DEVELOPMENT OF A FRAMEWORK FOR QUANTITATIVE ASSESSMENT OF ENVIRONMENTAL CHANGES ON STREAMFLOW AND SEDIMENT FLOW

（河川流量及び土砂流出に関する環境変化の定量的評価手法の開発）

山梨大学大学院
医学工学総合教育部
博士課程学位論文

2013 年 9 月
WANG JIE

DEVELOPMENT OF A FRAMEWORK FOR QUANTITATIVE ASSESSMENT OF ENVIRONMENTAL CHANGES ON STREAMFLOW AND SEDIMENT FLOW

（河川流量及び土砂流出に関する環境変化の定量的評価手法の開発）

ICRE
International Research Centre
for River Basin Environment

September 2013

JIE WANG

Development of a Framework for Quantitative Assessment of Environmental Changes on Streamflow and Sediment flow

河川流量及び土砂流出に関する環境変化の定量的評価手法の開発

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Engineering

Global Center of Excellence (GCOE)
Special Doctoral Course on Integrated River Basin Management
Interdisciplinary Graduate School of Medicine and Engineering
University Of Yamanashi

September 2013
Jie Wang

ABSTRACT

Our rapidly changing world is always changing hydrology and environment. Studies on ecohydrological processes in a changing environment have been the focus of hydrological science in the 21st century. Among all environmental changes, land use/cover change and climate change are two most important factors influencing hydrological conditions of catchments along with geology and topography. Climate change impact on streamflow and sediment yield has already been accepted. With the increase of population and rapid economic and social development, human activities have been seriously accelerating the speed of land use/cover changes, which accelerated climate change effects. Elucidating the impacts of land use/cover change at different scales on hydrological process, surface energy balance and surface roughness are not straightforward but rather complex to warrant any generalizations. Quantitative assessment of land use/cover and climate changes on streamflow and sediment load of past and future is a complex and difficult task that requires many aspects to be considered, including environmental, socioeconomic and institutional issues.

The main objective of this thesis is to develop a framework for quantitative assessment of environmental changes on streamflow and sediment flow. The developed framework was demonstrated and discussed in four subsequent sections, where Da River Basin was selected as a case study:

1. Developing new sediment rating curve considering temporal vegetation cover changes

A sediment rating curve can describe the average relation between discharge and suspended sediment concentration for a certain location. However, the sediment load of a river is likely to be undersimulated from water discharge using least squares regression of log-transformed variables and the sediment rating curve doesn't consider changes of vegetation cover monthly or yearly. The Normalized Difference Vegetation Index (NDVI) can well be used to analyze the status of the vegetation coverage well. Thus long time monthly NDVI data was used to detect vegetation change in the past 19 years in this study. And monthly suspended sediment concentration and discharge from 1988 to 2006 in Laichau station were used to develop and interpret one new sediment rating curve. Compared with the common sediment rating curve, the new curve can simulate and predict the suspended sediment concentration much better in the Da river basin. In addition, we also applied new sediment rating in another two basins and got promising results. The new curve can describe the relationship among sediment yield, streamflow and vegetation cover, which can be the basis for soil conservation and sustainable ecosystem management.

2. Developing model simulation method to quantitatively separate impacts on streamflow and sediment flow from climate change and human activities

It is critical to quantify the contribution of climate change and human activities on the change of historical streamflow and sediment flow, which can provide a scientific basis for future land conservation and river ecological conservation. In this part, Pettitt mutation method was employed to detect trends and changes in annual streamflow and 1993 was recognized as the mutation year for streamflow. SWAT model simulation method was then applied to separate different effects from climate change and human activities. Based on new sediment rating curve, one well fitted curve between sediment and runoff was introduced to simulate the suspend sediment. Results showed that effects of human activities on streamflow accounted for more than 50% of total streamflow changes both in the Laichau and Tabu catchments, which indicated that human activities are the main factor to affect the changes of streamflow and sediment flow into the Hoa Binh reservoir.

