




# Estimation of sediment load for Himalayan Rivers: Case study of Kaligandaki in Nepal

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Himalayan regions have increasing sediment yield due to undulating topography, slope and improper watershed management. However, due to limited observation data, and site accessibility issues, less studies have quantified sedimentation loads in the Himalayas, especially Nepal. This has hindered the investments on run-of-river hydropower projects as high and unpredicted sedimentation has increased losses in hydropower production. Therefore, there is a need to understand key physical processes driving sedimentation in these regions, with the available data. This study used the Soil and Water Assessment Tool (SWAT) to estimate the sedimentation yields in the Kaligandaki basin of Nepal, which is an important tributary that drains into the Ganges. Multi-source data from field observations, remote sensing platforms, surveys and government records were used to set up and run the SWAT model for the Kaligandaki basin from 2000 to 2009. Results for the 10-year model run indicate that 73% of the total sediment load is estimated to come from the upstream regions (also known as High Himalayan region), while only 27% is contributed from the Middle and High Mountain regions (where land management-based interventions were deemed most feasible for future scenarios). The average sediment concentration was 1986 mg/kg (ppm), with values of 8432 and 12 mg/kg (ppm) for maximum and minimum, respectively. Such high sedimentation rates can impact river ecosystems (due to siltation), ecosystem services and hydropower generation. In addition, model results indicate the need for better high frequency observation data. Results from this study can aid in better watershed management, which is aimed at reducing sedimentation load and protecting Himalayan rivers.

**Keywords.** Himalayan rivers; sediment load; hydropower; Nepal; SWAT.

## 1. Introduction

Across the Himalayan region, it is increasingly recognized that erosion and sedimentation in the rivers present serious concerns for the river discharge, water storage and riverine ecosystem. This also directly challenges the operation and long-term sustainability of major hydropower projects, especially in mountainous regions (Egger *et al.* 2000; Shrestha 2000). For reservoir-based

hydropower projects, sedimentation directly impacts hydropower production and contributes to the losses due to reduction of reservoir storage capacity, damages the turbines and reduces the lifespan of the reservoir (Thapa *et al.* 2012; Koirala *et al.* 2016). In addition, sedimentation increases the operation costs due to the need for more frequent and expensive dredging and maintenance of river banks (Duarte and Gioda 2014). Sedimentation also impacts the run-of-river

(RoR), or diversion hydropower projects by damaging the turbines and silting the channels leading to the turbines. All projects face increased wear-and-tear of electro-mechanical as well as civil components, at instances when sediment concentrations are high in incoming water flow. These factors increase the operation and maintenance costs of the hydropower projects in the Himalayan region, and such increases are not sustainable for the projects which are supplying power to rural and local communities in underdeveloped nations, such as the Himalayan regions of Nepal (Shrestha 2000; Sangroula 2009).

It is to be noted that due to the lithological formations and undulating topography, the sediment loading in Nepal Rivers is among the highest in the world (Egger *et al.* 2000; Shrestha 2000; Sangroula 2009), with the majority of sediments transported during the monsoon season. High sediment loading rates are mainly due to the young geologic age of the Himalayas, their active geology, and heavy seasonal rainfall (Chinnasamy *et al.* 2015; Chinnasamy 2017a,b; Chinnasamy and Shrestha 2019). In addition, climate driven natural disasters, especially landslides, debris flows, sheet flow, glacial lake and landslide dam outburst floods, are frequent in the Himalayan regions (ICIMOD 1996; Basnet *et al.* 2012; Devkota *et al.* 2013). These also trigger a lot of sediment erosion and increase sediment loading rates into the rivers. Anthropogenic activities also contribute to excessive sediment loads, in particular, unplanned developments, road construction and housing in critical zones and high risk areas. These also include, but not limited to, expansion of agriculture into unsuitable and highly sloping areas, degradation of forests through improper community management, conversion to anthropogenic uses, and the construction of rural roads without proper sediment management practices (Pantha *et al.* 2008; Dijkshoorn and Huting 2009; Ghimere 2011; Annandale *et al.* 2016).

Many hydropower facilities, both storage and RoR, in Nepal are facing economic and power losses due to high river sedimentation issues (Sangroula 2009; Chhetri *et al.* 2016). Nepal is characterized with the presence of Himalayan Rivers and undulating topography. The Kaligandaki project, a hydropower plant, operated by the Nepal Electricity Authority (NEA) is impacted by heavy sedimentation in the Kaligandaki River, an impact due to undulating topography and high discharge rates. The Kaligandaki project is the

largest power plant in Nepal with an installed capacity of 144 MW (figure 1). It is a RoR type facility, with a small storage reservoir and a large desilting basin designed to capture sediment before water enters the turbines. From 2002, the year of inception, the Kaligandaki project has experienced problems due to sedimentation issues, including turbine erosion due to the abrasion caused by inflowing sediment combined with cavitation, leading to frequent repairs (with an overhaul every 3 years) and unplanned shutdowns due to high damage on turbines. On the reservoir storage front, dead storage capacity in the reservoir (i.e., storage below the level of the lowest outlet, designed to trap excess sediment) fills up rapidly annually due to the small reservoir volume and large monsoon sediments. In terms of river morphology, the riverbed elevation of the reservoir has been rising steadily, which increases flood levels in the upstream areas of the reservoir, which is within 5.5 km above the dam. Due to these factors, over the past decade, the reservoir has gradually silted up, resulting in a 7% loss of active storage (World Bank 2017). In order to maintain the reservoir capacity, current operating rules, include taking advantage of high monsoon-season flows to flush the accumulated sediment, has resulted in successfully maintaining reservoir capacity. However, the operations and maintenance costs have increased beyond sustainable levels. Therefore, there is a need to identify drainage areas, upstream of the project and manage them for lower siltation rates. In addition, identification of upstream locations with heavy siltation and erosion rates can sensitize government agencies before new development projects are approved (e.g., construction of roads, industries).

Understanding the urge for upstream sediment management for the Kaligandaki hydropower plant, the World Bank has invested in a Rehabilitation project including up to a \$0.8 million grant for a sub-component – Catchment Area Treatment (CAT) Plan, which aims to manage sediment through investments in the upper catchment that covers an area of 7618 km<sup>2</sup> (World Bank 2017). However, less data and physical process understanding of sedimentation has limited the number of studies conducted in these regions. While the need for hydropower generation is ever increasing in Nepal regions, the need to understand impacts to hydropower turbines is also increasing to attract reduce risk to investments. This study will aim to

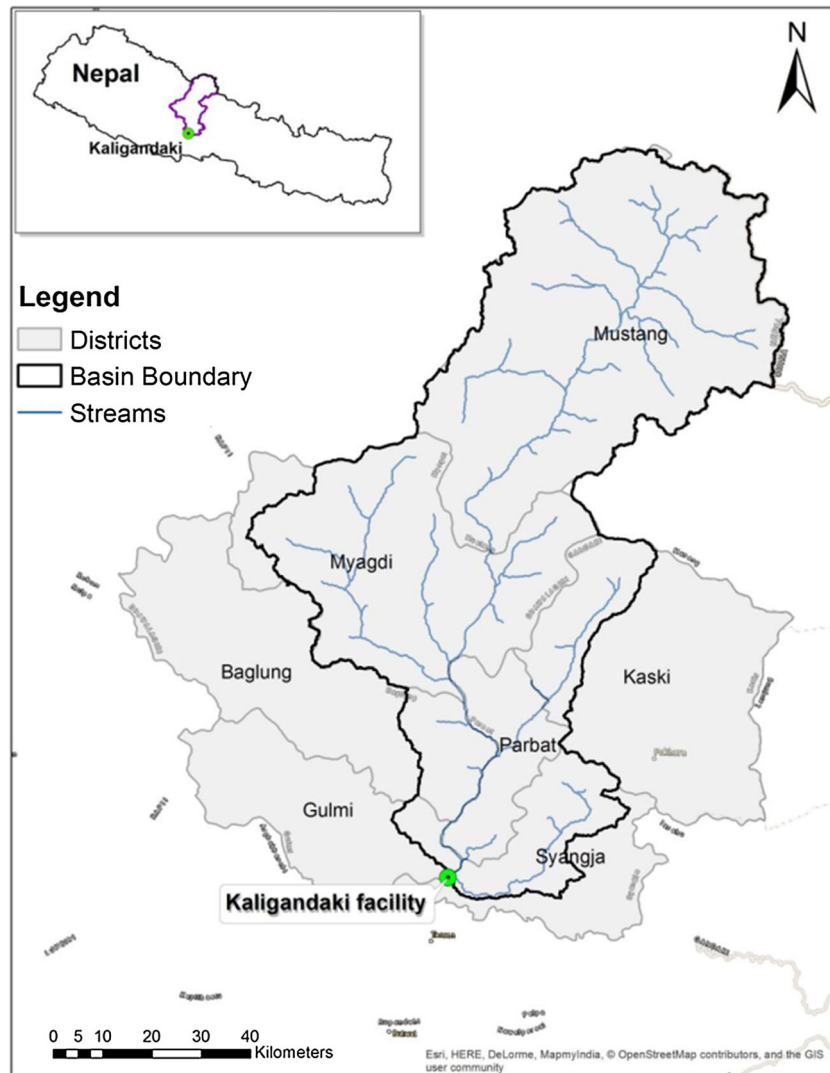


Figure 1. Kaligandaki Basin and location of hydropower facility.

use available multi-source data from various stakeholders to produce a baseline model that simulates the hydrologic regime and associated sedimentation in a Himalayan river. Such studies can aid in better investments for hydropower and assess watershed management activities to reduce losses and impact on hydropower generation in Nepal.

