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Simulation of Sediment Yield Using SWAT Model: A case of Kulekhani Watershed

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Hydropower Development
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Supervisor: Knut Alfredsen, IVM
Co-supervisor: Kiflom Belete, IVM

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Master's Thesis in Hydropower Development

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M.Sc. THESIS IN
HYDROPOWER DEVELOPMENT

Candidate: Lemma Tufa Bokan

Title: Simulation of Sediment Yield Using the SWAT Model. A case of Kulekhani Watershed, Nepal.

1 BACKGROUND

Sediments are a very important component in hydropower development in many countries. High sediment rates leads to filling of reservoirs and loss of live storage, which eventually leads to loss of production potential. Furthermore, evacuation of sediments from reservoirs is a costly process that can have large environmental impacts. Simulation of sediment yield can be a tool to estimate sediment influx to reservoirs, and to assess how much sediment is generated from various land types. This can be important in assessing the sustainability of reservoirs and to evaluate mitigation measures in catchments and in the evaluation of effects of compensatory land use in the case of new development. Such tools can also be important in studies of land use changes and to estimate the effect of rainfall intensity on sediment yield in studies of current and future sediment issues which are important in studies of global change. This thesis aims at evaluating the SWAT model for sediment yield simulation in Kulekhani watershed located in southwest of the capital Kathmandu.

2 MAIN QUESTIONS FOR THE THESIS

The thesis will be composed of a number of tasks related to assessing relevant literature and preparing and running the SWAT model. The Kulekhani watershed in Nepal will work as the study site for the initial setup and evaluation of the model. The tasks are detailed as follows:

1. Review current literature on sediment yield simulations in general and the SWAT model in particular. An important aspect of the review will be to find examples of using the SWAT model for yield computations and the yield values for various land use types.

The literature review will be basis for the initial states used in the simulation.

2. Data preparation for the Kulekhani watershed in Nepal. This involves GIS preparation of catchment and land use data into a format suitable for SWAT, preparation of runoff and climate data for model calibration and preparation of sediment data for model evaluation. All data should be delivered on digital form with the thesis, and any developed scripts or GIS procedures should be documented.
3. Calibrate and run the SWAT model for the Kulekhani watershed in Nepal. Compare sediment results and adapt the yield model to observed sediments.
4. Perform a thorough sensitivity and uncertainty analysis of the model parameters to assess the quality of simulation and importance of parameters.
5. Perform scenario simulations to assess impacts of land use changes and historical land use development on the sediment yield. Studies of impacts of altered precipitation events on the sediment yield should also be carried out.

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Knut Alfredsen will be the supervisor of the thesis work. Research scientist Kiflom Belete will provide advice on sediment issues.

Discussion with and input from colleagues and other research or engineering staff at NTNU, SINTEF, power companies or consultants are recommended. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

4 REPORT FORMAT AND REFERENCE STATEMENT

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified.

The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group.

The summary shall not contain more than 450 words it shall be prepared for electronic reporting to SIU. The entire thesis may be published on the Internet as full text publishing through SIU. Reference is made to the full-text-publishing seminar during NORADS winter-seminar. The candidate shall provide a copy of the thesis (as complete as possible) on a CD in addition to the A4 paper report for printing.

The thesis shall be submitted no later than 10th of June 2015.

Trondheim 13th of January 2015

Knut Alfredsen

Professor

Declaration

This report, entitled “Simulation of Sediment Yield Using SWAT Model: A Case of Kulekhani Watershed, Nepal”, is submitted to the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology as a partial fulfillment of the requirements of the Master of Science in Hydropower Development.

The study of this thesis was carried out from January 2015 to June 2015 at Norwegian University of Science and Technology under the supervision of Prof. Knut Alfredsen as a main supervisor and Dr. Kiflom Belete as a co-supervisor.

I, Lemma Tufa, hereby declare that the work presented in this thesis is my own work and significant outside input is acknowledged properly.

Where I have consulted the published work of others, this is always clearly attributed;
Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
I have acknowledged all main sources of help;

Lemma Tufa Bokan

June 2015

Trondheim, Norway

Acknowledgments

First, I would like to thank my GOD for giving me the strength to finish this study.

I would like to express my sincere gratitude to my supervisor, Professor Knut Alfredsen, Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, for his continuous guidance from the start and end of this thesis. His willingness to give his time so generously has been very much appreciated.

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My sincere thanks also goes to Mr. Michael Yu, GIS programmer and developer, Hydrologist, Water resource Engineer, ArcGIS, .NET, C++, Flex, Fortran and SWAT expert for his valuable support in solving several problems related to the model and regular and timely response to all my emails.

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Abstract

Soil erosion is the major cause of land degradation and reservoir sedimentation. Therefore, modelling of runoff and sediment yield at a watershed level is very important. A conceptual, distributed and continuous time, SWAT2012 (Soil and Water Assessment Tool) model was selected for the simulation of the runoff and sediment yield from Kulekhani watershed, in Bagmati river basin, Nepal. The main objective of the study was to examine the applicability of the SWAT model in Kulekhani watershed.

To set up the model for simulation a 30 m DEM (Digital Elevation Model), 1 km spatial resolution of land use map and 10 km spatial resolution of soil map was used. The daily precipitation and daily minimum and maximum air temperature from 1972 to 2013 was used as input to the model. The stream flow data was available from 2007 to 2009 and for four months from 2004. The daily sediment record for four months from 2004 was available. The model was calibrated by using both automated calibration and manual calibration for daily stream flow by using the flow data from 2007 to 2008 and validated for 2009 and 2004. The calibration for sediment was conducted for the whole period for which the sediment data was available. The model was not validated for sediment yield as there was not enough length of data to do so.

The performance of the model was evaluated by using a time series plots of observed and simulated value and the statistical measures of coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS). The statistical analysis of calibration results for Kulekhani watershed showed satisfactory agreement between observed and simulated daily values, with an R^2 value of 0.6, and NS of 0.44 in discharge simulation; and an R^2 value of 0.54, and NS of 0.53 at Palung Khola and an R^2 value of 0.4, and NS of 0.07 at Chitlang Khola for sediment simulation. The R^2 and NS value for flow validation period in 2009 was 0.59 and -0.59 respectively. The model was also validated for flow at Palung Khola for 2004 with R^2 and NS value of 0.66 and 0.29 respectively; and at Chitlang Khola for 2004 with R^2 and NS value of 0.81 and 0.74 respectively. In general, the model was capable of simulating runoff and sediment from Kulekhani watershed. But, the result from sediment simulation was not as good as the runoff. This is believed to be because of the inability of the SWAT model to realistically simulate the sediment from gully erosion, landslide and mass wasting. The result could have been improved by using distributed rainfall data, longer period of runoff and sediment record and better quality land use and soil data.

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1 Introduction

1.1 General

Water is the greatest gift of mankind. Water resources are very vital renewable resources that are the basis for the survival and development of any society. Human health and welfare, food security and industrial developments are dependent on adequate supplies of suitable quality of water. Conversely, too much water results in socioeconomic damages and loss of life due to flooding. The liveliness of natural ecological systems is dependent on mankind's stewardship of water resources. Proper utilization of these resources necessitates assessment and management of the quality and quantity of water resources both spatially and temporally (Dilnesaw, 2006).

Establishing a relationship among various environmental parameters is the central focus of hydrological modelling from its simple form of unit hydrograph to rather complex models based on fully dynamic flow equations. Models are generally used as efficacy in various areas of water resource development, in assessing the available resources, in studying the impact of human interference in an area such as land use change, climate change, deforestation and change of watershed management (Getachew and Melesse, 2012).

Soil erosion is the detachment and transportation of soil particles from their original place to further downstream by erosion agents such as water and wind. It is one of the normal aspects of landscape development. The severity of erosion increases with the decrease in cover material most likely vegetation. The vegetation cover decreases the soil erosion by decreasing the impact of raindrops that cause the detachment of the soil particles. Therefore, bare soil is more likely to be eroded by different soil erosion agents than soil with vegetation cover.

Soil erosion is a serious problem affecting the quality of soil, land, water resources upon which man depends for his sustenance. Today, soil erosion is universally recognized as a major environmental and agricultural problem. Because, as the top soil is eroded by erosion agents such as water, wind, avalanches, etc. its fertility and nutrient content decreases. This eventually results in the loss of productivity. Loss of the organic matter rich surface soil (topsoil) is known to decrease soil quality, which in turn reduces productivity (Verity and Anderson, 1990). Another major problem caused by erosion is sedimentation of reservoirs and irrigation canals. Reservoirs are the main destination of the sediment eroded from upland area.

Since the velocity of water in the reservoir is very low, sediments get deposited in the reservoir unless there exists a facility to avoid the settlement. The sedimentation of reservoirs causes another serious problem by decreasing the capacity of reservoirs. The loss in capacity of reservoirs increases the probability of floods. As more and more sediments get deposited in the reservoirs, its capacity decreases and ultimately will not be able to handle high flood. Sedimentation in irrigation canals will hamper and endanger proper irrigation management. To tackle all the aforementioned problems caused by erosion and sedimentation, identifying erosion prone areas and proper application of management options on those areas is crucial.

1.2 Statement of the problem

Soil erosion is a crucial problem in Nepal where more than 80% of the land area is mountainous and still tectonically active. Although deforestation, overgrazing and intensive agriculture, due to population pressure, have caused accelerated erosion, natural phenomena inducing erosion, such as exceptional rains, earth quakes and glacial-lake-outburst flooding in the Himalayas are also common. It is important to assess the magnitude of the problem so that effective measures can be implemented (Shrestha, 1997). The rate of natural erosion in the geologically young and seismically active mountains of Nepal is high, as is that of the subsequent down-slope transport and deposition of sediments.

Over the past 20 years, significant concerns have been raised over the degradation of the soil resource in the Middle Hills of Nepal as a result of the expansion of agricultural land and the increase in cropping intensity (Gardner and Gerrard, 2003). As more and more land is subjected to extensive farming and increased dropping intensity, more soils will be exposed to erosion.

Sediment production due to soil erosion in Nepalese watersheds has been acknowledged to be the highest in the world (Galay et al., 1995) and little reliable data of actual sediment production is available. The highest rate of erosion and sediment transport is during monsoon season when high intensity rainfall causes significant loss of soil. In addition to soil erosion by running water the high intensity rainfall causes severe landslides. In Nepal, landslide is one of the main cause of sedimentation.

In Kulekhani watershed, there is extensive agricultural activities in the valleys of the main river and the tributaries which is the main source of sediment. These and other related problems increase the sedimentation of Kulekhani reservoir which is the only seasonal reservoir in Nepal and loss in capacity. Therefore, understanding the impacts of soil erosion and looking for solutions to minimize is essential.

This study, focuses on estimating the sediment yield from Kulekhani watershed, identifying erosion prone areas in the watershed and proposing alternative management plan to minimize erosion rate in the watershed.

1.3 Objective of the Study

The overall goal of this study is to model the hydrological processes to estimate the sediment yield from Kulekhani watershed by making use of the SWAT (Soil and Water Assessment Tool) model.

The specific objectives are:

1. To test the applicability of SWAT model to Kulekhani watershed
2. To predict the sediment yield from Kulekhani watershed and compare the result with the previous studies
3. To analyze the impact of land use change on sediment yield under different scenarios

1.4 Limitations

Several limitations introduced during the course of this study. One of the major limitations was the spatial variability associated with precipitation. There was only one rain gauge station used in the Kulekhani watershed. This can cause considerable errors in runoff estimation if one gauge is used to represent an entire watershed as SWAT requires spatially distributed data. The land use and soil data used were of low quality. The daily stream flow record and sediment yield also was available only for short period which caused calibration process extremely difficult.

1.5 Description of the Study Area

1.5.1 Location of the Study Area

Kulekhani watershed is located at the north-eastern part of Makwanpur district in the Central Development Region of Nepal. The Kulekhani watershed is located about 30 km south of the Kathmandu valley between latitudes $27^0$41’00’’N and $27^0$35’04’’N and longitudes $85^0$12’08’’E and $85^0$02’22’’E. The watershed drains to the Kulekhani Hydropower Reservoir (also known as Indra Sarobar, Sthapit 1995) which is the only seasonal reservoir in Nepal located at the outlet of the watershed. Kulekhani hydropower plant is located at the outlet of the watershed, in the Middle Mountain Zone of Makawanpur District, Central Development Region of Nepal.

The Kulekhani reservoir operates two hydropower plants namely: Kulekhani I and Kulekhani II hydropower projects with a total capacity of 92MW of electricity located downstream of the Kulekhani dam. The reservoir was built in late 1970s and is still in operation. The Kulekhani watershed derived from google earth is shown in *Figure 1.1* below.

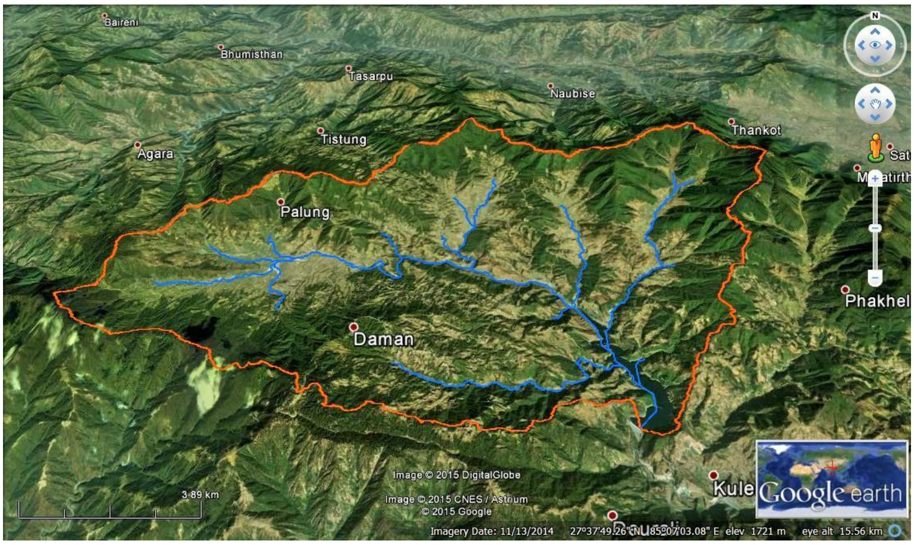


Figure 1.1 Kulekhani watershed (source: Google earth)

1.5.2 Topography

The Kulekhani watershed consists of an uneven terrain comprising steep hills and narrow valleys. The slope of the Kulekhani watershed varies from 0^0 to 86.5^0 (Kayastha et al., 2013). The Kulekhani watershed elevation varies from 1,534 masl at the dam site to 2,621 masl at the peak of Simbhanjyang of the Mahabharat range, which is located at the southern part of the watershed (Shrestha, 2012). More than 43% of the area falls between a slope of 25-50% and about 28% of the area is above 50% slope. Less than 15% of the area is between 0 and 15% slope. The Kulekhani watershed elevation varies from 1,534 masl at the dam site to 2,621 masl at the peak of Simbhanjyang of the Mahabharat range, which is located at the southern part of the watershed (Shrestha, 2012). The slope map of the watershed area is shown in *Figure 1.2* below.

Wide and relatively flat land spreads throughout the middle part of the watershed mainly consisting of Palung, Tistung and Chitlang valleys. These areas are well cultivated and densely populated. The river gradient of the tributaries are gentle in the flat valley, upstream of the Kulekhani reservoir. Gentler topography is found in the middle part of the watershed. The Kulekhani River, one of the major tributaries of the Bagmati River, joins the Bagmati River at Dobhan, about 9 km downstream of the Kulekhani dam.

The Kulekhani river system consists of a series of Kholas (Khola means a stream in the Nepali language). The major tributaries of Kulekhani River are Palung Khola, Tistung Khola and Chitlang Khola.

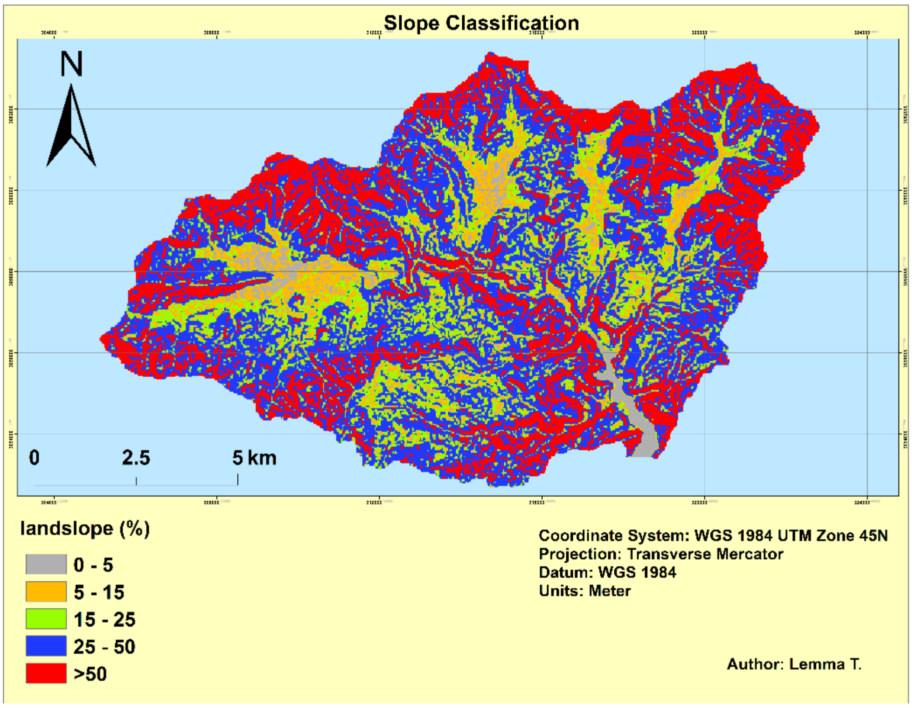


Figure 1.2 Slope map of the Kulekhani watershed

1.5.3 Climate and Hydrology

Due to the variation in topography, the climate of Kulekhani watershed varies from subtropical at low lands to temperate at higher altitudes. As the watershed is affected by monsoon, it has four distinct seasons viz., pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November) and winter (December to February) (Manjeet Dhakal, 2011).

It is under the influence of two major climatic zones namely warm temperate humid zone and cool temperate humid zone, which are mostly found in between the altitude 1500 to 2000m and above 2000m respectively. The average annual precipitation over the watershed is about 1500mm. The maximum and minimum daily temperature of the Kulekhani watershed according to the temperature data from Department of Hydrology and Meteorology is 35 ^{0}C and -4.75 ^{0}C respectively.

1.5.4 Land Use/Cover

The Kulekhani watershed is characterized by high cultivation along the valleys of the main river and the tributaries. The agriculture and forest are the two dominant land uses in the watershed.

The main land use types are forest, hill slope cultivation, valley cultivation, and waterbody (reservoir). Agriculture occupies about 47% of the watershed area. Forest cover is about 51% of the total area of the watershed. The reservoir covers about 2.4% of the watershed area. The summary of the land use of Kulekhani watershed is given in the Table 1.1 below. These percentages are different from those stated on different papers since are based on the total area of the catchment as delineated by ArcSWAT. For instance, different workers (Shrestha, 2012; Sangroula, 2005) stated the area of the Kulekhani watershed as 126 km^2 but the area used in this study was based on the area delineated by ArcSWAT. Therefore, the readers should not be confused by these differences.

Table 1.1 Summary of land use proportion of Kulekhani catchment

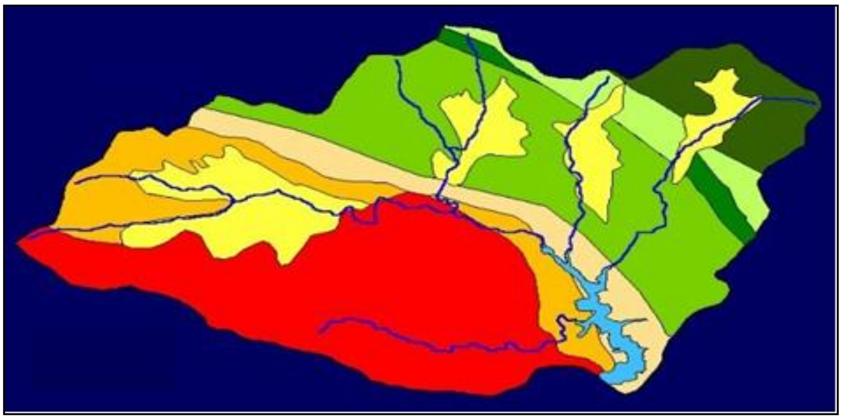
Land use/land cover	Area (km^2)	% area
Agriculture	55.23	47.1
Forest	59.6	50.8
Waterbody	2.38	2.0
Total	**117.21**	**100**

1.5.5 Geology and Soil

Kulekhani watershed is located in the Kathmandu complex of the lower Himalaya. The Kathmandu complex is divided into the Bhimphedi group and Phulchauki group separated by a disconformity. The rocks of the Bhimphedi group are represented by medium to high grade metamorphic rocks of Precambrian age. The rocks of the Phulchauki group are represented by low grade metamorphic rocks and Sedimentary rocks. The Kulekhani formation is well-bedded alteration of the biotic schist and micaceous quartzite of dark and light as well as green, grey colours. Rock slides observed around Phedigaon were located on the schist of the Kulekhani formation (Sangroula, 2005). The geological map of the Kulekhani watershed is shown in *Figure 1.3* below. The geological map of the watershed shown in *Figure 1.3* , indicates that the southern portion of the watershed is composed of Palung Granite while the northern part is predominantly Schist.

According to FAO (Food and Agriculture Organization), the dominant soil type in Kulekhani watershed is Cambisol (Inceptisol according to SSURGO- Soil Survey Geographic database). Cambisols are characterized by the absence of a layer of accumulated clay, humus, soluble salts, or iron and aluminum oxides.

Because of their favorable aggregate structure and high content of weather able minerals, they usually can be exploited for agriculture subject to the limitations of terrain and climate (http://global.britannica.com/EBchecked/topic/707510/Cambisol).



	Group	Description	area (%)
	Alluvial	Alluvial deposits	14.54
	Igneous rocks	Palung Granite (highly weathered)	30.03
	Bhimpedi group	Kulekhani formation (quartzite and biotic schist)	11.27
		Markhu formation (schists, phyllites and marble)	9.19
	Phulchauki group	Tistung schist formation (slate, quartzite and phyllite)	22.65
		Sopyang formation (phyllitic slate and limestone)	1.75
		Chandragiri limestone	4.43
		Chitlang formation (weathered phyllite, slate and limest	6.13

Figure 1.3 Geological map of the Kulekhani watershed (adopted from Shrestha, 2012)

2. Literature Review

2.1 General

The major objective of this chapter is to highlight some facts and results from different past works in the area of sediment yield assessment using the Soil and Water Assessment Tool (SWAT) and soil erosion in general. Here only a summary of the literature tailored to the main objective of the study was presented.

2.2 Previous applications of SWAT (Soil and Water Assessment Tool) model

Models are important tools to understand hydrologic processes, develop management practices, and evaluate the risks and benefits of land use over various periods of time (Spruill et al., 2000). There are many models that have been developed to simulate the sediments transport and runoff discharge from the watershed as well as to predict the impact of watershed management practices or land use changes on sediment transport. One of these models include CREAMS (Chemical, Runoff, and Erosion from Management Systems) (Knisel, 1980) model to simulate the long-term impact of land management on water leaving the edge of a field developed by The USDA-Agricultural Research Service (ARS). There are also many other models originated from CREAMS. These models were all developed for their specific reasons but have limitations for modelling watersheds with hundreds or thousands of sub-watersheds (Spruill et al., 2000). The SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998) model developed in the early 1990's by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) overcomes all these limitations. The detail of the model features, capabilities, scientific details, framework, strengths, limitations and application history will be described in a later chapter.

In mountainous watersheds, especially in Himalayan region, the spatial and temporal variability in terms of soil, land use/land cover, topography, rainfall and biotic forest cover, as well as young geologic materials have large interventions. The steep slopes along with exhausted land cover have been major factors in soil erosion and sedimentation in river reaches (Jain et al., 2004).

The applicability of Soil and Water Assessment Tool (SWAT) model in estimating daily discharge and sediment delivery from mountainous forested watersheds and the assessment of the impact of forest cover types on stream discharge pattern and sediment load was carried out by Tyagi et al., (2014) to two small watersheds located in lower Himalaya, India:

Arnigad (304.4 ha) and Bansigad (209.8 ha). The model was calibrated and validated for daily discharge and sediment concentration using the observed data. The model calibration result for Arnigad watershed showed very good agreement between observed and simulated daily values with an R^2 value of 0.91, and an E_{NS} value of 0.84 in discharge simulation; and an R^2 value of 0.89 and E_{NS} value of 0.83 for sediment simulation. The result from the second watershed, Bansigad watershed also showed high performance of the SWAT model with an R^2 value of 0.91 and E_{NS} value of 0.90 in discharge simulation; and an R^2 value of 0.86 and E_{NS} value of 0.82 for sediment simulation. The result of the study was a clear evidence of the capability of the SWAT model in estimating the discharge and sediment yield from Himalayan forested watersheds and can be used to assess the hydrology and sediment yield response of the watersheds in the region.

The performance of the SWAT model to some extent can be affected by the resolution of the time series dataset used in calibration and validation of the model. In general, the model is known to perform well with monthly data compared to daily data. This was shown by Jain et al., (2010).

Jain et al., (2010) applied SWAT model to part of Satlug River basin lying between Suni and Kasol in western Himalayan region to simulate the runoff and sediment yield from the watershed. The model was calibrated for the years 1993-1994 and validated with the observed runoff and sediment yield for the years 1995-1997. The R^2 value for daily and monthly sediment yield during calibration was found as 0.33 and 0.38 respectively and the c value for daily and monthly sediment yield during validation period was calculated as 0.26 and 0.47 respectively. For the same statistical parameter used as model performance evaluation, SWAT's daily flow predictions were not as good as monthly predictions. The simulation result showed that the R^2 value for daily simulation is lower than that of monthly values. The reason was due the monthly totals tend to smooth the data which in turn increases the value of R^2.

Ayana et al., (2012) applied SWAT model to Fincha watershed (3,251 km^2), located in western Oromiya Regional State, Ethiopia. The model was calibrated using a time series dataset of 22 years from 1985 to 2006 estimated monthly sediment yield with R^2 value of 0.82 and E_{NS} value of 0.80 during calibration and R^2 value of 0.80 and E_{NS} value of 0.78 during the validation period. The result of the study showed that the model adequately predicted the sediment yield from the study watershed with high performance and can be applied to other watersheds in the region with some catchment specific parameter modifications.

The development of the SWAT model was primarily for long time periods (2 years and more) simulations. But, this didn't prevent the researchers from applying the model to short simulation periods less than one year (few days). For instance, Saleh et al., 2009) applied the SWAT model to Mustang Creek Basin, San Joaquin Valley, California. Mustang Creek Basin is an ephemeral creek that flows only during large precipitation events. The model was calibrated for 29 days in February 2004 and validated for 58 days in January and February 2005. The result of the study showed that the model performed well simulating the monthly stream flow data with a Nash-Sutcliffe efficiency value of 0.72 during calibration. But, the model was not successful during validation period and the value of the Nash-Sutcliffe efficiency was 0.33. The author stated that this could be due to limited recorded stream flow data, ephemeral nature of the flows in the basin and limited number of simulation period. Having a much longer period of daily flow record for both calibration and validation likely would have resulted in better comparisons between recorded and simulated daily flows, because a longer record would not be affected by a few anomalous high values of discharge as a short record (Saleh et al., 2009).

Ndomba and Griensven (2011) tested the suitability of SWAT model for sediment yields modelling in the eastern Africa. Three different case studies were chosen in this study. The first case study was Koka Reservoir Catchment (KRC) (11,000 km^2) in Ethiopia, the second case study the Nyumba Ya Mungu (NYM) Reservoir Sub-catchment (140 km^2) located upstream of Pangani River Catchment (PRC) in Tanzania, and the third case study the Simiyu River Catchment (SRC) (10,659 km^2) located in the northern part of Tanzania southeast of lake Victoria. The result of the study indicated that, the SWAT model seems to be promising and can be relied up on as a tool for catchment sedimentation management in the tropics (Ndomba and Griensven, 2011).