3. Coupling new sediment rating curve and ecological model to evaluate human-induced land cover change effect on sediment flow

Sediment load can provide very important perspective on erosion of river basin. The changes of human-induced vegetation cover, such as deforestation or afforestation, affect sediment yield process of a catchment. In this last part, we have already known that human activities are main factors to affect sediment yield. However, we do not know whether land cover change or vegetation cover change is the main human activities or not. On purpose of this, a new sediment rating curve considering vegetation cover was developed to evaluate the impact of vegetation cover changes on sediment yield in Da River Basin. The Normalized Difference Vegetation Index (NDVI) and leaf area index (LAI) were used to analyze the status of the vegetation cover well. Thus long time series NDVI from satellite was applied to represent vegetation cover in the past years. Potential LAI from ecosystem model (Biome-BGC) was used to explain the vegetation cover without human activities. Observed streamflow and simulated streamflow from SWAT model were used to stand for the streamflow with and without human activities effects. Finally, standardized NDVI and LAI, observed streamflow and simulated streamflow were inputted into the new sediment rating curve to evaluate human-induced vegetation cover change effect on sediment load. Results showed effect of human-induced vegetation cover increased 13.7% of total sediment load in the Laichau station in the period of 1994 to 2004 and human-induced vegetation cover change was the main human activities to increase sediment yield. One new method to quantify of human-induced vegetation cover change impact on sediment load was presented, which may provide guidance for future similar studies. In addition, evaluation of human-induced vegetation cover effect on sediment load is critically important in directing efforts in managing land use, in improving agricultural practices, and in protecting soil erosion in the Da River.

4. Analyzing the impact on streamflow and sediment flow under different future climatic change scenarios and potential future land cover change scenarios

We have already evaluated that climate change and land cover change changed the historical streamflow and sediment yield, and land cover change is the main factor. But future streamflow and sediment yield changes under different future climatic change scenarios and potential future land cover change scenarios still have not been evaluated For this purpose, future scenario of land cover change is developed based on historical land cover changes and land change model (LCM). At the same time, climate change scenarios are built based on downscaling outputs of GCMs from the IPCC Fourth Assessment Report. In addition, future leaf area index (LAI) is simulated by ecological model (Biome-BGC model) based on future land cover scenario. Then future scenarios of land cover change, climate change and LAI are used to drive hydrological model and new sediment rating curve. Results showed that the annual streamflow would increase by 17.5% in Tabu catchment and 19% in Laichau catchment and the annual sediment load would increase significantly by 33% in Laichau catchment under combined impacts of future climate and land cover change. The results of this research provide information that decision-makers need in order to promote water resources planning efforts. Besides that, this study also makes contribute to the basic framework for assessing climate change impacts on streamflow and sediment yield that can be applied in the other basins around the world.

In this thesis, a comprehensive framework was developed for quantitative assessment of environmental changes on both historical and future streamflow and sediment flow, which was successfully applied in Da River Basin. In addition, this study is expected to provide information that decision-makers need for appropriate utilization of water resources, flood control, soil conservation and ecological protection. Besides that, this framework will also provide guidance for other potential applications for the other basins around the world.

Key words: climate change, land cover change, hydrological model, streamflow, sediment yield, impacts separation, future prediction

ACKNOWLEDGEMENT

Looking back on the fantastic journey of past three years, I found I could not gone so far without continuous help and strong support from many people. It is a great pleasure for me to thank for their scientific guidance, encouragement and patience.

First of all, I would like to express my topmost thankful to my supervisor, Associate Professor Hiroshi Ishidaira. His guidance, support, and inspiration from the very beginning to the concluding stage of this dissertation enable me to develop an understanding of the research topic. During my Ph.D. studies, his intelligent, optimistic and diligent research attitude deeply influenced me. He is more than an academic supervisor for me, but also a life mentor. Especially, I learned from him how to accomplishment the research through individual thinking, which would benefit me for the rest of my life.