### 1.1 Study objectives

The primary objective of this study was to simulate the sediment loading across the Kaligandaki basin. Secondary objectives include estimating the spatial variations in sediment loading in the basin and documenting regions of high erosion within the basin.

## 2. Study area

The Kaligandaki River in Nepal originates in the high Himalayan regions of Mustang Himalaya, near Tibet, above 2500 m elevation. At about 2500 m, the river enters a gorge which extends to and beyond the Kaligandaki dam. The river flows through the Mustang district, and then southward from Ghasa to Tatopani, finally draining into the river Ganga as one of its major tributaries (Egger *et al.* 2000; Fort 2000). It is to be noted that the Kaligandaki River has one of the deepest valleys on Earth (Egger *et al.* 2000), with its depth almost at 5000 m near Ghasa. The northern parts of the basin and upper valley regions have strong diurnal upvalley winds, contributing to high wind erosion and dust (Egger *et al.* 2000). Lithologically, most of the regions in the Kaligandaki valley are

characterized by the meta-sediments of the Tibetan series (Colchen *et al.* 1986).

### 3. Methods

#### 3.1 Hydrological modelling

The approach used in this study is to characterize sources of sediment and high risk areas within the basin with a calibrated watershed hydrologic model. The Soil and Water Assessment Tool (SWAT) is a physically-based, hydrologic model developed by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions (Arnold and Fohrer 2000; Neitsch *et al.* 2002). The SWAT model, a semi-distributed hydrological model, has been widely used across the globe to assess hydrological regimes, agricultural water assessments, erosion, water budgeting, infiltration, groundwater recharge and to estimate the impact of climate change parameters on hydrology and cropping. Many studies have used SWAT model in Himalayan regions to successfully model river discharge. In a study by Jain *et al.* (2017), SWAT tool was used to model river discharge, evapotranspiration and water yield in a snow and rain-fed catchment in the Himalayas. The study results showed that the snow precipitation contributed up to 20% of the river discharge in the Ganges. Shrestha *et al.* (2017), in a study of five Himalayan basins, found that SWAT was successful in modelling the river discharge in most locations and recommended SWAT as a water resources planning and management tool for the Himalayan region. In an another study by Singh *et al.* (2019), downscaled climate change model data was used to drive SWAT model for understanding future scenarios of river discharge in Himalayan catchments. Their study results indicated that, due to climate change scenarios there is consistent increase in precipitation and water yield across Himalayan catchments.

Since the SWAT model had been successfully and widely used in the Himalayan region, the SWAT model was set up in this study, calibrated and validated for the Kaligandaki River basin. As the objective of the current study was to estimate the sediment loading into the hydropower project, the watershed boundary was delineated having the Kaligandaki dam as the endpoint of the river

(i.e., pour-point). The SWAT model was set up using many data sources as described in the following sections.

#### 3.2 Data collection and processing

It is to be noted that, some data for this study were procured from the Government of Nepal (e.g., Survey Department, Ministry of Land Reform and Management, Department of Hydrology and Meteorology, Nepal Electricity Authority, Department of Roads) and from private agencies who were active in managing the hydropower stations. In addition, through a stakeholder consultation meeting held in March 2016, recommendations and new data sources were identified and used in the study. Broadly, the input data can be grouped into five categories (as described below): topography or terrain, soils, land use, climate, and land management.

##### 3.2.1 Topography: Digital elevation model (DEM)

The Digital Elevation Model (DEM) of the region was retrieved from ASTER Global Digital Elevation Model (ASTER GDEM), which is approximately 30 m resolution (NASA 2001). The analysis of DEM (figure 2) shows maximum elevation of 8147 m and minimum elevation of 533 m. In order to understand the sensitivity of DEM on SWAT model outputs, some literature on this topic were reviewed. As per this exercise, it was noted that, Gautam *et al.* (2019) compared ASTER, SRTM and contour maps of Nepal and found that the source and resolution (i.e., 30, 90 and 250 m) did not have significant influence on the SWAT model results for Nepal, thereby refuting the hypothesis that the SWAT model is sensitive to DEM source and resolution. As per Thomas *et al.* (2014), the ASTER GDEM has good and acceptable accuracy for the vertical elevation, in particular, for the Indian and Nepal regions, with a root mean square error (RMSE) of 24 m, which is better than global multi-resolution terrain elevation data, with an RMSE of 48 m. Using this information, five classes of slopes were created in SWAT, with the classes selected based on criteria required for modelling different management practices (table 1). All slopes above 30% are considered high slopes in the SWAT model and are assumed to behave similarly in terms of their erosion and sediment generation.

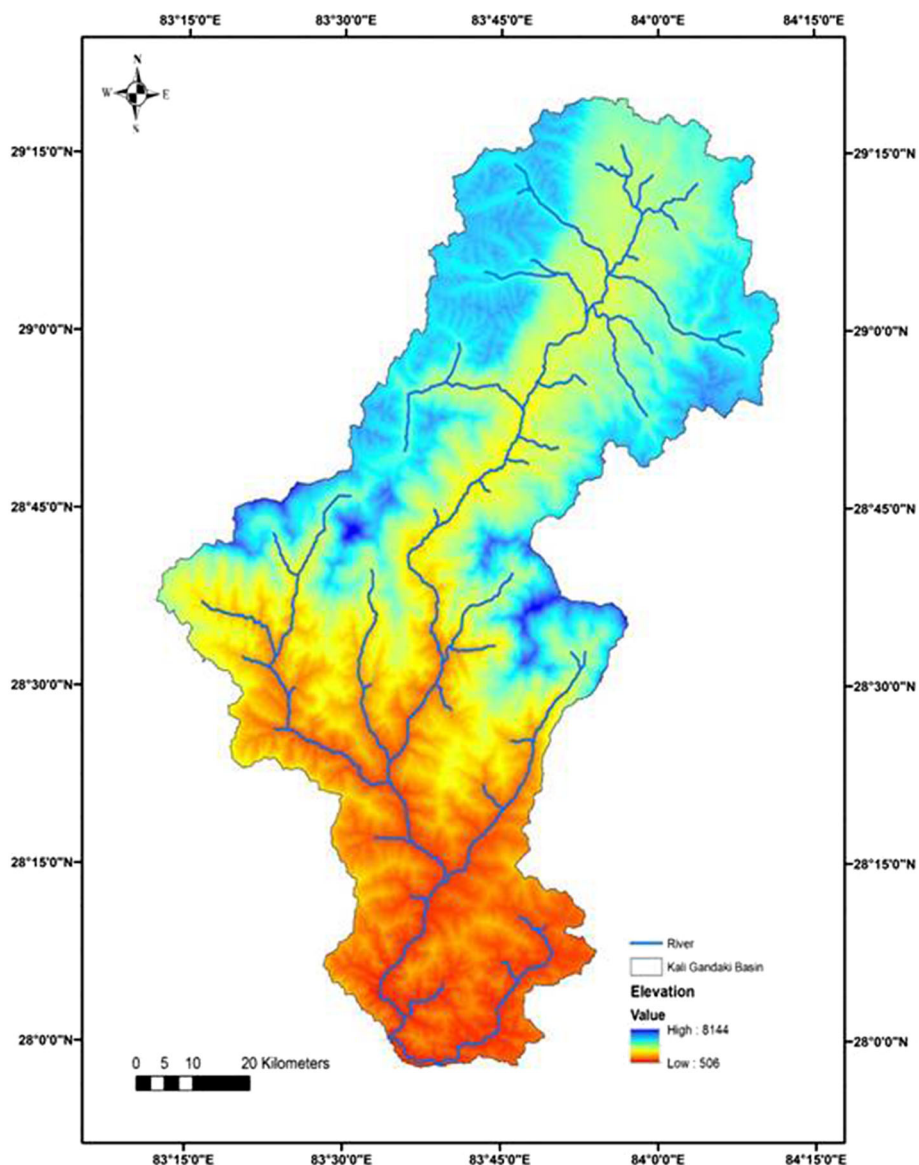


Figure 2. Digital elevation model for the Kaligandaki Basin.

