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# Impacts of Climate Change and Land Use Change on Streamflow: A Case of Seti Gandaki Watershed, Nepal

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**Abstract:** Recent research and IPCC reports extensively document the varied effects of climate change on basins worldwide. This study evaluates the impact of climate change and land use change on the Seti-Gandaki watershed's hydrological regime of Nepal. Using a calibrated hydrological SWAT model, forced with climate scenarios (SSP245 and SSP585), the study projects increased precipitation (2-129% and 3-139%) and a warming trend in temperature. Streamflow at the watershed's outlet is expected to rise (up to 49% in monsoon, 96% in winter in SSP245; up to 61% in monsoon, 89% in winter in SSP585), with increased flow extremes, potentially leading to floods and landslides. The combined impacts project a 52-125% increase in streamflow in SSP245 and a 100-136% increase in SSP585, attributed to the shift from rural to urban settlements. These findings provide crucial insights for water resource planners and managers to develop location-specific strategies for sustainable water resource use in the Seti-Gandaki Watershed.

***Keywords:*** *Climate change, CMIP6, Seti-Gandaki, SSPs, SWAT*

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Supporting agencies: None

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## 1. Introduction

Climate change is a frequently discussed topic in national development discussions, owing to its potential impact on future water supplies (Dixit et al., 2009; WECS, 2011; NCVST, 2009). The impacts of climate change in the region of the Himalayas have been reported to include changes in both temperature and precipitation, as well as wide-ranging consequences such as glacier retreat, wetland areas loss or functional change, increased flow variation, and changes in flow timing and amounts that affect agriculture, rural livelihoods, and the overall economy (Babel, 2009; Bates et al., 2008). According to the Stocker et al., (2013) a recent report by the Intergovernmental Panel on Climate Change (IPCC) showed a rise in temperature and a rise in summer monsoon precipitation across South Asia with high confidence. Climate change is reshaping the water system, with the direct effects on water being magnified by the effects on other sectors in the water-energy-food-environment-livelihood nexus. Globally rivers provide more than half of the world's extracted freshwater (Taft & Kühle, 2018). However, global waterways have undergone major modifications, particularly in streamflow, which are primarily the result of anthropogenic activities such as land-use change, forest clearing, damming rivers, water deviations and abstractions, sand mining, and, more recently, climate change impacts (Pandey et al., 2019a; Sirisena et al., 2021). The sixth assessment report (AR6) of the IPCC in 2021 confirmed that human-caused climate change has already affected many weather and climatic extremes around the world, as well as impacting the hydrological cycle and water availability. As a result, consistent, predictable seasonal water flows are unlikely to be maintained, and year-to-year variability will persist.

Changes in Land use Land cover (LULC) is typically caused by human actions rather than natural occurrences (Paul & Rashid, 2017). Human-made activities that produce LULC shifts include crop growth, burning activities or wood for energy use, forest clearing, grazed field expansion, certain building work, and development. Because they influence hydrological processes such as infiltration, groundwater recharge, base flow, and runoff, such changes can have a substantial impact on watershed habitats (Niehoff, 2002). The investigation of changes in runoff characteristics produced by human activities is crucial to comprehending the effects of LULC change on hydrological processes on Earth's surface (Shi et al., 2007). Understanding the impact of Land use and Land cover change (LULC change) as well as its impact on ecosystem functioning and its associated services is essential particularly in developing countries like Nepal, where agricultural land and ecosystem services support more than 60% of the total population (NPC, 2022).

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) reiterated that a global warming is taking place (Solomon, 2007). Climate change is commonly accepted and can impact the spatial and temporal distribution of water resources, as well as the intensity and frequency of extreme hydrological events (Bae et al., 2011). As a result, research into the effects of climate change on hydrology has recently become a hot topic. The most popular method for assessing the hydrological implications of climate change is to employ a hydrological model with climate change scenarios derived from the general circulation model (GCM) and forced with emission scenarios (Thompson et al., 2013). However, due to the presence of uncertainties in evaluations of climate change impacts on drainage and the difficulty in characterizing these uncertainties, these conclusions are rarely employed by decision-makers and managers in managing and planning water resources (Bae et al., 2011).

Changing climatic factors influence the cycle of water by influencing surface runoff, evapotranspiration, and aquifer recharge (Hiscock, 2011). Surface water plays an important role in human life (Ambade et al., 2022; Hasan et al., 2021). Floods, on the other hand, involve significant economic loss to people of vulnerable to floods locations (Kauffeldt et al., 2016). Water availability in an area is heavily influenced by how rainfall in the area is divided into various components such as surface runoff, interflow, groundwater recharge, and so on. The proportions of these components in the area are mostly influenced by the area's LULC. As a result, a change in an area's LULC can affect the proportions of the aforementioned components, resulting in a dramatic change in the area's biological system. It is widely acknowledged that there has been significant shift in LULC during the previous few decades in various places of the world. This modification modifies the proportions of the aforementioned components, which can impact water availability in the affected area (Emami & Koch, 2019). Generally, changes within the area of water availability and surface runoff can impact the LULC. This circular dependency - water availability on LULC and vice versa - might have a negative impact on the surrounding ecosystem (Sajikumar & Remya, 2015). The streamflow plays vital role in the developing landlocked countries like Nepal. As, the climatic condition is getting worse every single day the streamflow is also changing its intensity. So, in the context of Nepal, where hydropower is always expanding, knowing about future streamflow is critical in determining whether power generation and irrigation supply can meet future demand.

The Seti-Gandaki watershed is a small tributary of the Narayani River. Its surface runoff is controlled by a variety of factors, including direct climatic drivers such as temperature changes, rainfall changes, and snow melting, as well as non-climatic drivers such as change in LULC. Along with climate change, the change in LULC is a key issue. The LULC has also evolved tremendously during the past year. The overall objective of the research was to evaluate the impacts of climate change and LULC change on streamflow in Seti-Gandaki watershed. So, looking at the research article over the Hindu-Kush Himalayas, it still lacks the combined effect of LULC and future climate change projections. As a result, this research will bridge the gap in the Seti-Gandaki watershed.

