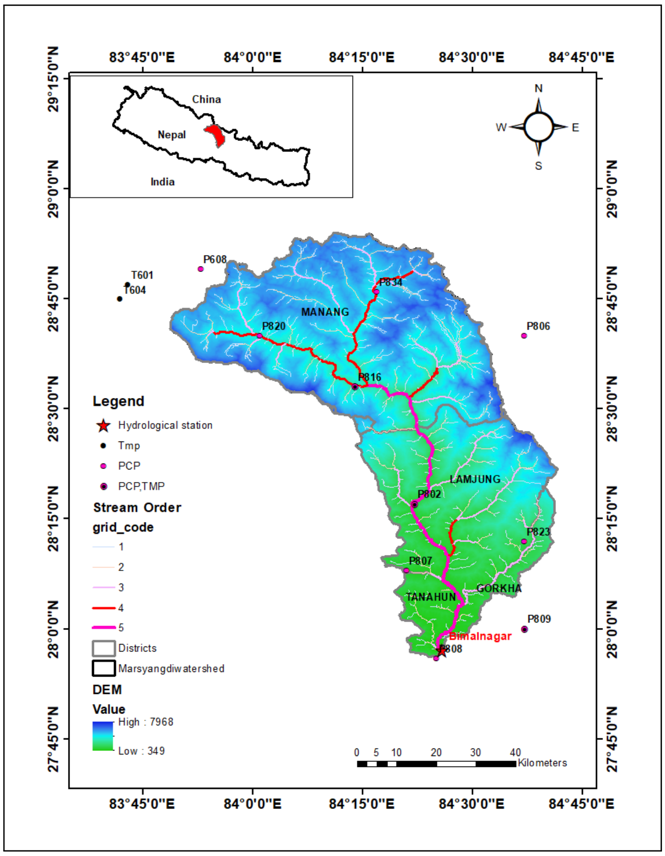

Figure 1: Location Map of Marsyangdi River Basin showing River networks, Hydro-meteorological stations

2.2 Methodological Framework

Figure 2 illustrates the methodology used in this investigation. In general, it includes data preparation, model setup, validation and calibration, projections of future snow cover areas, and an evaluation of the effects of changing snow cover areas on the hydrology of the Marsyangdi River Basin using the validated SWAT model.

2.2.1 Data Preparation

The necessary topography, soil, land use/cover map, hydrological, and meteorological data were gathered from various sources as shown in Table 1 and then preprocessed. The DEM, which is used to define the watershed and create the river stream, varies greatly, from 349 to 7968 masl. Higher resolution LULC maps include areas of mixed forest, water bodies, areas covered by snow and glaciers, barren terrain, built-up areas, and crop land where the amount of snow cover accounts for 20% of the total area. Soil Map consist of seven different types of soil with dominance are Lupin (Lpi) and Humic cambisols (CMu) covering 54.81% and 13.63% of watershed. The slope of Marsyangdi watershed is divided into five classes (0-5%, 5-10%, 10-20%, 20-50%, 50%). The hydrological and Meteorological data were collected from Department of Hydrology and Meteorology for 38 years long baseline period from 1980 to 2017 in this study. which includes daily mean precipitation, solar radiation, maximum and minimum temperatures, wind speed, and relative humidity which were purchased based on date range.

Table 1: Data used and their sources

Data(unit)	Description(type)	Resolution(time frame)	Source
Topography (m)	Digital Elevation Model (spatial grid)	30m x 30m (for 2009)	Aster Jasro, USGS
Soil (-)	Soil Classification and physical properties (spatial vector)	30 m x 30m (for 2010)	Soil and Terrain Digital Data Base(2010)
Land use/cover (-)	Land use/cover classification (spatial grid)	30 m x 30m (for 2000 to 2019)	International Center for Integrated Mountain Development (2010)
Precipitation (mm)	Daily observed precipitation (time Series)	7 precipitation station (1980-2019)	Department of Hydrology and Meteorology, Nepal
Temperature (°C)	Daily observed maximum and minimum temperature (time - series)	2 climate station (1980-2019)	Department of Hydrology and Meteorology, Nepal
Discharge (m^3/s)	Daily observed stream flow(time-series)	1 hydrological station(1988-2019)	Department of Hydrology and Meteorology, Nepal