Table 1. Slope classes designated in the SWAT model for the Kaligandaki Basin.

Slope category (% slope)	Area (acres)	Watershed area (%)
0–2	5198	0.28
2–5	26	0
5–12	9260	0.5
12–30	181669	9.75
30–9999	1666914	89.47

### 3.2.2 Soil types and soil properties

The soil hydrologic parameters for this study were obtained from Muthuwatta *et al.* (2015), wherein Muthuwatta *et al.* (2015) developed a SWAT model

for the Gangetic Plains and had already assessed soils and their hydrologic parameters through literature review and application of models. Since the Kaligandaki is also part of the Gangetic Plain, and there were many similar geologic settings in the basin, the current study assessed soils maps and compared against the model settings of Muthuwatta *et al.* (2015). Once an agreement on soils was achieved, the Kaligandaki SWAT model was applied using the same soil parameters from the calibrated and validated model from Muthuwatta *et al.* (2015). For example, the Eutric Regosols were found in both the Ganges SWAT model and the Kaligandaki model. Hence, the properties of the Eutric Regosols that were used in the Ganges SWAT model were incorporated into the

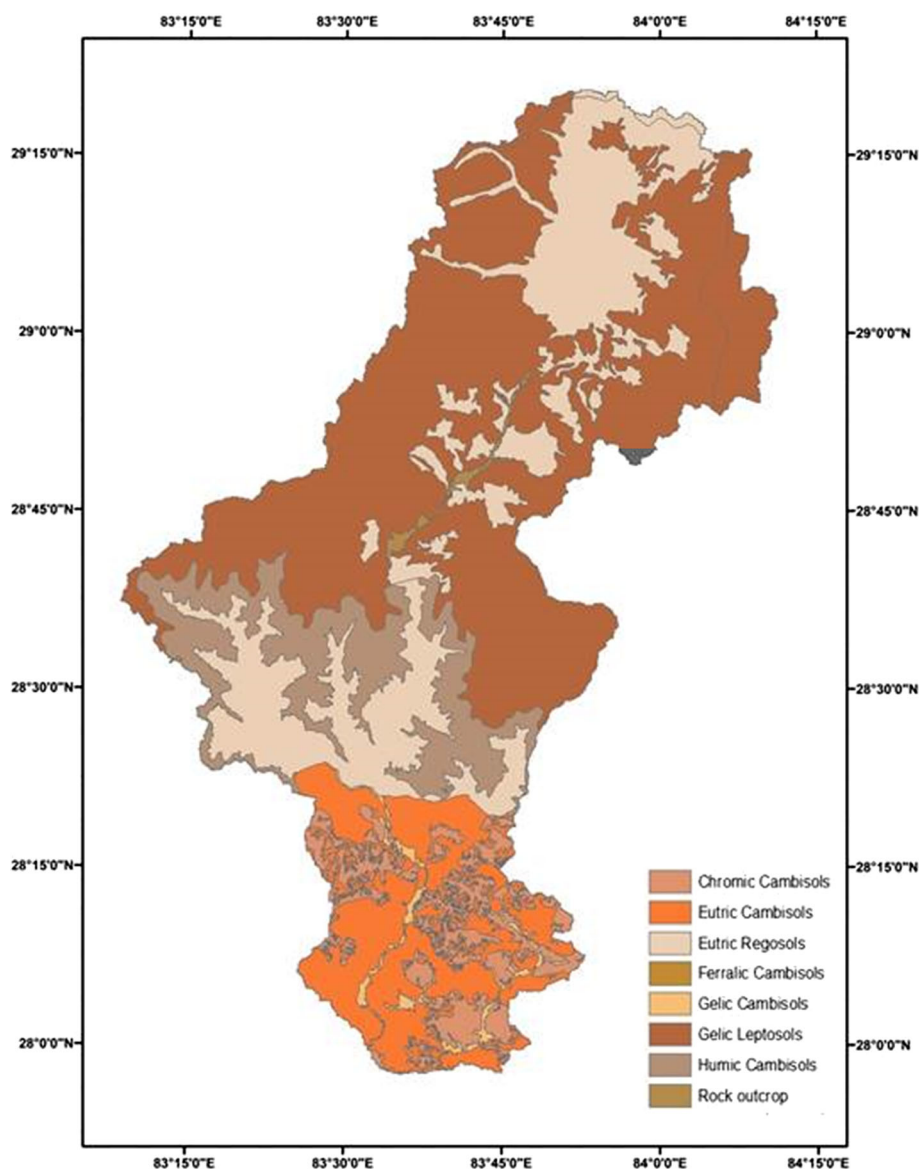


Figure 3. Dominant soil types in the Kaligandaki Basin.

Kaligandaki SWAT model (figure 3). Using detailed maps with different soil types, the study was able to build into SWAT the heterogeneity in the hydrological and erosion parameters of the soil in the study area. Dominant soil types used in the SWAT model are represented in table 2.

### 3.2.3 Land use and land cover (LULC)

A hybrid land use and land cover map was developed for this study, using past survey data, government records, previous hydrological models and literature. The year 2000 land use map from the survey department (Ministry of Nepal), had 16 dominant LULC types. This was combined with year 2014

Table 2. Dominant soil type and areas for the Kaligandaki Basin.

Soil type	Area (acres)	Watershed area (%)
Eutric Regosols	413291	22.18
Gelic Leptosols	883215	47.41
Rock outcrop	4247	0.23
Humic Cambisols	195097	10.47
Eutric Cambisols	256755	13.78
Gelic Cambisols	7821	0.42
Chromic Cambisols	102641	5.51

agricultural irrigated map produced by the International Water Management Institute–IWMI (Thenkabail *et al.* 2009), and with data on forest