SWAT model was also applied for modelling of daily stream flows and to evaluate parameter sensitivities in a small Central Kentucky watershed over a period of 2-years from 1995 to 1996. For this specific study stream flow data from 1995 were used for model calibration and the stream flow data from 1996 were used for model validation. The model prediction was adequate regarding the trends in daily stream flows although the Nash-Sutcliffe efficiency values were very low with the values of -0.04 and 0.19 for calibration and validation period respectively. The model poorly predicts the timing of some peak flows and recession rates during the last half of the 1995 (Spruill et al., 2000).

Betrie et al. (2011), applied the SWAT model to simulate daily sediment yield From the Upper Blue Nile basin under different Best Management Practice (BMP) scenarios on sediment reductions. The scenarios applied were maintaining existing conditions (baseline), introducing filter strips, applying stone bunds (parallel terraces) and reforestation. The results of the study showed that there is good agreement between the observed and simulated daily sediment concentrations as the value of Nash-Sutcliffe efficiency was 0.83. Applying the other management practices such as filter strips, terraces and reforestation scenarios reduced the sediment yield at both basin and subbasin level. For instance, applying stone bunds or parallel terraces reduce soil erosion and sediment transport by reducing the slope length. This because the slope length factor is directly involved in sediment yield calculation from the watershed by using MUSLE equation. The slope length will be affected by the terrace interval.

Xu et al. (2009) also applied SWAT model to simulate the runoff and sediment yield in the Miyun river catchment, China. The physiography of the watershed is characterized by mountain ranges, steep slopes and deep valleys. The model accurately predicted the daily and monthly runoff and sediment yield with the value of Nash-Sutcliffe efficiency of greater than 0.6. During this study, the sensitivity analysis carried out to identify parameters which affect runoff and sediment yield from the watershed showed that runoff was most sensitive to curve number (CN) and Baseflow alpha factor (ALPHA_BF) and sediment yield was sensitive to curve number (CN) and channel re-entrainment linear parameter (SPCON). This parameter sensitivity result is catchment specific and should not be applied directly to other catchments with different characteristics before conducting sensitivity analysis.

The application of the SWAT model to a data scarce tropical complex catchment was carried out by Ndomba et al., (2008) in Tanzania. The result showed that the model can be used in ungauged catchments for identifying hydrological controlling factors/parameters. The study also showed that the length of the period of simulation affects the result i.e. the longer the period, the more reliable is the result. The model performed well in simulating the daily runoff from the watershed with value of Nash-Sutcliffe efficiency coefficient of 0.55 and 0.68 for calibration and validation period respectively. Therefore, the study further suggested that using processed, adequate and reliable spatial rainfall data and relatively long flow records for SWAT model calibration can improve the performance of a fully distributed SWAT model.

Setegn et al, (2008) applied SWAT model to the Lake Tana Basin for modelling of the hydrological water balance. The objective of this study was to test the applicability of SWAT model for prediction of stream flow in the basin. The model was successfully applied to the basin in simulating the daily and monthly stream flows and found out that the flow was more sensitive to the HRU definition thresholds than subbasin discretization effect.

The application of SWAT model in catchment parameterization was also carried out successfully by Mulungu and Munishi, (2007). The result of the study showed that surface water model parameters were the most sensitive and have more physical meaning for instance, CN2 (curve number) and SOL_K (saturated hydraulic conductivity of soil layers). The model efficiency (R^2) value as low as 0.14 obtained in this study showed that other factors than the spatial land data were greatly important for improvement of flow estimation by SWAT in the catchment.

The effect of watershed subdivision on the water balance components was studied by Tripathi et al, (2006) for Nagwan watershed in eastern India. The result of the study revealed that the number and size of sub-watersheds do not significantly affect surface runoff but had noticeable effect on other components of the water balance: evapotranspiration, percolation and soil water content. Therefore, it is possible to conclude that the watershed subdivision has an effect of the water balance in general. The number and size of sub-watersheds for a given catchment depends on the resolution of spatial data used in the model. High resolution data results in higher number of sub-watersheds and thereby enhance the water balance prediction of the model.

Easton et al. (2010) applied SWAT model to a Blue Nile Basin, Ethiopia and found out that the SWAT model is incapable of realistically model gully erosion. The study showed that SWAT model under predicted the sediment from a basin where gully erosion is high. To compensate for this the USLE soil erodibility factor (USLE_K) in MUSLE (Modified Universal Soil Loss Equation) was increased.

3 Data Collection and Preparation

3.1 General

To get a better result, it is critical to use all relevant and good quality data required. The outcome/result depends on the quality and quantity of data used. The spatial and temporal resolution of data used in modelling will greatly influence the model performance. The SWAT (Soil and Water Assessment Tool) needs good quality of Digital Elevation Model (DEM), Soil and Land use/land cover data above all other necessary data to simulate the discharge and sediment from a given watershed. The length of period of weather and climatic data also affect the SWAT model performance. The output from the SWAT model can be affected by the DEM data resolution, mesh size, soil data resolution and soil map scale, watershed subdivision which on the other hand is affected by DEM data resolution etc. Bosch et al., (2004) found that SWAT stream flow estimates were more accurate when using high-resolution topographic data, land use/land cover data, and soil data. The required DEM data, soil data, land use/land cover data, flow data, climatic and sediment data was collected from different sources. The quality and quantity of data used in the development of SWAT project in this study will be discussed in the upcoming sections.

3.2 Digital Elevation Model (DEM) Data

Digital Elevation model (DEM) is one of the main inputs of the SWAT (Soil and Water Assessment Tool) model. DEM is used in the SWAT model along with soil and land use/land cover data to delineate the watershed and to further divide the watershed into sub-watersheds and hydrologic response units (HRUs). The resolution of the Digital Elevation Model (DEM) is the most critical input parameter when developing a SWAT model (Gassman et al., 2007). DEM resolution affects the watershed delineation, stream network and subbasin classification in the SWAT model. It affects the number of sub-basins and HRUs. The number of sub-watersheds in the subbasin affects the predicted sediment yield for a watershed (Bingner et al., 1997). Jha et al., (2004) found that SWAT sediment predictions were sensitive to HRUs and sub-watershed configurations. According to (Chaubey et al., 2005) a decrease in DEM resolution resulted in decreased stream flow and watershed area. Since the runoff volume and total sediment load depends on the watershed area, the decrease in the DEM resolution resulted in large error in the predicted output. Input DEM data resolution affected SWAT model predictions by affecting total area of the delineated watershed, predicted stream network and subbasin classification (Chaubey et al., 2005).

In general, the quality of the DEM data strongly affect the final output of the hydrological model (Defourny et al., 1999). Therefore, it is wise to use the finest available DEM data for model application.

For this project a digital elevation model (DEM) was extracted from the global U.S.Geological Survey's (USGS) in the format of SRTM (Shuttle Radar Topography Mission) with a spatial resolution of 30 m x 30 m. In the original data there was a missing data which creates a hole in the DEM. But, the hole was edited and filled in the ArcMap using the Raster Editor. The edited DEM was projected to WGS1984 UTM Zone45N using the raster projection in ArcMap toolbox before it was imported to ArcSWAT. The projected map was used in the watershed delineation in ArcSWAT which is the interface in the ArcMap to use it in SWAT model. The processed DEM map of the Kulekhani watershed is shown in *Figure* 3.1 below.

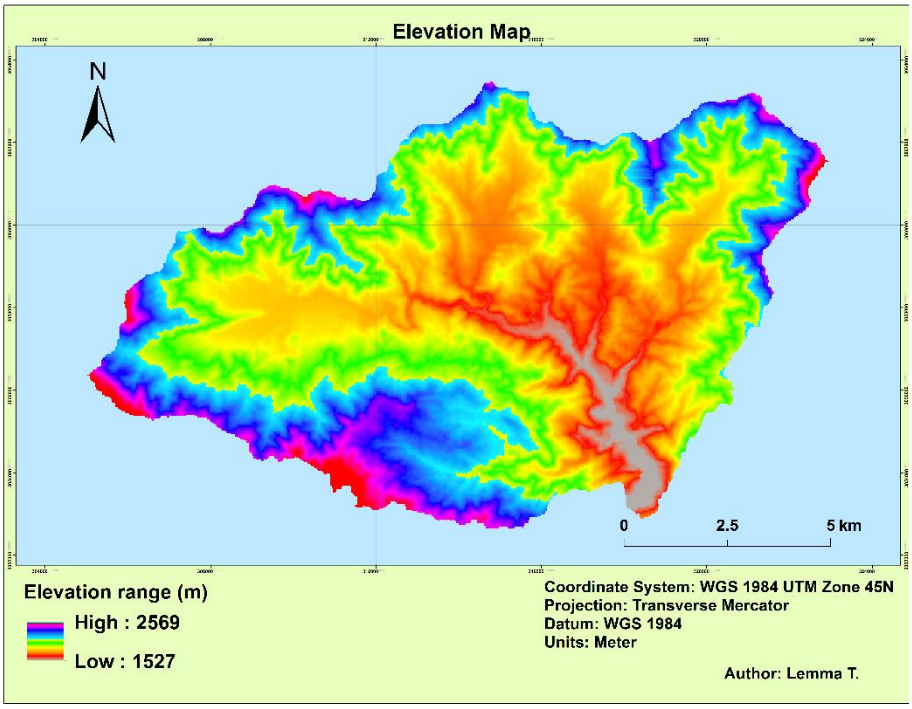


Figure 3.1 DEM map of Kulekhani Watershed

The highest point in the watershed rises up to 2569 masl and the lowest point is about 1527 masl as indicated in *Figure 3.1* above.

3.3 Soil Data

Like the Digital Elevation Model (DEM), soil data resolution has also a significant impact on the modelling of stream flow, sediment load and nutrient content.

Geza and McCray (2008), evaluated the dependency of the prediction accuracy of the Soil and Water Assessment Tool (SWAT) on how well the model input spatial parameters describe the characteristics of the watershed. Geza and McCray (2008) used the same number of watersheds to analyze the effect of soil data resolution. Then the SWAT model predictions were compared for the two US Department of Agriculture soil databases with different resolution, namely the State Soil Geographic Database (STATSGO) and the Soil Survey Geographic database (SSURGO). These two soil databases, STATSGO and SSURGO, produce different number of hydrologic response units (HRUs) 261 and 1301 respectively. SSURGO database which has the highest spatial resolution has 51 unique soil types in the watershed compared to STATSGO database which has only 3. This on the other hand affected the runoff and sediment prediction. If the low resolution soil data is used to generate the HRUs it assigns same soil type for larger area of the watershed that actually may have different soil types. Different soils have different soil erodibility factor, hydraulic conductivity, infiltration capacity etc. which affects the water balance and sediment yield from the watershed. Therefore, using high spatial resolution soil map will increase the prediction accuracy of the model.

In this study the soil data was obtained from Food and Agriculture Organization of the United Nations (FAO) (FAO, 1995) at a spatial resolution of 10 km. The Soil and Terrain database (SOTER) for Nepal, at scale 1:1 million compiled in 2004 by FAO and the Survey Department of Nepal (Dijkshoorn & Huting, 2009). The spatial resolution of this soil map is very low that after it is clipped to the watershed it assigns only one soil type for the whole watershed of about 117,21 km^2 which is actually not. This may have very high impact on the prediction of runoff and sediment yield. Therefore, it should be noted that the simulation result will be subject to the low quality of soil data used.

As it was described in the introductory part of this study, the soil type of the area is called Cambisol. The main problem in defining the soil data during HRU definition was that the Cambisol was not in the soil data base in both STATSGO and SSURGO. Later it was found that this Cambisol was known by another name in SSURGO database. Another name for Cambisol is Inceptisol which was included in the SSURGO database.

Therefore, all required soil properties were adopted from SSURGO database since there was no possibility of measuring all soil properties in the field due to time constraint. The soil map obtained from FAO was projected to WGS1984 UTM Zone45N using the raster projection in ArcMap before it was imported to ArcSWAT. The soil map of Kulekhani watershed used in the HRU definition in this study is shown in *Figure 3.2* below.

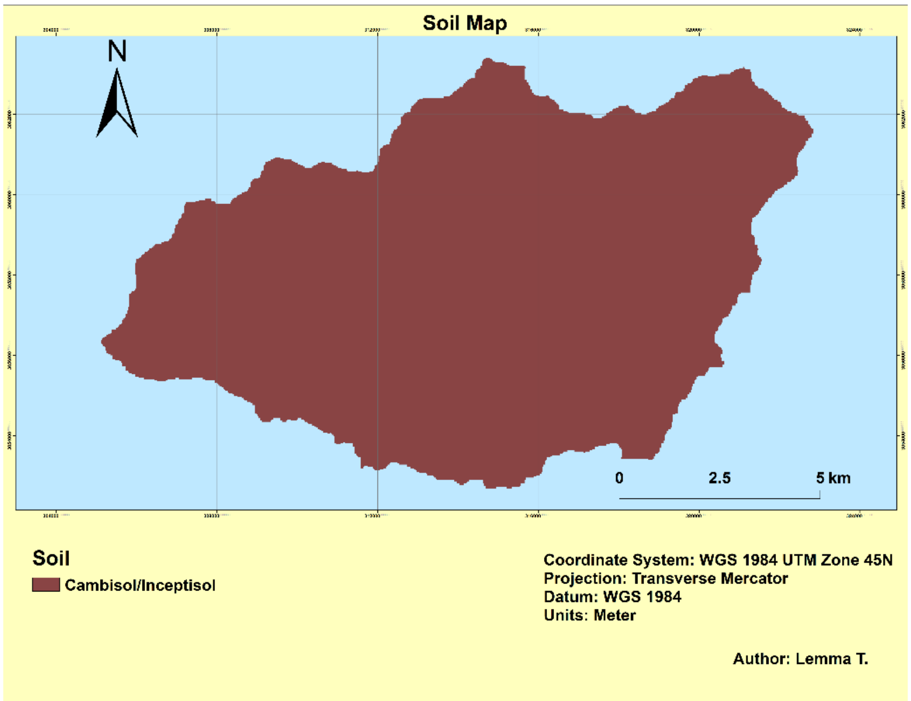


Figure 3.2 Soil map of Kulekhani watershed

3.4 Land use/land cover Data

Land use/land cover data has also a significant effect on the hydrological modelling. Therefore, a detail analysis and mapping of the land use/land cover is crucial for proper hydrological modelling. Land use/land cover affects the runoff and sediment transport in the watershed.

For this study land use/land cover data was obtained from the USGS Global Land Use Land – Cover Characterization (GLCC) database with a spatial resolution of 1 km, which distinguishes 24 land use and land cover classes. The land cover data was available in the form of Binary and ESRI Grid. The ESRI Grid format with a 1 km spatial resolution was used in this study. Three land use/land cover types were identified for Kulekhani watershed: Agricultural land, forest and water body. There were no specific crop type identified in the agricultural land use for this study. The land use for Kulekhani watershed was projected to WGS1984 UTM Zone45N using the raster projection in ArcMap before it was imported to ArcSWAT. The land use map of the Kulekhani watershed is shown in *Figure 3.3* below.

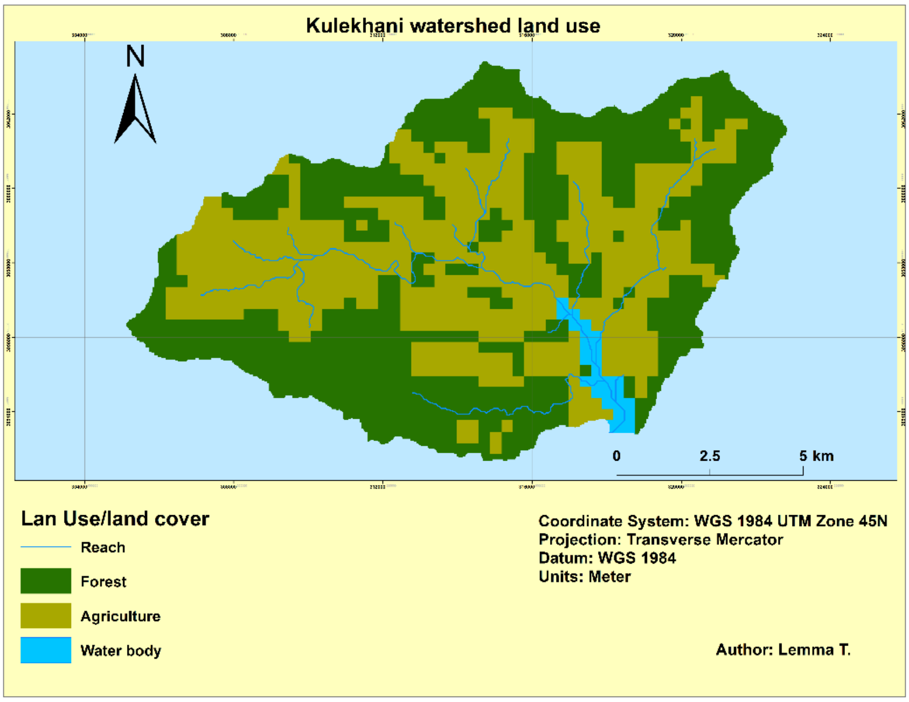


Figure 3.3 Land use/land cover map of Kulekhani watershed

3.5 Flow Data

Observed flow data was required for the Soil and Water Assessment Tool (SWAT) calibration and validation. The observed stream flow data was available from 2007-2009. The stream flow data from 2007-2009 used in this study was calculated by (Anup Khanal, 2013) for the study of 'inflow forecasting for Nepalese catchments'. The calculation was done by inflow forecasting using historical data, reservoir water level and energy production. The inflow was determined for the Kulekhani Reservoir which is located at the outlet of the watershed of study. This flow data was formatted as to the requirement of the SWAT model and used for model calibration and validation. The stream flow from 2007 to 2008 was used for model calibration and the 2009 flow data was used for model validation. Here, it should be noted that the efficiency of the model during calibration and validation depends on the accuracy of the calculation. Any error during calculation may cause significant problem in model calibration and validation.

In addition to flow data from 2007 to 2009, there was also flow data from 2003 and 2004 for four months from each year. Sangroula (2005), measured stream discharge at Palung Khola and Chitlang Khola. The measurement was from 21st of June to 18th of September 2004 two times in a day (Sangroula, 2005).

But, for the years from 2007 to 2009 the calculation was done for all the days in a year. The average monthly discharge from 2007 to 2009 is shown in *Table 1.1* below.

Table 3.2 Mean monthly flows at the outlet of the Kulekhani watershed.

Months	Year		
	2007	2008	2009
	Flow (m^3/s)		
Jan	2.03	1.76	1.14
Feb	2.14	1.85	1.59
Mar	1.82	2.09	0.83
Apr	1.98	1.71	0.62
May	1.96	1.61	1.49
Jun	3.12	2.35	0.88
Jul	4.27	3.51	2.93
Aug	9.01	5.03	7.31
Sep	11.09	4.91	3.32
Oct	4.05	1.99	2.54
Nov	2.48	1.29	1.33
Dec	1.87	1.80	1.30

3.6 Climate Data/Weather Data

Climate data is among the most important data required for the SWAT model. Obtaining representative meteorological data for watershed-scale hydrological modelling can be difficult and time consuming. Land-based weather stations do not always adequately represent the weather occurring over a watershed, since they can be far from the watershed of interest and can have a missing data series, or recent data are not available (Fuka et al., 2014). It is beneficial to have a meteorological station within the watershed of interest. Rain gauge data are point measurements which may not represent the whole watershed. This problem can be reduced only when there is multiple rain gauges within the watershed. Otherwise, the problem exists specially for large watersheds which may have large hydro-climatic gradients. The problems related to each weather data will be stated under the following sections.

3.6.1 Rainfall Data

The rainfall data was obtained from the Department of Hydrology and Meteorology (DHM), Ministry of Science and Environment. There were six meteorological stations located inside and outside the Kulekhani watershed (*Figure 3.4*). But, only three of them: Markhu, Daman and Thankot were considered for further analysis. The other three stations: Khokana, Chissapani and Hetaunda were not considered since they are far from the watershed of study.

The daily rainfall data of Markhu, Daman and Thankot are further analyzed below. The rainfall data for Markhu station was available from 1972 to 2013 but, the data for the other two stations: Daman and Thankot were available only from 2007 to 2011. Therefore, the data quality of the available data from these three stations was evaluated for the year 2007 to 2011 for comparison. The type and coordinates of the climate and meteorological stations are given in *Table* 3.3 below.

Table 3.3 coordinates of climate stations

Index no.	Station Name	Type of station	Longitude (Decimal degrees)	Latitude (Decimal degrees)
0915	Markhu	Precipitation	85.150	27.617
0905	Daman	Climatology	85.083	27.600
1015	Thankot	Precipitation	85.200	27.683
1073	Khokana	Climatology	85.283	27.633
0906	Hetaunda	Climatology	85.050	27.417
0904	Chisapani	Precipitation	85.133	27.550

Figure 3.4 below shows the locations of meteorological and climatological stations. From the figure it can be seen that Khokana, Chissapani and Hetaunda stations are outside the Kulekhani watershed and are very far. Thankot station is close to the watershed and Daman and Markhu are both located within the catchment. As SWAT model needs spatially distributed precipitation stations, it is beneficial to use the stations located within the watershed than using those outside the watershed.

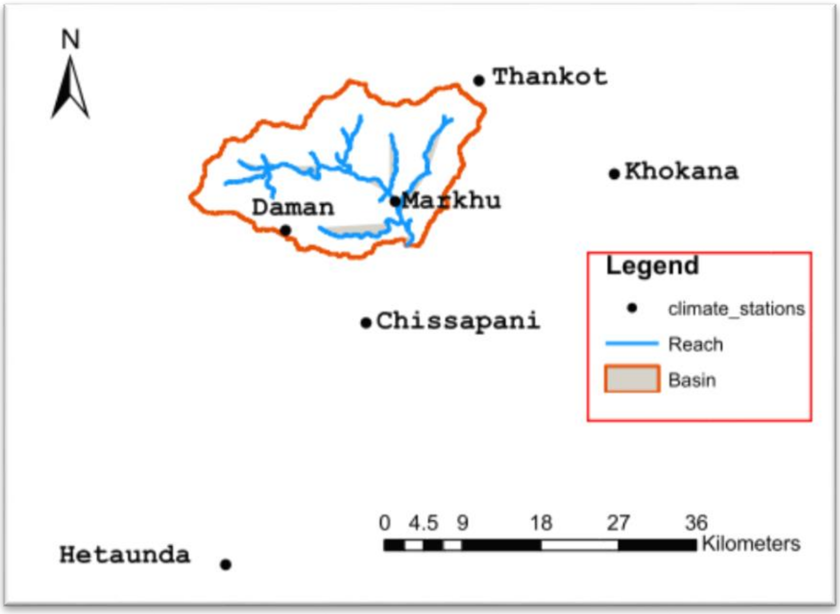


Figure 3.4 Meteorological stations at the vicinity of Kulekhani watershed

The daily precipitation data series from 2007 to 2011 for Markhu, Daman and Thankot stations is shown in appendix A.

3.6.1.1 Data quality control

The precipitation data must be checked for continuity and consistency before it is used for further analysis. The quality control can be done by visual inspection, filling of missing data if there is any, accumulated plot and double mass curve. This will help identify if there are any gaps or unphysical peaks in data series and correct them before the data is used or input to the model. Otherwise, using the erroneous data as input to the model will give erroneous output from the model.

3.6.1.1.1 Visual inspection

After the rainfall data is obtained from any source it must be checked for its quality. The first step in data quality control is by visual inspection. This can be done by checking if date and time record is complete, unphysical values (spikes and negatives), flat regions (sensor or transfer system fall out) and unphysical variation patterns (sensor malfunctioning). The visual inspection was done by plotting the time series data against time. The percentage of missing data points for all three precipitation stations from 2007 to 2011 is shown in Table 3.4 From the table, Markhu station has 33 missing data which accounts about 1.8% of the total data available. The next station which has higher missing data compared to Markhu was the Thankot station with 153 missing data points, about 8.4% of the total data points.

Daman station has the highest missing data points with 423 data missing which is about 23.2% of the total time. Therefore, these missing data must be filled using appropriate method for further analysis.

Table 3.4 Percentage missing precipitation data points for Markhu, Daman and Thankot stations

Index no.	Station Name	Total Number of data points	Number of Missing data points	% of missing data points
0915	Markhu	1826	33	1.8
0905	Daman	1826	423	23.2
1015	Thankot	1826	153	8.4

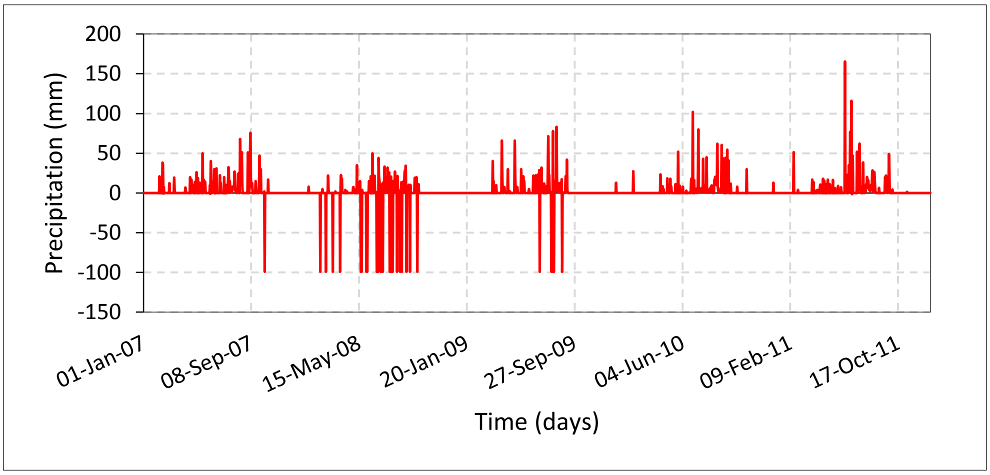


Figure 3.5 Precipitation data at Markhu as recorded (2007 – 2011)

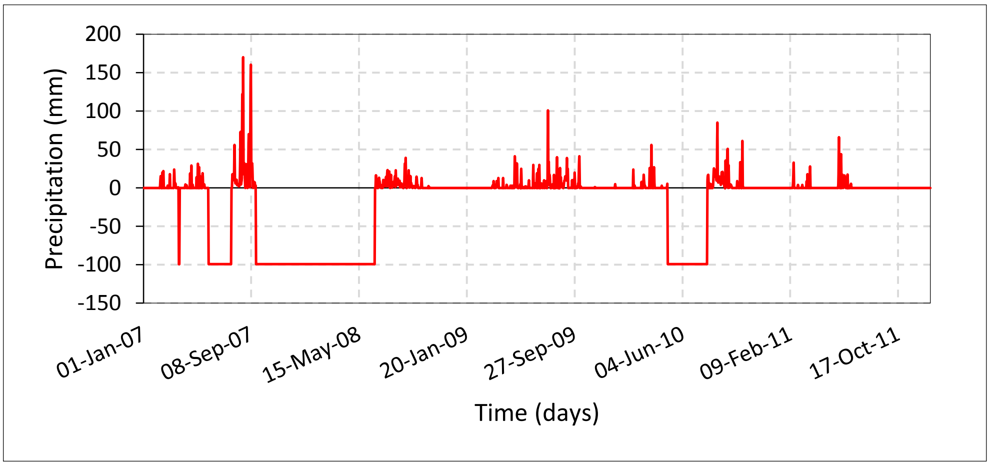


Figure 3.6 Precipitation data at Daman as recorded (2007 – 2011)

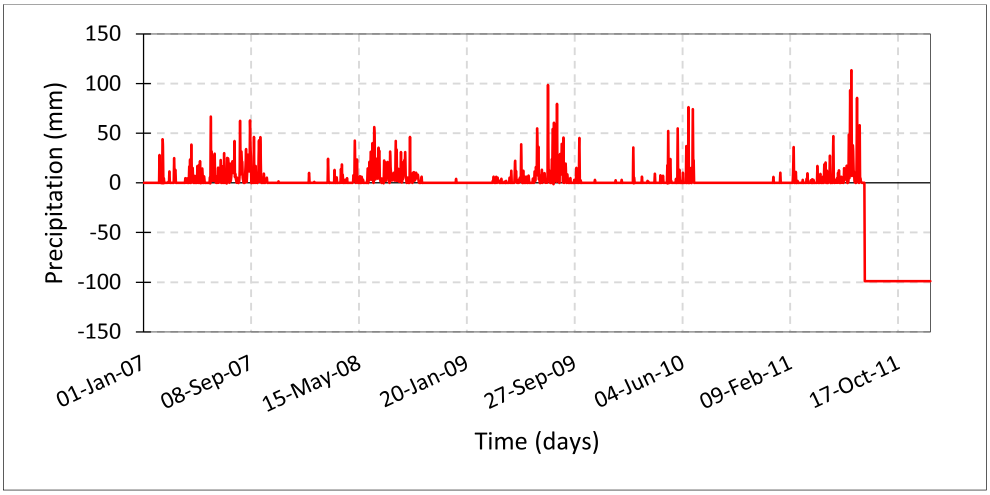


Figure 3.7 Precipitation data at Thankot as recorded (2007 – 2011)

3.6.1.1.2 Filling of missing data

Some precipitation stations may have short breaks in the records because of absence of the observer or because of instrumental failures. It is often necessary to estimate or fill in this missing record. The missing precipitation of a station was estimated from the observations of precipitation at some other stations as close to and as evenly spaced around the station with the missing record as possible. Here, the station whose data was missing is called interpolation station and gauging stations whose data are used to calculate the missing station data are called index stations.