## 2. Materials and methods

This research examined the effects of climate and LULC change on watershed hydrology. The tailspin concept was employed to complete the analysis of climate, LULC change, and its singular and combined consequences on streamflow using Figure 1.

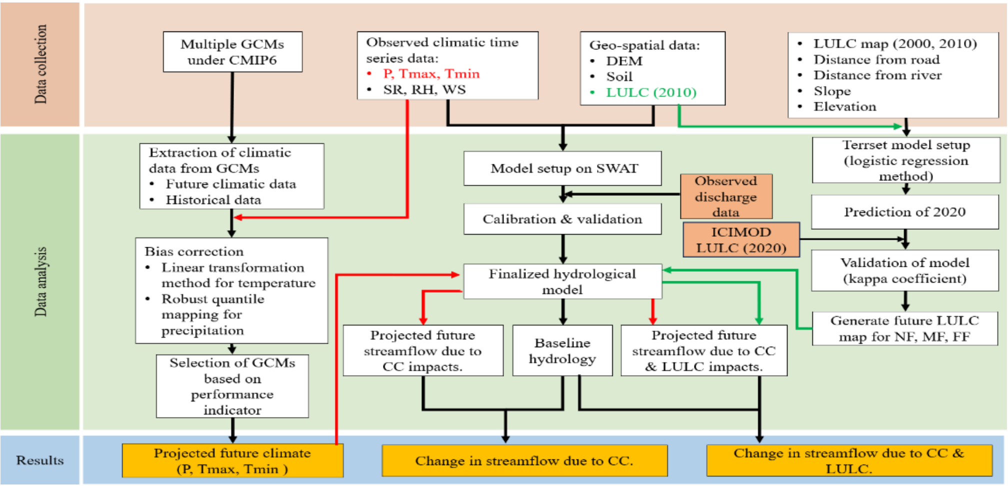


**Figure 1:** Methodological framework

## 2.1. Data quality assessment

The hydrometeorological data collected from DHM was subjected to a stringent quality assurance (QA) process. The QA method entailed inspecting each and every data point at each station to determine the presence of abnormal values. The missing data dates were then discovered and collated to determine the total amount of data missing in each month of each year at each station. The characterization produced the overall percentage of data missing at each site from 1989 to 2017. Stations with considerable missing data were excluded from the analysis (a 10% missing data criterion was used).

## 2.2. Future climate projection

Future climate data were obtained from the World Climate Research Programme website, focusing on CMIP6-GCM model outputs. Only 13 GCMs with daily precipitation and temperature data (minimum & maximum) were selected, as listed in Table 4.2 (Mishra, 2020). The middle-of-the-road strategy, aligned with the SSP245 emission scenario, was combined with the fossil-fueled growth method and the SSP585 emissions scenario to encompass a broad range of socio-economic pathways.

To assess GCM performance, precipitation projections were compared with baseline observed data from 1995 to 2014. Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE), and percentage bias (PBIAS) were used as performance metrics. The top 5 GCMs were selected for the multi-model ensemble based on their performance ratings, derived from Table 4.3 (Moriasi et al., 2007; Thapa et al., 2021).

## 2.3. Assessing climate change impact on streamflow

The Arc SWAT 2012.10.5 interface facilitated the creation of the SWAT model for the Seti-Gandaki watershed. Utilizing spatially distributed data for topography, land cover, and soil, the model was established. Meteorological data, including daily precipitation, maximum and minimum temperatures, solar radiation, wind speed, and relative humidity, were sourced from the Department of Hydrology (DHM) for this study.

Arc SWAT 2012.10.5 served as the model setup platform, generating a river network with a threshold area of 500 ha. Subbasin and river characteristics were extracted using Arc GIS tools, dividing the study region into subbasins based on monitoring points and ridges. The Hydrologic Response Units (HRUs), representing land areas with similar responses to weather inputs, were created using four GIS layer maps: sub-basin, land use/land cover, soil, and slope.

The Seti-Gandaki watershed was subdivided into 35 sub-basins, and LULC and soil files were generated using ICIMOD 2010 and SOTTER. A 10% threshold and two 500m elevation bands were established, resulting in 1980 HRUs within the watershed.

## 2.4. Assessing impact of climate change and LULC change on streamflow

Future LULC was predicted using Land Change Modeler (LCM), embedded in TerrSet Geospatial Monitoring and Modelling System (TGMMS) software. It operates on the philosophy of Multilayer Perceptron Markov Chain Neural Network (MLP-MCNN) method. Then calibrated and validated SWAT model was forced with projected future climate as well as predicted future LULC. Simulated streamflow was compared with baseline and changes are reported as combined impact of climate change and LULC change on streamflow.

# 3. Results and discussion

## 3.1. Future climate projection

The five GCMs values were projected, and the extracted value of the relevant station was calculated. The climatic data projected for the corresponding futures were 2025-2050 for the near future (NF), 2051-2075 for the mid future (MF), and 2076-2100 for the far future (FF). The projected future values of different selected GCMs were ensembled into single value for every meteorological station and the annual average value was taken to plot the graph the graph from 2015 to 2100. The precipitation in every station is projected to increase.

### Precipitation projection

This watershed has eight precipitation stations. The forecast precipitation projections for each station show an increasing order during the monsoon season and a decreasing during winter. The Figure 5 1 shows the alteration in precipitation in respective meteorological stations.