I further express my gratitude to all the Professors and researchers in Global Center of Excellence (GCOE) Program, International Research Center for River Basin Environment, University of Yamanashi, who instructed, helped and encouraged me in various ways during my doctoral study. My heartfelt appreciation goes to all members of my senior seminar: Professor Y. Sakamoto, Professor T. Suetsugi, Professor F. Kazama, Associate Professor Y. Ichikawa, Associate Professor K. Nishida, Dr. J. Magome, Dr. K. Souma, Dr. I. Inagaki, Dr. T. Sano, Dr. T. Nakamura, Dr. K. Kakizawa and Dr. V. Pandey. I also would like to specially thank the retired Professor K. Sunada for his helpful guidance and encouragement.

I will appreciate the kindly support from stuffs of GCOE project and International Student Center and Office of International Exchanges of University of Yamanashi, especially grateful to Ms. M. Ishihara, Ms, S. Maruyama Ms. W. Sano and Ms. M. Katou.

I would like to express my gratitude to all my friends in GCOE program, who accompany, support and encourage me during my life in Japan. My sincere thanks go to Dr. W. Sun, Dr. Q. Li, Dr. W. Khanitchaidecha, Dr. S.S. Wu, Dr. R. Hapsari, Dr. T. Ty, Dr. I. Inagaki, Dr. B. Seng, Dr. T. Khujanazarov, Dr. R.A. Kristanti, Dr. M. Sujata, Dr. D.T. Nga, Dr. D.N. Khoi, Dr. Y. Wijayanti, Mr. S. Manandhar, Ms. L. Li, Ms. S. Salina, Ms. R. Setyawaty, Mr. S. Park, Mr. M. Hashimoto, Ms. Y. Li, Mr. S. Heng, Ms. H. Widyasamratri, Ms. S. Shrestha, Mr. D. Amarathunga, Mr. P.D. Udmale, Ms. T.H. Bui, Mr. S. Ning, Ms. N.T.P. Mai.

I would like to give my sincere gratitude to Professor Z.X. Xu and Ms. J.Y. Li, who recommended me to study in Japan, and keeps encouraging and supporting me during my Ph.D. study. As well, I want to acknowledge my wife, my son and my parents, their love and support enabled me to overcome the frustrations of last three years.

Last but not least, thanks to GCOE Program and Ministry of Education, Culture, Sports, Science and Technology (MEXT) and for the financial support during the study period. I

would also like to thank everyone who directly or indirectly offered his or her help to this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CC	Climate change
LUCC	Land use/cover change
VCC	Vegetation cover change
IPCC	Intergovernmental Panel on Climate Change
GCM	General Circulation Model
SWAT	Soil and Water Assessment Tool
NDVI	Normalized difference vegetation index
LAI	Leaf area index
PCA	Principal Component Analysis
SSC	Suspended sediment concentration
SL	Suspended load
SDSM	Statistical Downscaling Model
ASD	Automatic Statistical Downscaling Model
DRB	Da River Basin
FAO	Food and Agriculture Organization of the United Nations
Corr	Correlation coefficient
MLP	Multi-layer perceptron

CHAPTER I

INTRODUCTION

1.1. Background

We live in a rapidly changing world. Studies on ecohydrological processes in a changing environment have been the focus of hydrological science in the 21st century. Among all environmental changes, Land use/cover change and climate change are two most important factors influencing hydrological conditions of catchments along with geology and topography (Ma, 2005; Zheng et al., 2009). Elucidating the impacts of land use/cover change at different scales on hydrological process, surface energy balance and surface roughness are not straightforward but rather complex to warrant any generalizations. Quantitative assessment of land use/cover and climate changes on streamflow and sediment load of past and future is a complex and difficult task that requires many aspects to be considered, including environmental, socioeconomic and institutional issues.

With the increase of population and rapid economic and social development, human activities have been seriously accelerating the speed of land use/cover changes, which is human-induced land use/cover change. On the other hand, global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change (Patrick et al., 2010), that is climate change-induced land use/cover change. Both human-induced and climate change-induced land use/cover change are directly linked to changes of hydrological cycle by altering the balance between rainfall and evaporation (Chomitz et al., 1998; Costa et al., 2003). Land use/cover change can also alter the velocity of water, whether in the form of streams or overland flow, by changing slope or gradient and the roughness encountered by the flow (Wardrop et al., 1998), which modify the surface resistance and soil erodibility, and consequently impact the sediment yield.