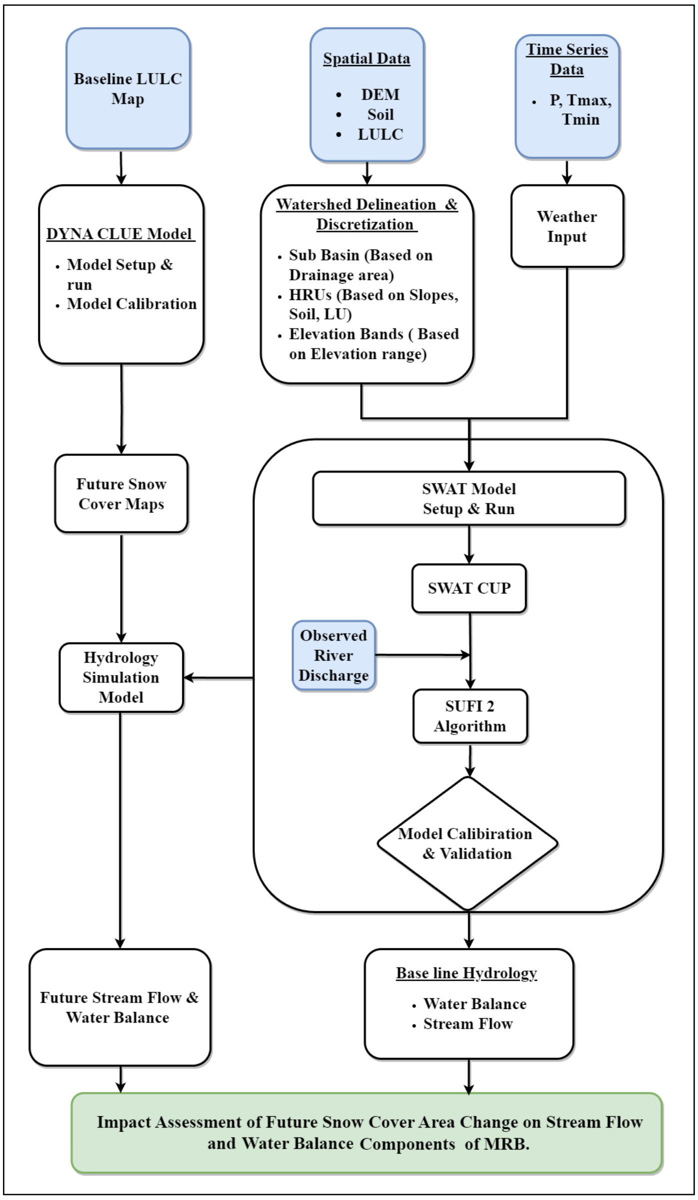

Figure 2: Methodological framework of the study

2.2.2 DynaCLUE Model Setup

The DynaCLUE Model, the latest version of the CLUE-S model, was developed specifically for the purpose of simulating land use change in a spatially explicit manner using an empirical assessment of location suitability. the dynamic simulation of interactions and rivalries between the temporal and spatial dynamics of different land use types. It is divided into two independent modules: one for spatial allocation and the other for demand. By employing LULC planning scenarios or historical patterns of LULC kinds, the first module determines the area demands for all LULC classes. In the meantime, the second module transforms the study region's spatial LULC requirements [13]. In this work, the DynaCLUE model was used to project the snow cover map to a regional scale. The optimal result is determined iteratively by the model using four inputs: geographic features, land-use requirements (demand), conversion settings appropriate to a given land-use type, and spatial policies and constraints [14].

The land use land cover map (LULC map) 2010 of watershed is taken as base map to project yearly snow cover map to 2100. Using logistic regression models (SPSS Model) made from the spatial cooperation of each LULC type with a set of driving forces of LULC change, the location suitability requirement were estimated. The driving factor used in model are Elevation, slope, aspect, rainfall, Tmax, Tmin, Population density, Distance to river, Distance to road and Soil map of 250 m resolution. All the layers in Arc-GIS should overlap properly and converted into raster to ASCII to run DynaCLUE model. In the trend scenario, no spatial policies were implemented and restricted region includes Annapurna Conservation Area which are not permitted to be changed. The rules of conversion between LULC types are determined by the conversion parameters, which include the conversion flexibility and conversion matrix. A particular LULC type may be capable of converting to other LULC types according to its conversion flexibility. The conversion elasticity ranges from 0 (no conversion possibility) to 1 (the greatest conversion possibility) [14] Using the trial and error approach, the values of conversion parameters of 0.6, 1, 08, 1, 0.9, 0.7, 0.8, and 0.4 were allocated to the following areas: built-up area, river bed, forest, snow and glacier, crop land, barren land, and grass land, according to this order [15]. There are two values in the conversion matrix: 0 (no conversion) and 1 (possible conversion). The conversion matrix values for the MRB shown in Table 2 were obtained from literature review of similar study with similar charateristic of basin. Based on annual historical fluctuations in the area of each LULC type, the simple extrapolation method was used to estimate the LULC demands. The receiver operating characteristic (ROC) is a useful tool for evaluating the goodness-of-fit of logistic regression models. The area under the curve, which has a value between 0.5 (complete randomness) and 1.0 (perfect match), is frequently used as a summary indicator to assess the model's overall effectiveness. The projected LULC map (2019) and LULC map (2019) from ICIMOD were compared to validate the model using Kappa statistics for reliability assessment of LUC simulations. A kappa statistic of 0 denotes a chance agreement, whereas a statistic of 1 denotes a perfect agreement.

