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Sediment Simulation and Impact of Land Cover Changes using SWAT Model in Karnali Basin

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Abstract
Understanding the impacts of land-use changes on hydrology at the watershed scale can facilitate development of sustainable water resource strategies as well as sediment studies when it comes to constructing headworks for hydropower projects. This paper investigates the hydrological effects of land-use change in Karnali basin(Phukot and Betan).The water balance was simulated using the Soil and Water Assessment Tool (QSWAT2000). Model calibration and uncertainty analysis were performed with sequential uncertainty fitting (SUFI-2).Simulation results from January 2018 to December 2018 were used for parameter calibration, and then the model was validated for annunal sediment produced when compared to nearby gauging station(Asaraghat). The predicted daily streamflow matched the observed values: during calibration the correlation coefficient was 0.78 at phukot and 0.81 at Betan and the Nash–Sutcliffe coefficient was 0.60 at phukot and 0.68 at Betan.Furtherore, daily Sediment matched the observed values: during calibration the correlation coefficient was 0.78 at phukot and 0.81 at Betan and the Nash–Sutcliffe coefficient was 0.60 at phukot and 0.63 at Betan. The model was used to simulate the main components of the hydrological cycle, in order to study the effects of land-use changes like conversion of forest and grass land to barren creating a hypothetical scenario of construction of roadways and development activities.

Keywords
land-use change, hydrological responses, QSWAT, surface runoff, Sediment

1. Introduction

Effective watershed management and ecological restoration require a thorough knowledge of the hydrological processes going on in the watersheds.Studies on the effect of land-use change on the water cycle tend to concentrate on mean annual runoff (Brown et al., 2005).Studies on the effect of land-use change on the water cycle tend to concentrate on mean annual runoff (Brown et al., 2005)[1]. Paired catchment studies can provide direct evidence of land-use change impacts on runoff; however, they generally require long time steps and cover small study areas.The scope of work, as per objectives, contains methodology for estimation of water at selected gauge point with application of numerical modeling tools, and GIS platform. For these reasons, hydrological models are becoming important for studying the effects of land-use change on the hydrological cycle (**Karvonen et al., 1999; Felix et al., 2002**). Therefore, distributed hydrological models are increasingly being used to investigate the hydrological impacts of land-use changes (**Calder et al., 1995; Lorup et al., 1998; Fohrer et al., 2001; VanShaar et al., 2002; Legesse et al., 2003; Bathurst et al., 2004; Krysanova et al., 2005; Li et al., 2005**).

This research includes acquisition, pre-processing and spatial analysis of the Digital Elevation Model (DEM) for catchment delineation and stream-network generation, preparation of hydro-meteorological data, formulation of the physically based, semi-distributed parameter model hydrologic model (SWAT) to calibrate and validate the stream flow and finally the analysis of results. Scope of work includes the use of tools like QGIS, QSWAT and SWAT-CUP for fulfilling the objectives mentioned above.

Nepal is a country with numerous river networks due to wide geographical variation from Himalayas to the lowest area of Terai within a short distance. The modelling for Nepal watershed has many challenges due to large spatial variation in small terrain. Weather data of Nepal for watershed modelling is not enough at every location due to which internet weather grid data was required to be used. Large variation in weather database for Nepal's climate station and the internet-based data creates difficulties while using it for watershed modelling.

For the preparation of weather database, these data are to be obtained from **Department of Hydrology and Meteorology (DHM)** for meteorological stations located within Nepal area basin and **Climate Forecast System Reanalysis (CFSR)**, **Global Weather data** for meteorological stations located within China, India and Northern Nepal watershed area for the Nepal River basins. The watershed area of Nepal River basin is to be incorporated with international catchment area, because of which weather database is required for hydrological modelling.

SWAT requires daily precipitation, maximum/minimum air temperature solar radiation, wind speed and relative humidity. Values for all these parameters may be read from records of observed data or they may be generated. The weather generator input file contains the statistical data needed to generate representative daily climate data for the sub basins. This WGEN file for all Nepal River watershed needs to be prepared since inbuilt SWAT database has stations widely spaced and for varying terrain as of Nepal, small sub basin are needed to be created and database for these areas are to be made in order to get realistic model output.

The two objective of this study were (1) to validate the SWAT model interms of runoff ; and (2) to simulate the impacts of landuse changes creating a hypothetical case like changing forest land and grassland to barren.