Land cover plays an important role for the hydrological systems in catchments. Streamflow and sediment load also responds to climate variability and it is necessary to consider the effect of climate variability in assessing streamflow and sediment load changes. The Intergovernmental Panel on Climate Change (IPCC) emphasized that global warming and climate change is unavoidable phenomenon (IPCC, 2007). It has been generally accepted that climate change have brought great impacts on the hydrological process of basin scale, especially for streamflow and sediment flow (Schulze, 2000; Li et al., 2007; Zhao et al., 2009). Climate change has resulted in the rise of atmospheric temperature and modified pattern of precipitation and evapotranspiration, which has directly led to alteration in streamflow (Li et al., 2007) and further affected sediment load.

In view of global environmental changes, faced to complex relationship between land use/cover change and climate change, quantitative assessment of environmental changes effect on both streamflow and sediment flow of past and future is essential and urgent. Investigating their contributions to affect the changes of the eco-hydrological processes is thus of paramount importance to improve the sustainable development of water resources and provide ecological conservation measures.

1.2. Necessity of the study

As well known, streamflow and sediment load of one catchment is intimately related to the geology, topography, climate, and land use/cover within the basin. The geologic and topographic variables are mostly fixed, but long term changes in climatic conditions, land use/cover will produce abrupt alterations in hydrological processes and sediment yield. Both land use/cover change and climate change are the major controls of water balance and sediment yield in a catchment, however, streamflow and sediment load changes are affected by climate change and land use/cover change in an integrated way. In order to evaluate effect of land use/cover change, the climate change effect assessment is also indispensable.

Generally, assessment effect of land use/cover change and climate change on streamflow and sediment flow should be studied from two perspectives, historical evaluation and future prediction assessment. Historical insight into these effects can not only improve the knowledge of river processes, but also is precondition for analysis of future environmental changes impacts on streamflow and sediment load. It is necessary to first investigate the main factor affecting the changes of historical streamflow and sediment load. Related to past researches, the most commonly used methods for estimating impacts of environmental changes on runoff or streamflow are statistical analysis method and catchment experiment method and to a lesser extent the hydrological simulation method. Statistical method is simple but lacking of a physical basis. The paired catchment experiment method is traditionally used for estimating the effect of forest management practices, such as afforestation and deforestation on catchment water availability (Hewlett et al., 1969; Garcia-Ruiz et al., 2008). Although the catchment experiment method is very useful in quantifying the impacts of past land cover change, paired catchment experiment method is quite costly, time-consuming, and it is difficult to find one reasonable paired catchment for most studies. Moreover, studies of paired catchments are typically less than 1 km^2 in size. Whether the results from these catchments can be used to larger basins is necessary to further investigate. The hydrological simulation approach is one growing method considering all these drawbacks, so it is encouraging to apply the hydrological simulation method for historical evaluation, complemented by the statistical analysis method.

Quantitative assessment impacts of future land use/cover and climate change on streamflow and sediment flow is continuation and further extension of historical changes analysis. Past studies of the impact of climate and land cover changes on streamflow and sediment load have been paid much attention worldwide. However, few published studies consider impacts of environmental changes on both streamflow and sediment load. Most studies have considered the impact of climate change and land cover change on streamflow (Middelkoop et al., 2001; Phan et al., 2011) or sediment yield itself (Leh et al., 2011; Wilson and Weng, 2011). Compared with streamflow, it is more complex and difficult to study changes of sediment yield, which is strongly affected by surficial materials, topography, rainfall seasonality, and land cover and can be increased by soil disturbance, which often occurs as the result of land use (Minella et al., 2009). Besides that, there was no agreement systemic research framework for quantitative assessment of double effects on streamflow and sediment load. Moreover, knowledge of the interface between land use-cover/climate, water and sediment yield required to undertake adaptation strategies is lacking worldwide. Consequently, more comprehensive and systemic research or project should be proposed for combined impacts of climate and land cover changes on both streamflow and sediment load, especially for sediment load.