There are methods to fill in missing data. These are: arithmetic mean method, normal ratio method and inverse distance weighing method. Arithmetic mean method can be used to fill in missing data when normal annual precipitation is within 10% of the gauge/station for which data are being reconstructed. The normal ratio method is used when the normal annual precipitation at any of the index station differs from that of the precipitation station by more than 10%. In the absence of normal annual rainfall for the stations inverse distance weighing method can be used to fill the missing data.

A) Arithmetic mean method

$$P_x = \frac{1}{n}\sum_{i=1}^{i=n} P_i \qquad [3.1]$$

Where, n is the number of nearby stations, P_i is precipitation at i^{th} station and P_x is the missing precipitation.

B) Normal ratio method

$$P_i = \frac{1}{n}\sum_{i=1}^{i=n}\frac{N_x}{N_x}P_i \qquad [3.2]$$

Where, P_x is the missing precipitation for any storm at the interpolation station x, P_i is the precipitation for the same period for the same storm at the i^{th} station of a group of index stations, N_x is the normal annual precipitation for station x, and N_i is the normal annual precipitation value for the i^{th} station.

C) Inverse distance weighing method

$$D = \sum_{i=1}^{i=n} d_i^{-b} \qquad [3.3]$$

$$P_x = \frac{1}{D}\sum_{i=1}^{i=n} d_i^{-b} * P_i \qquad [3.4]$$

Where, D is distance from gauge i to missing data point, $b = 2$ and the other symbols carry the same meaning as defined above.

Inverse distance weighing method has been used in this study to fill in the missing data. But, the data filled by this method was not used as input to the SWAT (Soil and Water Assessment Tool) model since the model itself has a built in function to fill in the missing data as it will be described in chapter 4.

3.6.1.1.3 Accumulated plot

After all the missing data are filled, it is important to check if the estimate was done with correct scaling. Correct scaling implies same gradient of accumulated plot of stations for long period of time. *Figure 3.8* Shows accumulated plot of precipitation time series for different stations from 2007 to 2011.

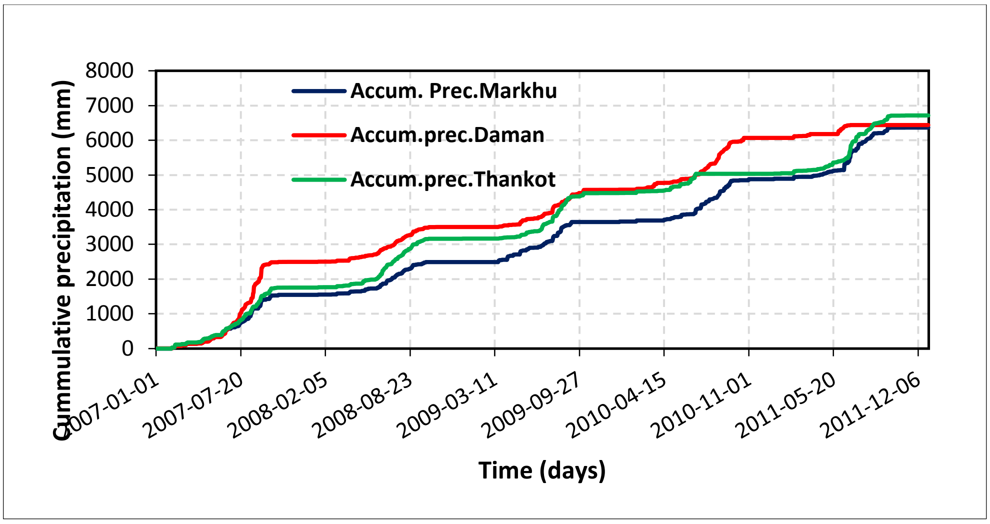


Figure 3.8 Accumulated plot of precipitation time series for Markhu, Daman and Thankot stations

The accumulated plots have almost the same gradient for all the stations which shows no significant error exists. To further check the quality of the data, it must be checked for consistency. The consistency of rainfall data was checked by double mass curve (see section 3.6.1.1.4).

3.6.1.1.4 Double mass curve

To check for consistency of the recorded data, the cumulative of Daman and Thankot was plotted against the Markhu station since Markhu station has very few missing data compared to the other two stations.

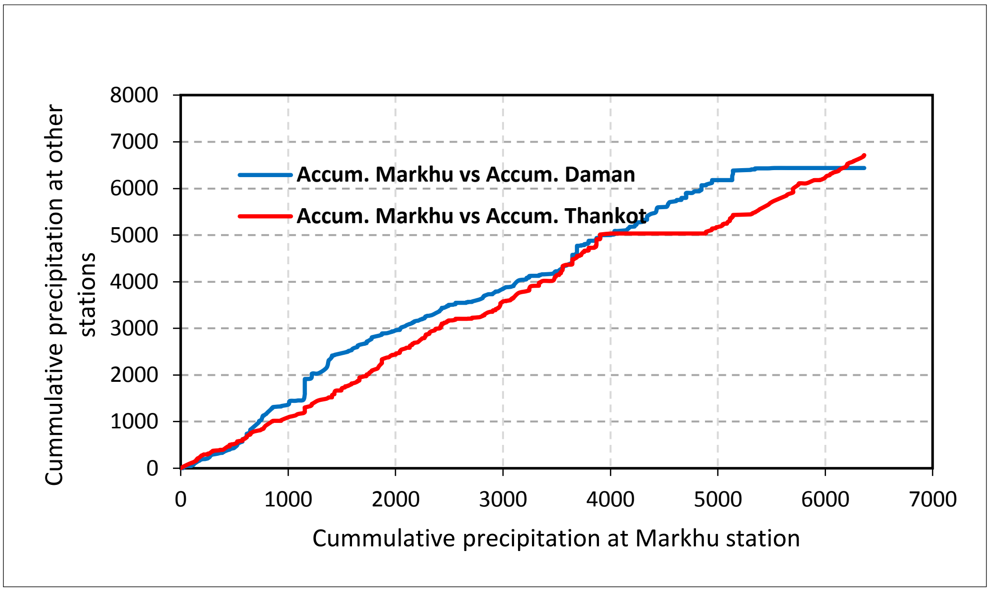


Figure 3.9 Double mass curve

From, figure 3.9 we can see that there is inconsistency in the recorded data. There is some flat period in both graphs in a later period. This can be proved to be true by referring to figures 3.5, 3.6 and 3.7 above that stations Daman and Thankot record no precipitation during the same period Markhu station has records of precipitation. Therefore, the precipitation recorded at stations Daman and Thankot has a series problem as we can see it from the double mass curve and the percentage of missing data also leads to the same decision. Due to this reason the precipitation record at Markhu was used as input to the model for further analysis.

3.6.1.2 Statistical parameters calculation for precipitation data

After the precipitation data was checked for quality and the appropriate station selected, the statistical parameters of precipitation data must be calculated before model set up. The statistical parameters for precipitation were calculated using the programme *pcpSTAT.exe*. This programme calculates the statistical parameters of daily precipitation data used by the weather generator of the SWAT model (userwgn.dbf) (Liersch, 2003). The programme can be found at (http://swat.tamu.edu/software/links/). The result is shown in *Table 3.5* below.

Table 3.5 Statistical Analysis of Daily Precipitation Data (1972 - 2013)

Month	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	22.47	4.1221	11.1441	0.0555	0.354	2.69
Feb.	35.1	4.461	5.8789	0.106	0.4286	4.67
Mar.	36.52	4.7121	6.7303	0.1052	0.4258	4.98
Apr.	78.91	7.2934	5.1926	0.2009	0.5363	9.5
May.	140.69	8.6329	3.5946	0.3322	0.6898	16.81
Jun.	250.47	16.4905	4.7569	0.3696	0.8069	20.6
Jul.	384.73	23.0233	6.2791	0.5865	0.8611	26.05
Aug.	294.17	16.271	4.6785	0.4315	0.869	25.26
Sep.	211.27	15.4318	4.5337	0.2425	0.7816	17.33
Oct.	53.78	8.2867	8.5646	0.086	0.5113	5.26
Nov.	9.75	3.8964	26.189	0.0255	0.2609	1.1
Dec.	19.47	4.9702	12.7216	0.0242	0.4516	1.48

Where,

PCPMM (Mon) = average or mean total monthly precipitation

PCPSTD (Mon) = standard deviation for daily precipitation in month

PCPSKW (Mon) = skew coefficient for daily precipitation in month

PR_W1 (Mon) = probability of a wet day following a dry day

PR_W2 (Mon) = probability of a wet day following a wet day

PCPD (Mon) = average number of days of precipitation in month

According to Lee and Haque (2004), the transition of occurrence of daily precipitation consists of two transition probabilities. These are the transition probability of a wet day, given that the previous day was a wet day P (W/W), and the transition probability of a wet day following a dry day P (W/D). Therefore, from statistical data, the probability of a wet day following a wet day (PR_W2) or P (W/W) and the probability of a wet day following a dry day (PR_W1) or P (W/D) can be calculated using the following relationship (Lee and Haque, 2004)

$$P(W/D) = a + bf$$
$$P(W/W) = (1-b) + P(W/D)$$

Where, f is the perennial mean monthly precipitation frequency, being the ratio of the number of perennial monthly rainfall days and number of days of the month, while a, b are regression coefficients. This relationship is used in the programme written by Liersch (2003), to calculate the statistical parameters in the table above.

The total yearly precipitation from year 1972-2013 is shown in *Figure* 3.10 below.

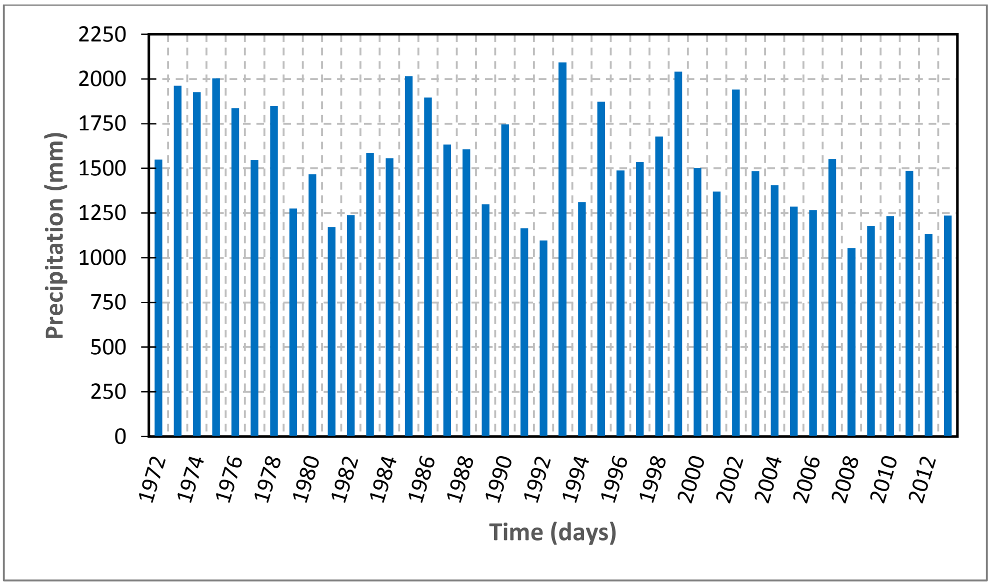


Figure 3.10 Total annual precipitation from (1972-2013)

From figure 3.10 the year 1993 is the wettest year and the year 2008 is the driest year in the period from 1972-2013. It is evident that, a maximum 24 hour rainfall of 540 mm was recorded during the largest observed storm in the Kulekhani watershed in July 1993 (Sangroula, 2005).

Total monthly precipitation from 2000 – 2010 is shown in table 3.5.

Table 3.6 Total monthly precipitation from 2000 to 2010

Total Monthly Precipitation												
Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2000	1.1	11.7	13.5	32.6	254.6	271.21	219.8	187.1	510.8	0	0	0.2
2001	9.3	19.71	18.1	57.3	122.3	246.3	366.4	321.3	174.2	34.4	0	0
2002	45.6	40.3	16.8	95.8	187.2	138.1	877.4	373.6	151.2	14.3	0	0
2003	23.3	118	49.9	59.6	61.9	161.8	501.7	332.5	142.3	0	0	33.3
2004	32	0	0	122.6	179.7	285	498	127.6	126.5	26.2	8	0
2005	73.4	34.4	68.2	104.7	104.8	170.4	247.5	366	12.1	104.7	0	0
2006	0	0	2	79.5	98.5	254.3	184.3	289.6	324.3	0	0	34.2
2007	0	105.1	38	78.9	164.3	227.1	224	368	323.6	23.21	0	0
2008	8	13.42	33.71	60.51	92.02	227.15	250.77	268.64	98.23	0	0	0
2009	0	0	65.5	153.1	172	69.3	294.41	334.05	89.6	0	0	0.1
2010	13	29.9	0	58.2	112.6	151.5	285.9	243.4	299.8	38	0	0

Average daily precipitation in a month from 2000 to 2010 is shown in *below*.

Table 3.7 below.

Table 3.7 Average daily precipitation in a month from (2000-2010)

Average Daily Precipitation in Month												
Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2000	0.04	0.4	0.44	1.09	8.21	9.04	7.09	6.04	17.03	0	0	0.01
2001	0.3	0.7	0.58	1.91	3.95	8.21	11.82	10.36	5.81	1.11	0	0
2002	1.47	1.44	0.54	3.19	6.04	4.6	28.3	12.05	5.04	0.46	0	0
2003	0.75	4.21	1.61	1.99	2	5.39	16.18	10.73	4.74	0	0	1.07
2004	1.03	0	0	4.09	5.8	9.5	16.06	4.12	4.22	0.85	0.27	0
2005	2.37	1.23	2.2	3.49	3.38	5.68	7.98	11.81	0.4	3.38	0	0
2006	0	0	0.06	2.65	3.18	8.48	5.95	9.34	10.81	0	0	1.1
2007	0	3.75	1.23	2.63	5.3	7.57	7.23	11.87	10.79	0.75	0	0
2008	0.26	0.46	1.09	2.02	2.97	7.57	8.09	8.67	3.27	0	0	0
2009	0	0	2.11	5.1	5.55	2.31	9.5	10.78	2.99	0	0	0
2010	0.42	1.07	0	1.94	3.63	5.05	9.22	7.85	9.99	1.23	0	0

Note that in all of the above tables the period between 2000 and 2010 was presented since the SWAT model simulation was done for only this period.

3.6.2 Temperature Data

The temperature data record was available from two weather stations: Khokana and Hetaunda (*Figure 3.4*).

But, the temperature record from both stations was incomplete and available for only few years. Therefore, the temperature data recorded at Kathmandu airport was transferred to Markhu station by using temperature lapse rate.

The Kathmandu airport has a temperature record from 1972 to 2013 the same length of year as the precipitation data recorded at Markhu station. This is very important to use as input to the SWAT model as it requires the same length of year for both precipitation and temperature data. The daily maximum and minimum air temperature was available with some missing data. The missing data was filled using linear interpolation only for checking the trend of the air temperature over time. When this data was used as input to the SWAT model again the filling of the missing data was left for the SWAT itself by replacing the missing values with -99.

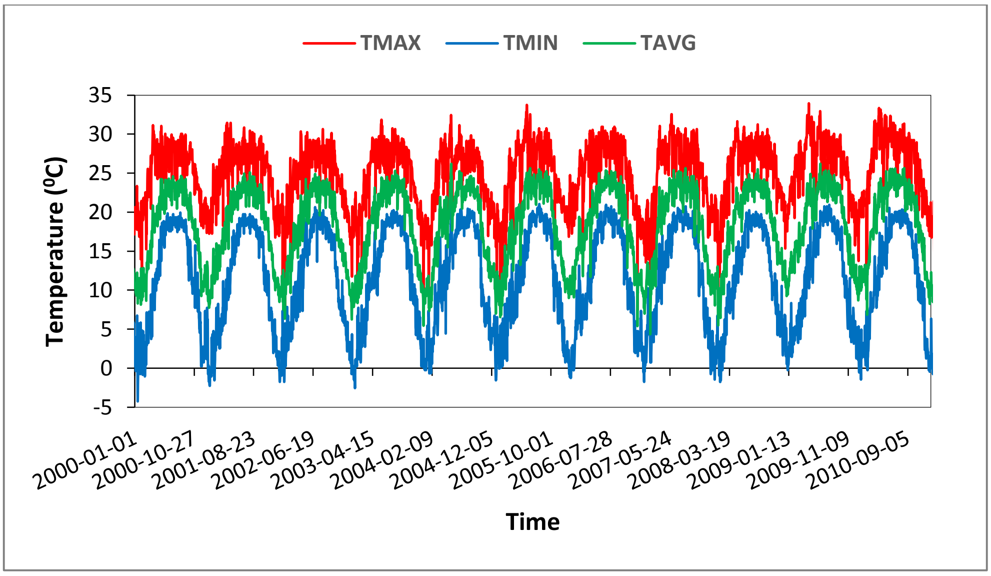


Figure 3.11 Daily maximum/minimum air temperature at Markhu

The daily air temperature plotted in *Figure 3.11* was transferred from Kathmandu airport station before it was used for further analysis.

3.7 Sediment Data

The daily observed sediment data for the watershed was taken from the work of Sangroula (2006). The gauging stations were established at two different stations within the watershed. The two major watersheds for which flow measurement and sediment sampling was made were Palung Khola and Chitlang Khola sub-watersheds. Palung Khola sub-watershed covers about

62 km^2 and Chitlang Khola sub-watershed covers about 21.5 km^2. These two sub-watersheds cover about 71% of the total watershed area; total watershed area being about 117.2 km^2. The gauging station in Palung Khola watershed was located at Tashar and in Chitlang Khola at Markhu. The sediment measurement was made for the year 2004 for four rainfall months during monsoon season when there is high sediment flux in the river expected due to heavy rainfall.

These months for which the measurement was made were June, July, August and September, 2004. This time was selected since it is monsoon time in Nepal and the major part of the flow as well as sediment load are expected to be transported by rivers during this time (Sangroula, 2005). *Table* 3.8 and *Table 3.9* shows the average monthly discharge and sediment concentration measured at Palung and Chitlang for the year 2004.

Table 3.8 Average monthly observed discharge and sediment concentration measured at Palung Khola

Palung Khola (2004)		
Month	Average Monthly Discharge (m^3/s)	Suspended Sediment Load (tonnes/month)
June	2.72	208
July	21	8335
August	1.67	106
September	3.82	326

Table 3.9 Average monthly observed discharge and sediment concentration measured at Chitlang Khola

Chitlang Khola (2004)		
Month	Average Monthly Discharge (m^3/s)	Suspended Sediment Load (tonnes/month)
June	0.51	7.1
July	3.39	779
August	1.19	75
September	0.6	76

A summary of all data types and sources used for Kulekhani watershed is presented in *Table 3.10* below.

Table 3.10 Types and sources of data for Kulekhani watershed

SN	Data type	No. of stations	Data availability	% missing	Source	Resolution	
						Spatial	Temporal
1	Rainfall	3	1972-2013	6.13 - 23.1	DHM	-	Daily
2	Temperature	1	1972-2013	0.4	DHM	-	Daily
3	Flows	1	2007-2009	0		-	Daily
4	DEM	-	2010	-	SRTM	30 m	-
5	Land use	-	2010	-	GLCC	1 km	-
6	Soil	-	2004	-	FAO/ NP_SOTER	1:50,000	-
7	Sediment	2	2004	0	Sangroula (2005)	-	Daily for four months

NOTE: DEM: Digital Elevation Model; DHM: Department of Hydrology and Meteorology; SRTM: Shuttle Radar Topographic Mission; GLCC: Global Land Cover Characterization; FAO: Food and Agricultural Organization; NP_SOTER: Nepal Soil and Terrain Database

4. Methods

4.1 Introduction

The conceptual framework followed to accomplish this work can be described as follows. The first and foremost important step is setting the project objective. This is the driving force and the target to be accomplished during the course of the project work. The next step is determining the model to be used for the project. For this specific project the SWAT (Soil and Water Assessment) model was selected. The reason for the selection of the SWAT model was that SWAT model is physically distributed and continuous time developed to predict the impact of land management practices on water, sediment and agricultural chemical yields from a watershed. After the objective is set and the suitable model is selected, the necessary data required to run the model was collected and prepared as to the requirement of the SWAT model format. The geospatial data such as the digital elevation map, land use/land cover map, soil map and the hydro-meteorological data such as the daily stream flow data (2007-2009), daily rainfall data (1972-2013), maximum and minimum daily air temperature data and sediment load/concentration data are all collected and processed as per the input requirement format of the model. The conceptual framework of the steps followed during the course of this project is shown below.

- Set objective
  Clearly specify the aim of the research
  List all tasks to be done to reach the aim of the research
- Data collection and preparation
  Collect all necessary data required for the model to run
  Prepare the collected data as per the requirement of the model (model input format)
- Import prepared data in to the model
- Model set up and run
  Delineate the watershed
  Create HRUs
  Model Setup
  Run the Model
- Sensitivity analysis
  Identify Sensitive parameters prior to calibration to save time during calibration

- Calibration and validation

  Calibrate the model for better prediction of the observed value

  Validate the model outside the calibration period to see if the model is applicable

4.2 SWAT Model Description

The SWAT (Soil and Water Assessment Tool, Arnold et al., 1998) model is a river basin model developed by US Department of Agriculture - Agricultural Research Service (ARS) in Temple, Texas. The SWAT model is a physically based, continuous time, long term simulation, lumped parameter, deterministic, and originated from agricultural models with spatially distributed parameters operating on a daily time steps (Arnold et al., 1995; Santhi et al., 2001). SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins) (Williams et al., 1985). Specific models that contributed significantly to the development of SWAT were CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984).

SWAT is an operational or conceptual model that operates on a daily time step. The main objective of model development was to predict the impact of land management practices on water, sediment and agricultural chemical yields (nutrient loss) in large and complex watersheds with varying soils, land uses and management conditions over a long period of time (Arnold et al., 1998; Santhi et al., 2001; Arnold and Fohrer, 2005; Behera and Panda, 2006; Gassman et al., 2007; Neitsch et al., 2011). To satisfy the intended objective, the model (a) is physically based (calibration is not possible on ungauged catchments); (b) uses readily available inputs; (c) is computationally efficient to operate on large basins in a reasonable time; and (d) is continuous in time and capable of simulating long periods for computing the effects of management changes (Neitsch et al., 2005, 2011). Therefore, the model is a computationally efficient simulator of hydrology and water quality at various scales. The model is semi-physically based, and allows simulation of a high level of spatial detail by dividing the watershed into large number of sub-watersheds (Abbaspour et al., 2007). It includes procedures to describe how CO_2 concentration, precipitation, temperature and humidity affect plant growth. It also simulates evapotranspiration, snow and runoff generation, and is used to investigate climate change impacts (Abbaspour et al., 2009).

A command structure is used for routing runoff and chemicals through a watershed. Commands are included for routing flows through streams and reservoirs, adding flows, and inputting measured data on point sources. Using the routing command language, the model can simulate a basin sub-divided into sub-watersheds and further into hydrological Response units (HRUs) (Arnold et al., 1998).

4.2.1 Model Components

SWAT includes the effects of weather, surface runoff, evapotranspiration, irrigation, sediment transport, nutrient yielding, groundwater flow, crop growth, pesticide yielding, water routing and the long term effects of varying agricultural management practices (Neitsch et al., 2011). The subbasin/sub-watershed components of SWAT can be classified into eight major components - hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (*Figure 4.1*). Each of the components are described below.

Hydrology: The hydrology component of the SWAT model is based on water balance equation. The water balance in the SWAT model relates soil water, surface runoff, interception, daily amount of precipitation, evapotranspiration, percolation, lateral subsurface flow, return flow or base flow, snow melt, transmission losses and ponds. The percolation and return flow or base flow considered in SWAT for hydrological modelling is only the percolation to shallow aquifer from vadose zone and base flow to the channel from the shallow aquifer. The groundwater flow from deep aquifer is not considered because the water that enters the deep aquifer is assumed to contribute to the stream flow somewhere outside the watershed. According to (Arnold et al., 1993), the water in the stream is contributed by surface runoff, lateral flow from soil profiles and return flow/base flow from shallow aquifer. The water percolated to the deep aquifer is assumed to be lost from the watershed system and is not included in the water balance (Neitsch et al., 2011).

Weather: The weather variables required to run the SWAT are precipitation, air temperature, relative humidity, wind speed and solar radiation. These variables can be entered directly in to the SWAT model as daily or sub-daily values.

Sediment: SWAT generates the sediment from the watershed using Modified Universal Soil Loss Equation (MUSLE).

Soil Temperature: Soil temperature is important for movement of water through the soil since water cannot flow through the frozen soil.

Therefore, for the water to infiltrate through the soil layers and all the way to saturated zone, the soil temperature must be above the freezing point. Daily average soil temperature is calculated at the soil surface and the centre of each layer (Neitsch et al., 2011).

Crop Growth/Plant Growth/Land Cover: This SWAT component is a simplified version of the EPIC (Erosion-Productivity Impact factor) plant growth model. As in EPIC, the phenological plant development in SWAT, is based on daily accumulated heat units, Monteith's method for potential biomass, a harvest index to calculate yield, and plant growth can be inhibited by temperature, water, nitrogen or phosphorus stress (Neitsch et al., 2011).

Nutrients: SWAT tracks the movement of different forms of Nitrogen and Phosphorus in the watershed. These nutrients are very important for plant growth. Amounts of $NO_3 - N$ contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the soil layer. The amount of soluble phosphorous (P) removed in runoff is predicted using solution P concentration in the top 10 mm of soil, the runoff volume and a partitioning factor (Neitsch et al., 2011).

Pesticides: In SWAT, the movement of pesticides in to the stream network by runoff and percolation (in solution form) is modelled by equations adopted from GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Neitsch et al., 2011).

Agricultural Management: For the computation SWAT uses physically based inputs such as weather variables (precipitation, air temperature, relative humidity, wind speed and solar radiation), soil types and properties, topography, and land use/land cover of the catchment under study and directly models all the processes associated with water flow, sediment transport, crop growth and nutrient cycling, etc. (Arnold and Fohrer, 2005; Arnold et al., 1998).

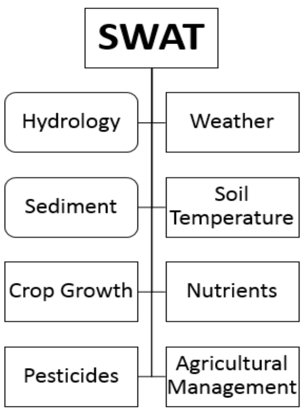


Figure 4.1 Main components of SWAT model

In this study, the ArcSWAT2012 was used, where the ArcGIS (version 10.2) environment was used for project development. Spatial parametrization of the SWAT model was performed by dividing a watershed into subbasins based on topography, soil, land use, and slope. This sub-division resulted in a smallest spatial unit in a watershed. This units, referred to as hydrologic response units (HRUs), are used as the basis of the water balance calculation. Water, sediment, and nutrient transformations and losses were determined for each HRU, aggregated at the subbasin level, and then routed to the associated reach and catchment outlet through the channel network (Abbaspour et al., 2009).