2. Study Area

River networks of Nepal are well distributed throughout the country with some part of watershed area lying the China and India. For hydrological studies, Nepal's watershed is divided into ten discharge basins, i.e. Mahakali River Basin, Karnali River Basin, Gandaki River Basin, Koshi River Basin, Bagmati River Basin, Babai River Basin, Rapti River Basin, Kamala River Basin, Mechi River Basin and Churiya River Basin. Figure 1 gives an overview of these watershed. It is clear that three largest watersheds cover eastern, central and western part of country and runs from high Himalayas to plain Terai.

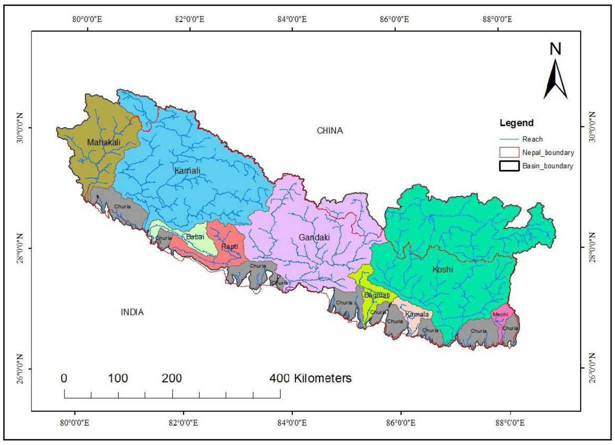

Figure 1: River Network of Nepal

Karnali River is located in northeast part of Nepal and is a perennial trans-boundary river originating on the Tibetan Plateau near Lake Manasarovar. It cuts through the Himalayas in Nepal and joins the Sharda River at Brahmaghat in India.Together they form the Ghaghara River, a major left bank tributary of the Ganges. The Karnali river basin, one of the major three rivers in Nepal originates from the south of Mansarovar and Rokas lakes located in China (Tibet). The total catchment area of the Karnali River basin is 45647.18sq. Km at Chisapani. Its catchment has an elevation ranging from 50 m.a.s.l. on the low-lying floodplain to 7457 m.a.s.l. on the ridge.

Table 1: Characteristics of Karnali Basin at Betan Outlet

SN	Catchment	Lat°	Lon°	Area(km2)
1	Phukot	29.23	81.67	16,603.18
2	Betan	28.90	81.21	22,370.52

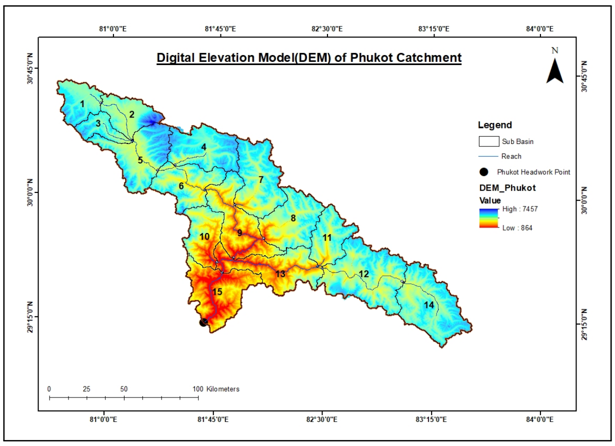

Figure 2: Phukot Location Map

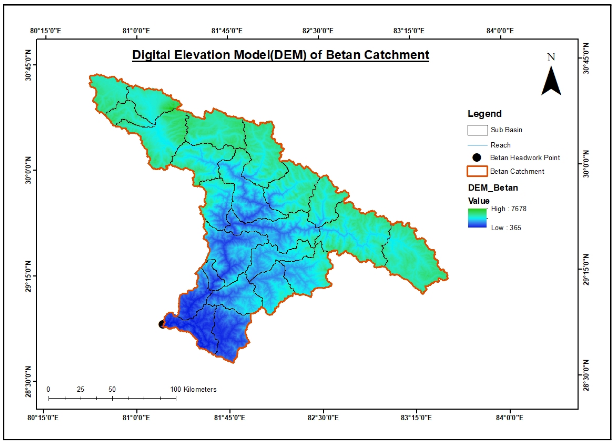

Figure 3: Betan Location Map

3. Swat Model

Soil and Water Assessment Tool, or SWAT, is very flexible and robust river basin hydrological model that can stimulate wide variety of watershed scenarios . It is used to predict the river's stream flow, sediment, water quality, and other parameters. It is also used to model the effect of land management practices and irrigation and agricultural effect on the basin. The SWAT model requires basic meteorological data such as precipitation, soil properties, land use, land cover, and DEM. Physical processes such as infiltration, evapotranspiration associated with water movement, sediment movement, and crop growth are modeled by SWAT with the help of input data[2]. The rainfall runoff model used by SWAT in this study is the SCS curve number model, which is described briefly below.