2.2.3 Hydrological Modelling using Soil and Water Assessment Tool (SWAT) Model

i) Soil and Water Assessment Tool (SWAT) Model Review and Setup

The hydrology and other environmental processes of the river basin were simulated using the continuous-time, semi-distributed, process-based Soil and Water Assessment Tool (SWAT) model [8] in this study. SWAT requires comprehensive knowledge about the land management practices, terrain, weather, soil properties, and vegetation existing in the watershed rather than relying just on regression models to describe the relationship between the input and output variables [12].

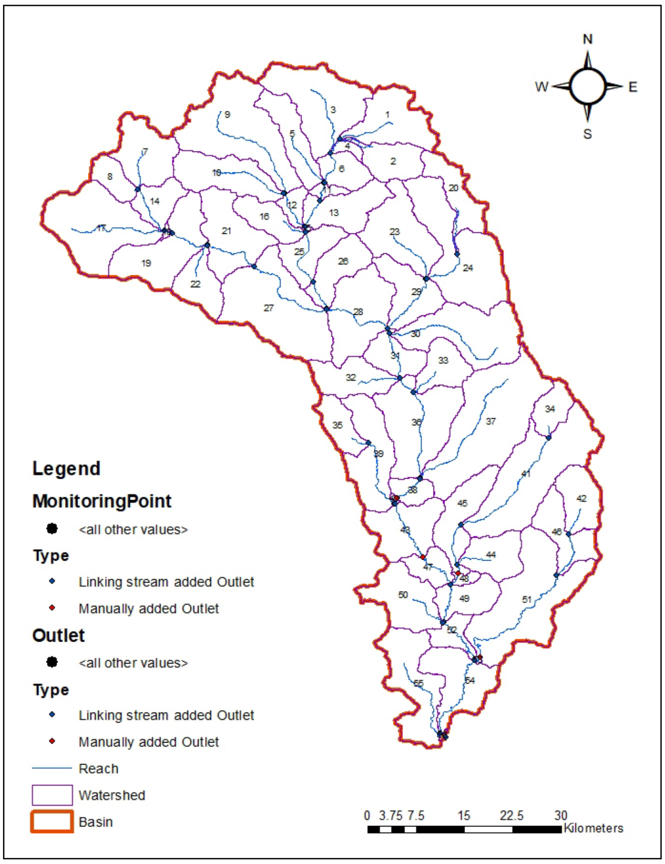

Figure 3: Historical Trend Analysis

The SWAT model was developed using Arc SWAT2012 as a platform. The watershed was delineated using topography map. Hydrologic response units (HRUs), elevation bands, and sub-basins are used to divide the study area and capture spatial heterogeneity throughout the basin model [9]. The Figure 3 shows the delineated Marsyangdi river basin. The area of basin was divided into 56 sub-basins and 2,593 HRUs were generated using spatially distributed data for lulc, soil and slope data with zero threshold values. Three elevation bands, each with a mean elevation of 500 m, were created to replicate snow melt and the orographic distribution of temperature and precipitation. Time series data, such as maximum and lowest temperatures (2 stations), daily precipitation (7 stations), sunshine hours (1 station), wind speed (1 station), and relative humidity (2 stations) were used as the meteorological input for the model development. The hydrological cycle is computed through a water balance approach, where the interactions and flows of water within a system are determined. This balance is intricately influenced by climate inputs, shaping the movement and distribution of water throughout the system. The Penman-Monteith approach was utilized to compute potential evapotranspiration (PET), while the SCS curve number methodology was employed to estimate surface runoff, and the variable storage method was employed to determine channel flow.