Some of the advantages of the SWAT model includes: modelling of ungauged catchments, prediction of the relative impacts of scenarios (alternative input data) such as changes in management practices, climate, vegetation on water quality, quantity or other variables (Mulungu and Munishi, 2007).

4.3 Hydrological processes in SWAT

SWAT allows a number of different physical processes to be simulated in a watershed (Neitsch et al., 2011).SWAT simulates various hydrological processes. The simulated processes include surface runoff, infiltration, evapo-transpiration (ET), lateral flow, percolation to shallow and deep aquifers and channel routing (Arnold et al., 1998). All these hydrological processes are simulated in surface, soil, and intermediate (vadose) zone, shallow and deep aquifers. Among the aforementioned hydrological processes, surface runoff, subsurface or lateral flow and return flow or baseflow contributed to stream flow in the main channel. As it was described earlier the water that enters the deep aquifer is assumed to be lost out of the system of the watershed under study. In SWAT, the local water balance is represented through four storage volumes. These storage volumes are: snow, soil profile (0-2 m), shallow aquifer (2-20 m) and deep aquifer storage (>20 m) (Abbaspour et al., 2009). Since there was no significant snow fall in the catchment no process related to snow was considered in this study.

SWAT has a weather simulation model that generates daily data for rainfall, solar radiation, relative humidity, wind speed and temperature from the average monthly variables of these data. This provides a useful tool to fill in missing daily data in the observed records.

SWAT first delineates a basin or a watershed and then, a basin is delineated into sub-basins, which are then further subdivided into hydrologic response units (HRUs). In this sub-division SWAT considers spatial variations in topography, land use, soil and other watershed characteristics.

Hydrologic Response Units (HRUs) are lumped land areas within the subbasin that are comprised of unique land cover, soil and management combinations (Neitsch et al., 2011) and based on two options in SWAT, they may either represent different parts of the subbasin area or subbasin area with a dominant land use or soil type (also, management characteristics). Therefore, each HRU is assumed to be spatially uniform in terms of slope, land use, soil type and climate. With this semi-distributed (subbasins) set-up, SWAT is attractive for its computational efficiency as it offers some compromise between the constraints imposed by the other model types such as lumped, conceptual or fully distributed, physically based models. A full model description and operation is presented in (Neitsch et al., 2011).

No matter what type of problem studied with SWAT, water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of pesticides, sediments or nutrients, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed. Simulation of the hydrology of a watershed can be divided in to two major divisions. (1) The land phase of the hydrologic cycle and (2) the water or routing phase of the hydrologic cycle. The first division controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. And, the second division is related to the movement of water, sediments, nutrient and pesticide through the channel network of the watershed to the outlet (Neitsch et al., 2011).

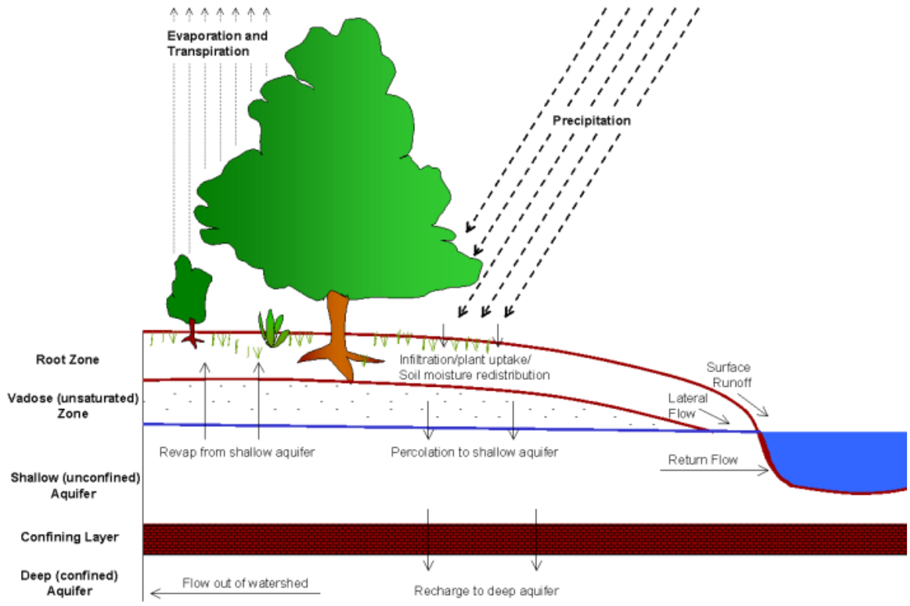


Figure 4.2 Schematic representation of the hydrologic cycle (adopted from Neitsch et al., 2011)

4.3.1 Land Phase of the Hydrologic Cycle

The hydrologic cycle simulated by SWAT is based on the water balance equation.

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right)$$

Where: SW_t -is the final soil water content (mm H_2O),

SW_0 -is the initial soil water content on day *i* (mm H_2O),

t -is the time (days),

R_{day} -is the amount of precipitation on day *I* (mm H_2O),

Q_{surf} -is the amount of surface runoff on day *i* (mm H_2O),

E_a -is the amount of evapotranspiration on day *I* (mm H_2O),

W_{seep} -is the amount of water entering the vadose zone from the soil profile on day *I* (mm H_2O), and

Q_{gw} -is the amount of return flow on day *I* (mm H_2O).

The subdivision of the watershed into sub-watersheds and further into HRUs enables the model to reflect the differences in evapotranspiration for various crops or land covers and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases the accuracy and gives much better physical description of the water balance.

4.3.1.1 Climate

Climatic variables among the most important variables required by SWAT to model the land phase of the hydrologic cycle. The climatic variables required by SWAT consist of daily precipitation, maximum/minimum daily air temperature, solar radiation, wind speed and relative humidity. The model allows values for daily precipitation, maximum/minimum air temperatures, solar radiation, wind speed and relative humidity to be input by the user form records of observed data or generated during simulation.

Weather Generator

If there is no daily values for weather, SWAT generates from average monthly values. The model generates a set of weather data for each subbasin.

The values for any subbasin will be generated independently and there will be no spatial correlation of generated values between the different sub basins. Precipitation, temperature, wind speed, solar radiation and relative humidity of a given station in the watershed are generated in this way.

For this study the daily measured precipitation and air temperature from 1972 - 2013 was used as input and the other variables were generated by SWAT.

SWAT uses a model developed by Nicks (1974) to generate any missing data in the measured records. The precipitation generator uses a first-order Markov chain model to define a day as wet or dry by comparing a random number (0.0 – 1.0) generated by the model to monthly wet-dry probabilities input by the user. If the day is classified as wet, the amount of precipitation is generated from skewed distribution or a modified exponential distribution (Neitsch et al., 2011).

Maximum and minimum air temperatures and solar radiation are generated from a normal distribution. A continuity equation is incorporated into the generator to account for temperature and radiation variations caused by dry and rainy conditions (Neitsch et al., 2011).

Snow

SWAT classifies precipitation as rain or freezing rain/snow using the average daily temperature (Neitsch et al., 2011). Snow is not significant in the watershed of study and was not considered in this study.

Soil temperature

The temperature of the soil affects the movement of water through the soil and the decay rate of the residue in the soil. Daily average soil temperature is calculated at the soil surface and centre of each soil layer (Neitsch et al., 2011).

4.3.1.2 Hydrology modelling

As the rain descends, it may be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as surface runoff. Runoff moves relatively quickly toward a stream channel and contributes to short term stream response. Infiltrated water may be held in the soil profile and later evapo-transpired or it may slowly make its way to the surface water system through underground paths (Neitsch et al., 2011).

4.3.1.2.1 Surface Runoff/overland Flow

Surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration (Neitsch et al., 2011). When water is initially applied to a dry soil, the infiltration rate is usually very high. However, it will decrease as the soil becomes wetter. When the rate of application is higher than the infiltration rate, surface depressions begin to fill. If the application rate continues to be higher than the infiltration rate once the all surface depressions have filled, surface runoff will commence (Neitsch et al., 2011). SWAT provides two methods for estimating the surface runoff: the SCS curve number procedure (SCS, 1972) and the Green and Ampt infiltration method (Green and Ampt, 1911).

The SCS curve number is a function of the soil's permeability, land use and antecedent moisture conditions (SCS, 1972) whereas the Green and Ampt infiltration method calculates infiltration as a function of the wetting front metric potential and effective hydraulic conductivity (Green and Ampt, 1911). SWAT uses the daily and hourly time steps to calculate surface runoff. For daily time steps, SWAT uses an empirical SCS curve number (CN) method and for daily time steps SWAT uses the Green and Ampt equation.

For this project the SCS curve number was adopted for the simulation of surface runoff in SWAT since it requires the readily available daily data that can be obtained from easily from government ministries and/or offices.

The SCS curve number equation is (SCS, 1972):

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \qquad [4.5]$$

Where Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O), R_{day} is the rainfall depth for the day (mm H_2O), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), and S is the retention parameter (mm H_2O). The retention parameter varies spatially due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad [4.6]$$

Where CN is the curve number for the day. The SCS curve number is a function of the soil's permeability, land use and antecedent moisture conditions: 1 – dry (wilting point), 2 – average moisture, and 3 – wet (field capacity).

The moisture condition 1 curve number is the lowest value that the daily curve number can assume in dry conditions. The curve numbers 2 and 3 are calculated from equations 4.3 and 4.4 below.

$$CN_1 = CN_2 - \frac{20*(100 - CN_2)}{\left(100 - CN_2 + \exp\left[2.533 - 0.0636*\left(100 - CN_2\right)\right]\right)} \qquad [4.7]$$

$$CN_3 = CN_2 * \exp\left[0.00673*\left(100 - CN_2\right)\right] \qquad [4.8]$$

Where, CN_1 is the moisture condition 1 curve number, CN_2 is moisture condition 2 curve number, and CN_3 is the moisture condition 3 curve number (Neitsch et al., 2011).

The initial abstractions, I_a, is commonly approximated as $0.2S$ and the above equation above becomes

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} + 0.8S\right)} \qquad [4.9]$$

Referring to the above equations, runoff will occur when $R_{day} > I_a$. Therefore, there is some amount of rainfall I_a (initial abstraction before ponding) for which no runoff will occur (i.e., runoff is zero) (Chow et al., 1998).

The peak runoff rate is the maximum is the maximum runoff rate that occurs with a given rainfall event (Neitsch et al., 2011). The peak runoff rate is an indicator of the erosive power of a storm and is used to predict sediment loss. SWAT uses a modified rational method to calculate the peak runoff rate.

$$q_{peak} = \frac{\alpha_{tc} Q_{surf} Area}{3.6 t_{conc}} \qquad [4.10]$$

Where, q_{peak} is the peak runoff rate (m^3/s), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm), Area is the subbasin area (km^2), t_{conc} is the time of concentration for the subbasin (hr) and 3.6 is a unit conversion factor.

4.3.2 Routing Phase of the Hydrologic Cycle

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972). In addition to keeping track of mass flow in the channel, SWAT models the transmission of chemicals in the stream and streambed.

SWAT routes water, sediment, nutrients and organic chemicals in the main channel. In this study attention had been given on the first two: water and sediment processes in the main channel. SWAT provides two methods routing (Neitsch et al., 2011):

a) Variable storage method, and
b) The Muskingum river routing method

Both Variable Storage and Muskingum routing methods are variations of the kinematic wave model. A detailed discussion of the kinematic wave flood routing model can be found in Chow et al. (1988). Since there is no reservoir considered in this study, Muskingum River routing method was adopted to model the storage volume in channel length as a combination of wedge and Prism storages.

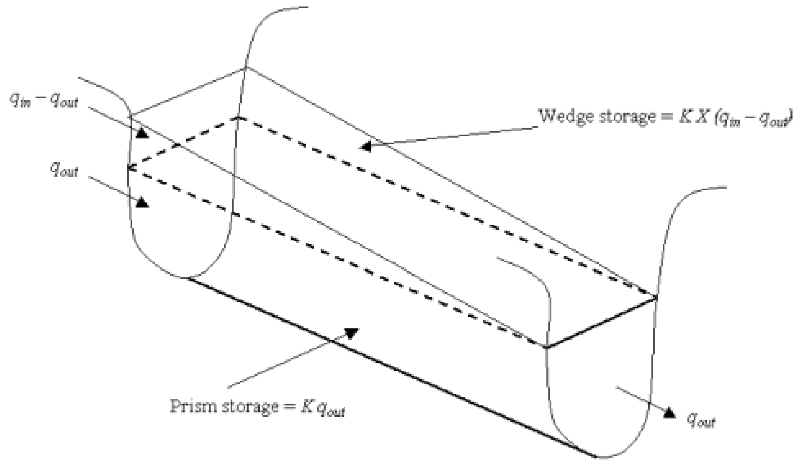


Figure 4.3 Prism and wedge storages in a reach segment (After Chow et al., 1988) (Adopted from Neitsch et al., 2011)

SWAT assumes the main channels, or reaches, have a trapezoidal shape. Therefore, Manning's equation for uniform flow in a trapezoidal channel was used to calculate the rate and velocity of flow in a reach segment for a given time step.

$$q_{ch} = \frac{A_{ch} * R_{ch}^{2/3} * slp_{ch}^{1/2}}{n} \quad [4.11]$$

$$v_c = \frac{R_{ch}^{2/3} * slp_{ch}^{1/2}}{n} \quad [4.12]$$

Where, q_{ch} is the rate of flow in the channel (m^3/s), A_{ch} is the cross-sectional area of the channel (m^2), R_{ch} is the hydraulic radius for a given depth of flow (m), slp_{ch} is the slope along the channel length (m/m) n is manning's coefficient for the channel, and v_c is the flow velocity (m/s).

SWAT routes water as a volume.

Manning's equation shows that there is a direct relationship between the cross-sectional area of flow and the discharge for a given reach segment. This assumption is used to express the volume of prism storage (*Figure 4.3*) as a function of the discharge,

$$V_{prsm} = K * q_{out} \quad [4.13]$$

Where, K is the ratio of storage to discharge and has the dimension of time. Similarly, the volume of wedge storage (*Figure 4.3*) can be expressed as,

$$V_{wdg} = KX(q_{in} - q_{out}) \quad [4.14]$$

Where, X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach. The total storage in a reach segment will be the sum of prism storage and wedge storage and expressed by equation,

$$V_{stored} = V_{prsm} + V_{wdg} = K * q_{out} + KX(q_{in} - q_{out}) \quad [4.15]$$

Where, V_{stored} is the storage volume (m^3), q_{in} is the inflow rate (m^3/s), q_{out} is the discharge or outflow rate (m^3/s), K and X as expressed above. Rearranging equation 4.11,

$$V_{stored} = K * (X * q_{in} + (1 - X) * q_{out}) \quad [4.16]$$

The waiting factor, X varies from 0.0 – 0.5 and it is a function of the wedge storage. The value of X depends on the type of storage.

For instance, reservoir-type storage does not have wedge and the value of X is 0.0 and for a full wedge, X =0.5. For rivers, the value of X falls between 0.0 and 0.3.

Considering a time step of Δt, the following simplified continuity equation known as Muskingum equation can be obtained.

$$q_{out,2} = C_1 * q_{in,2} + C_2 * q_{in,1} + C_3 * q_{out,1} \qquad [4.17]$$

Where, $q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s), $q_{in,2}$ is the inflow rate at the end of the time step (m^3/s), $q_{out,1}$ is the outflow rate at the beginning of the time step (m^3/s), $q_{out,2}$ is the outflow rate at the end of the time step (m^3/s), and

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \qquad [4.18]$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t}$$

Where, $C_1 + C_2 + C_3 = 1$. To maintain numerical stability and avoid the computation of negative outflows, the following condition must be met:

$$2KX < \Delta t < 2K(1-X) \qquad [4.19]$$

4.3.2.1 Soil Hydrologic Group

The U.S. Natural resource Conservation Service (NRCS) classifies soils into four hydrologic groups based on infiltration characteristics of the soils. NRCS Soil Survey Staff (1996) defines a hydrologic group as a group of soils having similar runoff potential under similar storm and cover conditions. Soil properties that influence runoff potential are those that impact the minimum rate of infiltration for a bare soil after prolonged wetting and when not frozen. This properties are depth to seasonally high water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer. Soil may be placed in one of four groups, A, B, C, and D, or three dual classes, A/D, B/D, and C/D (Neitsch et al., 2011). These soil hydrologic groups are defined below.

A: (Low runoff potential). Soils in this group have high infiltration rate even when thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.

B: The soils have a moderate infiltration rate when thoroughly wetted. They mainly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.

C: The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.

D: (High runoff potential): The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have high swelling potential, soils that have a permanent water table, soils that have a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow rate of water transmission.

Dual hydrologic groups are given for certain wet soils that can be adequately drained. The first letter applies to the drained condition, the second to the undrained. Only soils that are rated D in their natural condition are assigned to dual classes.

The soil type of the watershed of study is called Cambisol, and also known as Inceptisol in SSURGO (Soil Survey Geographic database) soil database. This soil is grouped under soil class B and has five layers. This soil was used in the HRU definition.

Properties of Cambisols

FAO coined the name ‘Cambisols’, and USDA (U.S. Department of Agriculture) Soil Taxonomy classifies these soils as ‘Inceptisols’. The parent material of Cambisols are medium and fine-textured materials derived from a wide range of rocks, mostly in colluvial, alluvial or eolian deposits. They are characterized by slight or moderate weathering of parent material and by absence of appropriate quantities of illuviated clay, organic matter, aluminium and/iron compounds. They can be found at level to mountainous terrain in all climates; wide range of vegetation types. Cambisol has an ABC-horizon sequence with an ochric, mollic or umbric A-horizon over a cambic B-horizon. The soil texture is loamy to clayey with high clay content in A-horizon.

4.3.2.2 Potential Evapotranspiration (PET)

There are numerous methods that have been developed to calculate potential evapotranspiration (PET). The SWAT model provides three of those methods to estimate the potential evapotranspiration: the Penman-Monteith method (Monteith, 1965), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985).

Among the aforementioned methods, Hargreaves method was selected for PET calculation in this study. The reason for this is that Hargreaves method requires only daily records of maximum/minimum air temperature to estimate PET. Since there are no measured solar radiation, wind speed and relative humidity for this watershed, Hargreaves method was found appropriate and used in SWAT to estimate PET. The other two methods need measured solar radiation, wind speed and relative humidity data to estimate PET.

The form of Hargreaves equation used in SWAT was published in 1985 (Hargreaves et al., 1985):

$$\lambda E_o = 0.0023 * H_o (T_{mx} - T_{mn})^{0.5} * (\overline{T}_{av} + 17.8) \qquad [4.20]$$

Where, λ is the latent heat of vaporization ($MJ\ kg^{-1}$), E_o is the potential evapotranspiration ($mm\ d^{-1}$), H_o is the extra-terrestrial radiation ($MJ\ m^{-2} d^{-1}$), T_{mx} is the maximum air temperature for a given day (^oC), T_{mn} is the minimum air temperature for a given day (^oC), and $\overline{T}_{av}$ is the mean air temperature for a given day (^oC).

4.4 Sediment modelling

4.4.1 Introduction

For a watershed in which erosion and sedimentation process is significant, it is important to identify the source erosion and what causes it. Identifying the source of erosion helps to apply different management practices to reduce the erosion rate. In addition to this, it is also very crucial to identify which erosion type is significant in the watershed of interest so that the correct and suitable erosion model can be applied. In this study since there was a time limitation to conduct field investigation to the watershed of study, it aimed at applying SWAT (Soil and Water Assessment Tool) model to simulate the sediment yield from Kulekhani watershed. Therefore, a semi-distributed, physics-based watershed model, Soil and Water Assessment Tool (SWAT) model was used for this study to quantify the sediment yield from the watershed of study.

SWAT uses a Modified Universal Soil Loss Equation (MUSLE) developed by Williams (1975) to simulate sediment yield from the upland watersheds. MUSLE is a modified version of Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978) (Neitsch et al., 2011).

$$Sed = 1.292 EI_{USLE} K_{USLE} C_{USLE} P_{USLE} LS_{USLE} CFRG \quad [4.21]$$

Where, Sed is the sediment yield on a given day (metric tons/ha), EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-mertic 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 coarse fragment factor. The value of EI_{USLE} for a given rainstorm is the product, total storm energy (E_{storm}) times the maximum 30 minutes intensity (I_{30}). The storm energy indicates the volume of rainfall and runoff, while the 30 minutes intensity indicates the prolonged peak rates of detachment and runoff (Neitsch et al., 2011).

$$Sed = 11.8 \left(Q_{surf} q_{peak} Area_{hru} \right)^{0.56} K_{USLE} C_{USLE} P_{USLE} LS_{USLE} CFRG \quad [4.22]$$

Where, Q_{surf} is the surface runoff volume (mm), q_{peak} is the peak runoff rate (m^3/s), $Area_{hru}$ is the area of the HRU (ha), and the other variables in the equation carries the same meaning as described in USLE equation. The equation for surface runoff and peak rate was discussed under hydrologic modelling topic earlier.

USLE predicts the average annual gross erosion as a function of rainfall energy. Whereas in MUSLE the rainfall energy is replaced with a runoff factor which improves the sediment yield prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events (Neitsch et al., 2011). Sediment yield prediction is improved because runoff is a function of antecedent moisture condition as well as rainfall energy (Neitsch et al., 2011). Delivery ratios (the sediment yield at any point along the channel divided by the source erosion above that point) are required by the USLE because the rainfall factor used by USLE represents energy used in detachment only.

Delivery ratios are not needed with MUSLE because the runoff factor represents energy used in detaching and transporting sediment (Neitsch et al., 2011). The detail of equations used to calculate K_{USLE}, C_{USLE}, P_{USLE}, LS_{USLE}, and $CFRG$ can be found in Neitsch et al (2011).

4.4.2 Sediment routing

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach (Neitsch et al., 2011). There are two options in SWAT to compute deposition and degradation in the reach. The first and traditional way is to keep the channel dimensions constant so that SWAT will compute deposition and degradation using the same channel dimensions throughout the simulation and the second is to activate channel degradation and allow channel dimensions to change and updated us a result of down cutting and widening (Neitsch et al., 2011). When channel down cutting and widening is simulated, channel dimensions are allowed to change during simulation period. Three channel dimensions are allowed to vary in channel down cutting and widening simulations: bankfull depth, channel width and channel slope. Channel dimensions are updated when the volume of water in the reach exceeds $1.4*10^6\,m^3$ (Neitsch et al., 2011). In this study the former option was adopted in channel routing since the latter option is still in the testing phase.

4.4.3 Landscape contribution to subbasin routing reach

From the landscape component, SWAT keep tracks of the particle size distribution of eroded sediments and routes them through ponds, channels, and surface waterbodies (Neitsch et al., 2011). The sediment yield from the landscape is lagged and routed through grassed waterway, vegetative filter strips, and ponds, if available, before reaching the stream channel. Thus, the sediment yield reaching the stream channel is the sum of total sediment yield calculated by MUSLE minus the lag, and the sediment trapped in grassed waterway, vegetative filter strips and/or ponds (Neitsch et al., 2011). There was no pond considered in this watershed of study.

4.4.4 Sediment routing in stream channels

Sediment routing is the function of peak flow rate and mean daily flow. When the watershed was delineated into smaller subbasin, each subbasins has at least one main routing reach. Therefore, the sediment from upland subbasins is routed through these reaches and then added to downstream reaches. To do this, SWAT uses the simplified version of Bagnold equation (Bagnold, 1977) and the maximum amount of sediment that ca be transported from a reach segment is a function of the peak channel velocity (Neitsch et al., 2011).

$$conc_{sed,ch,mx} = Csp * v_{ch,pk}^{\ sp\exp} \qquad [4.23]$$

Where, $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by water $(ton/m^3$ or $kg/L)$, Csp and $sp\exp$ are coefficient and exponent of the equation defined by the user, and $v_{ch,pk}$ is the peak channel velocity (m/s). The exponent $sp\exp$ normally varies from between 1.0 and 2.0 and was set at 1.5 in the original Bagnold stream power equation (Arnold et al., 1995). But, in SWAT2012 the value of this exponent varies between 1.0 and 1.5.

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \qquad [4.24]$$

Where, $q_{ch,pk}$ is the peak flow rate (m^3/s) and A_{ch} is the cross-sectional area of flow in the channel (m^2).

$$q_{ch,pk} = prf * q_{ch} \qquad [4.25]$$

Where, prf is the peak rate adjustment factor, and q_{ch} is the average rate of flow (m^3/s).

The routing in the river reach starts off by comparing the maximum concentration of sediment calculated with equation (4.19) above to the concentration of sediment in the reach at the beginning of the time step, $conc_{sed,ch,i}$. If $conc_{sed,ch,i} > conc_{sed,ch,mx}$, deposition is the dominant process in the reach segment and the net amount of sediment deposited is calculated as in equation (4.26) below.

$$sed_{dep} = (conc_{sed,ch,i} - conc_{sed,ch,mx}) * V_{ch} \qquad [4.26]$$

Where, sed_{dep} is the amount of sediment re-entrained in the reach segment (metric tons), V_{ch} is the volume of water in the reach segment (m^3). On the other hand, if $conc_{sed,ch,i} < conc_{sed,ch,mx}$, degradation is the dominant process in the reach segment and the net amount of sediment re-entrained is calculated as in equation (4.23).

$$sed_{\deg} = (conc_{sed,ch,mx} - conc_{sed,ch,i}) V_{ch} * K_{CH} * C_{CH} \qquad [4.27]$$

Where, sed_{dep} is the amount of sediment re-entrained in the reach segment (metric tons), K_{CH} is the channel erodibility factor $(cm/hr/pa)$, and C_{CH} is the channel cover factor.

The channel erodibility factor is conceptually similar to the soil erodibility factor used in the USLE equation (Neitsch et al., 2011). Channel erodibility is a function of properties of the bed or bank materials (Neitsch et al., 2011). The detail discussion of factors are found in Neitsch et al., (2011). In general, values for channel erodibility are an order of magnitude smaller than values for soil erodibility (Neitsch et al., 2011). The channel cover factor can be defined as the ratio of degradation from a channel with a specified vegetation cover to the corresponding degradation from a channel with no vegetation cover (Neitsch et al., 2011). The vegetation affects degradation by reducing the stream velocity, and consequently its erosive power, near the bed surface (Neitsch et al., 2011).

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined by equation (4.24),

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{\deg} \qquad [4.28]$$

Where, sed_{ch} is the amount of suspended sediment in the reach (metric tons), $sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (metric tons), sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and $sed_{\deg}$ is the amount of sediment re-entrained in the reach segment (metric tons).

Thus, the amount of sediment transported out of the reach is calculated using equation (4.25),

$$sed_{out} = sed_{ch} . \frac{V_{out}}{V_{ch}} \qquad [4.29]$$

Where, sed_{out} is the amount of sediment transported out of the reach (metric tons), V_{out} is the volume of outflow during the time step (m^3), and V_{ch} is the volume of water in the reach segment (m^3).

SWAT incorporates a simple mass balance model to simulate the transport of sediment into and out of water bodies (ponds, wetlands, reservoirs and potholes) (Neitsch et al., 2011). In this study no wetlands and potholes are identified. But, in Kulekhani watershed, the Kulekhani reservoir is located at the outlet of the catchment.

This reservoir was not considered in the study as the area of interest for which the sediment yield is calculated located upstream of the reservoir. This study focusses on two major sub-watersheds in the catchment namely: Palung khola and Chitlang Khola.

4.5 Sensitivity Analysis, Calibration and Validation of SWAT Model

4.5.1 Sensitivity Analysis

A complex hydrologic model is generally characterized by a multitude of parameters (Holvoet et al., 2005). SWAT (Soil and Water Assessment Tool) is known to have a large number of parameters. Over-parameterization is a well-known and often described problem in hydrological models, especially for distributed models such as SWAT. SWAT input parameters are process based and must be held within a realistic uncertainty range. The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed or sub-watershed (Abbaspour, 2013). Therefore, methods to reduce the number of parameters via sensitivity analysis are important for the efficient use of these models (Van Griensven et al., 2006). Sensitivity analysis is a process of testing and identifying model parameters that affects most the output from the model when changed. In other words, sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters) (Abbaspour, 2013). A parameter sensitivity analysis provides insights on which parameters contribute most to the output variance due to input variability (Holvoet et al., 2005). Therefore, a parameter is considered sensitive when the change in that parameter causes large change on model output.