For modeling purposes, the river basin is divided into a number of sub-basins and then divided further into a number of HRUs (Hydrological Response Units). For every model in SWAT, the first and essential step is to model the hydrological water balance. This water balance is the driving force behind every process that happens in the river basin. A water balance equation is given as::[3]

$$SW_f = SW_i + \Sigma(P_{day} - R_{surf} - Q_{seep} - E_a - D_{dw}) \quad (1)$$

Where SW_f = final water content in soil (mm water); SW_i = initial water content in soil on i day (mm water); R_{surf} = surface runoff on i day (mm water); Q_{seep} = water entering the unsaturated zone of soil on i day (mm); P_{day} = precipitation on day i (mm water); D_{gw} = return flow on day i (mm water); and E_a = amount of evapotranspiration on day i (mm water).

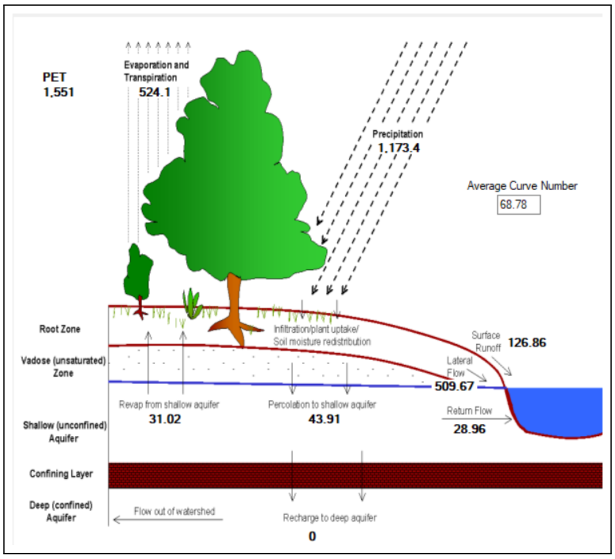

Figure 4: Schematic Representation of Hydrological Cycle

Figure 4 shows a general description of the hydrological cycle. The land phase (mainly the soil layer) controls the amount of water and sediment entering the main channel in each sub-basin. A sub-basin's output is treated as input for the following subbasin.

After the water balance phase, the next step is the routing of water, sediments, etc. through the streams to the basin's outlet. To calculate surface runoff, we used the SCS curve number method . We used the Penman Monteith method to estimate potential evapotranspiration (PET) , and then actual Evapotranspiration was calculated. The SCS curve equation is described as:

$$R_{surf} = \frac{(pday - 0.2S)^2}{(pday + 0.8S)} \quad (2)$$

Where P_{day} is rainfall depth for the day (mm); Q_{surf} is accumulated runoff or rainfall excess (mm); and S is the retention parameter (mm) that can be obtained by the following:[4]

$$S = 25.4(\frac{100}{CN} - 10) \quad (3)$$

The SCS curve number (CN) depends on the soil's permeability, infiltration, land use and, soil-water conditions. The CN value can be defined by three conditions: dry, average moist, and wet. A full description is available in and in the SWAT technical manual.The modified Soil Conservation Service (SCS) curve number method is used to compute runoff. [5]

SWAT computes the erosion caused by rainfall and runoff with the Modified Universal Soil Loss Equation (MUSLE) **(Willams, 1975)**, which is given by the equation 4. **MUSLE** is a modification of the **Universal Soil Loss Equation (USLE)** developed by **Wischmeier and Smith**.[6]

$$Sed = 11.8(Q_{surf}.q_{peak}.area_{hru})^{0.56}. K_{usle}.C_{usle}.P_{usle}.LS_{usle}.CFRG \quad (4)$$

Where sed is the sediment load on a given day (metric tons), is the surface runoff volume (mm H2O) , qpeak is the peak runoff rate (m3/s), $area_{hru}$ is the area of the HRU (ha), K_{usle} is the USLE soil erodibility factor (0.013 metric ton m2 hr/(m3-metric ton cm), C_{usle} is the USLE cover and management factor, P_{usle} is the USLE support practice factor, LS_{usle} is the USLE topographic factor and CFRG is the coarser fragment factor **(Neitsch et al., 2005)**.