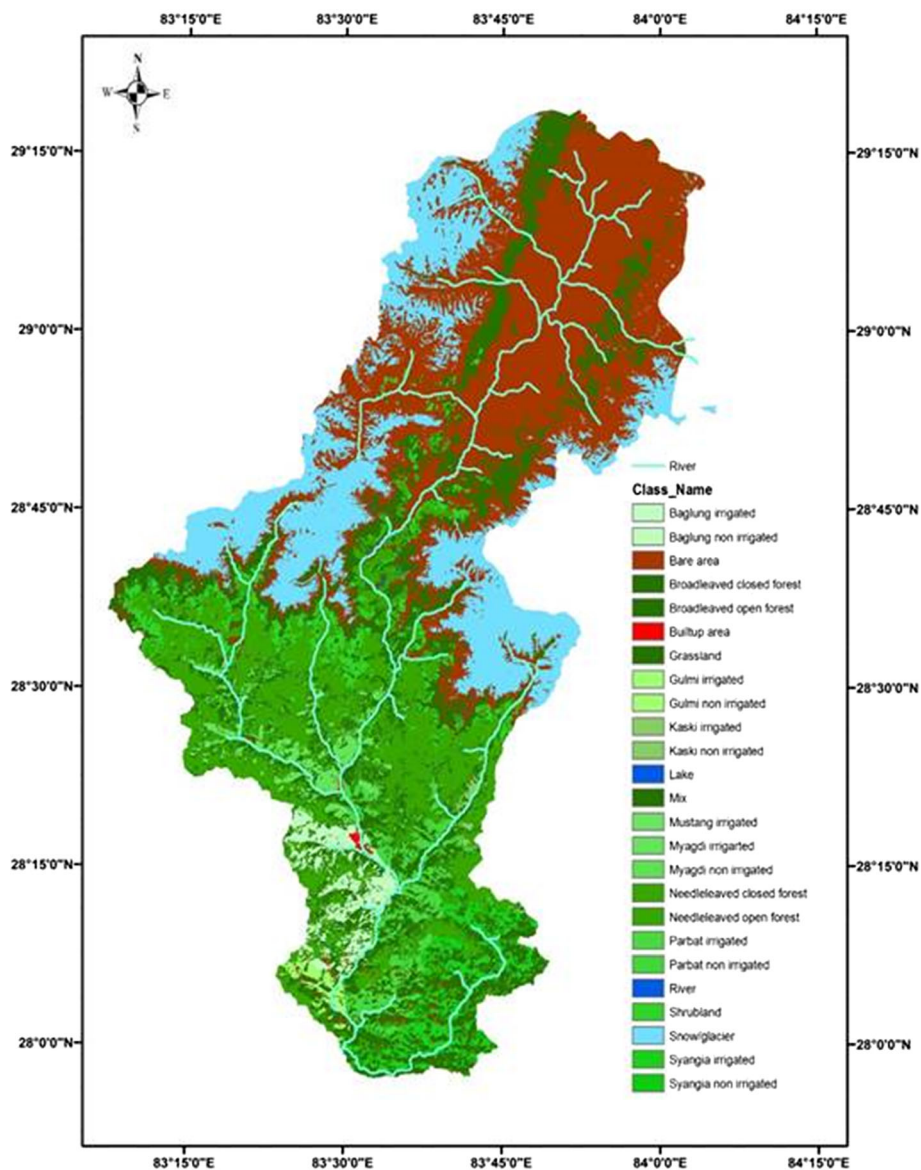


Figure 4. Dominant land use and land cover (LULC) for the Kaligandaki Basin.

cover loss retrieved from Global Forest Watch (Hansen *et al.* 2013). For example, agricultural lands in the 2000 year’s land use map were disaggregated into irrigated and non-irrigated land based on the IWMI data, and natural vegetation land cover classes (Bush, Forest-Mixed, Grassland, etc.) were disaggregated into degraded and non-degraded categories based on the Global Forest Watch data (<http://globalforestwatch.org/>). The Agricultural LULC type was further divided into irrigated and non-irrigated at district and Village Development Committee (VDC) level, enabling the application of crop-specific land management parameters by district and VDC (figure 4 and table 3).

Based on the generated land use map, approximately 38% of the land use is barren (which includes barren areas at low elevation as well as

those that fall above the tree-line but below the glaciers), about 24% of the study area is under mixed forest, about 19% area under grass, and about 10% of land under agriculture. From the land use map, government records and surveys, it was evident that agriculture is the major economic activity in the catchment. Major crop yield data and management parameters were set per district, as this was the highest level of spatial resolution data that could be obtained for cropping practices.

### 3.2.4 Climate, discharge and sediment

The Department of Hydrology and Meteorology (DHM), which is under the Government of Nepal,

Table 3. Major land use types and associated areas in the Kaligandaki Basin.

Land use type	SWAT code	Area (acres)	Watershed area (%)
Barren	BARR	715059.4	38.38
Agricultural land non-irrigated	MUAN	14386.26	0.77
Grassland non-degraded	GLND	347276.1	18.64
Barren sand	SAND	30625.72	1.64
Barren degraded	BARD	3.1135	0
Bush non-degraded	BUND	21552.85	1.16
Forest-mixed degraded	FODE	633.8243	0.03
Cropland	GLAD	51.1507	0
Bush degraded	BUDE	52.0403	0
Forest-mixed non-degraded	FOND	454558.6	24.4
Glacier	GLAC	20068.5	1.08
Myagdi agricultural land non-irrigated	MYAN	35526.41	1.91
Myagdi agricultural land irrigated	MYAI	22490.31	1.21
Mustang agricultural land irrigated	MUAI	25.5754	0
Kaski agricultural land non-irrigated	KAAN	5179.79	0.28
Baglung agricultural land non-irrigated	BAAN	13924.12	0.75
Kaski agricultural land irrigated	KAAI	4168.563	0.22
Parbat agricultural land irrigated	PAAI	35173.02	1.89
Agricultural land non-irrigated	PAAN	29419.23	1.58
Baglung agricultural land irrigated	BAAI	28226.53	1.52
Syangi agricultural land irrigated	SYAI	35778.83	1.92
Syangi agricultural land non-irrigated	SYAN	31839.33	1.71
Bush non-degraded VDC	BUNV	440.3411	0.02
Bush degraded VDC	BUDV	0.4448	0
Gulmi agricultural land irrigated	GUAI	6599.779	0.35
Gulmi agricultural land irrigated VDC	GAIV	66.7184	0
Gulmi agricultural land non-irrigated	GUAN	3278.54	0.18
Gulmi agricultural land non-irrigated VDC	GANV	103.4134	0.01
Forest-mixed VDC	FNDV	3231.392	0.17
Forest-mixed degraded VDC	FODV	15.79	0
Syangi agricultural land non-irrigated VDC	SANV	1078.391	0.06
Gulmi cropland non-degraded VDC	GNDV	706.5473	0.04
Cliff VDC	CLIV	27.1321	0
Syangi Agricultural land irrigated VDC	SAIV	1433.11	0.08
Sand VDC	SAVD	53.8195	0
Water bodies	WATV	1.5568	0

monitors climate parameters (temperature, precipitation, etc.) and stream flow across Nepal. Within the study catchment, DHM has 35 climate monitoring stations and 10 discharge monitoring stations (figure 5). Of these 10 stations, one was operated and maintained by NEA for the hydro-power project. In addition to the discharge data, sediment loading data were obtained from four sediment monitoring stations in the basin. A critical analysis of the data showed that some data from three of the stations had frequent data gaps, short length of record, and other irregularities. Therefore, these data with quality and quantity

issues were removed as they can impact the calibration of the SWAT model. Only one station had data of sufficient length and quality for calibration and validation, which was located at the watershed outlet and monitored by the Nepal Electricity Authority (NEA). A recommendation on issues related to sediment data were provided to DHM, so that they can improve data collection methods in the future. Since there were no solar radiation, humidity and wind speed monitoring stations, these data were downloaded from the global weather database, hosted within the SWAT website. The database had 20 solar radiation, 12



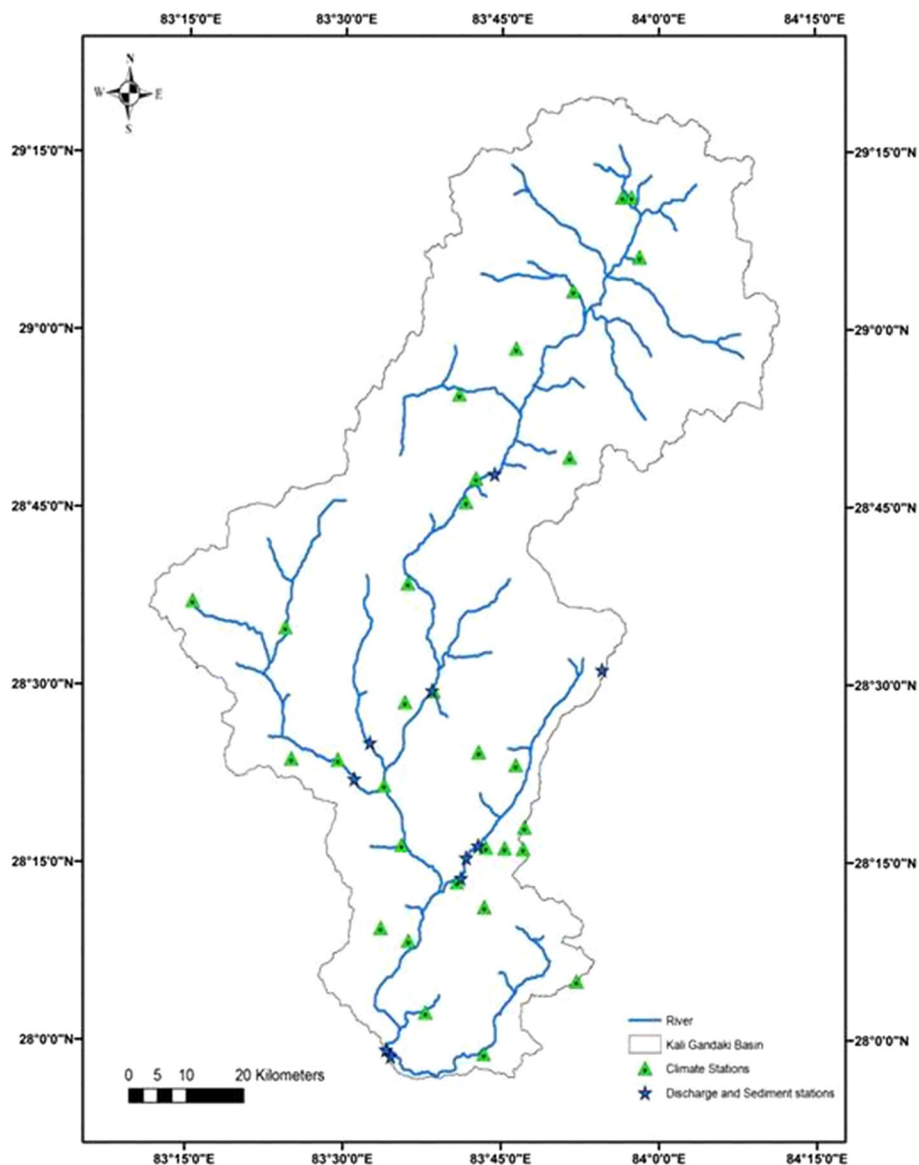


Figure 5. Location of climate, stream discharge and sediment monitoring stations in the Kaligandaki Basin.

humidity and 2 wind speed data points for the study area.