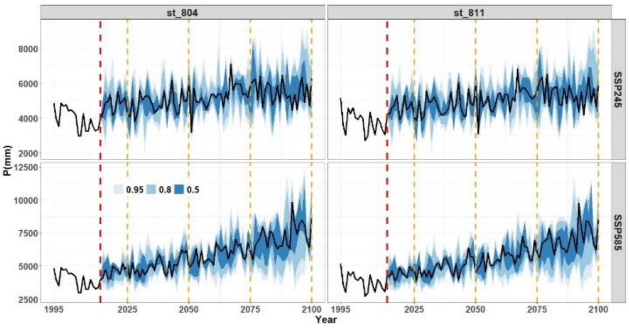


**Figure 5 1:** Future climate projection for precipitation of station 804 and 811

The precipitation is projected to increase in high amount during monsoon, post-monsoon and pre-monsoon but is expected to drier during winter season due to the decrease in the amount of the precipitation. But when seen in seasonal alteration the precipitation is expected to decrease during winter in SSP585 whereas all other are expected to increase with compare to the baseline. The findings are consistent with those obtained in the nearby

Koshi watershed and other minor watersheds of Nepal. This study's conclusions are similar to those of other studies conducted for Nepal and the Himalayan region (Agarwal et al., 2015; Nepal, 2016). The precipitation does not follow specific trend in the mean monthly projection with compared to the baseline(Adhikari & Mathema, 2023).

**Table 5 1:** Future projection of Precipitation compared to the baseline

| Months | Base line | ssp245 | | | ssp585 | | |
|---|---|---|---|---|---|---|---|
| | | NF | MF | FF | NF | MF | FF |
| Jan | 0.82 | -6% | -5% | 14% | 2% | -11% | -28% |
| Feb | 1.55 | -6% | 11% | -2% | -9% | 2% | -8% |
| March | 2.18 | -7% | 2% | -8% | -2% | 3% | 6% |
| April | 4.46 | 31% | 35% | 31% | 32% | 41% | 55% |
| May | 9.71 | 23% | 33% | 48% | 34% | 35% | 63% |
| June | 20.16 | 7% | 26% | 29% | 22% | 35% | 60% |
| July | 26.13 | 33% | 45% | 50% | 34% | 56% | 81% |
| Aug | 24.42 | 23% | 33% | 42% | 24% | 53% | 92% |
| Sept | 14.91 | 33% | 40% | 70% | 38% | 69% | 124% |
| Oct | 3.49 | 28% | 51% | 56% | 54% | 55% | 117% |
| Nov | 0.53 | 129% | 129% | 145% | 114% | 131% | 135% |
| Dec | 0.46 | 68% | 45% | 46% | 46% | 90% | 50% |

### Maximum temperature projection

This watershed has four temperature stations. The forecast maximum temperature projections for each station show an increasing order during every season. The climatic data projected for the corresponding futures were 2025-2050 for the near future (NF), 2051-2075 for the mid future (MF), and 2076-2100 for the far future (FF). The Figure 5 6 shows the alteration in maximum temperature in respective meteorological stations.

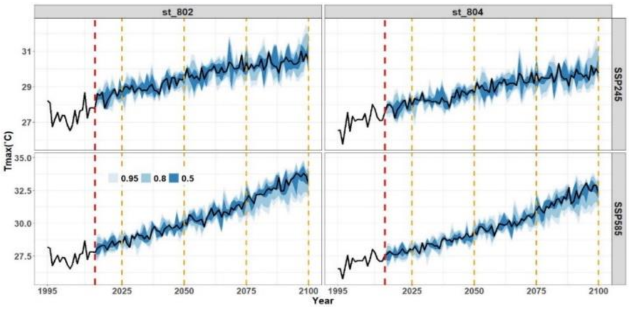


**Figure 5 6:** Future projection for maximum temperature

After averaging the data across the watershed, the baseline data was compared to the GCM scenarios. In the several GCMs, the scenarios show the two distinct outcomes. The maximum temperature is projected to increase throughout the seasons and years in the watershed with compare with the baseline. So, the all the season is expected to be hotter during the seasonal alteration. The finding result is similar to that of the Gandaki watershed (Thapa et al., 2021). The result does follow the specific trend where the maximum temperature has been projected to rise in the upcoming years (Adhikari & Mathema, 2023).

The outcomes are compared and shown below Table 5 3:

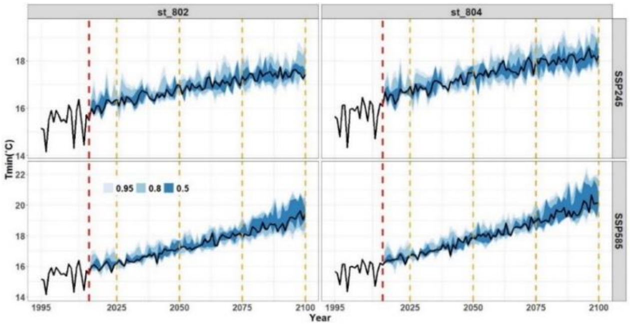
**Table 5 3:** Future projection of maximum temperature compared to the baseline

| Months | Base line | ssp245 | | | ssp585 | | |
|---|---|---|---|---|---|---|---|
| | | NF | MF | FF | NF | MF | FF |
| January | 19.12 | 0.94 | 1.71 | 2.01 | 1.23 | 2.31 | 3.96 |
| February | 21.94 | 1.17 | 1.91 | 2.24 | 1.37 | 2.84 | 4.47 |
| March | 26.05 | 1.47 | 2.04 | 2.57 | 1.51 | 2.77 | 4.64 |
| April | 28.66 | 1.08 | 2.13 | 2.47 | 1.51 | 2.76 | 4.59 |
| May | 29.18 | 1.09 | 1.74 | 2.07 | 1.03 | 2.21 | 3.72 |
| June | 29.25 | 0.80 | 1.46 | 1.87 | 0.91 | 2.07 | 3.42 |
| July | 28.93 | 1.80 | 2.91 | 3.78 | 2.14 | 4.33 | 6.88 |
| August | 28.89 | 2.58 | 3.81 | 4.75 | 2.93 | 5.34 | 8.20 |
| September | 28.17 | 2.33 | 3.49 | 4.06 | 2.48 | 4.70 | 7.48 |
| October | 25.85 | 1.63 | 2.49 | 3.10 | 1.68 | 3.53 | 5.61 |
| November | 22.40 | 1.43 | 2.22 | 2.63 | 1.76 | 2.93 | 4.44 |
| December | 19.45 | 1.02 | 1.78 | 2.11 | 1.30 | 2.34 | 3.89 |

### Minimum temperature projection

The forecast minimum temperature projections for each station show an increasing order during every season. The image below depicts the ensemble data of five chosen GCMs with confidence bands of 0.95, 0.8, and 0.5. The climatic data projected for the corresponding futures were 2025-2050 for the near future (NF), 2051-2075 for the mid future (MF), and 2076-2100 for the far future (FF). The Figure 5 11 shows the alteration in minimum temperature in respective meteorological stations.