4. Input Data

To create a SWAT dataset, the interface will need to access QGIS compatible raster (GRIDs) and vector datasets (shape-files and feature classes) and database files, which provide certain types of information about the watershed. The spatially distributed data needed for the SWAT model as input are listed below:

DEM The Digital Elevation Model (DEM) is the very basic data that is required to start processing a watershed. A Digital Elevation Model can be defined as the representation of continuous elevation values over a topographic surface by a regular array of z-values, referenced to a common datum. DEMs are typically used to represent terrain relief. A DEM can be represented as a raster (a grid of squares, also known as a height map when it represents elevation) or as a vector-based Triangular Irregular Network (TIN). Digital Elevation Model (DEM) is the digital representation of the topographic surface. A 90m resolution raster DEM developed by USGS (United States Geological Survey), was used for the purpose of this study.

Landuse Data The landuse is one of the most important factors that affect runoff, evapotranspiration and surface erosion in a watershed. The landuse map of the study area was also obtained from earth explorer, USGS. The reclassification of landuse map was done to represent landuse according to the specific landuse types and respective parameters were selected from SWAT database.

Soil Data Soil impacts on many hydrological processes like infiltration to swallow aquifer, percolation to deep aquifer and discharge to the river in the form of interflow and base flow. The SWAT model requires different soil textural and physio-chemical properties such as soil hydrological group, soil texture, hydraulic conductivity, bulk density etc. for different layers of each soil type in order to replicate the hydrological processes.

Land Slopes Land Slopes of Nepal River basin are divided into four categories.

Weather Data The weather data that are necessary for carrying out hydrological balance by the model are daily precipitation in mm, minimum and maximum air temperature in degree Celsius, relative humidity in percentage, wind speed in m/s and daily solar radiation in MJ/m2/day.

5. Performance Evaluation

In this study, the goodness of fit was evaluated based on the visual comparisons and statistical criteria. NSE (Nash-Sutcliffe coefficient of efficiency) and correlation coefficient are the most common evaluation techniques. The statistics of stream flow and sediment can be considered as highly applicable when NSE is higher than 0.7 and correlation coifficient is close to one. NSE computes the efficiency of the model by relating the model's goodness of fit to the variance of the measured data, which ranges from 0 to 1. Whenever efficiency value is greater than 0.6, the model performance can be considered as satisfactory.

$$NSE = 1 - \frac{\sum_{i-1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i-1}^{n}(Q_{obs} - Q^{-})^2} \quad (5)$$

Where NSE = Nash-Sutcliffe coefficient; Q_{sim} = simulated flow (m^3/s); Q_{obs} = Observed flow (m^3/s); Q^{-} = Average of observed flow (m^3/s). The coefficient of determination (R^2) represents the degree of collinearity between observed and simulated data, and the range of R^2 lies between 0 and 1. A value of R^2 closer to 1 indicates that descriptions of the predicted values are almost equal to the observed values. Contrarily, a value of 0 signifies no correlation between observed and simulated values. R^2 is computed as shown in Equation :

$$R^2 = \frac{\sum_{i-1}^{n}(Q_{sim} - Q^{-})^2 (Q_{obs} - Q_o^{-})^2}{(\sum_{i-1}^{n}(Q_{sim} - Q^{-})^2)(\sum_{i-1}^{n}(Q_{obs} - Q^{-})^2)} \quad (6)$$

6. Result and Disscussion

For the calibration period, the simulation of flow with the observed values suggested that the model had a strong predictive capability with NSE = 0.73 and R2 = 0.78 at Phukot followed by NSE = 0.70 and R2 = 0.81 at Betan.