### 3.2.5 Land management

Considerable efforts were devoted to the collection and processing of the data, used to construct the SWAT management files, to accurately reflect the available district-level data on cropping practices. The study obtained crop management data from the Department of Irrigation (DoI), Government of Nepal (DoI 2009). The major crops in the basin include paddy, maize, wheat, millet, barley, vegetables, orchards, oil seeds, pulses and buckwheat. Land management parameters in SWAT were set for each district based on these data.

## 4. Modelling

### 4.1 *SWAT model watershed delineation and sub-basin discretization*

The number of sub-basins is determined by the area-threshold that is defined when setting up the SWAT model. The selection of area-threshold is subjective and is done to balance the needs of the analysis for detailed output with the resolution of data inputs, while reducing computational time. Smaller area-threshold implies more sub-basins and hence higher spatial resolution of outputs, but at the cost of higher computational time. For this study, an area-threshold of 5000 ha was used. As a result, the Kaligandaki basin was divided into 93 sub-basins (figure 6).

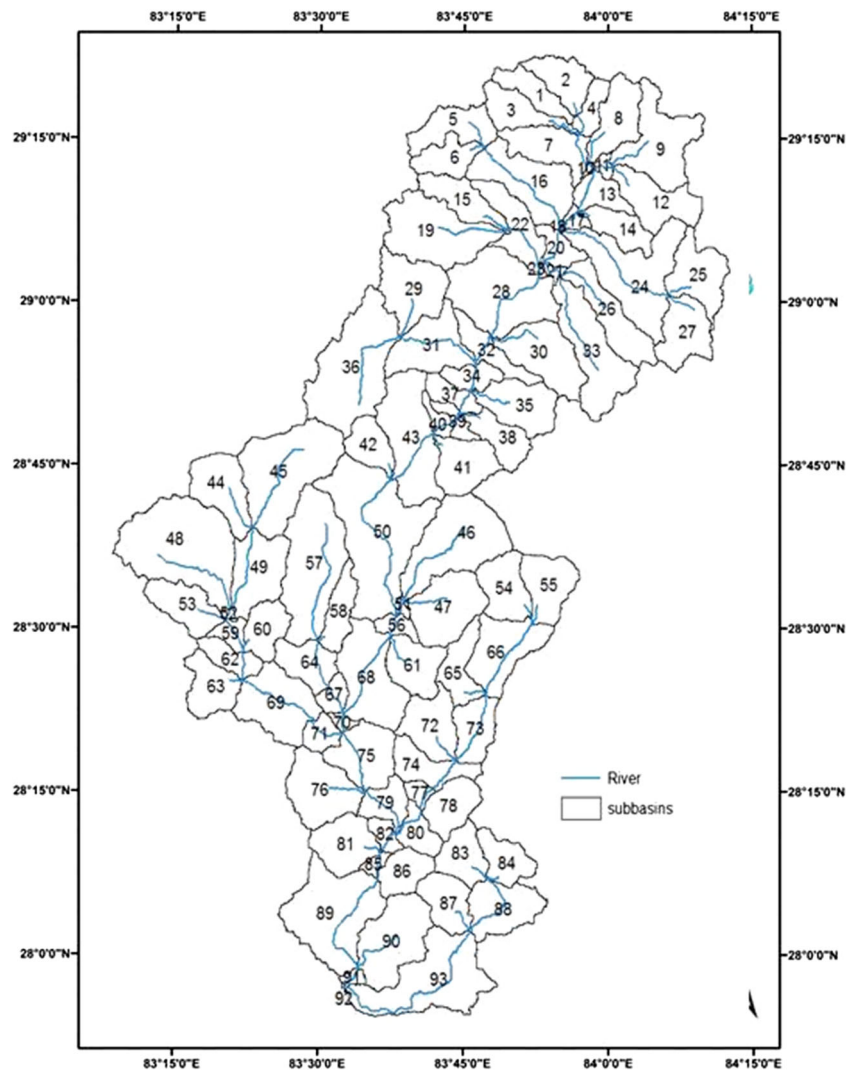


Figure 6. Sub-basins in the Kaligandaki Basin, with labels indicating sub-basin number.

Based on the unique combination of land use, soil and slope, and the selected sub-basin threshold, the 93 sub-basins were further divided into 1201 hydrological response units (HRUs). The average area of sub-basins delineated by SWAT was  $81.07 \text{ km}^2$ , with the maximum area of  $286.65 \text{ km}^2$  for sub-basin 50, while sub-basin 18 had the least area with  $0.01 \text{ km}^2$ . The standard deviation of the sub-basin areas was  $61.47 \text{ km}^2$ .

#### 4.2 SWAT model time setup

The SWAT model was set up from 1998 to 2009 with the years 1998 and 1999 serving as a warm-up period for the model. The warm-up period allows certain steady-state parameters (such as soil water storage and groundwater levels) to equilibrate prior to calculating hydrologic statistics. The warm-up time (or steady state time) is necessary for the model to fill hydrological components (e.g., surface storage

structures, wetlands, aquifers, soil moisture, ponds, etc.). In a review of warm-up times by the SWAT module developers, Douglas-Mankin *et al.* (2010) reported that the range of 1–3 yrs have been used for warm-up period simulations. Since there was enough observation data, the current study used 2 yrs (i.e., 1998 and 1999) for warm-up period. This was followed by a calibration period from 2000 to 2003 and a validation period from 2004 to 2005, since river flow and sediment data were available during that time period for comparison. Eventually, the model was run from 1998 to 2009, with first 2 years (1998 and 1999) as warm-up period and 2000–2009 (10 years) used for scenario analysis. It was noted that the model was set up to run at daily time intervals.

#### 4.3 SWAT calibration and validation

The SWAT Calibration and Uncertainty Program (SWAT-CUP), a widely used program for SWAT

Table 4. *Key parameters used for SWAT calibration for the Kaligandaki Basin.*

Sl. no.	Par name	Details
1	SFTMP	Snowfall temperature
2	SMTMP	Snow melt base temperature
3	SMFMX	Maximum melt rate for snow during the year
4	SMFMN	Minimum melt rate for snow during the year
5	TIMP	Snow pack temperature lag factor
6	SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover
7	SNO50COV	Snow water equivalent that corresponds to 50% snow cover
8	ALPHA_BF	Baseflow alpha factor
9	CN2	SCS runoff curve number
10	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur
11	HRU_SLP	Average slope steepness
12	OV_N	Manning's 'n' value for overland flow
13	SLSUBBSN	Average slope length
14	SOL_AWC	Available water capacity of the soil layer
15	SOL_K	Saturated hydraulic conductivity
16	ESCO	Soil evaporation compensation factor
17	GW_REVAP	Groundwater 'revap' coefficient
18	REVAPMIN	Threshold depth of water in the shallow aquifer for 'revap' to occur
19	GW_DELAY	Groundwater delay (days)

Table 5. *Key parameters used for calibration of sediment outputs in SWAT for the Kaligandaki Basin.*

Sl. no.	Par name	Details
1	USLE_K	USLE equation soil erodibility (K) factor
2	USLE_P	USLE equation support parameter
3	USLE_C	Min value of USLE C factor applicable to the land cover/plant
4	ADJ_PKR	Peak rate adjustment factor for sediment routing in the sub-basin
5	SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing
6	SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing
7	RSDCO	Residue decomposition coefficient
8	BIOMIX	Biological mixing efficiency

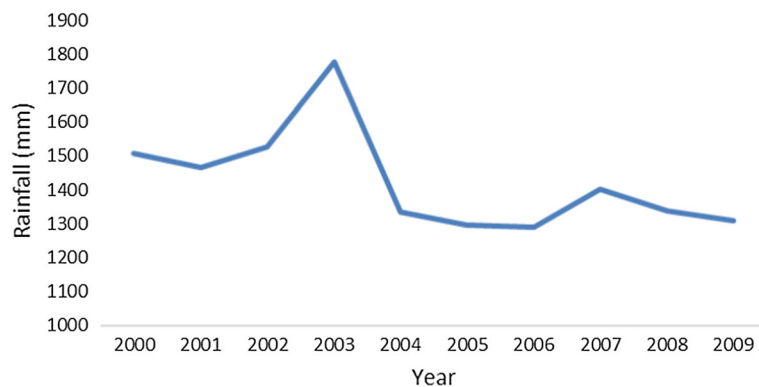


Figure 7. Average rainfall over the 10-yr study period for the Kaligandaki Basin.