**Figure 5 11:** Future projection for minimum temperature



The data was then averaged across the watershed, and the baseline data was compared to the GCM scenarios, which depict two distinct outcomes in the various GCMs. The minimum temperature does follow the specific increasing trend and is projected to increase all four season and annually throughout the year within the watershed (Adhikari & Mathema, 2023). This may result in the melting of the snow and outthrusting of the glacier. Which ultimately results in the increase in the streamflow of the watershed. The increase in the minimum temperature of the watershed is not good for the upcoming days because it may result in Glacial Lake Outburst Flood (GLOF) as the Kapuche glaciers lake and Annapurna Himalayas lie in this region (MoHA, 2015). The outcomes are compared and shown in Table 5 5:

**Table 5 5:** Future projection of minimum temperature compared to the baseline

| | | ssp245 | | | ssp585 | | |
|---|---|---|---|---|---|---|---|
| **Months** | **Base line** | **NF** | **MF** | **FF** | **NF** | **MF** | **FF** |
| January | 6.57 | 0.50 | 0.86 | 1.27 | 0.69 | 1.43 | 2.32 |
| February | 8.92 | 0.73 | 1.01 | 1.49 | 0.79 | 1.81 | 2.88 |
| March | 12.25 | 1.27 | 1.68 | 2.16 | 1.34 | 2.33 | 3.69 |
| April | 15.17 | 1.35 | 2.12 | 2.56 | 1.77 | 2.97 | 4.72 |
| May | 17.74 | 1.92 | 2.69 | 3.24 | 1.96 | 3.32 | 5.44 |
| June | 20.05 | 1.01 | 1.74 | 2.18 | 1.32 | 2.29 | 3.64 |
| July | 20.99 | 1.23 | 1.76 | 2.09 | 1.40 | 2.40 | 3.49 |
| August | 20.72 | 1.41 | 1.93 | 2.35 | 1.62 | 2.77 | 4.03 |
| September | 19.27 | 1.35 | 1.92 | 2.41 | 1.55 | 2.76 | 4.09 |
| October | 15.06 | 1.42 | 2.03 | 2.63 | 1.51 | 3.17 | 5.10 |
| November | 10.88 | 1.04 | 1.55 | 1.85 | 1.19 | 2.10 | 3.03 |
| December | 7.29 | 0.93 | 1.36 | 1.66 | 1.10 | 1.85 | 2.70 |

## 3.2. Impacts of climate change on streamflow

The five GCMs values were forecasted, and the extracted value of the relevant station was calculated. And the climatic component of the future data was fed into the SWAT model, and the results reflect the discharge throughout the hydrological station. The following discharge data after projecting future meteorological data for the relevant future (near future, mid future, and far future). The climatic data projected for the corresponding futures were 2025-2050 for the near future (NF), 2051-2075 for the mid future (MF), and 2076-2100 for the far future (FF). Three years of the warmup period was taken during the simulation of the model.

SWAT model performance

The hydrological performance was carried out by the SWAT model and its results in the Tanhaun outlet and sishaghat outlet with parameter are shown in Table 5 7 and Table 5 8. Each and every parameter shows the satisfactory result and each of them fall within the provided range provided by the SWAT-CUP. Final nine parameters were taken as the most sensitive parameters from the initial 31 parameters.

**Table 5 7:** SWAT parameter selected for Seti Gandaki watershed

| **S.N.** | **Parameters** | **Definitions** | **Units** | **Range** | **Fitted Value** | **P-value** |
|---|---|---|---|---|---|---|
| 1 | ALPHA_BF | Baseflow recession constant | days | 0.15-0.47 | 0.362 | 0.00 |
| 2 | GW_DELAY | Delay time for aquifer recharge | days | 0-250 | 8.75 | 0.00 |
| 3 | GW_REVAP | Groundwater revap coefficient | - | 0.01-0.1 | 0.09 | 0.48 |
| 4 | GWQMN | Threshold depth of water in shallow aquifer for groundwater return flow to occur | mm | 500-2500 | 1383.333 | 0.81 |
| 5 | RCHRG_DP | Deep aquifer percolation fraction | - | 0.02-0.61 | 0.556 | 0.99 |
| 6 | REVAPMN | Threshold depth of water in shallow aquifer for revap to occur | mm | 300-600 | 590.5 | 0.18 |
| 7 | CANMX | Maximum canopy storage | mm | 21.4-64.5 | 22.477 | 0.19 |
| 8 | EPCO | Plant uptake compensation factor | - | 0.06-0.56 | 0.548 | 0.52 |
| 9 | ESCO | Soil evaporation compensation factor | - | 0.67-1 | 0.963 | 0.95 |
| 10 | LAT_TTIME | Lateral flow travel time | days | 0-79.21 | 37.097 | 0.05 |
| 11 | SOL_AWC | Available water storage capacity of the soil layer | - | -0.1-0 | -0.06 | 0.06 |
| 12 | SOL_K | Saturated soil conductivity | mm/hr | -0.1-0.1 | 0.098 | 0.39 |
| 13 | SOL_Z | Depth from soil surface to bottom of layer | mm | -0.1-0.1 | 0.099 | 0.50 |
| 14 | CN2 | SCS runoff curve number for moisture condition II | - | -0.1-0.1 | -0.08 | 0.00 |
| 15 | CH_S1 | Average slope of tributary channels | - | -0.1-0.1 | -0.001 | 0.39 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 16 | CH_N1 | Manning’s “n” value for the main channel | - | 0.01-13.3 | 7.74 | 0.01 |
| 17 | TLAPS | Temperature lapse rate | °C/km | -10- -5.45 | -6.534 | 0.86 |
| 18 | PLAPS | Precipitation lapse rate | mm/km | 7.74-13.92 | 9.543 | 0.13 |
| 19 | ALPHA_BNK | Baseflow alpha factor for bank storage | - | 0-0.38 | 0.355 | 0.63 |
| 20 | CH_L1 | Longest tributary channel length in subbasin. | - | -0.1-0.1 | -0.052 | 0.22 |
| 21 | SURLAG | Surface runoff lag time. | - | 0.05-9.97 | 7.308 | 0.05 |
| 22 | SFTMP | Snowfall temperature | - | 9-20 | 12.832 | 0.60 |
| 23 | SMFMN | Minimum melt rate for snow during the year | - | 2.5-8.33 | 7.038 | 0.46 |
| 24 | SMFMX | Maximum melt rate for snow during year | - | 3.84-11.6 | 7.966 | 0.87 |
| 25 | SMTMP | Snow melt base temperature | - | 6.72-20 | 6.742 | 0.98 |
| 26 | TIMP | Snow pack temperature lag factor | - | 0-0.44 | 0.247 | 0.09 |
| 27 | SLSOIL | Slope length for lateral subsurface flow. | - | 0-51.0998 | 14.393 | 0.30 |
| 28 | HRU_SLP | Average slope steepness | - | -0.1-0.1 | -0.031 | 0.14 |
| 29 | SOL_ALB | Moist soil albedo | - | -0.1-0.1 | -0.057 | 0.69 |
| 30 | SLSBSSN | Average slope length | - | -0.1-0.1 | 0.061 | 0.45 |
| 31 | OV_N | Manning's "n" value for overland flow | - | -0.1-0.1 | 0.008 | 0.77 |