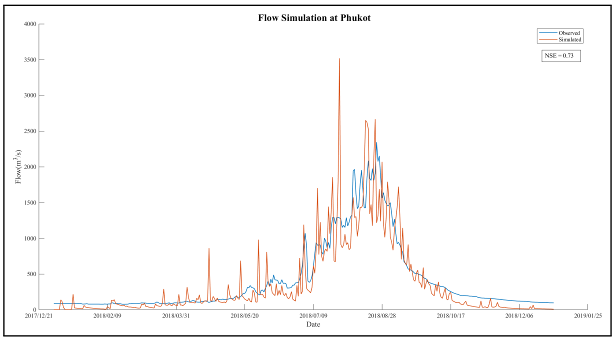

Figure 5: Flow Result and Analysis at Phukot

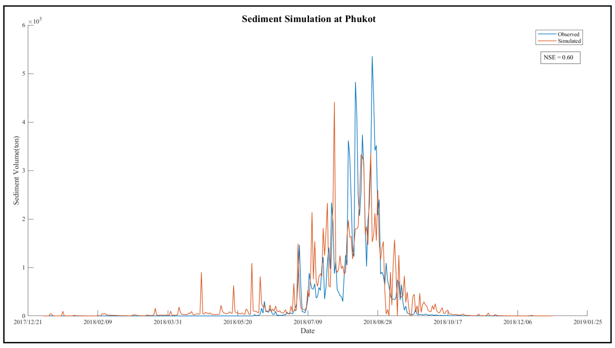

Figure 6: Sediment Result and Analysis at Phukot

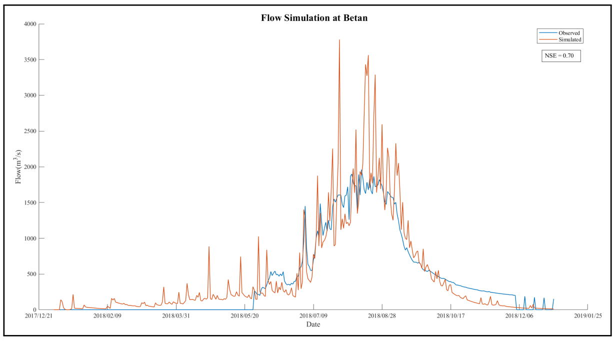

Figure 7: Flow Result and Analysis at Betan

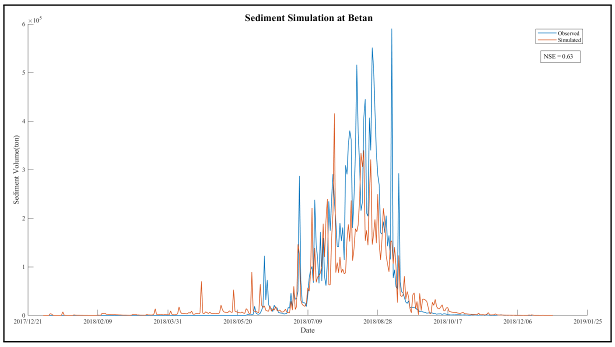

Figure 8: Sediment Result and Analysis at Betan

Likewise, the simulation of sediment with the observed values showed a good prediction with the NSE = 0.60 and R2 = 0.60 at Phukot Catchment followed by NSE = 0.63 and R2 = 0.68 at Betan Catchment which is shown in the figures .

7. Behaviour of Basin with respect to the landuse change for Betan Catchment

Human intervention over the basin for development purposes like road networks etc. will have impacts on sediment as well as water discharges at Head work site. These impacts are mainly due to changes in land uses of part of sub-basins and subsequent changes in erodibility properties of land surface. As a result, there will be apparent changes in sediment load at the outlet of basin. Although there will be changes in flow hydrograph at the outlet of basin, the changes in sediment yield will be more significant.

Scenario 1 In general, an increase in discharge is observed during dry season months and a reduction during wet ones. Increases in discharge for dry months are in the range 0.47 to 5.11%, while during the wet months, decreases reach the percentage of 0.62 to 2.52%. Similar pattern can be seen in terms of sediment as well with different figures which reaches a value in a range of 0.45 to 1.47% increase in dry period and 0.03 to 8.40% decrease in case of wet period. as shown in figure below.