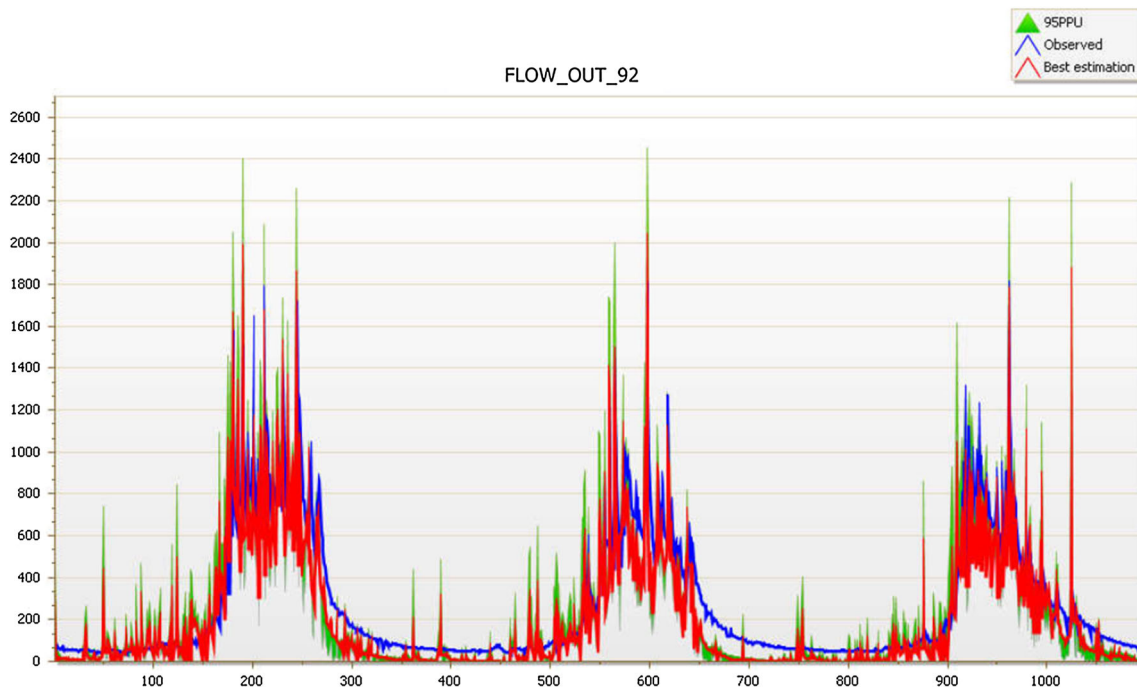


Figure 8. SWAT model calibration output, for the Kaligandaki Basin, showing 95% confidence limit at sub-basin 92.

Table 6. Summary of calibration results for the SWAT model under hydrology and sediment calibration.

Hydrology calibration			
P-factor ( $\times 100$ )	R-Factor	NSE	$R^2$
0.26	0.30	0.80	0.82
Sediment calibration			
0.38	1.48	0.60	0.63

model calibration (Abbaspour 2009), was used to calibrate the model parameters. SWAT-CUP is a public-domain program that is widely used in research for calibration, sensitivity and uncertainty analysis of SWAT models. A sequential uncertainty fitting (SUFI2) was used to quantify the uncertainty in the model. The uncertainty in the model is measured in SWAT-CUP by two parameters: (1) the P-factor, which indicates the percentage of observed data that falls within 95% of prediction uncertainty (95PPU). To calculate 95PPU, multiple runs of the model are made by selecting the parameter values from a pre-defined parameter range. The top 2.5% and bottom 2.5% output from the simulation are ignored, to form a band of 95% prediction uncertainty. (2) the R-factor, which is the average thickness of the 95PPU band divided by the standard deviation of the observed data (Abbaspour 2009). P-factor ranges from 0 to 100% and R-factor from 0 to 1.

A P-factor of 100% and an R-factor of 0 indicates perfect fit.

Two model performance indicators were used to quantify performance of the model: Coefficient of determination ( $R^2$ ), which quantifies degree of collinearity between observed and simulated data and the Nash–Sutcliffe Efficiency (NSE) factor, which quantifies relative magnitude of the residual variance as compared to the observed data variance. The value of NSE can range from  $-\infty$  to 1.0. Negative NSE values imply unacceptable performance, while NSE of 1 indicates a perfect fit between observed and simulated values. The NSE equation (Nash and Sutcliffe 1970) is given below (equation 1):

$$NS = \frac{v_0 N - \sum_{i=1}^N (x_i - y_i)^2}{v_0 N} = 1 - \frac{\sum_{i=1}^N (x_i - y_i)^2}{\sum_{i=1}^N (x_i - \bar{x})^2} \quad (1)$$

where the variance of the observed values is represented as  $v_0$ ,  $N$  is the total number of data points to be analyzed,  $x_i$  is the observed value,  $y_i$  is the corresponding simulated value, while  $\bar{x}$  is the average observed value for the study period. For details on NSE, refer Nash and Sutcliffe (1970). Nineteen key parameters (table 4) that affect runoff, groundwater recharge, and evapotranspiration were selected and variations in land use/land cover and slope were used for calibration (table 5).

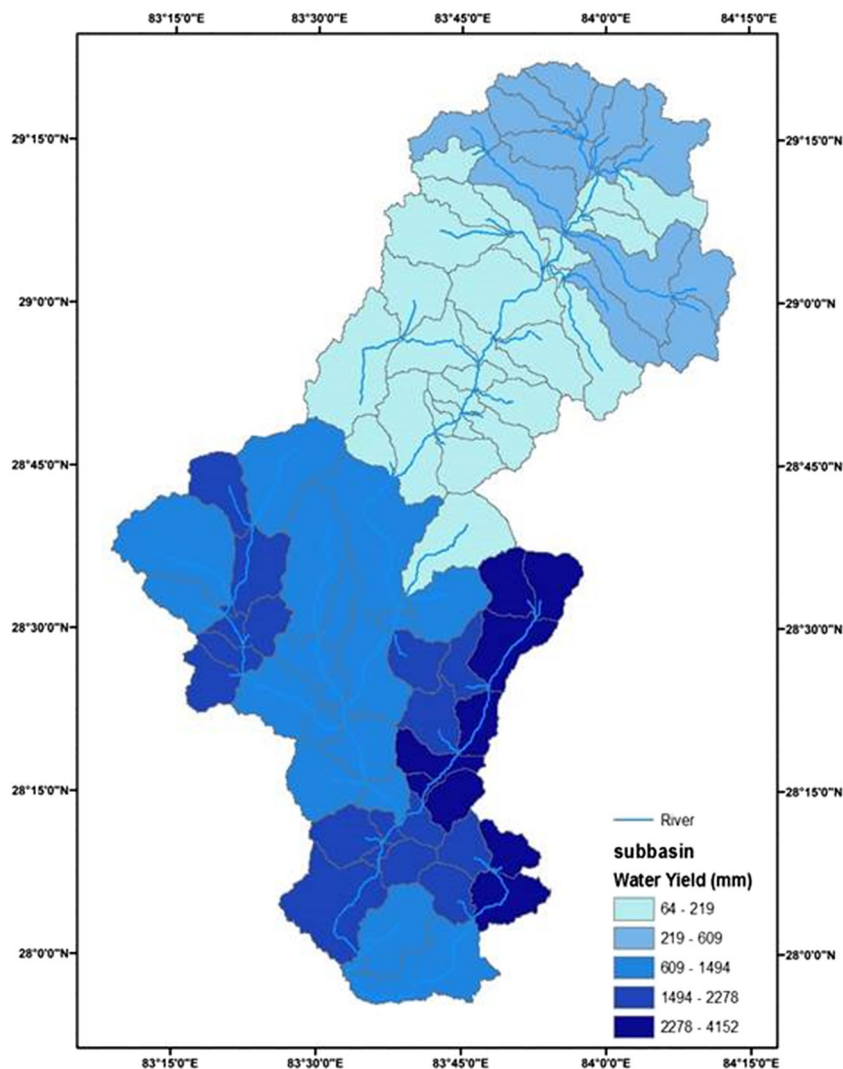


Figure 9. Average annual water yield for the Kaligandaki Basin for the period 2000–2009.