In general identifying sensitive parameters prior to model calibration helps to allow the possible reduction in the number of parameters that must be calibrated thereby reducing the computational time required for model calibration. Once the sensitivity analysis is done calibration can be performed for limited number of influential parameters.

The current version of SWAT model, SWAT2012, provides the algorithmic techniques for sensitivity analysis. Two types of sensitivity analysis are allowed when using SUFI2 (Sequential Uncertainty Fitting version 2). Global Sensitivity and One-at-a-time sensitivity analysis. The two aforementioned sensitivity analysis methods may yield different results since the sensitivity of one parameter depends on the value of other related parameters. In this study both local (OAT) and global sensitivity analysis were performed and the ranking of the parameters in both cases compared.

4.5.1.1 Local (one-at-a-time) sensitivity Analysis

The one-at-a-time (OAT) sensitivity analysis is performed for one parameter at a time only by keeping the value of other parameters constant. OAT sensitivity analysis shows the sensitivity of a variable to changes in a parameter if all other parameters are kept constant at some reasonable value. This constant value can be the value of parameters from the best simulation (simulation with the best objective function value) of the last iteration. The drawback with the OAT sensitivity analysis is that the correct value of other parameters that are fixed are never known (Abbaspour, 2013). The objective function used in this project for ranking of the parameters based on OAT sensitivity analysis was *the sum of the squares of the difference of the measured and simulated values after ranking (SSQR).* The SSQR method aims at the fitting of the frequency distributions of the observed and the simulated series (Abbaspour, 2013).

After independent ranking of the measured and the simulated values, new pairs are formed and the SSQR is calculated as

Minimize: $$SSQR = \frac{1}{n}\sum_{j=1}^{n}\left[Q_{j,m} - Q_{j,s}\right]^2 \quad [4.30]$$

Where, Q_m and Q_s are the measured and the simulated values.

4.5.1.2 Global sensitivity analysis

Global sensitivity analysis performs the sensitivity of one parameter while the value of other related parameters are also changing. Global sensitivity analysis uses t-test and p-values to determine the sensitivity of each parameters. The t-stat provides a measure of the sensitivity (larger in absolute values are more sensitive) and the p-values determine the significance of the sensitivity. A p-value close to zero has more significance. This type of sensitivity can be performed after an iteration. The main problem related to global sensitivity analysis is that it needs a large number of simulations (Abbaspour, 2013).

4.5.2 Model calibration and validation

Model calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions (Arnold et al., 2012).

Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate predictions. This implies the application of the calibrated model without changing the parameter values that were set during the calibration, when simulating the response for a period other than the calibration period (Refsgaard, 1997).

The model calibration and validation process were conducted by using the SUFI2 (Sequential Uncertainty Fitting Version 2 programme) in SWAT_CUP. SWAT_CUP is a computer programme for automatic calibration of SWAT models. The programme links SUFI2 procedures to SWAT. The auto-calibration procedure was supported by manual calibration for the values of parameters that were physically wrong. The values of parameters that are provided by SUFI2 during calibration as the best parameter value may not be physically correct or it may be outside recommended uncertainty range and needs to be adjusted manually to better match the existing situation.

The overall programme structure of SWAT_CUP is shown in *Figure 4.4* below. The programme shows that the parameters of SWAT model should be edited in SWAT model after each iteration using SUFI2 or other programme. The SWAT model should be updated with a new set of parameters and then run the SWAT model. After the model was run using the new set of parameters, the new SWAT output must be used for the nest iteration and so on.

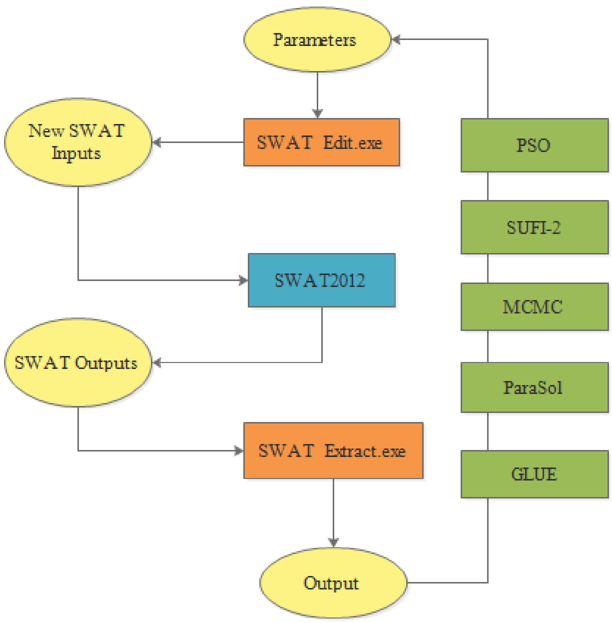


Figure 4.4 Overall programme structure of SWAT_CUP

4.5.3 Efficiency criteria

The systematic and dynamic behavior of the model can be visualized by plotting simulated flow and observed flow on the same coordinate system. By looking at the graph a modeler can understand whether the model over predicted or under predicted and also the timing of the rising and falling limb of the hydrograph and give subjective decision on the performance of the model. But, to quantitatively evaluate the model, we need mathematical measures of model performance.

Reasons to evaluate model performance (Krause et al., 2005),

1) To provide a quantitative estimate of the model's ability to reproduce historic and future watershed behavior;
2) To provide a means for evaluating improvements to the modelling approach through adjustment of model parameter values, model structural modifications, the inclusion of additional observational information, and representation of important spatial and temporal characteristics of the watershed;
3) To compare current modelling efforts with previous study results.

To assess the goodness-of-fit of the model, two methods were used during the calibration and validation periods. These are: coefficient of determination (R^2) and the Nash-Sutcliffe efficiency coefficient (NS). These two statistical parameters are used to measure the model performance.

4.5.3.1 Coefficient of determination (R^2)

The coefficient of determination R^2 measures the fraction of the variation in the measured data that is replicated in the simulated model results.

The coefficient of determination R^2 is defined as (Krause et al., 2005) the squared value of the coefficient of correlation and is given by equation 4.26.

$$R^2 = \frac{\left[\sum_i \left(Q_{m,i} - \overline{Q}_m\right)\left(Q_{s,i} - \overline{Q}_s\right)\right]^2}{\sum_i \left(Q_{m,i} - \overline{Q}_m\right)^2 \sum_i \left(Q_{s,i} - \overline{Q}_s\right)^2} \qquad [4.31]$$

Where, Q_m is the observed (measured) stream flow on day i (m^3/s), Q_s is the simulated stream flow on day i (m^3/s), and bars indicate averages.

The value of R^2 ranges from (0-1) where a value close to 1.0 indicates good performance (good correlation) of the model and the value close to 0.0 indicates poor performance (poor correlation) of the model. The main drawbacks of R^2 is that it only quantifies dispersion. A model which systematically over-or under-predicts all the time will still result in good R^2 values close to 1.0 even if all predictions were wrong (Krause et al., 2005). To avoid this ambiguity, it is advisable to use additional information which can cope with that problem.

4.5.3.2 Nash-Sutcliffe efficiency coefficient (NS)

The Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) is used to assess the predictive power of the hydrological models. The value of NS varies from 1.0 (perfect fit) to $-\infty$. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model (Krause et al., 2005). The NS value of 0.0 indicates that the model predictions are as accurate as the mean of the observed data. According to Krause et al, (2005) the major disadvantage of the Nash-Sutcliffe efficiency is the fact that the differences between the observed and simulated values are calculated as squared values. This leads to an over estimation of the model performance during peak flows and an under estimation during low flows.

The Nash-Sutcliffe efficiency (NS) is calculated using equation 4.27,

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i \left(Q_{m,i} - \overline{Q}_m\right)^2} \qquad [4.32]$$

This method is highly affected by a few extreme errors and it can be biased if a wide range of events is experienced.

4.6 Summary of methods

The methods used in this project are summarized below.

1. **Creation of database**
   Digital elevation model (DEM) was downloaded from SRTM and then projected to WGS1984 UTM Zone45N using the raster projection in ArcMap (http://earthexplorer.usgs.gov/). Then the projected DEM was edited to fill the 'no data' points using the raster editor. (There was a hole with no data in the original DEM map that needs editing)

Land use map that includes the study area was downloaded from GLCC (http://earthexplorer.usgs.gov/) and also projected to WGS1984 UTM Zone45N using the raster projection in ArcMap. Like the DEM, the land use map was also not representative of the area of study and it should be edited based on the existing land use of the catchment. Three land use classes were identified: Agriculture, Forest and Water body.

Soil map was also obtained from FAO and projected to the same coordinate system as above (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116). Only one soil type was identified for the whole watershed area for further analysis.

The precipitation and temperature data obtained from Department of Hydrology and Meteorology of Nepal was analyzed and processed as to the SWAT requirement format (the quality and quantity of data obtained was discussed in chapter 3)

2. **Model set up**

The first step in model set up was creating the new SWAT project in ArcSWAT. Then the projected DEM map was imported in to ArcSWAT. Next the area of interest was delineated by selecting a point at the outlet of the watershed and found to be 11721 ha. The drainage network, flow accumulation and flow direction all were automatically processed in ArcSWAT. A total 29 subbasin were delineated by SWAT for Kulekhani watershed.

Land use and soil map in Arcshape format were imported in to the ArcSWAT model for HRU analysis. Both the maps were classified in ArcSWAT. The land slope of the study area was also classified in to five slope classes and made to overlay with land use and soil maps to subdivide the study watershed into hydrologic response units (HRUs). Subdividing areas in to hydrologic response units enables the model to reflect the evapotranspiration and other hydrologic conditions for different land use, soils and slopes. The HRUs are the elementary units with unique land cover, soil and slope angle lumped together. A total of 318 HRUs (Appendix B) were defined for the whole catchment.

After HRUs are defined, the nest step in model set up is importing the climate data. Climate data is one of the main sets of input for simulating the hydrological processes in SWAT. Precipitation and temperature data was the only climate data available for use. These available climate data were prepared in text (.txt) format and imported in to the SWAT model. Then the SWAT input tables were written into the model.

Some SWAT input files were edited before the model was run for simulation. Soil parameters were also edited. The statistical parameters of daily precipitation and minimum and maximum daily temperature were also edited.

Hargreaves mothed was selected for calculating the potential evapotranspiration since it needs only daily minimum and maximum air temperature, SCS curve number was chosen to calculate surface runoff, initial curve number was estimated using soil moisture method, and Muskingum method was selected for channel routing.

Finally, the model was run for the year 2000 to 2010 by fixing the warm up period of three years. The warm up period of (3-5) years is generally recommended for SWAT model to reach at hydrological equilibrium.

5 Results and Discussion

5.1 Sensitive Parameters

The sensitivity analysis was done for flow and sediment separately since some parameters are sensitive to both flow and sediment, some sensitive to flow only and others sensitive to sediment only (Abbaspour et al., 2007). Therefore, it is wise to test the sensitivity of the parameters for flow and sediment separately. Sensitivity analysis was carried out before calibrating the model to save time during calibration. Identifying sensitive parameters enables us to focus only on those parameters which affect most the model output during calibration since SWAT model has a number of parameters to deal with. Some parameters does not have any influence on the model output while some may have little effect.

5.1.1 Parameters sensitive to flow

The 21 parameters listed in *Table 5.11* were used in sensitivity analysis. These parameters are used to calculate the amount of flow from the watershed. The parameter identification was done by using the daily flow data from 2007 to 2008. *Table 5.11* shows all the parameters used in the sensitivity analysis for flow calibration.

Table 5.11 List of parameters used in flow sensitivity analysis

S/NO	Parameter	Description of Parameters	Range of value
1	CN2	SCS runoff curve number	35 – 98
2	surlag	Surface runoff lag time	1 – 24
3	SOL_Z	Soil depth (for each layer)	0 – 3500
4	SOL_AWC	Available water content of soil	0 – 1
5	SOL_K	Saturated hydraulic conductivity (mm/hr)	0 – 2000
6	SOL_BD	Moist bulk density	0 – 0.25
7	GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur	0 – 5000
8	GW_REVAP	Groundwater revap coefficient	0 – 0.2
9	GW_DELAY	Groundwater delay	0 – 500
10	REVAPMN	Threshold depth of water in the shallow aquifer for revap to occur	0 – 1000
11	RCHRG_DP	Deep aquifer percolation fraction	0 – 1
12	ALPHA_BF	Baseflow alpha factor	0 – 1
13	SLOPE/HRU_SLP	Average slope steepness	
14	SLSUBBSN	Average slope length	10 – 150
15	ESCO	Soil evaporation compensation factor	0 – 1
16	EPCO	Plant uptake compensation factor	0 – 1
17	CH_N2	Manning's "n" value for the main channel	-0.01 – 0.3
18	CH_K2	Effective hydraulic conductivity in the main channel alluvium	-0.01 – 500
19	CANMX	Maximum canopy storage	0 – 100
20	BIOMIX	Biological mixing efficiency	0 – 1
21	OV_N	Manning's "n" value for overland flow	0.01 – 30

5.1.1.1 Global sensitivity analysis

Global sensitivity analysis was done for the parameters shown in *Table 5.11* . According to the result from the global sensitivity analysis, the curve number (CN2) was found to be the most sensitive parameter followed by manning's "n" value for overland flow (OV_N), effective hydraulic conductivity in the main channel (CH_K2), manning's "n" value for the main channel (CH_N2), and saturated hydraulic conductivity of soil layers (SOL_K) ranking up to fifth position as shown in *Table 5.12* below.

Table 5.12 Summary of global sensitivity analysis

Parameter Name	Parameter description	t-Stat	P-Value	Rank
CN2	SCS runoff curve number	-19.96	0	1
OV_N	Manning's "n" value for overland flow	19.47	0	2
CH_K2	Effective hydraulic conductivity in the main channel alluvium	-8.51	0	3
CH_N2	Manning's "n" value for the main channel	7.02	0	4
SOL_K	Saturated hydraulic conductivity	4.15	0	5
SOL_BD	Moist bulk density	3.01	0	6
GW_DELAY	Groundwater delay	-2.96	0	7
RCHRG_DP	Deep aquifer percolation fraction	-2.49	0.01	8
SOL_Z	Soil depth (for each layer)	1.6	0.11	9
SOL_AWC	Available water content of soil	1.57	0.12	10
ALPHA_BF	Baseflow alpha factor	1.44	0.15	11
BIOMIX	Biological mixing efficiency	1.36	0.17	12
GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur	-1.35	0.18	13
CANMX	Maximum canopy storage	-1.18	0.24	14
SURLAG	Surface runoff lag time	1.05	0.29	15
ESCO	Soil evaporation compensation factor	-1.01	0.32	16
HRU_SLP	Average slope steepness	0.75	0.45	17
REVAPMN	Threshold depth of water in the shallow aquifer for revap to occur	0.49	0.63	18
EPCO	Plant uptake compensation factor	0.37	0.71	19
GW_REVAP	Groundwater revap coefficient	0.33	0.74	20
SLSUBBSN	Average slope length	0	1	21

In *Table 5.12* , the rank for each parameter was assigned depending on P-value and t-stat. Here, t-stat provides a measure of sensitivity and hence larger in absolute values are more sensitive. On the other hand, P-value indicates the significance of the sensitivity and hence a value close to zero has more significance. Therefore, ranking in both cases (t-stat or P-value) give the same result i.e. a parameter will have the same rank whether it is ranked based on the t-stat or P-value.

5.1.1.2 Local sensitivity analysis

The local sensitivity analysis was carried out using the Latin-Hypercube One-Factor-at-a-Time (LH-OAT) sensitivity analysis method.

As described earlier in section 4.5.1.1, this method should be performed for one parameter at a time only while the other parameters are fixed at a value of the best iteration. Then the parameter was varied independently and its effect on the model output was evaluated. Based on the analysis result groundwater delay (GW_DELAY), deep aquifer percolation fraction (RCHRG_DP), groundwater revap coefficient (GW_REVAP), average slope length (SLSUBBSN), soil evaporation compensation factor (ESCO), Base flow alpha factor (ALPHA_BF), runoff curve number (CN) and saturated hydraulic conductivity of soil layers were found to be most sensitive parameters in the order appearance. On the other hand parameters such as surface runoff lag time (surlag), available water content the soil (SOL_AWC), plant uptake compensation factor (EPCO), average slope steepness (HRU_SLP), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) and threshold depth of water in the shallow aquifer for revap to occur (REVAPMN) were found to be least sensitive. The remaining parameters have moderate effect on the model output. In general, the global sensitivity analysis and the local sensitivity analysis produce different result. Therefore, attention was given to most sensitive parameters during model calibration process.

5.1.2 Parameters sensitive to sediment

The most sensitive parameters for erosion simulations were: USLE land cover and management factor (USLE_C), USLE support practice factor (USLE_P), USLE soil erodibility factor (USLE_K), channel re-entrainment exponent parameter (SPEXP), channel re-entrainment linear parameter (SPCON), channel erodibility factor (CH_EROD), and channel cover factor (CH_COV). Other parameters included in the table below were also affecting the soil erosion simulation to some extent. These sediment parameters are used to compute the amount of sediment from a catchment (from upland) and from the channel (instream sediment). The parameters that were used to evaluate the sensitivity to sediment are shown in

Table 5.13 below.

Table 5.13 List of parameters used in sensitivity analysis to sediment

S/N	Parameters	Description of parameters	Range of value (Min-Max)
1	SPCON	Linear re-entrainment parameter for channel sediment routing	0.0001 – 0.01
2	SPEXP	Exponential re-entrainment parameter	1 – 1.5
3	USLE_K	USLE soil erodibility factor	0 – 0.65
4	USLE_P	USLE support practice factor	0 – 1
5	USLE_C	USLE cover and management factor	0.001 – 0.5
6	BIOMIX	Biological mixing efficiency	0 – 1
7	RSDIN	Initial residue cover [kg/ha]	0 - 10000
8	CH_COV1	Channel erodibility factor	-0.05 – 0.6
9	CH_COV2	Channel cover factor	-0.001 – 1
10	SLSUBBSN	Average slope length	10 – 150
11	HRU_SLP	Average slope steepness	0 – 1

To see which parameter is highly sensitive to sediment from the list of parameters in Table 5.13 One-factor-at-a-time (OAT) sensitivity analysis was applied. OAT keeps the value of other parameters constant or fixed to the best simulation value of the last iteration and vary the value of one parameter at a time. Then, the value of the Sum of the Squares of the difference of the measured and simulated values after Ranking (SSQR) was compared to rank the parameters. Eleven parameters that directly affect the sediment yield and sediment transport in the watershed were analyzed and the result is tabulated in *Table 5.14* below.

Table 5.14 List of parameters sensitive to sediment and their rankings

Parameters	Description of parameters	Rank
USLE_K	USLE soil erodibility factor [t.ha.h./(ha.MJ.mm]	1
USLE_C	USLE cover and management factor	2
USLE_P	USLE support practice factor	3
SPCON	Linear re-entrainment parameter for channel sediment routing	4
CH_COV2	Channel cover factor	5
SPEXP	Exponential re-entrainment parameter	6
BIOMIX	Biological mixing efficiency	7
HRU_SLP	Average slope steepness	8
CH_COV1	Channel erodibility factor [cm/h/pa]	9

SLSUBBSN	Average slope length	10
RSDIN	Initial residue cover [kg/ha]	11

As the sediment transport consists of landscape and channel components, each transport component is affected by different factors. The parameters used in the sensitivity analysis are related to the corresponding transport component. Therefore, the parameters can be categorized in to upland factors which affect the landscape component of the sediment transport and channel factors which affect the channel component of the sediment transport. Parameters such as $USLE\_K$, $USLE\_C$, $USLE\_P$, $BIOMIX$, $RSDIN$, HRU_SLP, and $SLSUBBSN$ are included in upland factors whereas $SPCON$, $SPEXP$, CH_COV1, and CH_COV2 are categorized under channel factors. As we can see from *Table 5.14* the upland factors occupy higher rank in the table that shows upland parameters are very sensitive in this case. The sensitivity of the parameter decreases with increasing rank number value and therefore, parameters at the bottom of the table are less sensitive.

5.2 Model Calibration and Validation

5.2.1 Model calibration and validation for runoff

5.2.1.1 Model calibration

The calibration of SWAT model for runoff was done by using the daily observed runoff data at the outlet of the study watershed (Kulekhani watershed) for the years 2007 and 2008. As it was mentioned in the chapter three, this flow was not actually measured at the site rather it was calculated from energy production and reservoir water level of Kulekhani hydropower station. The simulated and observed daily discharge at the outlet of the watershed were plotted for visual comparison in *Figure 5.1* below. The model was calibrated by using the values of parameters that were identified as highly sensitive to runoff as it was described under sensitivity analysis section. At the initial run of the model i.e. model run using the default values of parameters, there were three major problems in the water balance of the shallow aquifer (SWAT considers only shallow aquifer water balance): a) Low surface runoff, b) High lateral flow and c) Low base flow (inter flow or return flow). Fixing these problems was quite challenging task.

Low surface runoff was adjusted by:

- Increasing the curve number (CN2),
- Decreasing the soil available water content (SOL_AWC), and

- Decreasing the soil evaporation compensation factor (ESCO).

In addition, the saturated hydraulic conductivity (SOL_K) of the soil layers was also adjusted. High lateral flow is related to the saturated hydraulic conductivity of the soil layers.

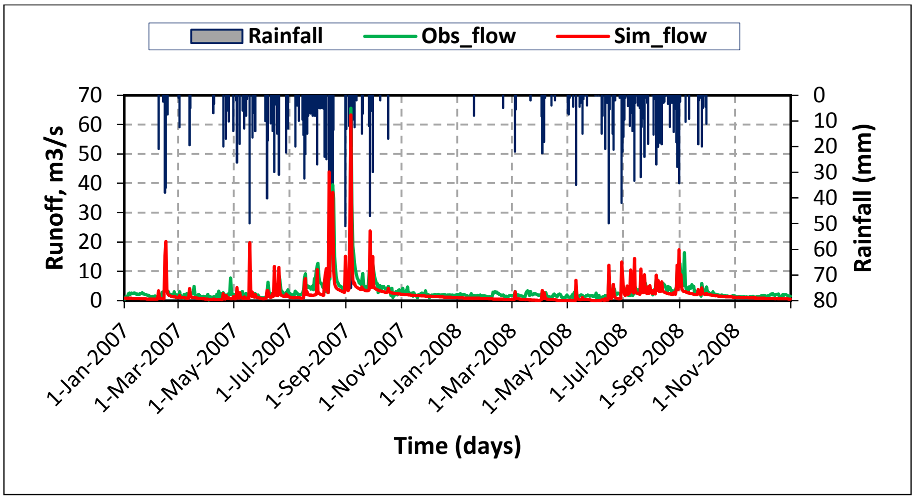


Figure 5.1 Comparison of observed and simulated daily runoff at the outlet of Kulekhani watershed for calibration period 2007-2008

For a soil with multi-layers, if the hydraulic conductivity of the soil layer at the surface is high and the hydraulic conductivity of the soil layers at shallow depth is impermeable or semi-permeable, then the rainfall will percolate vertically until it encounters the impermeable layer. Then it starts ponding above the impermeable layer and forms a saturated zone of water i.e. Perched aquifer. This saturated zone of water is the source of lateral sub-surface flow. This effect was manifested in this study with a very high lateral flow (higher than surface and interflow) at the beginning of the simulation. The soil type used to generate the HRUs in this project has five layers with saturated hydraulic conductivity of 1342.8 mm/hr for the first layer and 33.12 mm/hr for the second, third and fourth layers. Due to low hydraulic conductivity of the lower layers compared to the top layer, the lateral flow was high. Therefore, the hydraulic conductivity of the first layer was decreased to lower the lateral flow. Decreasing the soil hydraulic conductivity also increase the surface runoff by lowering infiltration rate.

Low base flow was adjusted by:

- Decreasing the deep percolation loss (decrease threshold depth of water in shallow aquifer required for the base flow to occur, GWQMN,
- Decrease groundwater revap coefficient , GW_REVAP, and
- Increasing threshold depth of water in shallow aquifer for revap to occur, REVAPMN.

After all these adjustments in SWAT model, the simulation was done and parameters were calibrated using both manual and auto calibration tool (SUFI2 in SWAT_CUP) and the calibrated parameters were updated in the model and the final simulation was run.

From *Figure 5.1* it can be observed in general that the model over predicted some peaks in calibration period. On February 14, 2007 and May 18, 2007, the simulated peak runoff is higher than that of observed value. But, when we look at the rainfall event on that day it is 38 mm and 50 mm respectively for February 14, 2007 and May 18, 2007. Since the observed runoff was the calculated runoff, the discrepancy between observed and simulated value was believed to come from calculation error. The model is reasonably responding to the rainfall event.

The total annual runoff volume for calibration years 2007 and 2008 is shown in *Table 3.6* . From the table, the total observed runoff and total runoff computed by the model were found to be $4.40*10^{10}m^3$ and $3.29*10^{10}m^3$ in 2007 and $1.89*10^{10}m^3$ $2.39*10^{10}m^3$ in 2008 respectively. The result showed that the model performance can be considered robust.

Table 5.15 total annual runoff volume from Kulekhani watershed

Year	Total Runoff Volume (m^3)	
	Simulated	Observed
2007	3.29E+10	4.40E+10
2008	1.89E+10	2.89E+10
2009	2.28E+10	2.44E+10

The observed and simulated runoff for the calibration period were also plotted against each other in order to determine the goodness of fit (*Figure 5.2*) by using the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient of efficiency (NS). The coefficient of determination (R^2) value for daily runoff for the calibration period was 0.6 and the Nash-Sutcliffe coefficient of efficiency (NS) for the same period was found to be 0.44. The relatively low value of NS was due to the fact that the model overestimated some peaks and underestimated the base flow, and since NS squared the difference of observed and simulated values the error appeared to be very high and lowers the value of NS. On *Figure 5.2* in February and May 2007, the model over predicted the runoff which appeared to be reasonable since there was a rainfall corresponding to these peaks which can create these events whereas the observed runoff didn't show any significant response. In general, the model performs well in predicting the runoff from Kulekhani catchment by responding to each rainfall events. The discrepancy between observed and simulated flow may occur since the observed flow used in this case was the calculated flow (not measured at the site).

Therefore, the low performance of the model in predicting the daily runoff from the catchment may also came from using unreliable observed data to calibrate the model and the measure of performance values also reveal the same.

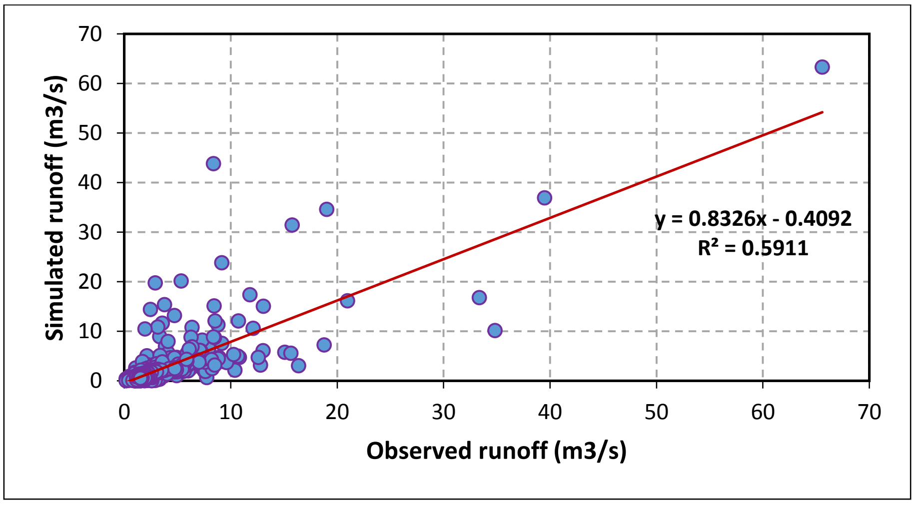


Figure 5.2 Goodness-of-fit for observed and simulated daily runoff for calibration period

In addition to the observed runoff, the low quality of land use/land cover and soil data used early in the project development also affected the result. The effect of land use/land cover and soil data quality model performance was discussed in chapter three.