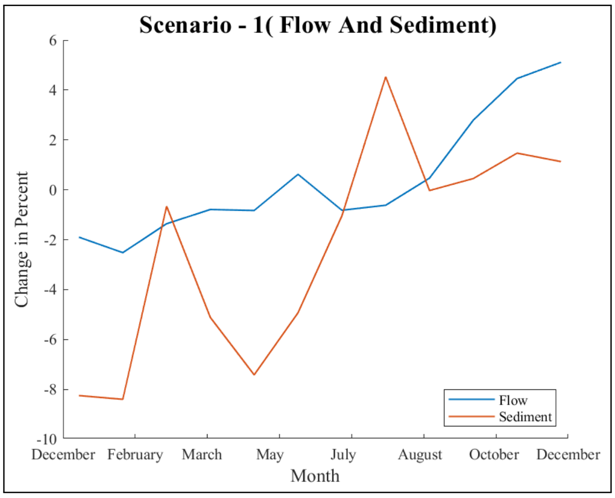

Figure 9: Result and Analysis Scenario 1

Scenario 2 An increase in discharge is observed during dry season months and a reduction during wet ones. Increases in discharge for dry months are in the range 0.04 to 4.19%, while during the wet months, decreases reach the percentage of 0.03 to 0.64%, Whereas in case of sediment increase trend can be observed in each month whose value ranges from 3.61 to 14.96% as shown in figure below.

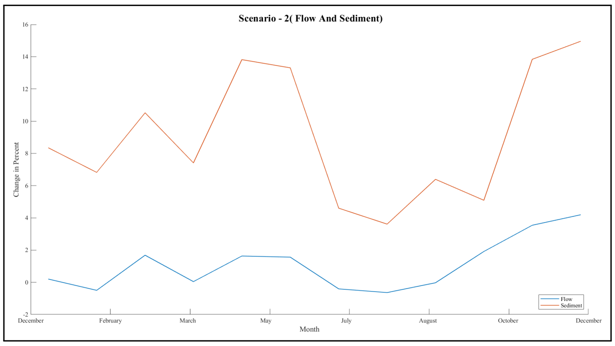

Figure 10: Result and Analysis Scenario 2

Scenario 3 An increase in discharge is observed during dry season months and a reduction during wet ones. Increases in discharge for dry months are in the range 0.1 to 4.74%, while during the wet months, decreases reach the percentage of 0.29 to 1.83%, Whereas in case of sediment increase trend can be observed in each month whose value ranges from 4.15 to 14.85% as shown in figure below.

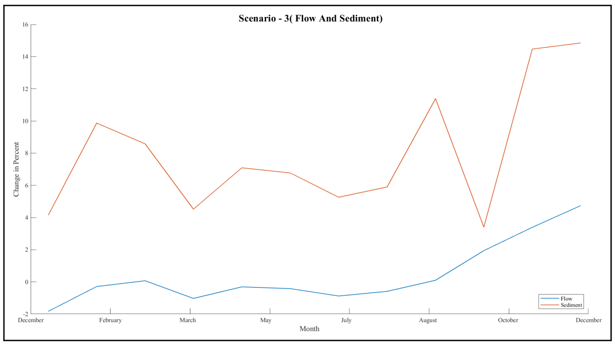

Figure 11: Result and Analysis Scenario 3

Scenario 4 An increase in discharge is observed. Increases in discharge are in the range 8.42 to 28.74%, while decreases reach the percentage of 8.13 to 41.64%, whereas in case of sediment increase trend can be observed whose value ranges from 9.75 to 57.24%, Furthermore decrease in sediment range in 2.48 to 52.33% as shown in figure below.

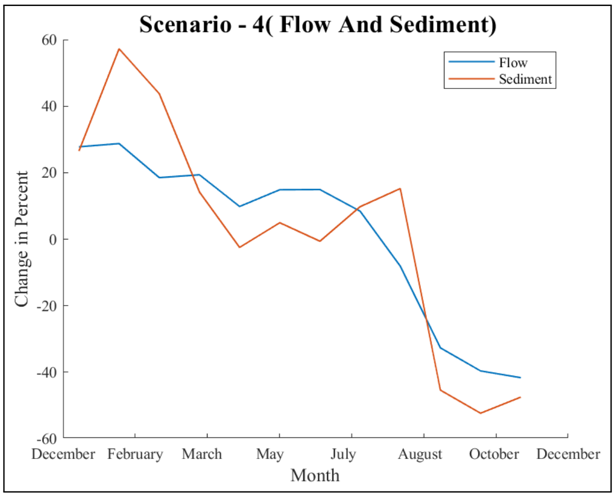

Figure 12: Result and Analysis Scenario 4

Scenario 5 An increase in discharge is observed. Increases in discharge are in the range 16.05 to 74.98%, while decreases reach the percentage of 14.97 to 43.03%, whereas in case of sediment increase trend can be observed whose value ranges from 12.82 to 181.06%, Furthermore decrease in sediment range in 10.50 to 51.85% as shown in figure below.