ii) Model Calibration and Validation

The auto calibration process was carried out using the SUFi-2 algorithm and SWAT CUP to target and reduce each parameter's effective range. The initial parameter ranges are defined following the works of bhatta2020 et al. [9]. The global sensitiviy approach is adopted in this study to analyze the sensitivity of parameter. The sensitive parameter was defined as the one having the highest t-sat value and the lowest p-value (P value less than 0.05). Calibration is the process of parameterizing a model to a particular set of circumstances in order to reduce the uncertainty of the predictions. The first thirty-seven parameters were employed for this purpose [16]. The model was validated for the years 2009 to 2017 and calibrated for the years 1988 to 2008 using daily discharge data obtained at the study area's outlet. An eight-year warm-up phase was used to find the ideal soil and groundwater conditions prior to calibration.The level of calibration that the model has received determines how reliable and accurate its output is. Strength of calibration is measure using R-factor and P-factor and the optimal value of p and r factor is 1. The p-factor and r-factor have respective ranges of 0 to 1 and 0 to infinity. The simulated and observed data are considered to be an exact match when the P-value is 1. While a lower r-factor value is required to attain reduced uncertainty, its lowest value (0) suggests a larger possibility of uncertainty in the model outputs. Obtaining greater p-factor values requires balancing both the r and p-factors. The coefficient of determination (R2), the Nash-Sutcliffe simulation efficiency (NSE), the percentage bias (PBIAS), the R-factor, and the P-factor are the five metrics used to evaluate the model's performance in this study. The NSE ranges from (minus infinite to 1), measures the best fit and its optimal value is 1. PBIAS measure the average tendency of simulated data. The lower value of PBIAS indicates accuracy of simulation of variables and its optimal value is 0. The positive value of PBIAS indicates over estimations while negative value indicates over estimation bias [17] The calibration is done until the acceptable performance metrics value is obtained, after that same parameter is used for validation. The value of parameter from SWAT-CUP is assigned manually in SWAT model after calibration and validation. The less sensitive parameter during auto

Table 2: Conversion Matrix for the Dyna-CLUE model in the MRB

Landuse Type	Forest	Water Body	Snow and Glacier	River Bed	Builtup area	Cropland	Barren land	Grassland
Forest	1	0	0	0	1	1	1	1
Water Body	0	1	0	0	0	0	0	0
Snow and Glacier	0	0	1	0	0	0	1	1
River Bed	0	0	0	1	0	0	0	0
Builtup area	0	0	0	0	1	1	0	0
Cropland	1	0	0	0	1	1	1	1
Barren land	0	0	1	0	0	0	1	0
Grassland	1	0	0	0	1	0	1	1

calibration may found to be sensitive during manual calibration so there also needed to adjust the parameter value manually for the best value of statistical parameter (NSE, PBAIS, R2). The model's performance was evaluated using daily and monthly simulations. The hydrographs (peaks, time to peak, hydrograph shape, and base flow), scattered plots, flow duration curve, statistical parameters, and the water balance (actual vs. simulated) at daily, monthly, and annual scales were all used to visually evaluate the model's performance [16].

iii) Future Snow Cover Variation Impact assessment

To assess the impact of future snow cover variation the simulated future hydrology and baseline hydrology is compared on annual, seasonal and sub-basin wise. Then Swat model was run for the climate data from 1980-20017 and Land use land cover map of 2010, with eight-year warm-up period and baseline hydrology of basin was estimated. The projected snow cover map was used as input to a calibrated SWAT model using the same climate data in order to evaluate the impact of the future snow cover map. The future simulated hydrology of the basin was then compared to the baseline.

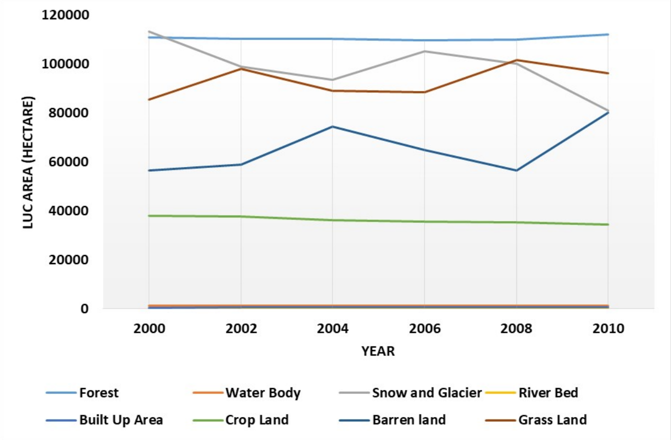

Figure 4: Historical Trend Analysis

3. Result and Discussion

3.1 Historical Trend Analysis

The LULC map from 2000 to 2010 in yearly basis is taken for the historical trend analysis of landuse type. Figure 4 shows that land use type: snow and glacier, crop land, grassland are in decreasing trend, while forest, barren land and built up are in increasing trend, and the water body and river bed are constant. The observed annual snow cover area in 2010 is in LULC map (2010) is 1124.148 km^2 area and has reduced at rate of 0.7% per year. The change in snow cover area may be associated with change in temperature due to climate change. In the present study, the trend of LULC change in the period of 2000–2010 was applied for the for the simulation of future snow cover map of Marsyangdi river basin in 2030, 2050, and 2090.