The R^2 value of 0.6 indicates that the model predicts well the observed runoff and the dispersion of simulated runoff and observed runoff is very close to each other though the overall prediction of the model is about 30% lower than the observed runoff.

5.2.1.2 Model Validation

The model validation was carried out for daily runoff for the year 2009. In addition to 2009 the validation was also carried out for the year 2004 in which sediment sampling was done. Sangroula (2005) measured stream discharge for June, July, August and September during sediment measurement and the model was tested for verification during this period at two outlets: Palung Khola and Chitlang Khola at which sediment sampling was carried out. The value of coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS) for daily runoff in 2009 were 0.59 and -0.59 respectively. The observed and simulated daily runoff for the year 2009 is shown in *Figure 5.3*

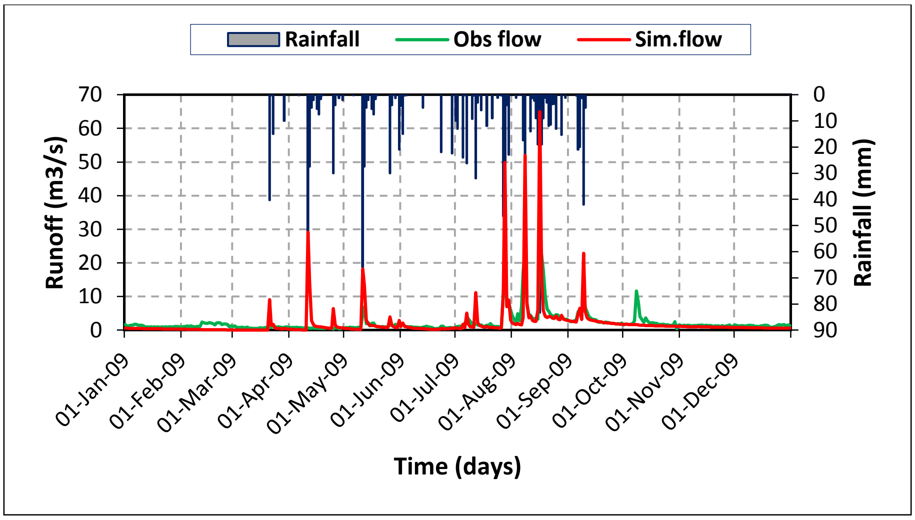


Figure 5.3 Comparison of observed and simulated daily runoff at the outlet of Kulekhani watershed for validation period 2009

The negative value for the Nash-Sutcliffe efficiency (NS) was not a surprise since there was strange thing in the observed data. Looking at the plot of observed versus simulated runoff shown in *Figure 5.3* one can see that on 21st of March, and 11th and 26th of April 2009 there was a corresponding rainfall event of 40.3 mm, 66 mm and 30 mm respectively and the observation did not respond to these events. The graph of the observation value is rather smooth on these dates. On contrary to this, the model responded well to these rainfall events. Likewise, on 9th of October 2009, there is a peak in the observation plot (see *Figure 5.3*) while the rainfall during the same date was zero. Unlike the graph of observation, the simulated plot is smooth at this point showing that there was no rainfall on that day.

Therefore, the high percentage of the error goes to the unreliability of the observed discharge. The goodness-of-fit of observed and simulated daily discharge for 2009 using scatter plot can be visualized from *Figure 5.4* below.

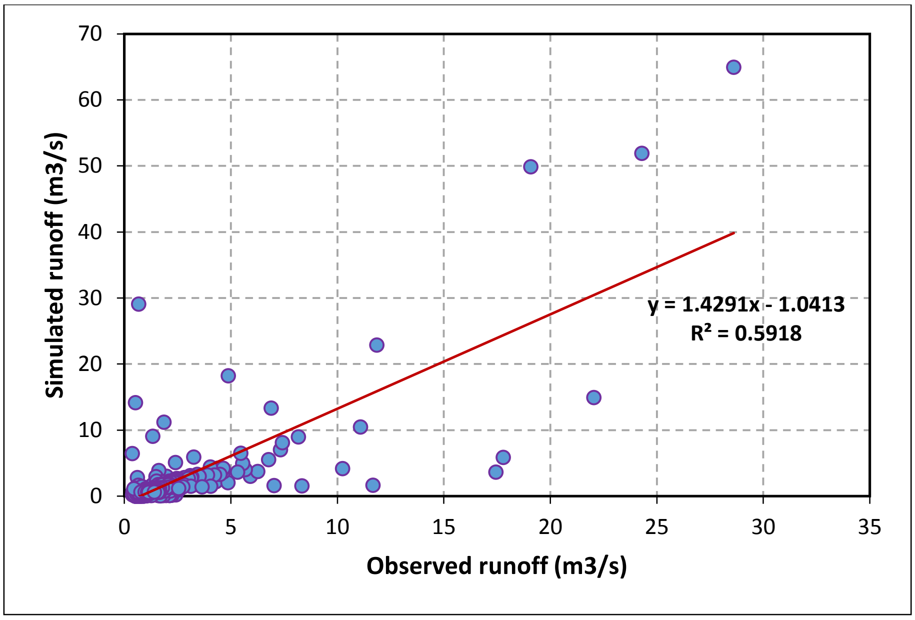


Figure 5.4 Goodness-of-fit for observed and simulated daily runoff for validation period 2009

The graphical comparison of the observed and simulated runoff at the outlet of the Palung Khola and Chitlang Khola sub-watersheds (*Figure 5.5* and *Figure 5.6* respectively show that the model under predicted at both Palung Khola and Chitlang Khola mostly during peak flows. Workers such as Spruill et al., (2000), Chu and Shirmohammadi (2004) showed that the SWAT model was unable to simulate an extremely wet year or poorly predicted peak flows and hydrograph recession rates. The value of coefficient of determination (R^2) (*Figure 5.7*) and the Nash-Sutcliffe efficiency (NS) were found to be 0.66 and 0.29 respectively for Palung Khola and for Chitlang Khola, the R^2 (*Figure 5.8*) and NS value were found to be 0.81 and 0.74 respectively. The model predicted well for Chitlang Khola but under estimate peak flow for Palung Khola sub-watershed during validation period of 2004.

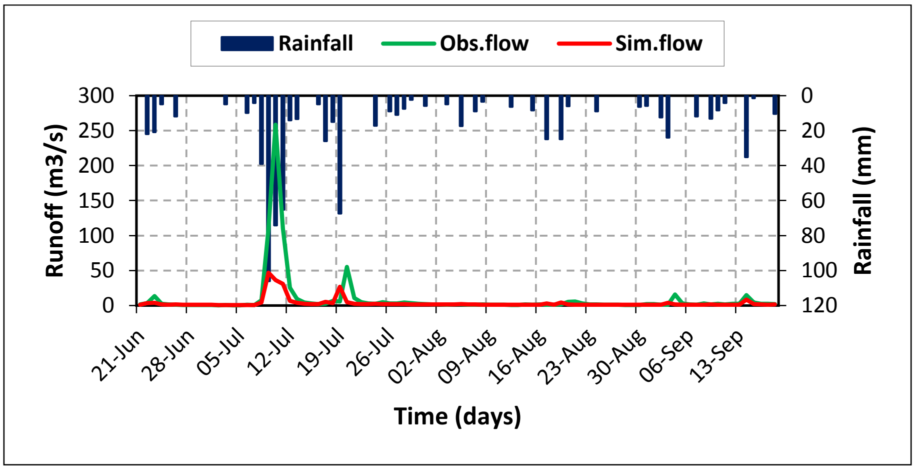


Figure 5.5 Comparison of observed and simulated daily runoff at the outlet of Palung Khola, 2004

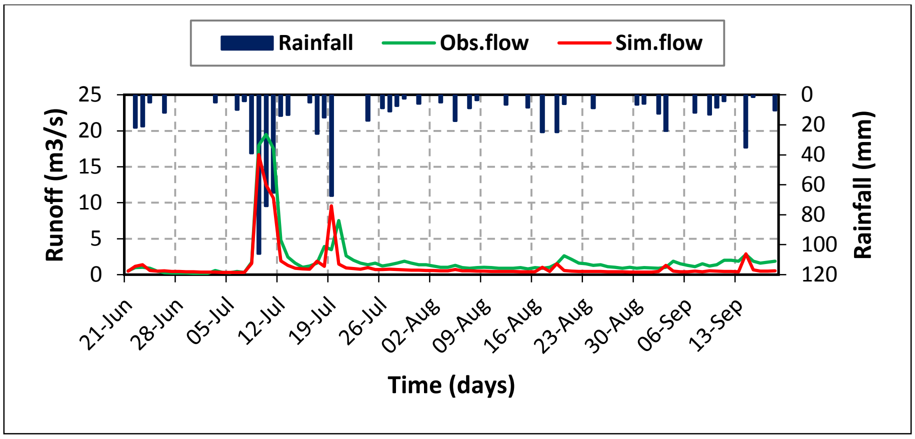


Figure 5.6 Comparison of observed and simulated daily runoff at the outlet of Chitlang Khola. , 2004

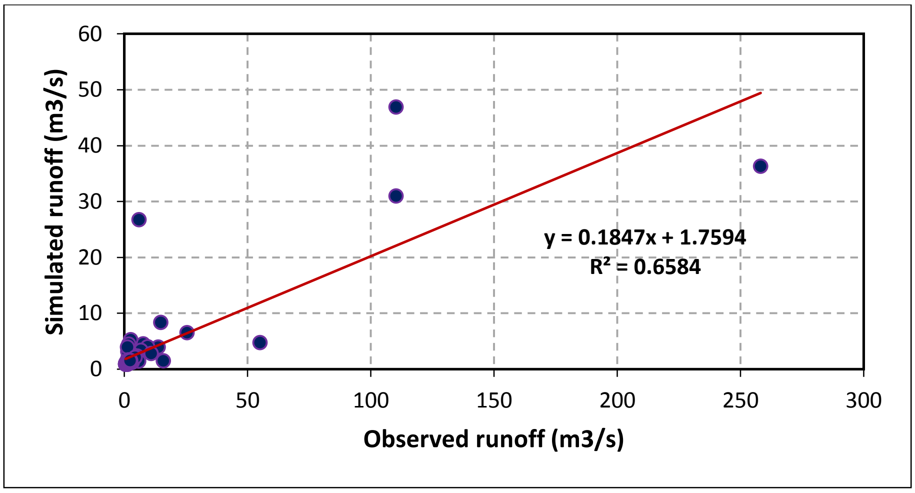


Figure 5.7 Goodness-of-fit for observed and simulated daily runoff from Palung Khola, 2004

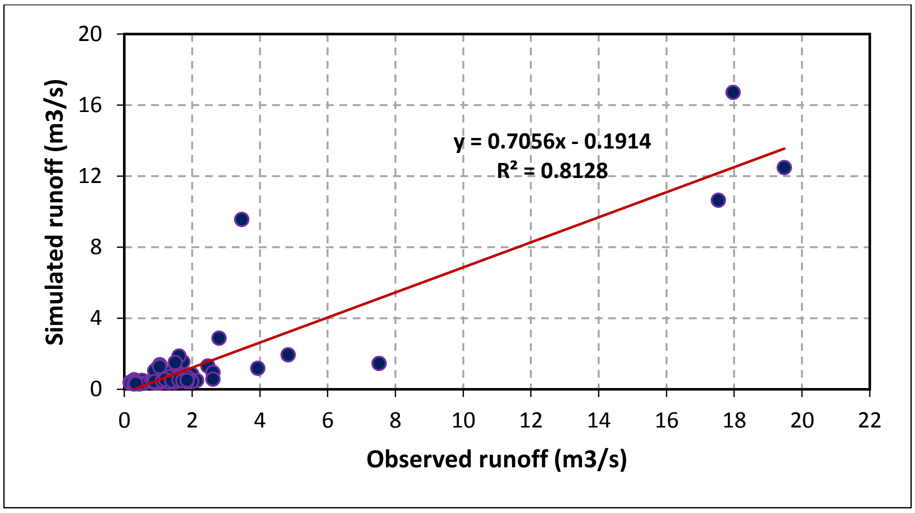


Figure 5.8 Goodness-of-fit for observed and simulated daily runoff from Chitlang Khola , 2004

Here it should be noted that the Soil and Water Assessment Tool (SWAT) model is a semi-distributed model that needs physically distributed input data.

The spatially and temporally distributed data should be used in the development of SWAT project to get a good result. The SWAT model looks for rain gauges or precipitation station close to the center of each subbasin to generate runoff. Therefore, having precipitation station distributed throughout the watershed helps the model to better predict the runoff from each subbasin. In this study there was only one precipitation measurement station located close to the center of the watershed. This precipitation station was used for all subbasins. It is obvious that rainfall distribution may not be uniform throughout the watershed and as the subbasin gets far from the precipitation station, it is likely to have higher or lower rainfall intensity than the precipitation recording station and this could affect the runoff generated by the model. Therefore, rain gauge density is also very important input requirement.

5.2.2 Model calibration for sediment

The model was calibrated for sediment for the year 2004. There was an observed sediment yield for monsoon season from 21st of June 2004 to 18th of September 2004 at Palung Khola and Chitlang Khola sub-watersheds and the graph of observed and simulated sediment yield is shown in *Figure 5.9* and *Figure* 1.1 From *Figure 5.9*, it is clear that the model under predicted the sediment yield from Palung Khola sub-catchment during high peak flow on 9th to 10th of July, 2004 and for most of the low flow periods but over predicted the other time. There are some periods (*Figure 5.9*) during which the model over predicted sediment yield where the observed sediment yield was very low. Since SWAT uses the simulated runoff to determine the sediment yield from the watershed, the model under predicted the sediment yield where the simulated runoff from the same watershed is less than the observed runoff. By comparing *Figure 5.5* and *Figure 5.9* one can understand that the sediment yield from Palung Khola sub-watershed correspond to the simulated discharge from the same watershed. Likewise, *Figure 5.9* shows that the sediment yield peaks correspond to rainfall event.

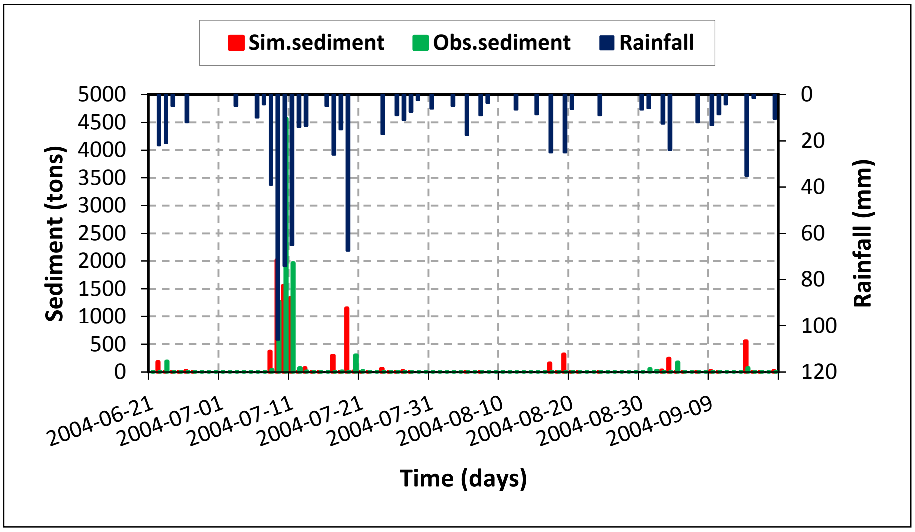


Figure 5.9 Comparison of observed and simulated daily sediment load from Palung Khola sub-watershed for the calibration period 2004

The total simulated and observed sediment yield from Palung Khola sub-catchment during the period from 9th of June, 2004 to 18th of September, 2004 was 8694.12 tons and 8974.6 tons respectively. The specific sediment yield for Palung Khola sub-catchment of 62 km^2 area was 137.4 tons/km^2 compared to the specific sediment yield of 145 tons/km^2 calculated by Sangroula (2005). The result shows that the model prediction was promising as it closely estimate the sediment yield.

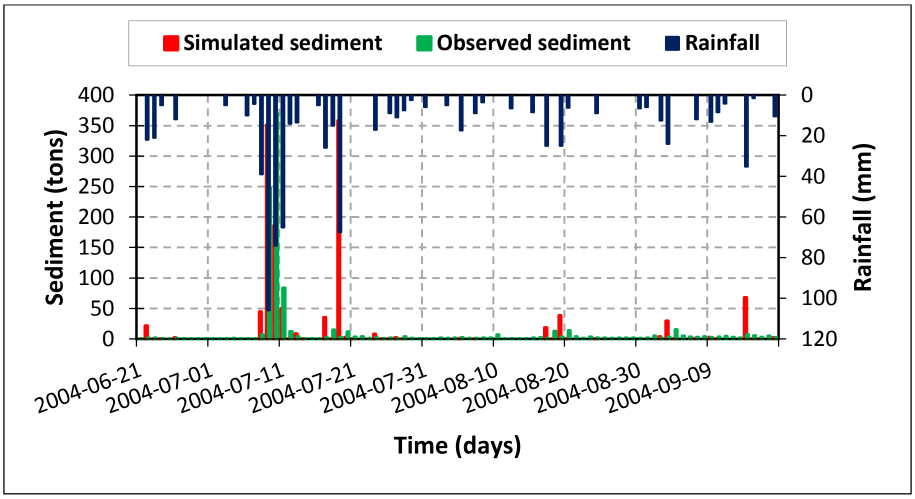


Figure 5.10 Comparison of observed and simulated daily sediment load from Chitlang Khola sub-watershed for the calibration period 2004

The model over predicted the sediment yield from Chitlang Khola sub-catchment compared to the observed sediment yield.

On 19th of July the model predicted 358.3 tons of sediment yield whereas the measured sediment on the same date was only 2.9 tons per given hours while rainfall event on 19th of July 2004 was 67.5 mm. Therefore, the model responded well for rainfall event. The total observed and simulated sediment yield from Chitlang Khola sub-catchment of 21.5 km^2 area was 937 tons and 1262 tons respectively. The specific sediment yield for Chitlang Khola sub-catchment of 21.5 km^2 area was 57.6 tons/km^2 compared to the specific sediment yield of 43.5 tons/km^2 calculated by Sangroula (2005).

The observed and the simulated values of the sediment yield were plotted against each other to determine the goodness-of-fit criterion of coefficient of determination both for Palung Khola and Chitlang Khola sub-catchments (Figure 1.1 and *Figure 5.12*). The coefficient of determination (R^2) and the Nash-Sutcliffe efficiency were found to be 0.54 and 0.53 for Palung Khola and 0.40 and 0.1 for Chitlang Khola. The range of Nash-Sutcliffe efficiency varies between 1.0 (perfect fit) and $-\infty$. Since the NS coefficient is sensitive to extreme values (as it squared the difference of observed and simulated values), it might yield suboptimal results when the dataset contains large outliers. This was manifested in the Chitlang Khola sub-catchment (*Figure 5.10*) with a value of NS 0.1. This suboptimal value of NS was as a result of outliers in *Figure 5.10* .

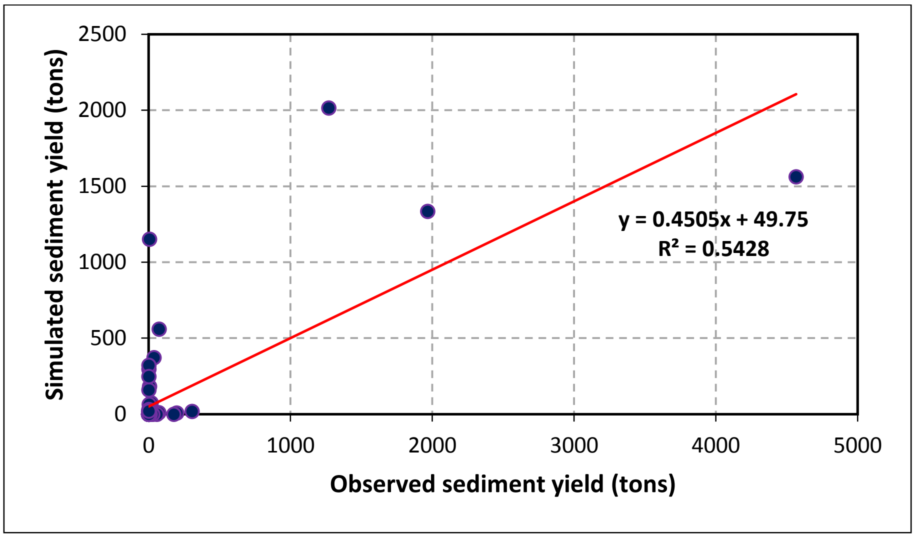


Figure 5.11 Goodness-of-fit for observed and simulated daily sediment load from Palung Khola sub-watershed for the calibration period 2004

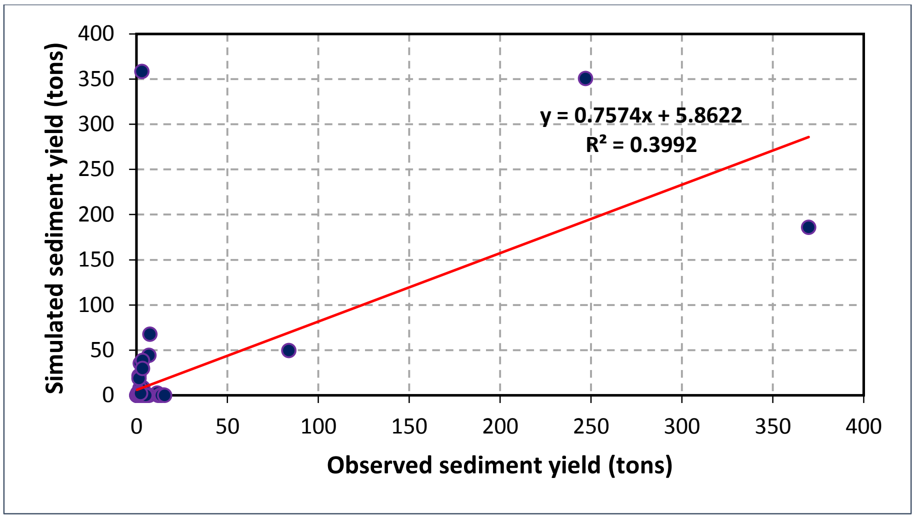


Figure 5.12 Goodness-of-fit for observed and simulated daily sediment load from Chitlang Khola sub-watershed for the calibration period 2004

The model was not validated for sediment since there were not enough data to do so. The observed sediment data was only available for four months this was not long enough to perform model validation.

5.2.3 Sediment concentration

In addition to sediment load or sediment yield from a basin, SWAT also simulates the concentration of sediment in mg/kg or ppm (parts per million) from a basin. The relationship between sediment concentration and discharge will be presented in the next section.

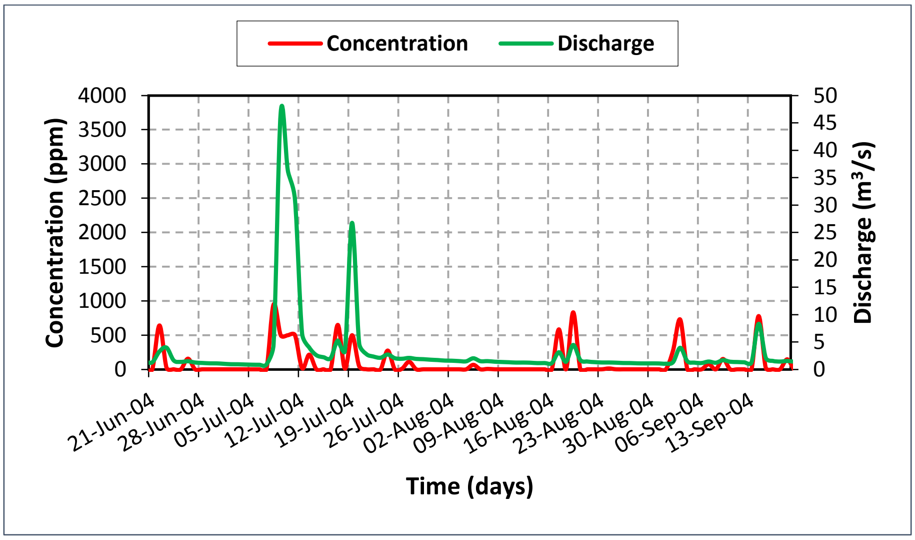
5.2.3.1 Concentration and discharge

The concentration of suspended sediment in the stream is related to the amount of discharge flowing in the river. But, this may not be the case in the area where gully erosion, land sliding and mass wasting are dominant factors that add sediment to the river. This is because of the fact that land slide or mass wasting add a large amount of sediment to the river in a single event. Therefore, the relationship between sediment concentration and discharge depends on the catchment slope characteristics. The maximum and average sediment concentration and discharge of Palung Khola and Chitlang Khola in 2004 as simulated by SWAT is shown in Table 3.8 below.

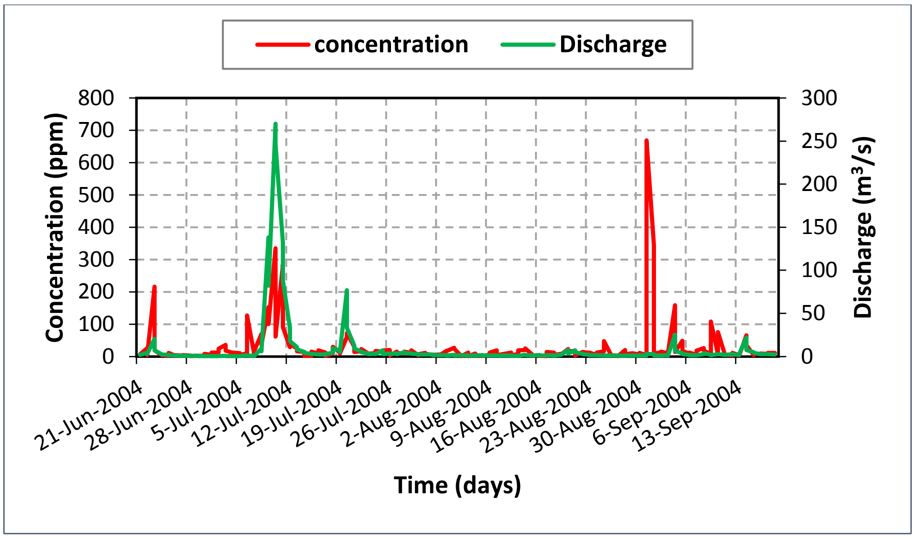
Table 5.16 Summary of sediment concentration by weight in 2004

Months	Palung Khola				Chitlang Khola			
	Simulated (ppm)		Observed (ppm)		Simulated (ppm)		Observed (ppm)	
	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.
June	641	82	216	85	218	27	66	16
July	947	138	335	148	434	55	338	86
August	832	48	669	24	297	17	234	24
September	778	121	158	57	272	43	142	32

The time series concentration and discharge for Palung Khola sub-watershed is shown in *Figure 5.13* (a) and (b). The figure shows that the sediment concentration in the stream is high where the discharge is high. The observed time series of concentration and discharge (*Figure 5.13* (b)) shows that there is high sediment concentration (669.4 ppm) on 31st of August 2004 for a discharge of 0.98 m^3/s. Sangroula (2005) described this as the mass wasting in the catchment might cause it. Kulekhani watershed is prone to mass wasting and land slide (Dhakal et al., 1999; Dhital, 2003; Kayastha et al., 2013). Since SWAT does not consider events such as gully erosion, land slide and mass wasting, the sediment concentration simulated by SWAT is different from that measured by Sangroula (2005). SWAT considers only rill and sheet erosion as erosion mechanisms in the simulation by MUSLE.