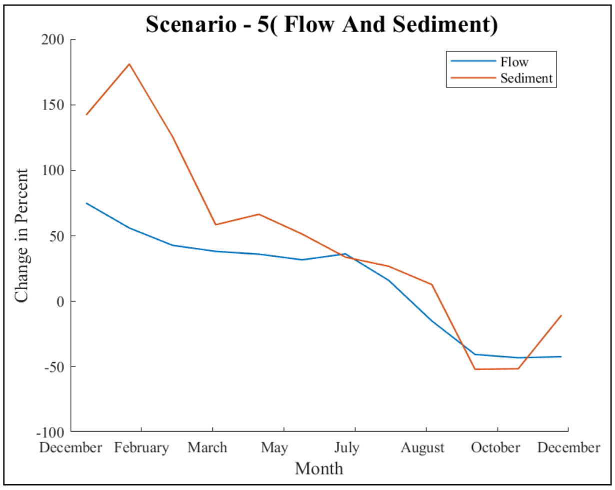

Figure 13: Result and Analysis Scenario 5

Scenario 6 An increase in discharge is observed. Increases in discharge are in the range 10.70 to 34.05 %, while decreases reach the percentage of 5.43 to 44.86%, Whereas in case of sediment increase trend can be observed whose value ranges from 0.93 to 66.20%, Furthermore decrease in sediment range in 41.62 to 51.45% as shown in figure below.

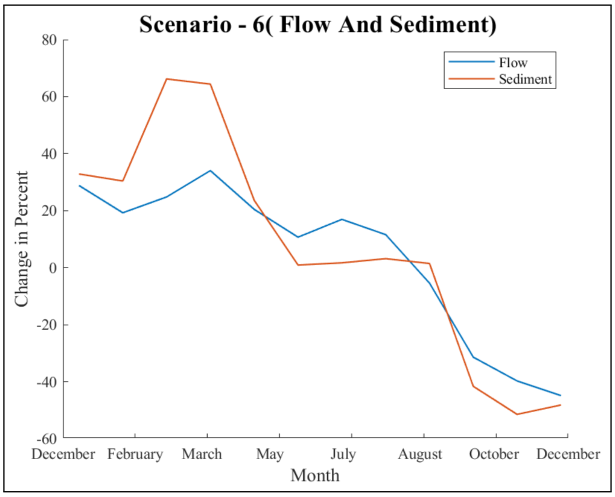

Figure 14: Result and Analysis Scenario 6

8. Prediction of long term sediment

After the Calibration of parameter 15 year rainfall and temperature data were taken from DHM in order to predict the long term annual sediment at Phukot as well as Betan Catchment Site. The long term generated sediment was then compared with sediment data taken from Asaraghat (240) station. The following table shows the data generated from the swat model.

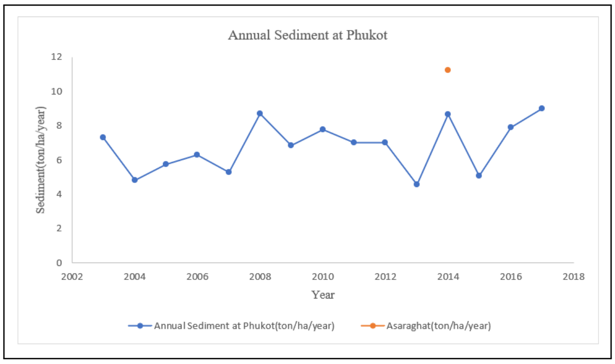

Figure 15: Annual Sediment Plot in Phukot

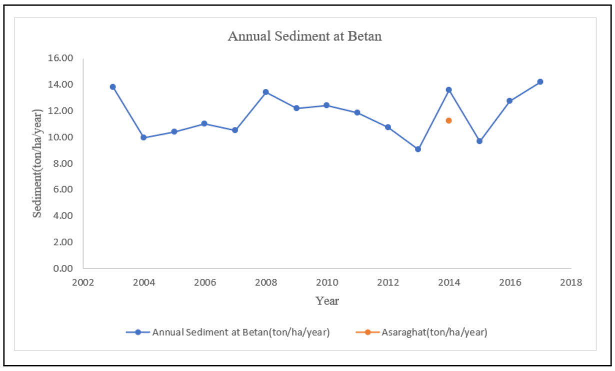

Figure 16: Annual Sediment Plot in Betan

9. Land cover of 1990, 2000 and 2010 of Phukot and Betan

Landuse of year 1990, 2000 and 2010 were used to simulate flow and sediment of Phukot and Betan. Landuse comparison is shown in figure 17 and figure 18 for Phukot and Betan respectively.