## 5. Results and discussion

### 5.1 Rainfall

The average rainfall was 1478 mm per year for the 10-yr run, with a maximum of 4927 mm recorded for sub-basin 78 and a minimum of 196 mm recorded in sub-basin 18. The standard deviation was at 1129 mm. Over the study period of 10 yrs, the average rainfall in the basin ranged from 1289 to 1778 mm. Except for year 2003, which was a wet year, the average rainfall during the study period showed a decreasing trend (figure 7).

### 5.2 SWAT model results

The calibration and the validation results for both the water yield and sediment outputs are shown

in table 6. According to Moriasi *et al.* (2007),  $R^2$  over 0.5 is acceptable, while the value of NSE over 0.75 is considered ‘very good’; between 0.65 and 0.75 as ‘good’; and between 0.5 and 0.65, as ‘satisfactory’ performance rating. For the current model, 0.8 and 0.6 NSE values indicate ‘very good’ and ‘satisfactory’ calibration for hydrology and sediment, respectively. The calibrated Kaligandaki SWAT model produced a higher  $R^2$  value for hydrology (0.82) as compared to sediment (0.63), which indicate better calibration of the model for hydrology than sediments. The low P- and low R-factor in hydrology calibration indicate moderate uncertainty, whereas a low P-factor and high R-factor in sediment calibration indicates much higher uncertainty. Calibration result for watershed 92, as an example, is shown in figure 8.

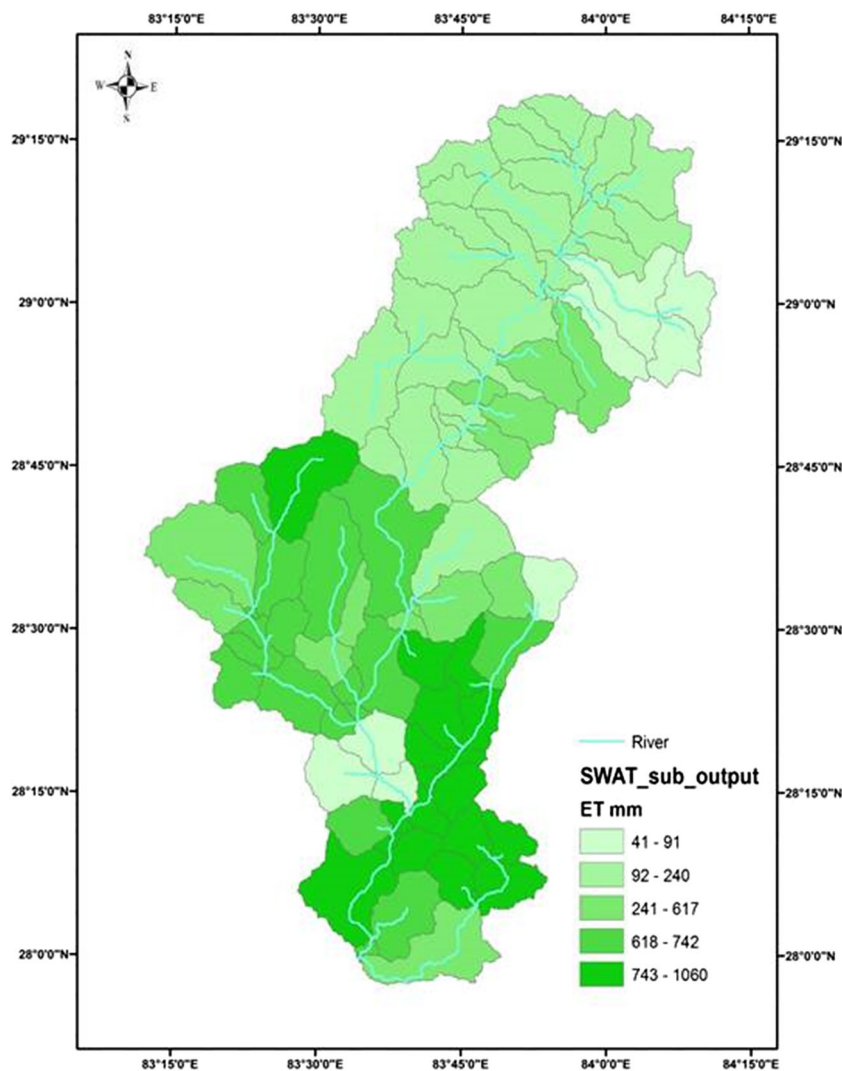


Figure 10. Average annual ET for the Kaligandaki Basin for the period 2000–2009.

Using the calibrated and validated SWAT model, the model was reset to run from 1998 to 2010, with 2 yrs of warm-up time. The model was set to run daily (from 2000 to 2009) and the 10-yr average results are summarised and discussed in the following sections.

### 5.3 Water yield

The SWAT model results indicated that water yield (i.e., the flow in the river generated by each sub-basin) followed the rainfall patterns across the watershed. The average water yield was 1023 mm per year for the 10-yr run, with a maximum of 4152 mm recorded for sub-basin 78 and a minimum of 64 mm recorded in sub-basin 22. The standard deviation for the water yield was at 940 mm. Similar to the rainfall, the water yield also shows a decreasing trend over the 10 years period. The distribution of water yield is shown in figure 9.

### 5.4 Evapotranspiration

The Evapotranspiration (ET) results indicated that the ET followed the land use and land cover patterns across the watershed. The average ET was 457 mm per year for the 10-yr run, with a maximum of 885 mm recorded for sub-basin 78 and a minimum of 135 mm recorded in sub-basin 19. The standard deviation for the ET was at 230 mm. The distribution of ET is shown in figure 10.

### 5.5 Sediment yield

The sediment yield results indicated that high regions of erosion occurred in the barren land and lands with high elevation and slope difference. The average sediment yield was 17.3 tons/ha/yr for the 10-yr run, with a maximum of 137 tons/ha/yr