3.2 Projected Snow Cover Map

The logistic regression model's Roc values are consistently over 0.8 for each kind of land use, indicating that the chosen driving forces have a strong explanatory power for that particular Land Use and Land Cover (LULC) type. The comparison of simulated and observed LULC map 2019 shows a good agreement, confirmed by Kappa value of 0.67 which is a reliable result of simulated LULC data. Therefore, the calibrated dyna-clue model is accepted for the future projection of snow cover map. The projected snow cover area is gradually decreasing towards future. The percentage variation in snow cover area from Base snow cover map (2010) are 2.03%, 4.03%, and 14.20% for 2030, 2050, and 2090 with respect to baseline as shown in Figure 6 . The future projected snow cover map for 2030, 2050, and 2090 are as shown in Figure 5 and . The snow cover area of sub basin 24, 30, 37, 34, and 41 which lie at lower elevation than other snow fed sub basin of study area were decreased during future projection which may be due to increasing rate of temperature is greater in lower elevation than higher elevation.

3.3 Performance Evaluation of SWAT Model

The most sensitive parameters (p-value less than 0.05 and greatest t-sat) for the Marsyangdi River basin were determined to be PLAPS, CH-K2, SMFMX, TLAPS, SMTMP, SMFMN, and Cn$\hat{2}$ among the thirty-seven parameters that were originally selected for the global sensitivity analysis. This indicates that the snow melt plays an important role in the hydrological process. In snow fed watersheds, such as the Marsyangdi River Basin, the contribution of snow melt to the hydrological cycle is indeed a dominant and critical factor. During calibration and validation, the value of parameters were adjust to match the simulated flow with observed flow. The uncertainty analysis in this study demonstrates satisfactory results, as indicated by the performance metrics. The percentage of daily

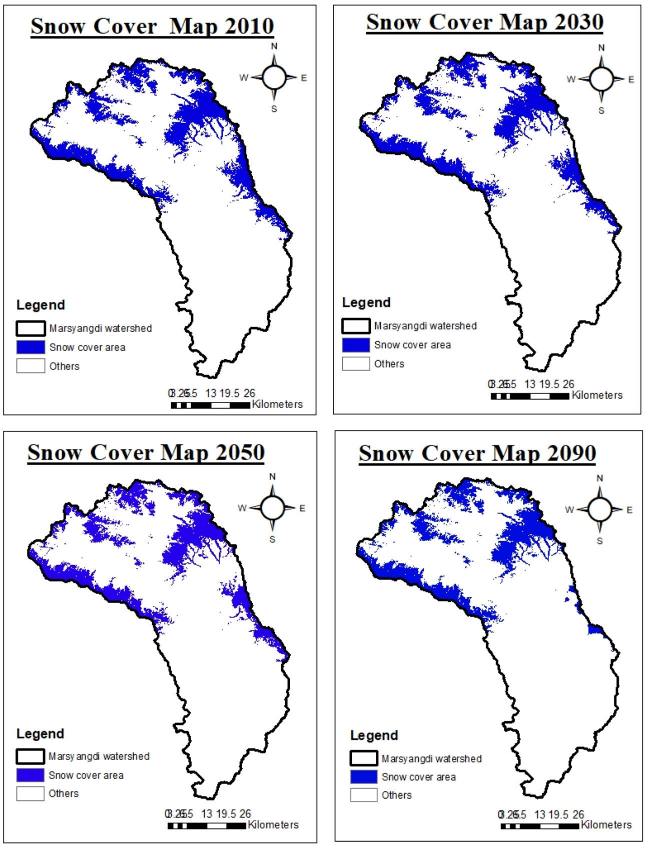

Figure 5: Future Projected Snow Cover Map.

observed data that is included in the 95% prediction uncertainty (95PPU) band is measured by the p-factor, and it obtains a value of 0.8. This indicates that the expected uncertainty band successfully contains 80% of the daily observed data points. Furthermore, the uncertainty band's width, or the r-factor, is 0.7. These findings suggest a reliable and accurate model performance, reflecting a good match between predicted and observed data. This level of uncertainty analysis provides confidence in the model's ability to make robust predictions and contributes to the credibility of the study's results.

It is possible to assess the model's performance both graphically and statistically. The performance metrics NSE, PBIAS, and R2 were used for statistical evaluation of model. The model evaluated considering the criteria are shown in Table3 . The NSE value is greater than 0.65 and R2 is nearer to 1 for daily and monthly dataset which denotes the good performance of model. Whereas the PBIAS is near to zero for daily and monthly data set for both callibration and validation period which indicates the good performance of model. which shows that model is acceptable for further evaluation in the study.