Area covered by BSVG type (barren) landuse is maximum in year 2000 and minimum in year 2010 and in-between in year 1990, while combined forest and grasses are maximum in year 2010 and minimum in year 2000 and in-between in year 1990. Since barren land causes less infiltration and hence results in more surface runoff causing more sediment yield and landuse of year 2000 has maximum barren type landuse compared to years 1990 and 2010, hence, maximum sediment yield is obtained in year 2000 in both Phukot and Betan as shown in table 2 and table 3 respectively.

Table 2: Comparision of flow and sediment yield in phukot

Parameter	1990	2000	2010
Flow (m^3/s)	408.30	414.85	352.60
Sediment(tons) in mil	12.90	12.85	11.67

Table 3: Comparision of flow and sediment yield in Betan

Parameter	1990	2000	2010
Flow (m^3/s)	538.89	500.91	472.88
Sediment(tons) in mil	16.24	17.28	12.64

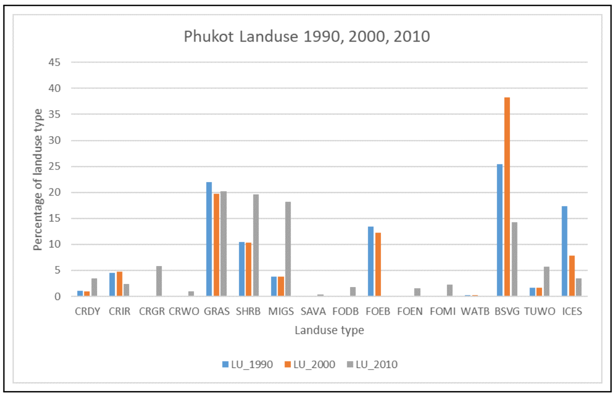

Figure 17: Comparison of land cover for years 1990, 2000 and 2010 at Phukot

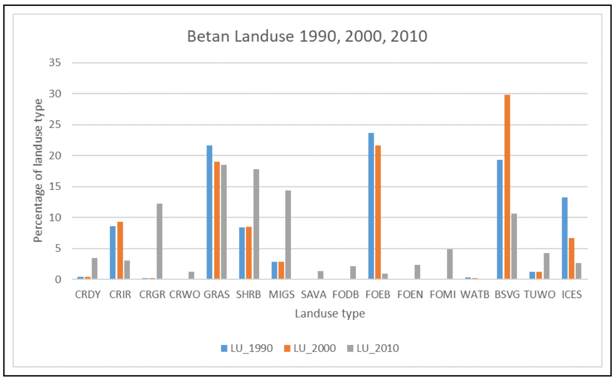

Figure 18: Comparison of land cover for years 1990, 2000 and 2010 at Betan

10. Conclusion

The Soil and Water Assessment Tool (SWAT) model is run at Betan Catchment and calibrated with data provided. Based upon result analysis and discussion in previous chapter, the following conclusions can be made. Following conclusions are drawn from SWAT analysis carried out for assessing impact of infrastructure development in Betan - Karnali basin.

1. The extent of impact of conversion of forest or grass land to barren land on flow and sediment hydraulics of the river due to infrastructure development in the basin is very sensitive to the location in the basin where changes had taken place.
2. Removal of forest in the areas near the headwork sites impart less adverse impact than removing on far upland forests. This is mainly because of conversion into steep sloping barren land susceptible to more erosion.
3. Conversion of grass land to barren land lying near the headwork sites results high increase in sediment load to river flow as compared the same on other parts of the basin.
4. The percentage increase in sediment load at outlet of the basin is directly proportional to total area of land use being converted.
5. There is apparent temporal variation in the extent of impacts on flow and sediment hydraulics due to conversions of one type of land use to another.
6. A specific finding of this study is that the numerical results show that the hydrological response to land cover change is nonlinear and exhibits a threshold effect.

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