1.3. Research objective

The general objective of this thesis is to develop of a framework for quantitative assessment of environmental changes on streamflow and sediment flow. The specific objectives of the study are as follows.

(1) To develop new sediment rating curve considering temporal vegetation cover changes.

(2) To develop model simulation method to quantitatively separate impacts on streamflow and sediment flow from climate change and human activities.

(3) To couple new sediment rating curve and ecological model to evaluate human-induced land cover change effect on sediment flow.

(4) To analyze the impact on streamflow and sediment flow under different future climatic change scenarios.

(5) To analyze the effect of potential future land cover change on streamflow and sediment flow based on land use change model.

1.4. Organization of the dissertation

This thesis is structured in seven chapters. The brief content and outline of these chapters is presented as follows:

Chapter 1: Introduction

This chapter discusses general information of climate and land use/cover change impacts on streamflow and sediment flow, motivation and necessity of the study, objectives of the research. In addition, the structure of the thesis is also presented. In this chapter, the organization of dissertation is presented to give the overview of the study.

Chapter 2: Literature review

This chapter summarizes the main relevant information and previous research results. They are presented in six topics, including: relationship among land/vegetation cover, climate, human activities related to streamflow and sediment yield; sediment flow calculation methods; separation of integrated impacts on historical streamflow and sediment yield, impact of future climate change on streamflow and sediment flow, impact of future land cover change on streamflow and sediment flow, combine impacts of climate and land use/cover change.

Chapter 3: Study area and general research framework

In this chapter, a description of the study area is firstly presented including the physical features and climate conditions. In addition, general framework of this research is discussed for the whole thesis, including model development, historical changes analysis and future changes evaluation.

Chapter 4: New sediment rating curve development and its validation in Asian river basins

In this chapter, new sediment rating curve which could describe the relationship among sediment yield, streamflow and vegetation cover, is developed for our following research. We will firstly check the shortage of common rating curve and find out the relationship between vegetation cover change and SSC in this study. Then new sediment rating curves will be carried out and validated in some other East-south Asian basins.

Chapter 5: Developing model simulation method to separate impacts from climate change and human activities on streamflow and sediment flow

In this chapter, quantification of climate change and human activities contributions to changes of historical streamflow and sediment load is partitioned and evaluated.

Firstly, the historical trend of hydro-meteorological data of our study area was calculated based on the Mann-Kendall test and Pettitt test in the past. Then, SWAT model is applied and evaluated in our research basin. Finally, the validated SWAT model and new sediment rating curve are proposed to calculate the individual effects of climate change and human activities on streamflow and sediment flow. Moreover, land cover change is determined as the main human activities in this area.

Chapter 6: Coupling new sediment rating curve and ecological model to evaluate human-induced vegetation cover change effect on sediment flow

In this chapter, one new approach to analyze effect of human-induced vegetation cover change on the historical sediment load is proposed, which cross validation with results of chapter 4. On purpose of this, time series NDVI from Global Inventory Modeling and Mapping Studies (GIMMS) is introduced to analyze the changing trend of vegetation cover in the past years. In addition, potential LAI is simulated by one ecosystem model to describe the potential vegetation cover condition without human activities effects. Based on the relationship between NDVI and LAI, they are then converted into standardized values. Finally, standardized NDVI and LAI are inputted into new sediment rating curve to evaluate vegetation cover change effect on sediment load.

Chapter 7: Analyzing the potential effect of future land cover and climate change on streamflow and sediment flow based on land use change model and GCMs

In this chapter, potential effects of future land cover and climate change on streamflow and sediment flow based on land use change model and GCMs are presented. Specifically, based on spatial physical and socioeconomic drive factors of the basin, future potential land cover map is calculated. In addition, future precipitation from two selected GCMs is downscaled to all stations by different methods. And then, both future land cover and future precipitation scenario are used to feed hydrological model. Finally, streamflow and sediment flow response to changes in land cover and climate are discussed.

Chapter 8: Summary of the study

This chapter summarizes the results and contributions of this study, and then gives suggestions for the future works.