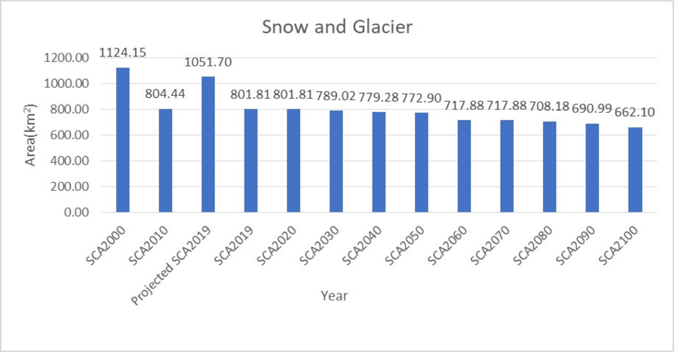

Figure 6: Future Trend Snow Cover Map

Table 3: Indicators of model performance during validation and calibration

Time step	Period	NSE	PBAIS	R2
Daily	Callibration	0.7	-0.7	0.78
	validation	0.68	1.6	0.75
Monthly	Callibration	0.88	-1.5	0.89
	validation	0.84	1.7	0.86

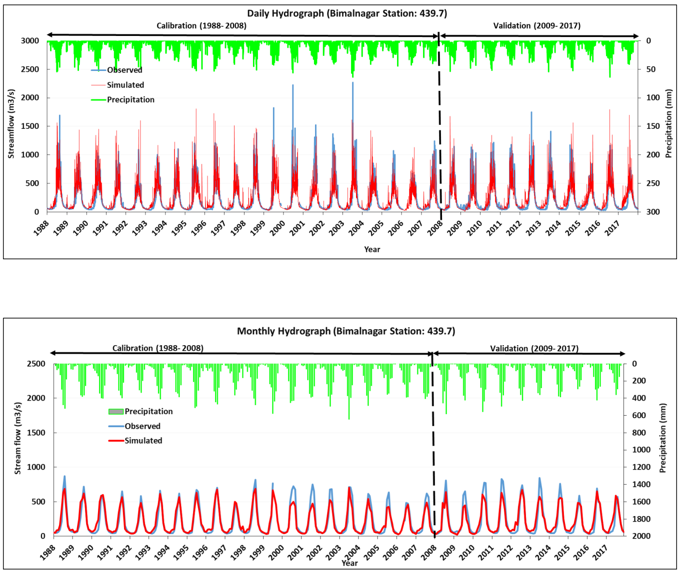

Figure 7: : Observed (blue line) and Simualted (red line) Daily and Monthly Hydrographs for Calibration (1988-2008) and validation (2009-2017) periods at Q439.7 (Bimalnagar) hydrological station

For graphical evaluation of model, the daily and monthly hydrograph were plotted for the simulated and observed discharge at Bimalnagar outlet which is shown in Figure 7. The model appears to simulate the low flows better than it simulates the high flows. SWAT model struggles to simulate the peak flows in parallel to the peak flows of observed series [18]. This might be partly because days with several storms make it difficult for the existing curve number technique to predict runoff effectively. In Figure 8, In both the calibration and validation stages, there is a significant correlation between the simulated and observed daily and monthly variables, $R^2 = 0.88$ and $R^2 = 0.7$. The scatter plot of the daily discharge data set displays a notable high degree of data dispersion, which can likely be attributed to the observed discharge data exhibiting considerable fluctuations throughout the year. This variation in discharge data may result from seasonal changes, weather patterns, or other factors influencing the hydrological processes within the watershed. The graphical and statistical analysis shows the acceptable runoff simulation during the calibration and validation stages.These findings suggest that the SWAT model

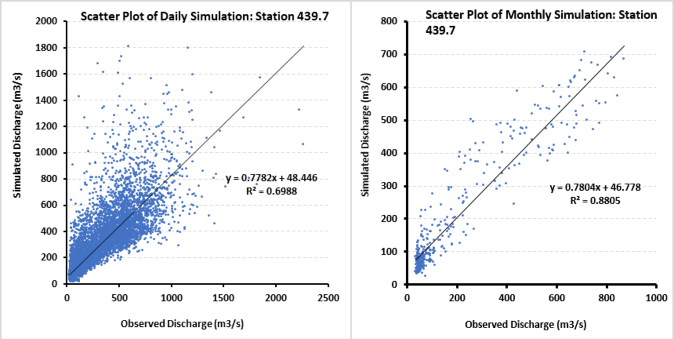

Figure 8: : Scatters plot of observed versus simulated daily and monthly dicharge

can be effectively applied to hydrological modeling in the Marsyangdi River Basin in order to assess water resources and examine the basin's water balance.