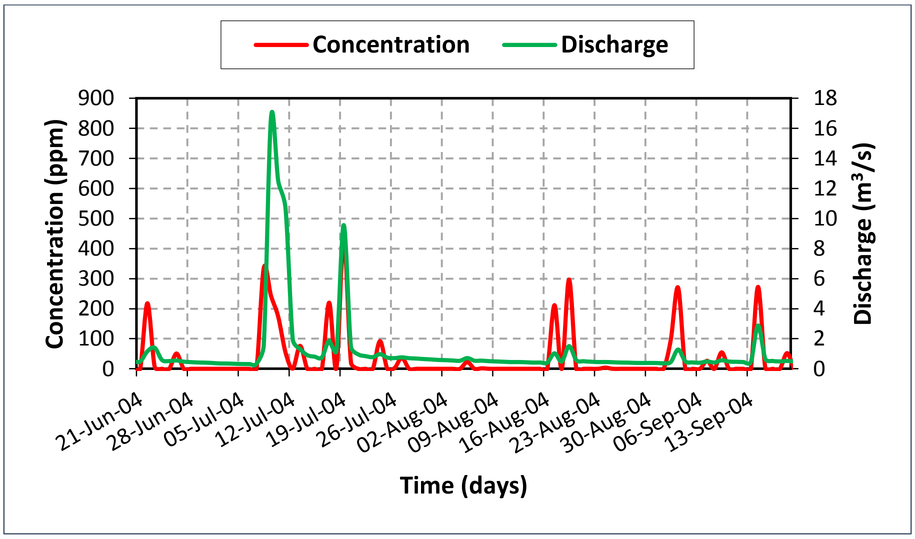
(a)



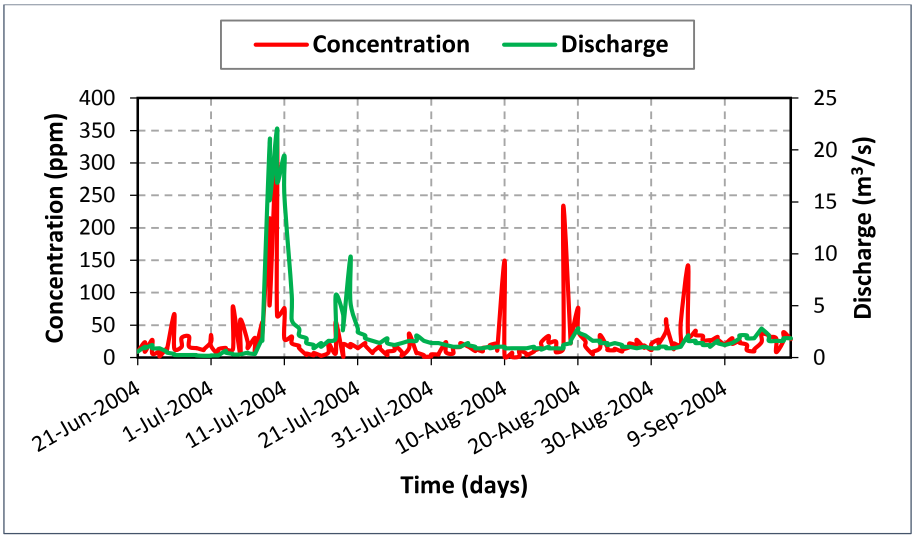
(b)

Figure 5.13 Time series of concentrations by weight and discharge for Palung Khola in 2004 (a) simulated and (b) observed

The simulated and observed time series of concentration and discharge for Chitlang Khola in 2004 is shown in *Figure 5.14* (a) and (b) below. The sediment concentration both during simulation and observation from Chitlang Khola sub-watershed follows the same pattern as Palung Khola. The simulated sediment concentration from Chitlang Khola corresponds to the discharge while the observed sediment concentration might be affected by land slide and mass wasting (*Figure 5.14* (b)).

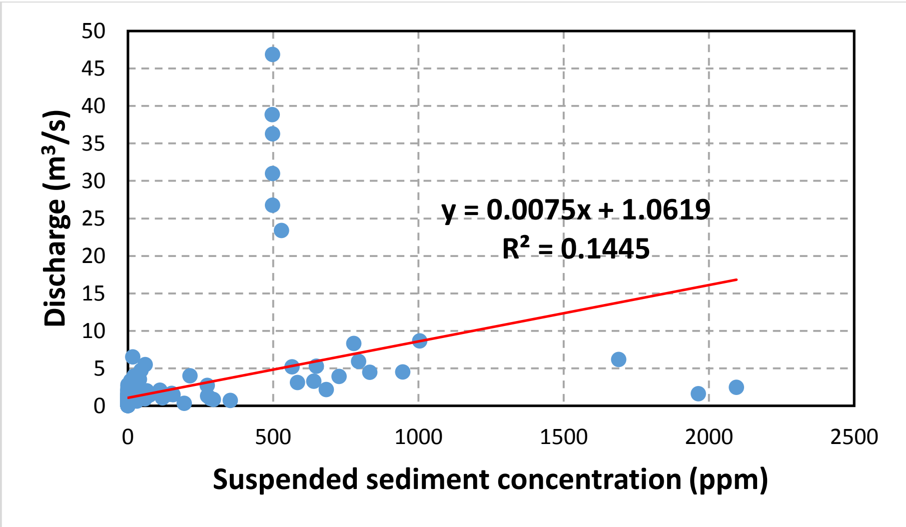


(a)

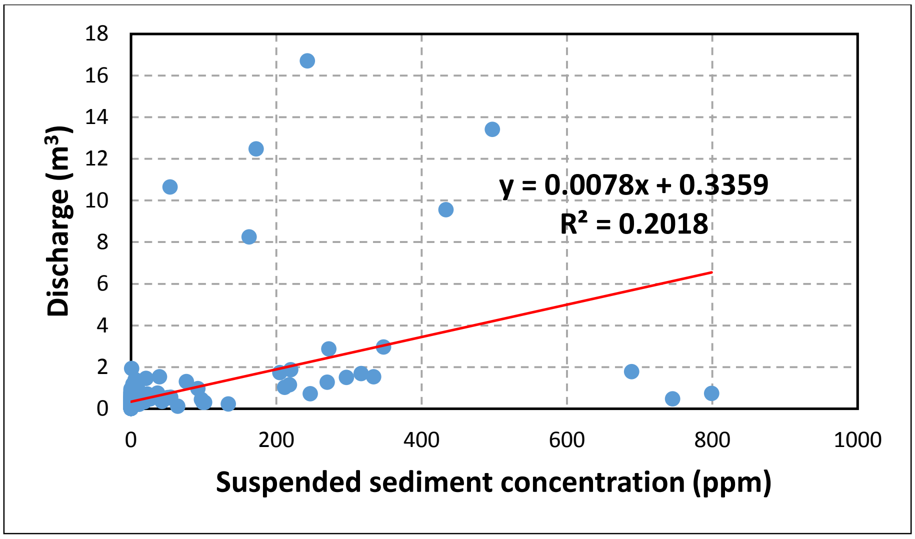


(b)

Figure 5.14 Time series of concentrations by weight and discharge for Chitlang Khola in 2004 (a) simulated and (b) observed



(a)



(b)

Figure 5.15 Simulated sediment concentration by weight and discharge for (a) Palung Khola and (b) Chitlang Khola watershed, 2004

The correlation between sediment concentration and discharge for both Palung Khola and Chitlang Khola is shown in *Figure 5.15* (a) and (b) respectively in 2004. The correlation coefficient for both Palung Khola and Chitlang Khola was very low that shows poor correlation between sediment concentration and discharge.

5.2.4 Sediment load

Focus has been given on the two major sub-watersheds of Kulekhani watershed: Palung Khola and Chitlang Khola for sediment analysis. This was because the sediment measurement was carried out only for these two watersheds and for the sake of comparison these two watersheds were given more attention. Another reason was that these two watersheds drain about 71% of the total watershed. The total monthly simulated and observed sediment yield both for Palung Khola and Chitlang Khola is shown in *Table* 5.17 below.

Table 5.17 Summary of simulated and measured sediment load from Palung Khola and Chitlang Khola , 2004

Months	Palung Khola		Chitlang Khola	
	Simulated sediment load (tonnes)	Observed sediment load (tonnes)	Simulated sediment load (tonnes)	Observed sediment load (tonnes)
June	213	208	26	7
July	7064	8335	1067	779
August	504	106	60	75
September	913	326	109	76
Total load (tonnes)	8,694	8,975	1,262	937
Area (km^2)	62		22	
Specific Yield (tonnes/km^2)	140	145	59	44

The total simulated and observed sediment load for Palung Khola from 21st of June to 18th of September 2004 is 8694 tonnes and 8975 tonnes respectively.

According to Sangroula (2005), the specific sediment yield for this period in Palung Khola watershed was 145 tons/km^2. The specific sediment yield based on the simulated sediment load by SWAT model from Palung Khola watershed was 140 tonnes/km^2. Based on this result, the SWAT model gives quite good estimation of the sediment yield from the catchment.

Likewise, the total simulated and observed sediment load for Chitlang Khola watershed during the same period as for Palung Khola was 1262tonnes and 937tonnes respectively. The specific sediment yield using the observed sediment load was 44 tonnes/km^2 and 59 tonnes/km^2 using simulated sediment load. The result shows that the model result is comparable to the measured result.

The total simulated sediment load from the entire Kulekhani watershed including the above two major sub-watersheds and the remaining area for the period from 21st of June to 18th of September 2004 was 14169 tonnes. Therefore, the specific sediment yield calculated based on this simulated total sediment load from the entire watershed area of 117.21 km^2 for the observation period was 121 tonnes/km^2. In the same manner, the total annual sediment load from Kulekhani watershed estimated using the SWAT model was 24019 tonnes. The specific sediment yield from the watershed can be calculated as the ratio of the total annual sediment yield to the area of the watershed and the value is 205 tonnes/km^2/yr.

Sharma, (2001) estimated the total sediment transport in Kulekhani watershed to be about 20000 tonnes and calculated the specific sediment yield as 175 tonnes/km^2/yr.

The specific sediment yield value of 205 tonnes/km^2/year obtained by using SWAT model is comparable to the one estimated by Sharma, (2001) as 175 tonnes/km^2/year.

The accumulated observed and simulated sediment load for Palung Khola and Chitlang Khola sub-watersheds from 21st of June to 18th of September for the year 2004 is shown in

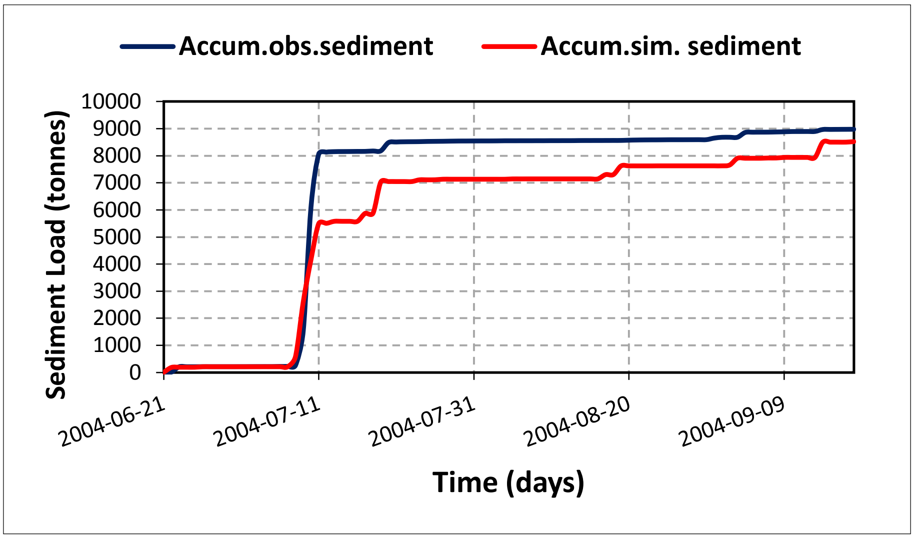


Figure 5.16 Accumulated observed and simulated sediment at Palung Khola , 2004

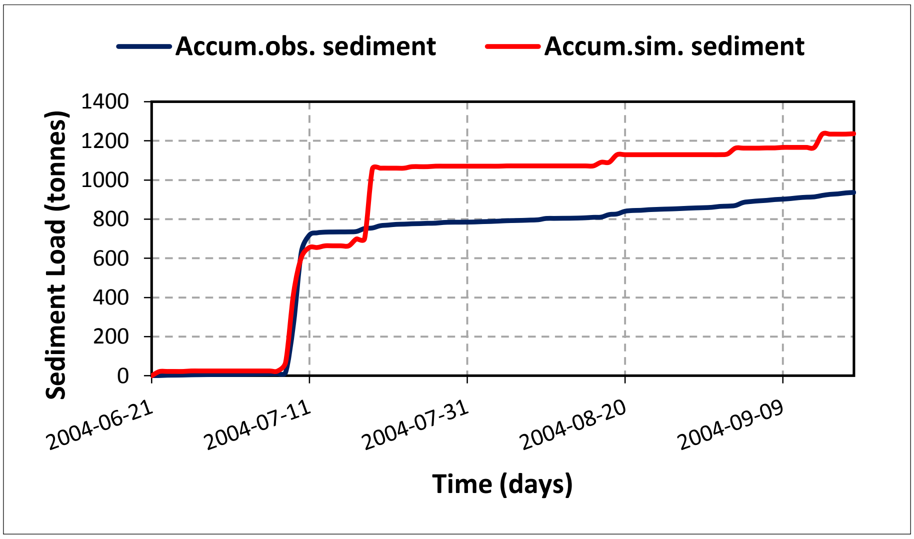


Figure 5.17 Accumulated observed and simulated sediment load at Chitlang Khola , 2004

5.2.5 Sediment volume

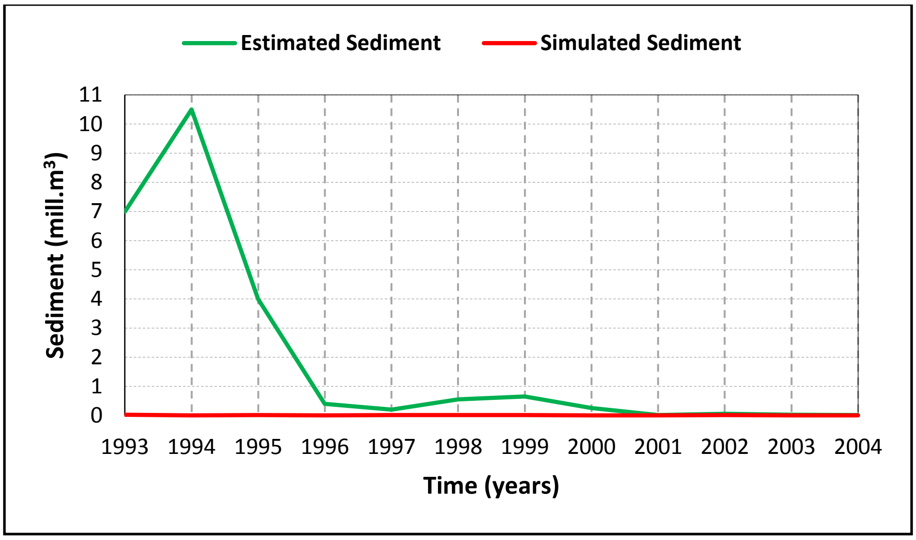
In the past few years, different researchers and organizations tried to estimate the capacity of the Kulekhani reservoir which is found at the outlet of the study watershed (not considered in SWAT project) and also sediment deposition in different years. The comparison of the result from (Sthapit, 1995; Galay et al., 1995; NEA, 2004) and the one simulated by SWAT model will be discussed here. The summary of sediment deposition from 1993 to 2004 is show below.

Table 5.18 Summary of annual volume sediment deposition (Modified from Sangroula, 2005)

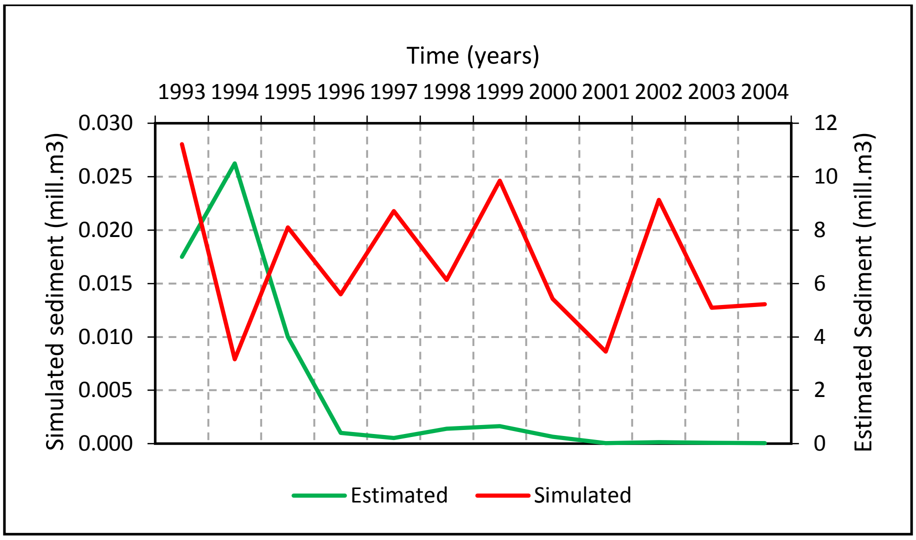
Year	Estimated sediment deposition (mill.m^3)	SWAT simulated sediment deposition (mill.m^3)
1993	7	0.028
1994	10.5	0.008
1995	4	0.02
1996	0.4	0.014
1997	0.21	0.022
1998	0.56	0.015
1999	0.66	0.025
2000	0.26	0.014
2001	0.02	0.009
2002	0.06	0.023
2003	0.03	0.013
2004	0.02	0.013

Note: Thirty percent has been added to initial value to consider the bad load since SWAT does not simulate bed load.

From the year 1993 to 1996 (*Figure 5.18*) there was huge gap between estimated sediment deposition and the simulated sediment by SWAT model. One reason for this could be the disastrous flood occurred in 1993 that causes large scale sediment deposition in the reservoir. Other factors could be minor land slide and mass wasting in the watershed. Gully erosion could also contribute significant sedimentation. On the other hand, from 1996 onwards the difference between the observed the simulated volume of sediment deposited diminishes. This result showed that SWAT is able to reasonably simulate the sediment from a watershed where the land slide or gully erosion is not dominant. As it was discussed in methods section of this study, SWAT uses MUSLE (Modified Universal Soil Loss Equation to calculate rill or sheet erosion.



(a)



(b)

Figure 5.18 Estimated and simulated sediment at Kulekhani watershed outlet

The simulated sediment yield shown in *Figure 5.18* (a) looks like all the values are zero but the actual value of yield can be read from table 5.18 above. For more visualization look at the figure 5.18 (b) above.

5.3 Spatial distribution of sediment yield in Kulekhani watershed

Identifying erosion prone areas in the watershed enables the watershed management to be applied to the proper areas to reduce the sediment yield. Spatial analysis of sediment prone areas is one of the many tasks SWAT can do while modelling sediment. SWAT is powerful in spatial visualization of subbasin or HRU level detail so that one can see which area produces high sediment and which area produces less. The spatial visualization of subbasin wide sediment yield in tons/ha is given in *Figure 5.19* below. The average sediment yield from 2003 to 2010 for all 29 subbasins is given in Appendix D.

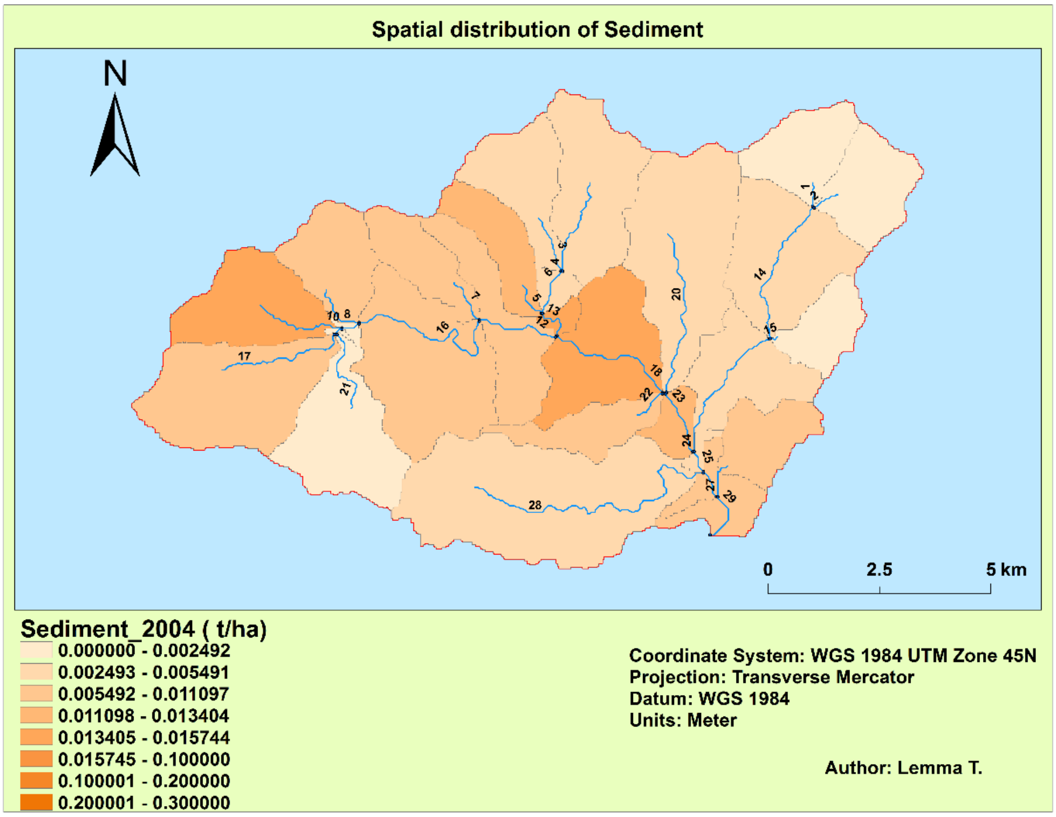


Figure 5.19 Spatial visualization of sediment output from SWAT model

Compared to Chitlang Khola, Palung Khola sub-watershed produces more sediment per hectare. Subbasin 10 and 18 produce high sediment compared to the other subbasins.

5.4 Developing land use/land cover and management scenarios

Land use refers to human activities that are directly related to land, making use of its resources and interfering in the ecological processes that determine the functioning of land cover (Niehoff et al., 2002). Land cover refers to the surface appearance of the landscape, which is mainly affected by its use its cultivation and the seasonal phenology (Niehoff et al., 2002). Land use/land cover patterns are highly dynamic and rarely in a stable equilibrium (Niehoff et al., 2002). Changes in land use/land cover affect the hydrological cycle, biodiversity, radiation budgets and other processes. These changes on the other hand affect the storm runoff and sediment transport in the catchment. Therefore, analyzing the effect of land use/land cover change on the hydrology and sediment transport is one of the essential part of this study. To do this it is necessary to develop scenarios that reflect the changes made to the watershed land use.

Scenario analysis is the process of evaluating possible future events through the consideration of alternative possible outcomes. Therefore, when scenario is developed it should be able to present several alternative future developments.

The scenarios may be developed based on future land use master plan in the watershed if there is any. But, in the absence of future master plan, the scenarios can be developed by changing the land use by a specified percentage and quantify the changes caused by the conversion of one land use type to the other.

One the main advantage of scenario analysis in the watershed is that it enables us to apply improved management practices and decision making.

Based on the watershed area delineated by ArcSWAT and the land use adopted in this study, Kulekhani watershed consists of about 47% of agricultural land, 51% of forest cover and 2% of waterbody (Kulekhani reservoir). The scenario development was made by changing the agricultural land to forest cover by 10%, 30%, 50%, 70%, 100%, and two best Management Practices (BMP): applying filter strip and terracing. Therefore, seven scenarios were compared to the baseline i.e. the original land use. These scenarios were developed to evaluate the sediment yield change from the watershed. Applying filter strip and terracing (stone bunds) in low slope areas of the catchment could give potential effect of BMPs (Betrie et al., 2011).

Filter Strips: A filter strip is a strip of dense vegetation located to intercept runoff from upslope pollutant sources and filter it. Filter strips increase sediment deposition by reducing overland flow velocity before it joins the tributary and main channel. Filter strips reduce sediment, nutrients, bacteria, and pesticides, but do not affect surface runoff in SWAT (Arnold et al., 2012). Filter strip was applied to the land slope between 0 and 25%.

Terracing: a terrace is an embankment within a field designed to intercept runoff and prevent erosion. It is constructed across slope on a contour. Terracing in SWAT is simulated by adjusting both erosion and runoff parameters (Arnold et al., 2012). The USLE practice (TERR_P) factor, the slope length (TERR_SL) factor and curve number (TERR_CN) were adjusted to simulate the effects of terracing. Like filter strip, terracing was also applied to a slope between 0 and 25%.

The scenarios are:

1. Scenario_1: 10% of agricultural land is changed to forest
2. Scenario_2: 30% of agricultural land is changed to forest

3. Scenario_3: 50% of agricultural land is changed to forest
4. Scenario_4: 70% of agricultural land is changed to forest
5. Scenario_5: 100% of agricultural land is changed to forest
6. Scenario_6: Applying filter strip to agricultural and forest area between a slope of 0 to 25%
7. Scenario_7: Applying terracing to agricultural and forest area between a slope of 0 to 25%

The result from the simulation was summarized in Table 3.10 below.

Table 5.19 summary of scenario development result

Scenarios	Period (2003-2010)		
	Total annual sediment load (tons)	Average sediment yield (tons/km^2/yr)	Sediment change (%)
S0	154,890	165	0
S1	148,458	158	-4
S2	136,106	145	-12
S3	124,005	132	-20
S4	111,464	119	-28
S5	92,351	98	-40
Terracing	147,469	157	-5
Filter strip	149,923	160	-3

Where, S0 is the original land use/land cover patter, S1 is scenario 1, S2 is scenario 2, S3 is scenario 3, S4 is scenario 4, and S5 is scenario 5.

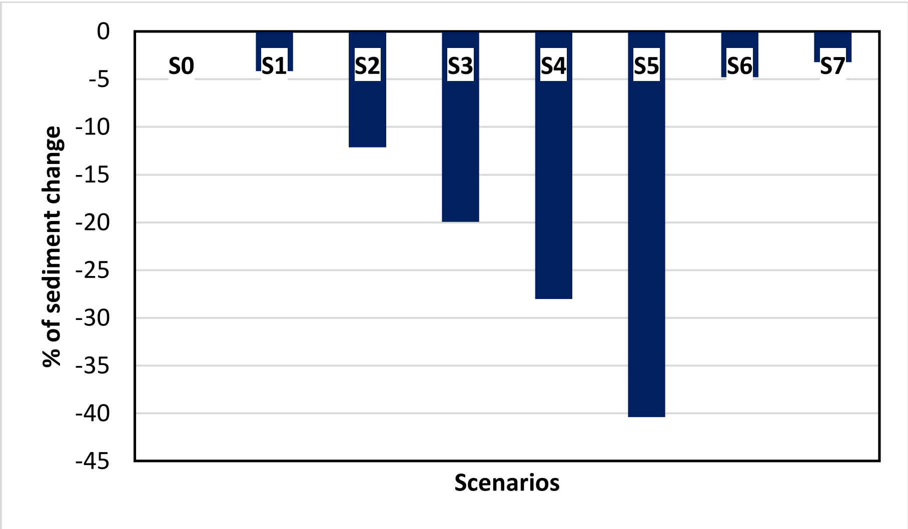


Figure 5.20 Comparison of change of sediment load.

6. Conclusions and Recommendations

6.1. Conclusions

In this study, a conceptual, distributed parameter, continuous time, river basin model, SWAT2012 was used to simulate runoff and sediment from Kulekhani watershed of Bagmati river basin in Nepal. The model operates on a daily time step and allows a basin to be subdivided into grid cells or natural sub-watersheds. The objective of the study was to determine whether the SWAT could be used to simulate stream flow and sediment yield giving priority to the later from Kulekhani watershed where soil erosion is not solely driven by rill and sheet erosion. A GIS interface was used to prepare and process a geospatial data required to run the model. Automatic calibration of SWAT model using Sequential Uncertainty Fitting version two was used together with enormous support of manual calibration.