The Model was further calibrated using the sensetive parameter only and the result is in Table 5 8:

**Table 5 8 :** SWAT sensitive parameters

| S.N. | Parameters | Definitions | Range | Fitted Value |
|---|---|---|---|---|
| 1. | SURLAG | Surface runoff lag time. | 0.05-9.97 | 6.25 |
| 2. | TIMP | Snow pack temperature lag factor | 0-0.44 | 0.09 |
| 3. | SOL_AWC | Available water storage capacity of the soil layer | -0.1-0 | -0.033 |
| 4. | ALPHA_BF | Baseflow recession constant | 0.15-0.47 | 0.445 |
| 5. | PLAPS | Precipitation lapse rate | 7.74-13.92 | 8.191 |
| 6 | CH_N1 | Longest tributary channel length in subbasin. | 0.01-13.3 | 6.057 |
| 7. | LAT_TIME | Lateral flow travel time | 0-79.21 | 31.446 |
| 8. | GW_DELAY | Delay time for aquifer recharge | 0-250 | 16.75 |
| 9. | CN2 | SCS runoff curve number for moisture condition II | -0.1-0.1 | -0.095 |

### SWAT model performance at Tanahun station (430.5)

The calibration period for this station was picked from 2000 to 2009 based on the availability of flow data, and the validation period was taken from 2010 to 2015. The hydrological model can accurately recreate the low flows, as seen by the daily and monthly hydrographs in Figures a and b. The model simulates the low flows rather well, but it slightly overestimates the big flows. based on scatter graphs of the simulated and real-world flow during the calibration and validation periods. The model can faithfully replicate the annual average flow pattern at the calibration station, according to the flow duration curve. Good performance statistics are presented in Table 5 9 & Table 5 10 and the calibration accurately depicts the volume balance.

**Figure 5 16:** Results 1 of SWATCUP at Tanahun Station

Note: The graph in the Figure 5 16 represents a) Daily Hydrograph from 2000 to 2015 b) Monthly Hydrograph from 2000 to 2015 c) Flow Duration Curve & d) Cumulative Flow (Daily) at Station 430.5

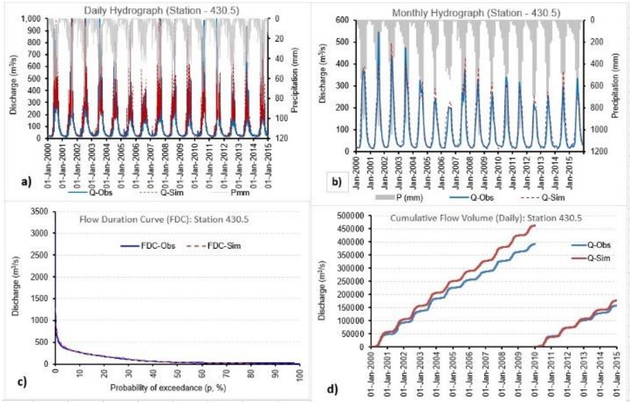
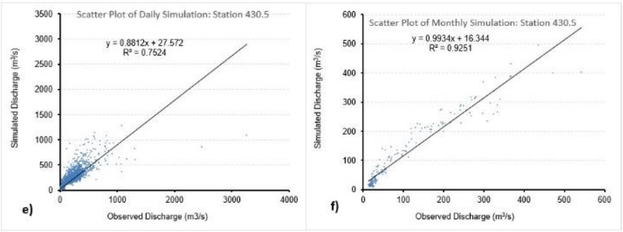


**Figure 5 17**: Results 2 of Tanahun Station



Note: The graph in the Figure 5 17 represents the e) Scatter plot of daily simulation & f) Scatter plot of monthly simulation at Tanahun Station

The Model Performance at the Tanahun Station is Table 5 9 & Table 5 10:

**Table 59:** Model Performance at Tanahun Station (Q430.5)-I

| | | **Calibration (2000-2009)** | **Validation (2010-2015)** | **Entire period (2000-2015)** |
|---|---|---|---|---|
| Daily | NSE | 0.69 | 0.80 | 0.72 |
| | $R^2$ | 0.73 | 0.82 | 0.75 |
| | PBIAS | 18.2 | 10.7 | 15.7 |
| Monthly | NSE | 0.90 | 0.90 | 0.90 |
| | $R^2$ | 0.93 | 0.92 | 0.93 |
| | PBIAS | 18.3 | 10.7 | 15.8 |