3.4 Impact of Future Snow Cover Change

While the climatic data remained the same as the baseline, the projected snow cover maps for 2030, 2050, and 2090 were provided as input to the calibrated and validated model for the modeling of the basin's future hydrology. The percentage change in the estimated future hydrology for 2030, 2050, and 2090 with the baseline hydrology is used to evaluate the effect of future snow cover area on stream flow and water balance components of the basin.

3.4.1 Impacts on Water Balance Components

The analysis of water balance in the Marsyangdi river basin estimate the baseline annual average precipitation of 1994 mm, with baseline net water yield constituting 76% of precipitation where as evapotranspiration comprises about 21% of annual average Precipitation for the entire basin.Water yield , which is how much water we get from this, mainly comes from surface runoff (48%), lateral flow (38%), and groundwater (13%), with contribution from snowmelt (more than 10%). Surface runoff tends to be higher due to the significant contribution of melted snow to the stream in snow fed watershed. This study aimed to assess the impact of future changes in snow cover area on water balance components, highlighting a small increase in the annual water yield in near future then decrease, while evapotranspiration, the loss of water through evaporation and plant uptake, is decreasing in near future and slightly increasing toward far future. It can be because there is less snow cover on the land and more bare ground and woodland has taken its place. The annual surface runoff, which is water flowing over the land, has increased by 11.4% in 2030, 8.07% in 2050, and decreased by -2.18% in 2090. This reflects the ongoing decrease in snow cover. This trend is closely associated with the expanding forest and barren land areas, which may facilitate increased infiltration and evapotranspiration. These dynamics are poised to shape the future of the region's water balance, with lateral flow, groundwater contributions to water yield, and evapotranspiration playing more substantial roles in the distant future as compared to the near future. It reveals several significant trends in the Marsyangdi river basin's water balance components for future scenarios (SCA2030, SCA2050, and SCA2090) which refers to snow cover map of 2030, 2050 and 2090. The Figure 9 shows the change in annual value of water balance components.

On seasonal basis, the highest surface runoff and water yield occur during the monsoon season, but the most significant percentage increases are observed in the pre-monsoon period, aligning with the snow melt peak. These findings underscore the intricate interplay between climate, land use, and snow cover, providing valuable insights into how changes in snow cover can influence water balance in the absence of changing climate data. For a more detailed seasonal breakdown, Figure 10 presents a comprehensive overview of water balance components for each season relative to the baseline, offering additional insights into the dynamics of the basin's water resources.

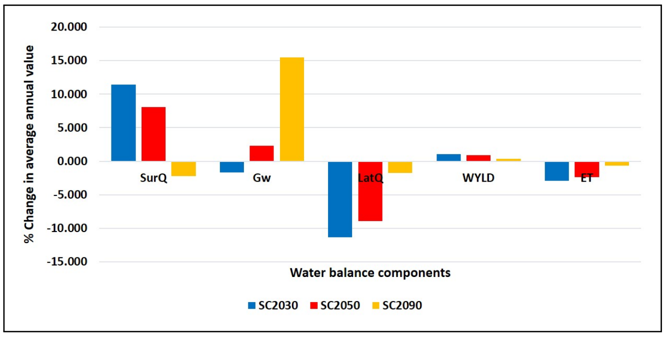

Figure 9: Projected changes in average annual water balance components

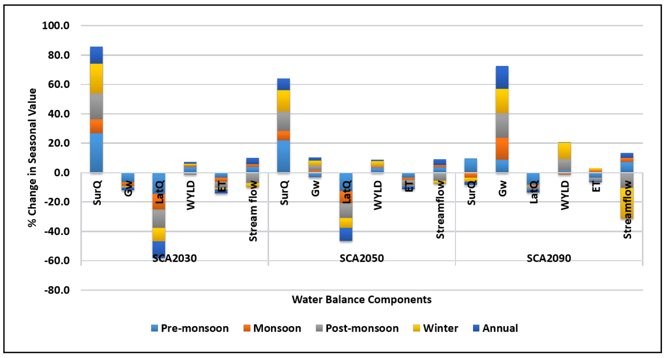

Figure 10: Projected changes in seasonal water balance components

3.4.2 Impacts on Stream flow

In our study, we found that because of stable climatic data, important climate variables including temperature, precipitation, snowfall, and snowmelt remained mostly unchanged in the future, even though the amount of snow cover area decreased significantly. In relation to the observed discharge, we discovered an overall increase in annual average stream flow of 4.1% (SCA2030), 4% (SCA2050), and 3.5% (SCA2090). The reason for the initial rise in stream flow is that some of the snow cover region turned to bare ground, which made it possible for precipitation to enter streams quickly and with little loss. Then, as the amount of forested and arid land rose, the precipitation changed. Some of it soaked into the soil, raising the moisture content of the soil, while the rest increased evapotranspiration. In the far future, stream flow grew much more as soil moisture reached its maximum potential.