The available stream flow and sediment data for calibration and validation were limited. A model was calibrated by using two years (2007 to 2008) of daily stream flow data collected from Nepalese Department of Hydrology and Meteorology (DHM) at the outlet of the study watershed. The model calibration for sediment was carried out for daily sediment data from 2004 available for only four months of the monsoon season (June, July, August and September). The sediment data was obtained from Sangroula (2005). The flow was validated for the year 2009 and 2004 at three outlets. The flow from 2009 was collected at the outlet of the Kulekhani watershed and the 2004 was measured at the outlet of two sub-watersheds: Palung Khola and Chitlang Khola. The model was not validated for erosion or sediment since there was no available length of data enough for validation. The average simulated daily runoff and daily sediment yield by SWAT were compared with the corresponding average values of the observation using graphical and statistical methods.

Coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS) have been used to measure the performance of the model. The coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS) for the daily runoff was obtained as 0.60 and 0.44 for the calibration period respectively. The coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS) for the daily runoff at the outlet of the Kulekhani watershed for validation period (2009) was obtained as 0.6 and -0.6 respectively. The validation of the daily runoff for the year 2004 at Palung Khola sub-watershed gives (R^2) and (NS) value of 0.66 and 0.29 respectively.

The validation of the daily runoff for the year 2004 at Chitlang Khola sub-watershed gives (R^2) and (NS) value of 0.81 and 0.74 respectively. The calibration of the model for the daily sediment observed at Palung Khola gives (R^2) and (NS) value 0.54 and 0.53 respectively. The coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS) in estimating daily sediment yield during calibration period was 0.4 and 0.07 respectively.

In general, the daily stream flow and the daily sediment yield predicted by SWAT corresponded well with observed values. However, the model seems to over predicted surface runoff and under predicted the base flow in some years. The reason for this was that the daily stream flow data used for calibration and validation was not reliable. Three years of flow data (2007 to 2009) was a calculated from power production and reservoir water level at Kulekhani hydropower plant located at the outlet of the Kulekhani watershed. It was believed that there might be some error during calculation or particularly the data used for calculating the flow might be erroneous. This was clearly indicated during flow validation in 2009 (*Figure 5.3).* The model response for each rainfall event was quite better than what the observation showed.

In addition to predicting the daily stream flow satisfactorily, SWAT also simulated soil erosion and sediment transport within Kulekhani watershed in a promising way. But, the simulation of runoff was better than that of sediment yield. The relatively poor performance of the SWAT model in simulating the sediment yield from Kulekhani watershed is due the incapability of the SWAT model to realistically model gully erosion and landslide which are believed to be common in the watershed.

Calibration and validation of the SWAT model show that the simulated daily stream flow and sediment yields were in reasonable agreement with measured values. The study demonstrated that the river basin scale model, SWAT has the capability of simulating runoff and sediment from Kulekhani watershed.

The global sensitivity analysis of the SWAT parameters showed that runoff is most sensitive to curve number (CN), Manning's "n" value for overland flow (OV_N) and effective hydraulic conductivity in the main channel alluvium (CH_K2). The sensitivity analysis of the SWAT parameters showed that sediment yield is most sensitive to upland factors such as USLE soil erodibility factor (USLE_K), USLE cover and management factor (USLE_C) and USLE support and practice factor (USLE_P).

In general, it can be concluded that the ability of the SWAT model in predicting the sediment from a watershed depends on which erosion or sediment transport mechanism is dominant in the watershed. If most of the sediment added to the channel is caused by gully erosion and landslide, then the SWAT prediction could not match with the observation as it only considers rill and sheet erosion by MUSLE equation.

On the basis of the results obtained in this study, SWAT may be believed to be a reasonable selection for the simulation of runoff and sediment from Kulekhani watershed. The result of this study could have been better if spatially distributed precipitation data, long period of runoff and sediment yield data, high resolution of land use and soil data, good knowledge of the watershed area and enough time had applied.

6.2. Recommendations

This study of applying SWAT model to Kulekhani watershed to simulate runoff and sediment yield can be considered as a preliminary work as there was no application of SWAT in the same watershed before.

Calculated value of stream flow data was used as observation data to calibrate the model. The unreliability of the calculated data greatly affect the result of the calibration.

Short period of runoff and sediment yield record of observation data was used in this study. Using longer period of runoff and sediment data will improve the calibration result.

Rainfall data was available only from one station. Using spatially distributed rainfall data could have increased the accuracy of the simulation result.

Land use/land cover and soil map was of poor quality. Therefore, this might greatly affect the water balance and sediment yield and representative and high resolution geospatial data is recommended to improve the result.

There is plenty of rooms for improvement of this work in the future.

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Appendices

Appendix A

Daily precipitation data series from 2007 to 20011 for three stations

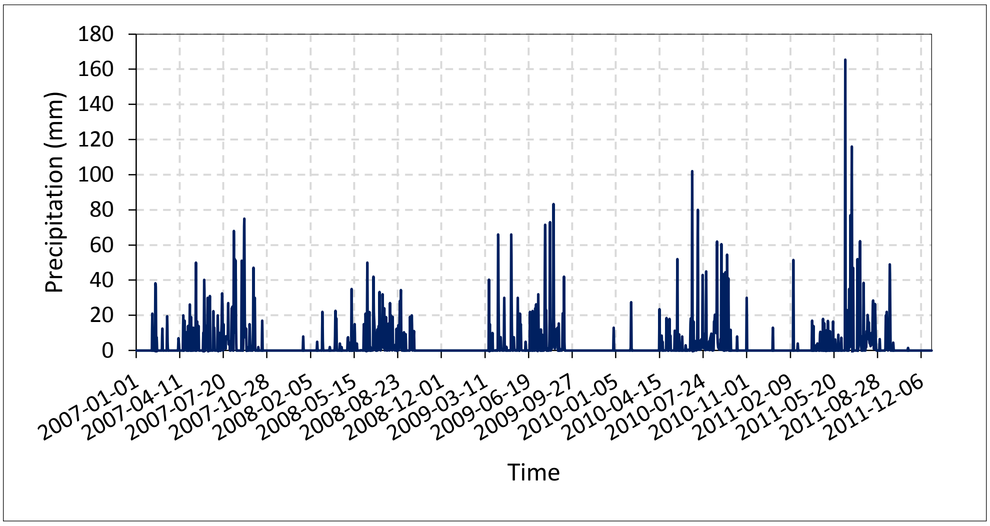

Figure A.1 Precipitation record at Markhu station (2007 to 2011)

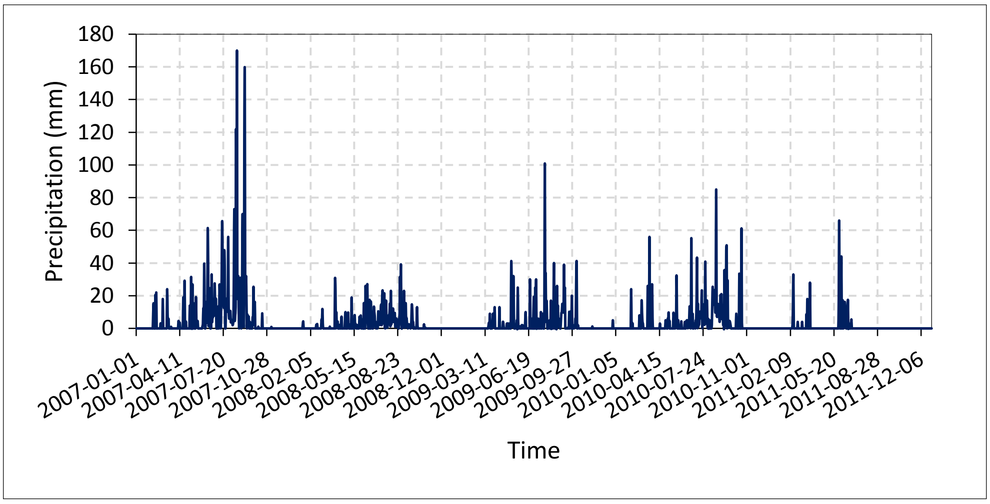

Figure A.2 Precipitation record at Markhu station (2007 to 2011)

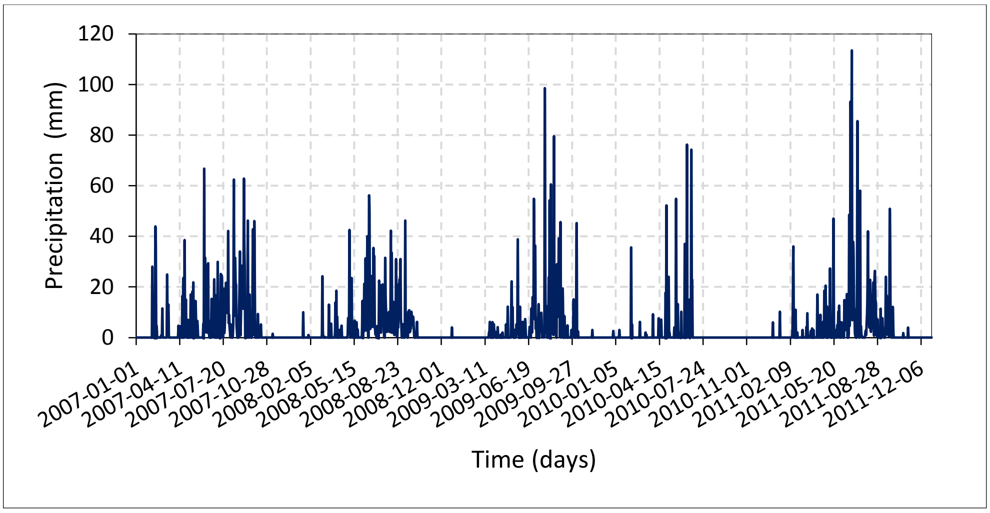

Figure A.3 Precipitation record at Markhu station (2007 to 2011)

Table A.1 Total Monthly Precipitation

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total yearly PCP
1972	6.21	50.13	10.5	30.92	53.13	195.54	741.63	135.71	197.9	108.41	19.4	0	1549.46
1973	60.51	55	73.21	97.2	131.54	442.25	288.44	226.43	362.63	221.22	3.4	0	1961.81
1974	15.6	17.6	36.82	79.63	122.42	191.25	436.61	654.83	336.44	16.61	0	18.01	1925.81
1975	36.21	36.64	14.62	60.63	207.64	256.44	434.01	554.41	320.55	70.25	12.63	0	2004
1976	48.83	18.42	8.42	84.13	172.82	630.65	403.65	298.84	152.51	14.42	4.21	0	1836.88
1977	6.5	14.7	32.51	164.02	177.74	195.64	300.32	329.34	148.51	64.77	36.42	76.63	1547.08
1978	10.42	36.92	95.83	127.44	162.25	288.73	442.5	279.85	247.67	147.64	4.21	5.9	1849.34
1979	18.13	58.21	6.91	47.42	100.45	229.85	387.75	233.45	70.65	44.44	20.92	56.83	1274.99
1980	12	47.75	40.92	75.53	144.77	356.83	352.13	184.15	211.84	32.92	0	7.71	1466.54
1981	47.75	4.21	78.25	108.42	111.05	97.13	110.12	190.44	407.55	0	16.21	0	1171.11
1982	24.42	64.35	29.91	67.62	83.42	150.24	108.02	384.91	269.03	17.93	27.42	10.21	1237.46
1983	4.21	6.41	40.71	138.05	170.95	142.12	432.93	212.25	269.13	137.42	0.3	32.5	1586.97
1984	25.9	22.71	13.9	78.11	86.03	182.03	372.4	258.91	445.71	50.53	4.21	15.9	1556.33
1985	24.22	4.21	1.1	49.83	257.43	141.75	435.9	280.51	483.41	234.93	0	102.81	2016.09
1986	4.21	36.61	19.44	133.94	214.05	387.83	338.5	310.25	313.75	59.74	8.41	70.2	1896.9
1987	4.41	55.51	35.33	56.65	70.32	120.56	638.41	289.15	124.14	221.81	0	17.4	1633.68
1988	0	45.65	97.01	57.57	153.41	260.18	338.35	309.55	169.29	29.94	9.21	135.32	1605.46
1989	82.61	19.51	35.33	0	265.24	199.09	342.72	127.14	175.85	32.76	18.4	0	1298.64
1990	0	88.65	110.14	130.08	162.08	191.68	428.64	371	216.6	39.25	0	6.81	1744.93
1991	27.21	20.21	83.03	42.04	112.5	206.25	182.03	318.83	129.92	4.21	0	37.61	1163.82
1992	13.8	12.51	0	57.72	156.11	161.94	273.67	195.15	131.55	67.01	26.4	1.2	1097.04
1993	25.53	36.22	63.31	111.8	235.75	281.18	704.56	475.14	154.74	0	0	4.31	2092.54
1994	82.11	37.02	42.52	57.96	166.13	215.44	153.55	272.64	282.23	0	1.3	0	1310.89
1995	3.4	54.83	73.73	9.61	150.35	620.35	340.72	289.67	172.85	0	157.61	0	1873.11

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total yearly PCP
1996	72.82	64.45	4.21	27.55	95.16	398.97	379.64	262.25	146.54	35.81	0	0	1487.41
1997	22.8	2	17.8	157.42	88.42	220.4	368.53	400.45	35.11	43.71	29.21	150.7	1536.54
1998	0	30	152.43	48.65	142.45	196.2	604.22	419.91	83.23	0	0	0	1677.08
1999	0	0	1.3	0	131.01	508.4	728.51	387.8	100.7	182.9	0	0	2040.62
2000	1.1	11.7	13.5	32.6	254.6	271.21	219.8	187.1	510.8	0	0	0.2	1502.61
2001	9.3	19.71	18.1	57.3	122.3	246.3	366.4	321.3	174.2	34.4	0	0	1369.31
2002	45.6	40.3	16.8	95.8	187.2	138.1	877.4	373.6	151.2	14.3	0	0	1940.3
2003	23.3	118	49.9	59.6	61.9	161.8	501.7	332.5	142.3	0	0	33.3	1484.3
2004	32	0	0	122.6	179.7	285	498	127.6	126.5	26.2	8	0	1405.6
2005	73.4	34.4	68.2	104.7	104.8	170.4	247.5	366	12.1	104.7	0	0	1286.2
2006	0	0	2	79.5	98.5	254.3	184.3	289.6	324.3	0	0	34.2	1266.7
2007	0	105.1	38	78.9	164.3	227.1	224	368	323.6	23.21	0	0	1552.21
2008	8	13.42	33.71	60.51	92.02	227.15	250.77	268.64	98.23	0	0	0	1052.44
2009	0	0	65.5	153.1	172	69.3	294.41	334.05	89.6	0	0	0.1	1178.05
2010	13	29.9	0	58.2	112.6	151.5	285.9	243.4	299.8	38	0	0	1232.3
2011	13	55.5	0	96.5	91.3	391.7	422.4	250.5	158.8	4.5	1.5	0	1485.7
2012	27.9	48.4	0	170.5	51.3	200.3	380	0	255.1	0	0	0	1133.5
2013	17.5	57.1	9	44.6	91.7	256.5	337.5	239.9	46.6	134.9	0	0	1235.3

Table A.2 Average Daily Precipitation in a Month

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1972	0.2	1.73	0.34	1.03	1.71	6.52	23.92	4.38	6.6	3.5	0.65	0
1973	1.95	1.96	2.36	3.24	4.24	14.74	9.3	7.3	12.09	7.14	0.11	0
1974	0.5	0.63	1.19	2.65	3.95	6.38	14.08	21.12	11.21	0.54	0	0.58
1975	1.17	1.31	0.47	2.02	6.7	8.55	14	17.88	10.68	2.27	0.42	0
1976	1.58	0.64	0.27	2.8	5.57	21.02	13.02	9.64	5.08	0.47	0.14	0
1977	0.21	0.52	1.05	5.47	5.73	6.52	9.69	10.62	4.95	2.09	1.21	2.47
1978	0.34	1.32	3.09	4.25	5.23	9.62	14.27	9.03	8.26	4.76	0.14	0.19
1979	0.58	2.08	0.22	1.58	3.24	7.66	12.51	7.53	2.35	1.43	0.7	1.83
1980	0.39	1.65	1.32	2.52	4.67	11.89	11.36	5.94	7.06	1.06	0	0.25
1981	1.54	0.15	2.52	3.61	3.58	3.24	3.55	6.14	13.58	0	0.54	0
1982	0.79	2.3	0.96	2.25	2.69	5.01	3.48	12.42	8.97	0.58	0.91	0.33
1983	0.14	0.23	1.31	4.6	5.51	4.74	13.97	6.85	8.97	4.43	0.01	1.05
1984	0.84	0.78	0.45	2.6	2.78	6.07	12.01	8.35	14.86	1.63	0.14	0.51
1985	0.78	0.15	0.04	1.66	8.3	4.73	14.06	9.05	16.11	7.58	0	3.32
1986	0.14	1.31	0.63	4.46	6.9	12.93	10.92	10.01	10.46	1.93	0.28	2.26
1987	0.14	1.98	1.14	1.89	2.27	4.02	20.59	9.33	4.14	7.16	0	0.56
1988	0	1.57	3.13	1.92	4.95	8.67	10.91	9.99	5.64	0.97	0.31	4.37
1989	2.66	0.7	1.14	0	8.56	6.64	11.06	4.1	5.86	1.06	0.61	0
1990	0	3.17	3.55	4.34	5.23	6.39	13.83	11.97	7.22	1.27	0	0.22
1991	0.88	0.72	2.68	1.4	3.63	6.87	5.87	10.28	4.33	0.14	0	1.21
1992	0.45	0.43	0	1.92	5.04	5.4	8.83	6.3	4.38	2.16	0.88	0.04
1993	0.82	1.29	2.04	3.73	7.6	9.37	22.73	15.33	5.16	0	0	0.14
1994	2.65	1.32	1.37	1.93	5.36	7.18	4.95	8.79	9.41	0	0.04	0
1995	0.11	1.96	2.38	0.32	4.85	20.68	10.99	9.34	5.76	0	5.25	0
1996	2.35	2.22	0.14	0.92	3.07	13.3	12.25	8.46	4.88	1.16	0	0
1997	0.74	0.07	0.57	5.25	2.85	7.35	11.89	12.92	1.17	1.41	0.97	4.86
1998	0	1.07	4.92	1.62	4.6	6.54	19.49	13.55	2.77	0	0	0
1999	0	0	0.04	0	4.23	16.95	23.5	12.51	3.36	5.9	0	0
2000	0.04	0.4	0.44	1.09	8.21	9.04	7.09	6.04	17.03	0	0	0.01
2001	0.3	0.7	0.58	1.91	3.95	8.21	11.82	10.36	5.81	1.11	0	0
2002	1.47	1.44	0.54	3.19	6.04	4.6	28.3	12.05	5.04	0.46	0	0
2003	0.75	4.21	1.61	1.99	2	5.39	16.18	10.73	4.74	0	0	1.07
2004	1.03	0	0	4.09	5.8	9.5	16.06	4.12	4.22	0.85	0.27	0
2005	2.37	1.23	2.2	3.49	3.38	5.68	7.98	11.81	0.4	3.38	0	0
2006	0	0	0.06	2.65	3.18	8.48	5.95	9.34	10.81	0	0	1.1
2007	0	3.75	1.23	2.63	5.3	7.57	7.23	11.87	10.79	0.75	0	0
2008	0.26	0.46	1.09	2.02	2.97	7.57	8.09	8.67	3.27	0	0	0
2009	0	0	2.11	5.1	5.55	2.31	9.5	10.78	2.99	0	0	0
2010	0.42	1.07	0	1.94	3.63	5.05	9.22	7.85	9.99	1.23	0	0
2011	0.42	1.98	0	3.22	2.95	13.06	13.63	8.08	5.29	0.15	0.05	0
2012	0.9	1.67	0	5.68	1.65	6.68	12.26	0	8.5	0	0	0
2013	0.56	2.04	0.29	1.49	2.96	8.55	10.89	7.74	1.55	4.35	0	0

Appendix B

Hydrologic Response units

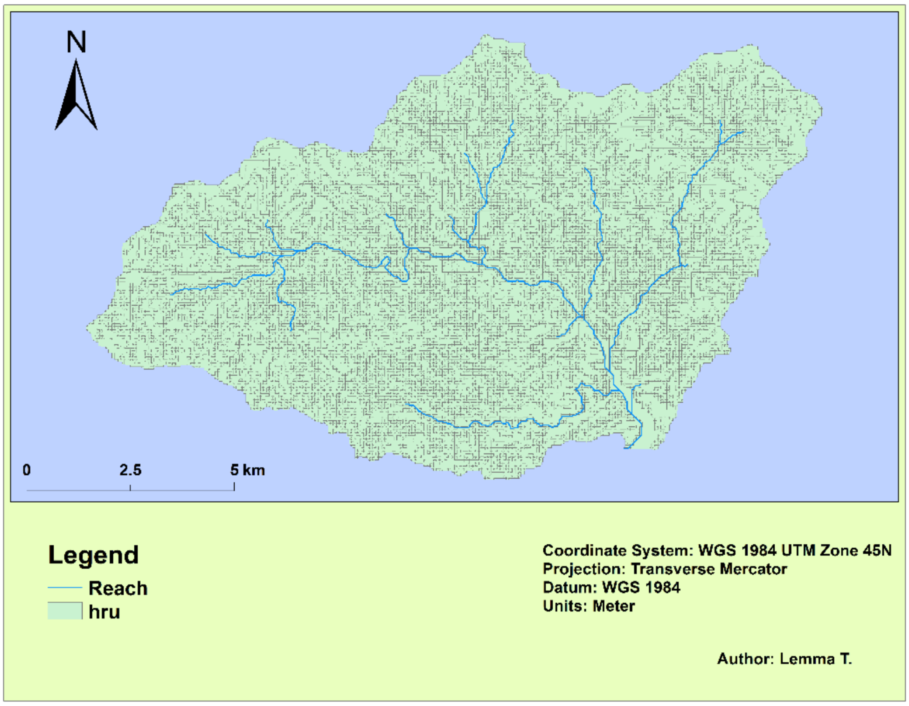

Figure B.1 Hydrologic response units.

There are 318 hydrologic response units defined for the whole watershed are containing 29 subbasins.

Appendix C

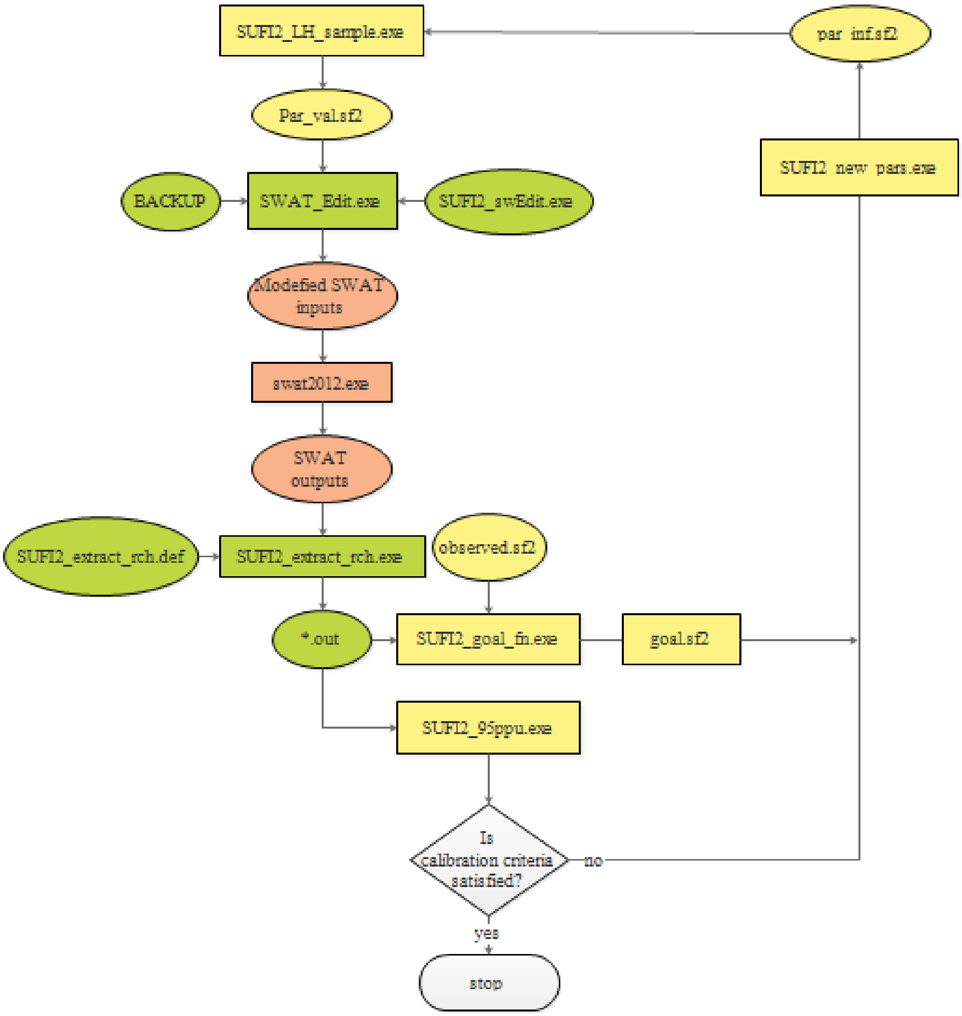

Figure C.1 The link between SWAT (orange), iSWAT (green), and SUFI2 (yellow)

The entire algorithm is run by two batch files: SUFI2_pre.bat and SUFI2_post.bat (Modified from user manual for SWAT_CUP by Abbaspour, 2007)

Appendix D

Table D.1 Average sediment yield (tons/ha)

Subbasin	2003	2004	2005	2006	2007	2008	2009	2010
1	0.00180	0.00175	0.00137	0.00180	0.00140	0.00073	0.00174	0.00138
2	0.00183	0.00178	0.00139	0.00182	0.00142	0.00075	0.00176	0.00141
3	0.00385	0.00380	0.00292	0.00378	0.00308	0.00157	0.00370	0.00294
4	0.00551	0.00543	0.00418	0.00539	0.00436	0.00224	0.00525	0.00420
5	0.01286	0.01262	0.00971	0.01251	0.01005	0.00519	0.01214	0.00976
6	0.00363	0.00362	0.00276	0.00354	0.00292	0.00149	0.00345	0.00277
7	0.00908	0.00881	0.00689	0.00903	0.00709	0.00370	0.00874	0.00695
8	0.01094	0.01060	0.00827	0.01087	0.00853	0.00444	0.01054	0.00836
9	0.00157	0.00170	0.00116	0.00142	0.00130	0.00061	0.00142	0.00112
10	0.01575	0.01541	0.01190	0.01548	0.01231	0.00641	0.01501	0.01201
11	0.00106	0.00116	0.00077	0.00095	0.00088	0.00041	0.00095	0.00075
12	0.01132	0.01110	0.00858	0.01115	0.00889	0.00462	0.01081	0.00866
13	0.01621	0.01574	0.01230	0.01618	0.01256	0.00664	0.01563	0.01243
14	0.00393	0.00384	0.00298	0.00389	0.00306	0.00160	0.00374	0.00301
15	0.00206	0.00201	0.00157	0.00206	0.00163	0.00085	0.00198	0.00159
16	0.00770	0.00759	0.00580	0.00751	0.00610	0.00312	0.00731	0.00585
17	0.00735	0.00720	0.00556	0.00726	0.00585	0.00300	0.00705	0.00562
18	0.01478	0.01445	0.01119	0.01455	0.01154	0.00602	0.01411	0.01129
19	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
20	0.00557	0.00549	0.00422	0.00543	0.00442	0.00226	0.00530	0.00424
21	0.00251	0.00249	0.00190	0.00246	0.00213	0.00103	0.00241	0.00192
22	0.01125	0.01098	0.00850	0.01110	0.00883	0.00458	0.01076	0.00859
23	0.01386	0.01340	0.01046	0.01383	0.01069	0.00565	0.01333	0.01059
24	0.00426	0.00417	0.00322	0.00418	0.00332	0.00173	0.00403	0.00325
25	0.00336	0.00329	0.00257	0.00334	0.00262	0.00139	0.00324	0.00258
26	0.01055	0.01024	0.00801	0.01050	0.00816	0.00433	0.01015	0.00808
27	0.01082	0.01053	0.00820	0.01075	0.00848	0.00443	0.01041	0.00829
28	0.00496	0.00485	0.00375	0.00490	0.00399	0.00202	0.00476	0.00379
29	0.00781	0.00756	0.00590	0.00779	0.00610	0.00318	0.00753	0.00598