### SWAT model performance at Sishaghat station (Q438)

Based on the availability of flow data, the calibration period for this station was taken from 1998 to 2009, and the validation period was taken from 2010 to 2015. According to the daily and monthly hydrographs in Figure 5 18, the hydrological model can faithfully reproduce the low flows but it cannot replicate high so the high simulation is not perfectly matched up may be due to the snow fed area in the upstream of the hydrological station. According to scatter plots of the observed and simulated flow throughout the calibration and validation periods, the high flows are also reasonably precisely duplicated, but they are somewhat exaggerated during the validation period and slightly underestimated during the calibration period. To define the scatter plot perfectly the long-term average of the station is taken which is perfectly accurate within the pattern. According to the flow duration curve, the model can reproduce the calibration station's annual average flow pattern. The performance data shown in Table are good, and the calibration effectively captures the volume balance.

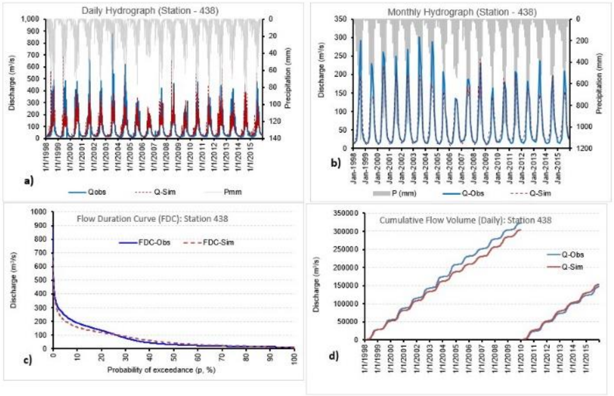


**Figure 5 18:** Result of SWATCUP at Station 438 - I

Note: The graph in the Figure 5 18 represents a) Daily Hydrograph from 1998 to 2015 b) Monthly Hydrograph from 2000 to 2015 c) Flow Duration Curve & d) Cumulative Flow (Daily) at Station 438

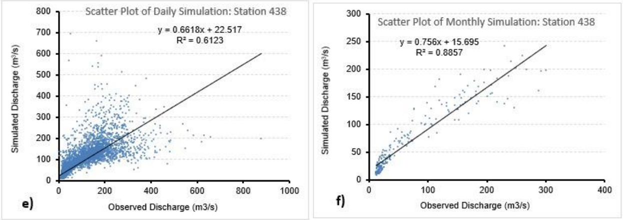


Figure 5 19: Results of SWATCUP at Station 438 – II

Note: The graph in the Figure 5 19 represents the e) scatter plot of daily simulation & f) Scatter plot of monthly simulation at Tanahun Station

The Model Performance at the Sishaghat Station in Table 5 11:

**Table 5 11**:Model Performance at Sishaghat Station-I

| **Performance parameter** | | **Calibration (1998-2009)** | **Validation (2010-2015)** | **Entire period (1998-2015)** |
|---|---|---|---|---|
| Daily | NSE | 0.67 | 0.72 | 0.69 |
| | $R^2$ | 0.68 | 0.78 | 0.70 |
| | PBIAS | -4.8 | -23.4 | -10.6 |
| Monthly | NSE | 0.86 | 0.89 | 0.87 |
| | $R^2$ | 0.88 | 0.91 | 0.89 |
| | PBIAS | -5.5 | 4.7 | -2.3 |

### Climate change impact on Seti-Gandaki outlet

The streamflow was approximated using meteorological data generated from GCMs. The results are displayed on the graph as a percentage when compared to the base value and shows increase in the watershed's streamflow throughout every month of the year. The streamflow of the baseline period of the catchment’s outlet were 99.25 m3/sec annually, 24.37 m3/sec during winter, 25.81 m3/sec during pre-monsoon, 224.28 m3/sec during monsoon and 71.68 m3/sec during post monsoon. Figure 5 22 and Figure 5 23 shows the change in the seasonal alteration among the two scenarios SSP245 and SSP585 respectively. Where the streamflow is projected to increase in seasonal alteration in the catchment outlet. The flow of the catchment follows the same trends as that of Indrawati river where the streamflow was projected to increase in the future scenarios (S. Shrestha et al., 2016).

**Table 5 13:** Future discharge data at watershed outlet compared to baseline data

| | | ssp245 | | | ssp585 | | |
|---|---|---|---|---|---|---|---|
| **Mth** | **Baseline** | **NF** | **MF** | **FF** | **NF** | **MF** | **FF** |
| Jan | 15.64 | 60% | 74% | 68% | 68% | 52% | 71% |
| Feb | 26.69 | 47% | 98% | 37% | 37% | 51% | 72% |
| March | 37.00 | 40% | 68% | 49% | 49% | 58% | 62% |
| April | 74.38 | 90% | 96% | 79% | 79% | 90% | 97% |
| May | 188.29 | 57% | 67% | 66% | 66% | 70% | 93% |
| June | 440.30 | 35% | 59% | 49% | 49% | 68% | 58% |
| July | 715.30 | 49% | 61% | 40% | 40% | 64% | 75% |
| Aug | 709.63 | 25% | 38% | 26% | 26% | 56% | 54% |
| Sep | 484.34 | 30% | 38% | 28% | 28% | 57% | 51% |
| Oct | 149.26 | 16% | 39% | 31% | 31% | 39% | 41% |
| Nov | 45.27 | 33% | 44% | 33% | 33% | 48% | 52% |
| Dec | 15.08 | 128% | 114% | 104% | 104% | 154% | 137% |

## 3.3. Combined Impacts of Climate Change and LULC Change on Streamflow

The SWAT projected the following discharge data after projecting future landuse data and meteorological data for the relevant future (near future, mid future, and far future). The landuse data projected for the corresponding futures were 2030 for the near future (NF), 2060 for the mid future (MF), and 2085 for the far future (FF). Three years of warmup period was taken during the simulation of the data for each future scenario.