In particular, stream flow during the pre-monsoon and monsoon seasons continuously increases in comparison to the baseline, highlighting the critical impact that snowmelt and precipitation dynamics play throughout these seasons. On the other hand, stream flow during the post-monsoon and winter seasons shows a downward tendency in comparison to the baseline, demonstrating the intricate relationship between temperature, snow cover, and seasonal precipitation fluctuations. Importantly, in the far future, we observe the most pronounced rate of decrease in stream flow by 20% during the winter periods,possibly due to higher evapotranspiration rates, specifically a 1.55 increase in 2090 during the winter season. Table 4 shows the changes in stream flow for each season with respect to baseline. This emphasizes the heightened influence of changing snow cover and its subsequent impact on stream flow, particularly during these critical seasons.

Table 4: Impacts of future changes in snow cover on stream flow based on baseline data from 2010. Pre-monsoon season (S1) runs from March to May; monsoon season (S2; June to September); post-monsoon season (S3); and winter season (S4; December to February).

	Streamflow				
Seasons	S1	S2	S3	S4	Annual
Baseline	66.2	488.1	143.4	54.1	216.7
SCA2030	4.03	1.83	-6.95	-2.80	4.1
SCA2050	3.66	1.47	-5.64	-1.77	4.0
SCA2090	7.37	2.53	-10.31	-20.77	3.5

4. Conclusions

In this study, we projected the future snow cover map to analyze the impact of future snow cover area change on hydrology of Marsyangdi river basin. The future simulated hydrology of watershed were compared with baseline hydrology to assess its impact on water balance component and stream flow. In order to achieve this, the basin's baseline and future hydrology were simulated using the SWAT model for hydrological modeling. Watershed was delineated into 56 sub basin and 2963 hydrological response unit. The SWAT-CUP model was calibrated (1988 to 2008) and validated (2009 to 2017) using the observed discharge data of station no. 439.7 from 1988 to 2017. The model was allowed to warm up for eight years. To assess the model's performance for a daily simulation that indicates a good simulation, performance measures were estimated. After that, the calibrated SWAT model was used for additional analysis, and the calibrated parameter value from SWAT-CUP was manually assigned to the SWAT model.

Future snow cover map was projected using the DynaCLUE model with two different scenarios out of which historical trend scenario gave the better performance than other. The Marsyangdi River Basin's future snow cover map indicates that the area covered by snow cover will decrease by 2.03%, 4.03%, and 14.20% in 2030, 2050, and 2090, respectively. Human activities that alter land surface features and affect snow cover, like deforestation, urbanization, and agriculture, may be the root causes of this decline. This, in turn, significantly influences the watershed's hydrology. The predicted snow cover maps were then incorporated into the calibrated SWAT model to examine their effects on stream flow and other aspects of the water balance in more detail. According to the study, stream flow increases when the amount of snow cover decreases, yet there is little to no change in climate data. During the winter season, there is an anticipated decrease in stream flow by 20.77%, which has the potential to affect water availability in the dry season. Interestingly, the study showed that a decrease in snow cover area caused significant annual and seasonal shifts in surface runoff, lateral flow, groundwater contribution, and evapotranspiration, resulting in an increase in stream flow with surface runoff playing a dominant role, even in the absence of changes in climate data.

In conclusion, while there have been numerous studies on the impact of Land Use and Land Cover (LULC) changes, there's a gap when it comes to understanding how future variations in snow cover might affect the hydrology of a basin. This study fills that gap and offers valuable insights for future water resource projects. Understanding the impact of snow cover changes on stream flow and water balance is crucial for effective management and planning of water resource projects. It provides essential data for decision-makers and project planners to make informed choices about future developments. Future studies might, naturally, examine the combined effects of changing snow cover and climate change on the hydrology of the watershed, providing a more thorough grasp of the key variables affecting the watershed's hydrology. This approach would further enhance our ability to make informed decisions and adapt to changing environmental conditions effectively.

Acknowledgments

The author are thankful to the Department of Hydrology and Meteorology, International Centre for Integrated Mountain Development (ICIMOD), and Soil and Terrain database (SOTER) for providing hydro-meteorological data, land-use/land-cover map and soil map respectively.

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