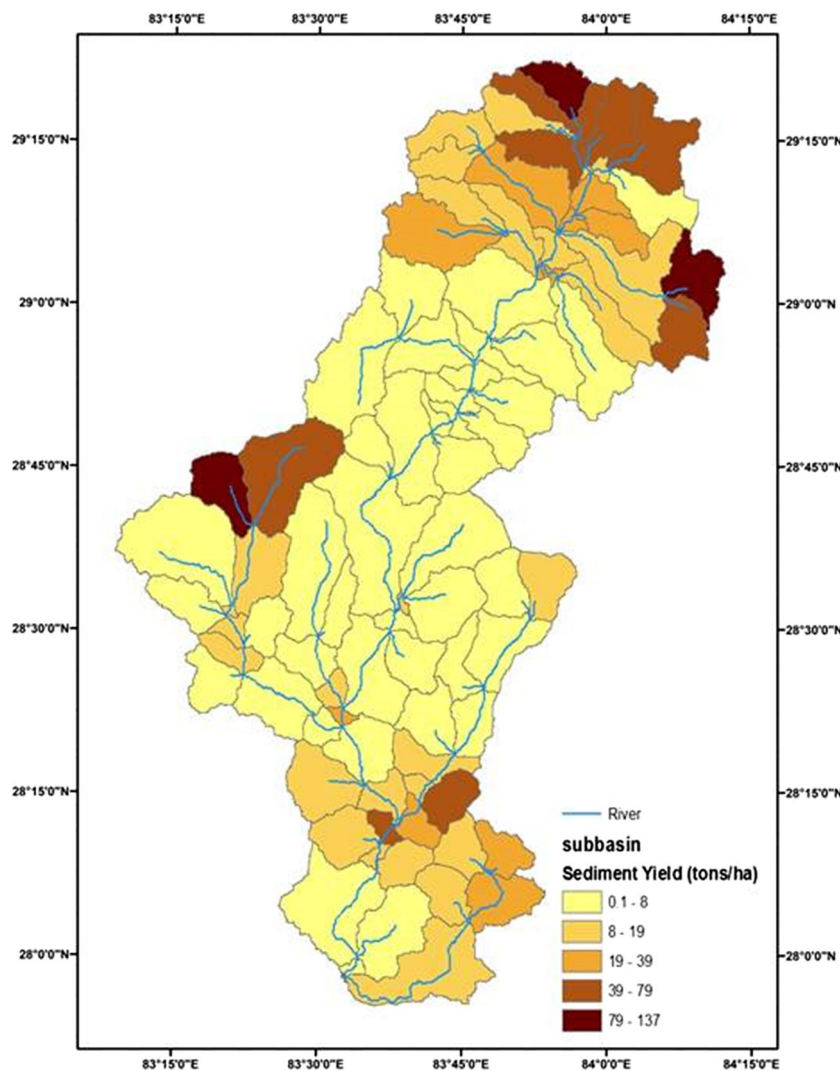


Figure 11. Average annual sediment yield for the Kaligandaki Basin for the period 2000–2009.

recorded for sub-basin 44 and a minimum of 0.1 tons/ha/yr recorded in sub-basin 41. The sediment load modelled at the basin outlet averaged 13.0 Mt/yr, 16% lower than the 15.4 Mt/yr estimated by Morris (2014), but is consistent with the high sediment loads reported for other Himalayan areas (Lupker *et al.* 2012; Struck *et al.* 2015). Not much inter-annual variation is seen in terms of sediment rates. For the 10-yr period, the average annual sediment rates vary from 16.8 to 17.9 tons/ha. The standard deviation for the sediment yield was at 25 tons/ha. The distribution of sediment yield in terms of volume per unit area (tons/ha) is shown in figure 11. The Kaligandaki Basin, based on elevation difference can be divided into the High Himalayan regions (upstream), middle and high mountain regions. SWAT predicts that 73% of the total sediment load is estimated to come from the upstream regions (also known as High Himalayan

region), while only 27% is contributed from the Middle and High Mountain regions (where land management-based interventions were deemed most feasible for future scenarios).

### 5.6 Sediment concentration

The sediment concentration results indicated that high sediment loading increases along the river channel network downstream of high sediment yield sub-basins. Sediment concentration is a function of both sediment load from upstream areas and the flow rate. Therefore, it varies throughout the year, with the highest concentrations during the monsoon season and the lowest during the dry season.

The average modelled sediment concentration was 1986 mg/kg (ppm) for the 10-yr run, with a maximum of 8432 mg/kg (ppm) recorded for sub-basin 2 and a minimum of 12 mg/kg (ppm) recorded in sub-basin 47.

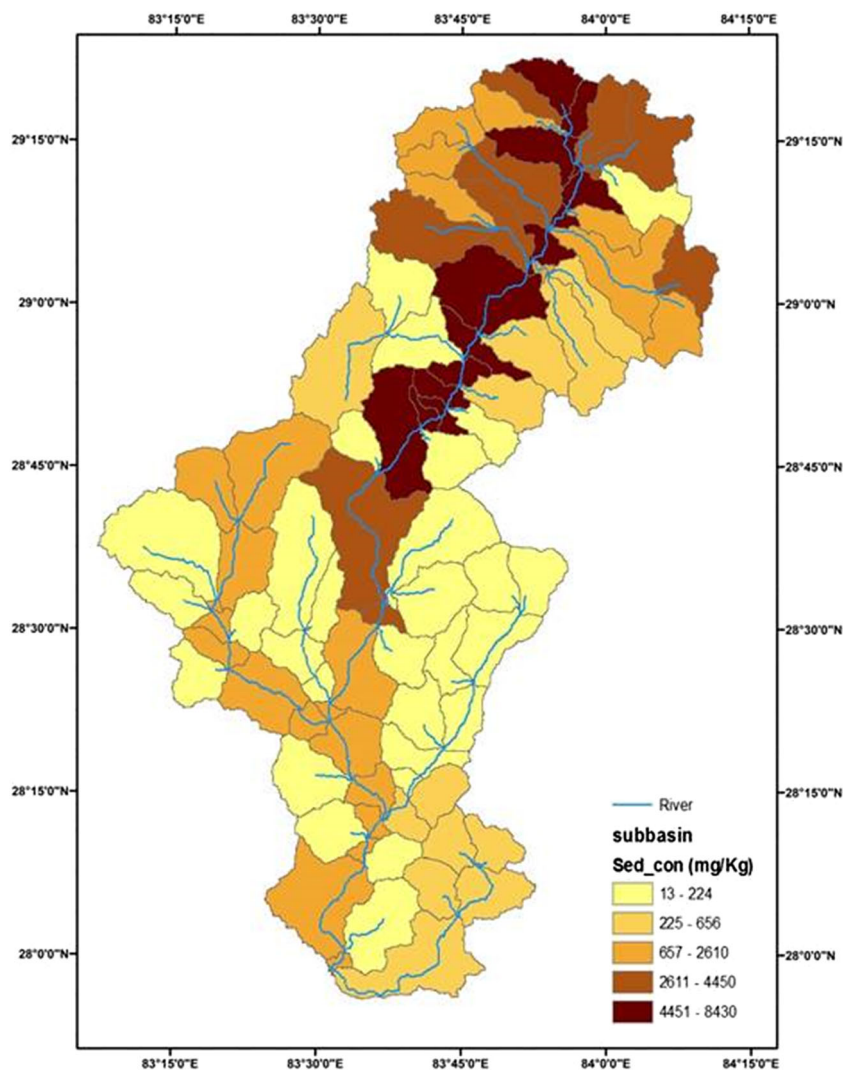


Figure 12. Ten-year average annual sediment concentration for the Kaligandaki Basin.

The standard deviation for the sediment concentration was at 2169 mg/kg (ppm). The distribution of sediment concentration is shown in figure 12. It is also noted that the sediment concentration seems to have deposited in the central parts of the watershed (dark brown areas along the upper part of the river in figure 12), evidenced by a sudden drop in sediment concentration as one moves downstream through the middle portion of the watershed (change from darkest brown to light brown in the center of figure 12). However, because sediment observation data of sufficient quality were not available for the upstream reaches of the watershed, the modelled sediment dynamics within the channels have not been fully calibrated and should therefore be interpreted with caution. This is an area that may be improved in future investigations, through on-going monitoring of sediment in different locations throughout the basin, and

targeted studies of sediment fate and transport within the channels.

## 6. Conclusion and recommendations

Sediment management will continue to be an issue for newly proposed and on-going hydropower projects, as well as other infrastructure, in the Himalayan regions due to its geologic and climatic setting. In particular, the currently commissioned Kaligandaki project faces much losses due to sedimentation. Under these circumstances, watershed management can provide a useful mechanism to control excess erosion and sedimentation from anthropogenic activities, which can increase operation and maintenance costs and reduce the useful life of the facility. For proper watershed management, associated data and understanding of



physical processes and drivers for sedimentation is important. In Himalayan regions, with limited data sources, hydrologic models can aid in understanding the hydrologic regime and resulting sedimentation in the rivers. This study demonstrates the important role that hydrologic modelling (in particular SWAT modelling) can aid in identifying and prioritizing high risk areas for watershed management activities focusing on sedimentation control. The SWAT hydrologic model allowed for a characterization of the areas of high sediment load across the basin, and also highlighted the need for better sediment monitoring to refine this understanding. In addition, the detailed hydrologic modelling provided insights into acquiring better data for Himalayan regions, which will subsequently improve the modelling efficiency. It is to be noted that the current study used the available limited sediment concentration data to calibrate and validate the SWAT hydrological model, and hence the quality of the results is dependent on the quantity and quality of observation data. Due to the harsh geologic and climatic conditions, maintaining sediment concentration gauges could be difficult, however, there is a need for good quality and quantity of sedimentation data to assist the development of complex and holistic hydrological models. Better data driven hydrologic models can aid in development of scientifically validated watershed management plans that can be used to assess current management strategies, and for future scenarios that involve addressing climate change impacts.

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