### Terrset Change analysis

The land cover map of 2010 and 2000 A.D. from ICIMOD (2020) is used in this study to evaluate the change in the land cover as shown in below. The Figure 5 24 clearly shows huge gain in grassland and forest area and losses in cropland and snow/glacier area between 2010 and 2000.

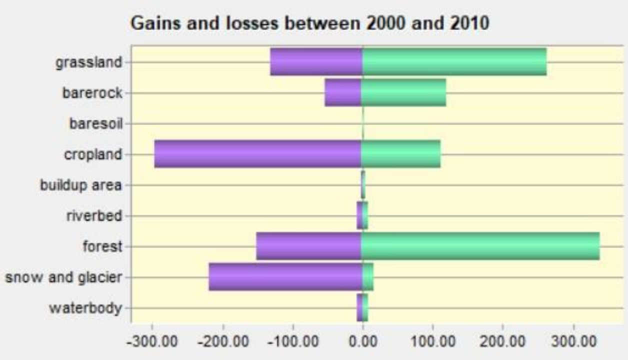


**Figure 5 24:** Gain and loss for different LULC classes between 2000 and 2010 (in hectare)

### Model validation

Model validation is necessary to assess the accuracy. In this study, Kappa index is used to evaluate the accuracy of the predicted LULC map. Kappa variations that compared the projected land use/cover map with the actual one yields overall accuracy (Kno) = 0.94, Kappa Location = 1.00, K location strata = 1.00 and K standard = 0.91 which falls in fair to good category. Similarly, a comparison between the actual 2020 LULC and predicted 2020 LULC was done, and the result is presented in Figure 5 25 and Table 5 15.

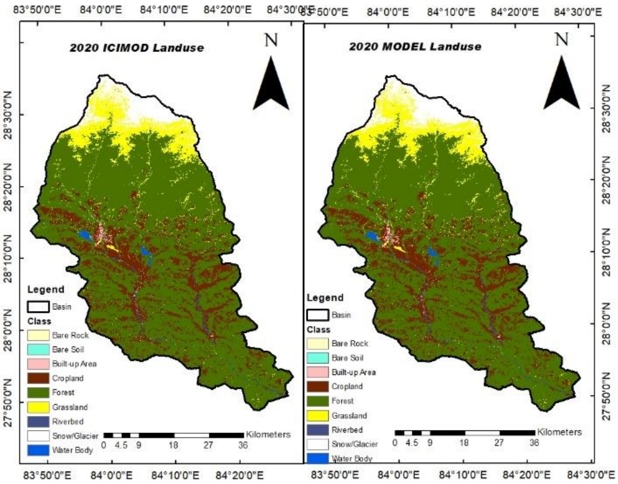


**Figure 5 25:** Comparison plot between 2020 actual and predicted LULC of watershed

**Table 5 15:** Comparison between 2020 actual and predicted LULC for Seti watershed

| LULC Class | ICIMOD 2020 LULC | | Predicted 2020 LULC | | Error (%) |
|---|---|---|---|---|---|
| | **Area (sq. km)** | **Percentage (%)** | **Area (sq. km)** | **Percentage (%)** | |
| Water body | 16.887 | 0.581115 | 16.589 | 0.5708 | -0.01027 |
| Snow/glacier | 142.726 | 4.911418 | 110.260 | 3.7942 | -1.11721 |

| | | | | | |
|---|---|---|---|---|---|
| Forest | 1948.563 | 67.05309 | 1977.290 | 68.0415 | 0.988426 |
| Riverbed | 0.640 | 0.022036 | 12.315 | 0.4238 | 0.401731 |
| Built-up Area | 33.640 | 1.157599 | 9.739 | 0.3351 | -0.82247 |
| Cropland | 489.632 | 16.849 | 479.078 | 16.4858 | -0.3632 |
| Bare soil | 0.071 | 0.002452 | 0.002 | 0.0001 | -0.00239 |
| Bare Rock | 55.712 | 1.917128 | 62.939 | 2.1658 | 0.24869 |
| Grassland | 218.129 | 7.506168 | 237.794 | 8.1829 | 0.676694 |

**Projection of future LULC**

After the validation of the LULC map, future LULC map is projected for the area 2035, 2060 and 2085. The comparison of the projected LULC for different period shows the gain in forest area and loss in cropland area in Table 5 16 and Figure 5 26.

**Table 5 16:** Area covered by different LULC for historical and future period in Seti-Gandaki watershed

| Class Name | Historical (From ICIMOD) (km$^2$) | | | Predicted area (km$^2$) | | | |
|---|---|---|---|---|---|---|---|
| | 2000 | 2010 | 2020 | 2020 | 2035 | 2060 | 2085 |
| Water Body | 16.1463 | 16.6149 | 16.8872 | 16.5888 | 16.5888 | 16.5888 | 16.5888 |
| Snow | 196.546 | 118.734 | 142.726 | 110.26 | 89.7309 | 85.2642 | 90.9684 |
| Forest | 1747.93 | 1847.73 | 1948.56 | 1977.29 | 2104.47 | 2214.49 | 2266.44 |
| River bed | 13.7724 | 12.3259 | 0.64037 | 12.3147 | 12.3147 | 12.3147 | 12.3147 |
| Built up area | 7.83884 | 9.73302 | 33.6398 | 9.7389 | 9.7389 | 9.7389 | 9.7389 |
| Cropland | 698.029 | 608.545 | 489.632 | 479.078 | 351.899 | 241.878 | 189.932 |
| Bare Soil | 36.2045 | 0.00177 | 0.07124 | 0.0018 | 0.0018 | 0.0018 | 0.0018 |
| Bare Rock | 189.5356 | 62.86051 | 55.71174 | 62.9388 | 62.9388 | 62.9388 | 62.9388 |
| Grass land | 0 | 229.4539 | 218.1292 | 237.7944 | 258.3234 | 262.7901 | 257.0859 |

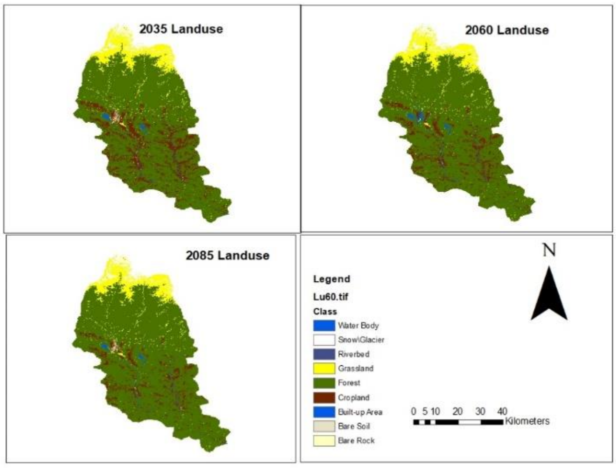


**Figure 5 26:** Projected LULC map for future time period of Seti-Gandaki watershed.

**LULC and climate change impact on Seti-Gandaki outlet**

When the data are compared to the baseline of the watershed outlet (1998-2015), they projected the increment on the streamflow throughout every month on future except June of SSP245. Different LULC map were used for different future scenarios (NF, MF, FF). The streamflow of the baseline period of the catchment's outlet were 99.25 m3/sec annually, 24.37 m3/sec during winter, 25.81 m3/sec during pre-monsoon, 224.28 m3/sec during monsoon and 71.68 m3/sec during post monsoon. Figure 5 29 and Figure 5 30 shows the change in the seasonal alteration among the two scenarios SSP245 and SSP585 due to the combined impact of climate change and land use change in the watershed's outlet respectively. Where the streamflow is projected to increase in seasonal alteration in the catchment outlet. The watershed outlet does follow the specific trend.

**Table 5 17:** Future discharge data at watershed outlet compared to baseline data.

| Months | Baseline | ssp245 | | | ssp585 | | |
|---|---|---|---|---|---|---|---|
| | | NF | MF | FF | NF | MF | FF |
| January | 15.64 | 117% | 68% | 82% | 143% | 65% | 52% |
| February | 26.69 | 35% | 72% | 49% | 43% | 52% | 38% |
| March | 37.00 | 18% | 52% | 42% | 30% | 60% | 54% |
| April | 74.38 | 22% | 82% | 68% | 15% | 92% | 125% |
| May | 188.29 | 15% | 61% | 79% | 29% | 64% | 113% |
| June | 440.30 | -2% | 54% | 50% | 17% | 71% | 106% |
| July | 715.30 | 23% | 51% | 57% | 35% | 61% | 90% |
| August | 709.63 | 26% | 35% | 44% | 27% | 57% | 100% |
| September | 484.34 | 44% | 33% | 55% | 48% | 57% | 106% |
| October | 149.26 | 123 | 45% | 48% | 138 | 53% | 99% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | % | | | % | | |
| November | 45.27 | 188 % | 60% | 80% | 203 % | 75% | 103 % |
| December | 15.08 | 291 % | 130 % | 150 % | 293 % | 190 % | 204 % |

## 4. Conclusion

In this comprehensive study, the integration of hydrological modeling through the Soil and Water Assessment Tool (SWAT) and the projection of future climate data using the Coupled Model Intercomparison Project Phase 6 (CMIP6) at a resolution of 25 kilometers provided a nuanced understanding of the Seti-Gandaki watershed. The strategic selection of five General Circulation Models (GCMs) for ensemble projections facilitated a holistic examination of the potential shifts in precipitation and temperature and their subsequent impacts on the hydrological dynamics of the region.

The climate projections highlight an anticipated increase in precipitation and both minimum and maximum temperatures in the coming years. These changes are poised to exert considerable influence on the local ecosystem, particularly affecting seasonal crop yields due to the altered monsoon patterns. The rising temperatures also present a significant threat to the process of snowmelt in the Himalayas, further complicating the region's hydrology.

The study's forecasted intensification of streamflow signifies elevated river levels, posing heightened risks of floods and landslides. Projections under the Shared Socioeconomic Pathway (SSP) scenarios indicate a substantial increase in streamflow during monsoons, with percentages reaching 49% and 61% for SSP245 and SSP585, respectively. This poses a grave threat to communities along the Seti River, exacerbating the existing challenges of floods and landslides.

In addition to climate change, the transformation of Land Use and Land Cover (LULC) emerges as a critical issue. Urbanization and diminishing rural populations contribute to problems such as dwindling agricultural land and expanding barren areas. The projected shrinkage of snow-covered regions further compounds the challenges. However, an intriguing finding is the potential positive impact of increased streamflow within the watershed, offering opportunities for enhanced hydropower generation and meeting agricultural water demands.

To address these challenges and contribute to sustainable water resource management and climate resilience, a set of strategic recommendations is proposed. Implementing robust water management plans that address precipitation variability through improved storage, efficient irrigation systems, and water-saving practices is paramount. Simultaneously, active efforts to reduce greenhouse gas emissions by transitioning to clean energy sources, enhancing energy efficiency, and adopting sustainable transportation practices are essential.

Investments in infrastructure preparedness, including the development of systems to mitigate the impacts of rising river levels and the establishment of flood and avalanche early warning systems, are crucial. Concurrently, ongoing research to deepen the understanding of climate change effects and adaptation measures is imperative. Maintenance of fish ladders to preserve aquatic biodiversity amid increased silt flow in the river is vital for ecosystem health.

Lastly, advocating for green spaces and sustainable urban planning in metropolitan areas can significantly contribute to carbon absorption. Establishing a comprehensive monitoring system for tracking LULC changes and their impact on climate is essential for refining climate strategies over time. By embracing these recommendations, stakeholders can actively contribute to the resilience and sustainability of the Seti-Gandaki watershed.

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