CHAPTER II

LITERATURE REVIEW

2.1. Introduction

As well known, streamflow, sediment yield are the integrated product of climate, geology, soil, land/vegetation cover, human activities and so on. Understanding the interactions between terrestrial ecosystems and hydrological system are fundamental in addressing issues of climate change and environmental degradation. However, quantifying these dynamic interactions both in space and time are compounded by challenges. Specifically, elucidating the impacts of land use/cover change and climate change at the basin scales on surface hydrology, water quality as well as sediment load are not straightforward but rather complex to warrant any generalizations. Subsequently, many insights into consequences of land use/cover and climate change on hydrology have been investigated at small spatial, observable scales. However, extrapolating findings from such small scales to larger scales such as river basins is confounded by the diversity of land use/cover and climate change as well as hydrological systems. Not only does the diversity in land use/cover and climate change complicate such a study, but also quantifying the effect of land use/cover and climate change on hydrology and sediment load have been considered as the difficult problem in hydrology.

In this chapter, previous researches related to the six specific objectives addressed in Chapter 1 have been reviewed. Relationships among land/vegetation cover, climate, and human activities related to streamflow and sediment yield, and relationship between streamflow and sediment yield are first reviewed. Followings this, models to estimate sediment yield of basin scale will be sorted out and analyzed. Based on these complex interactions, studies on impacts of land/vegetation cover change and climate change on streamflow and sediment yield will be listed and concluded from view of historical evaluation and future potential impacts. In addition, land use/cover change prediction methods to predict future land cover change are also reviewed in this Chapter.

2.2. Relationships among land/vegetation cover, climate, human activities related to streamflow and sediment yield

As well known, streamflow, sediment yield are the integrated product of climate, geology, soil, land/vegetation cover, human activities and so on. As a result, all these factors could be divided into input group (climate, geology, soil, land/vegetation cover, human activities) and output group (streamflow, sediment yield). In order to evaluate impacts of climate change and land cover change on streamflow and sediment yield, making this interactive relationships among input group clearer appears necessary and indispensable, should be firstly investigated. Many studies have already carried out to investigate the interactive feedback among land/vegetation cover, climate and human activities.

2.2.1. Researches on relationship between climate change and land or vegetation cover

Climate change is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. The climate exerts the dominant control on the spatial distribution of the major vegetation types on a global scale. In turn, vegetation cover affects climate via alteration of the physical characteristics of the land surface like albedo, roughness, water conductivity (biogeophysical mechanisms) and atmospheric gas composition, for example, CO_2 and CH_4 (biogeochemical effects). Faced to this interrelation, most studies have been conducted in different ways. One way to understand these feedbacks is coupled vegetation–climate model simulation. For example, Ziegler et al. (2003) made the strong case for a link between air mass dynamics, consequent climate patterns, and vegetation distribution, beginning with the Permian and advancing to the present day. Levis et al. (2004) applied the Community Climate System Model (CCSM2) with dynamic vegetation model to conclude that soil feedbacks, linked to surface albedo changes, contributed to the northward advance of the North African monsoon during the mid-Holocene. Based on the Fast Ocean Atmosphere Model–Lund Potsdam Jena (FOAM-LPJ), Gallimore et al. (2005) simulated a poleward expansion of boreal forest cover and an increase in midlatitude grasslands during the mid-Holocene, compared to simulated vegetation under modern orbital forcings. The expanded boreal forest, by masking snow cover, led to springtime warming through the albedo feedback. Another way is to apply observational data to determine the impact of vegetation feedbacks. Several researches made a conclusion that springtime leaf emergence initiates discontinuities in numerous meteorological variables (Schwartz 1996; Fitzjarrald et al. 2001), and McPherson et al. (2004) showed that Oklahoma’s winter wheat belt locally induces feedbacks on temperature and moisture. In addition, with the help of a satellite-based normalized difference vegetation index (NDVI) and gridded temperature data, Kaufmann et al. (2003) quantified the effects of inter-annual variations in vegetation on temperature over North American and Eurasian forests. They concluded that increased NDVI over North America resulted in warming during winter and spring and cooling during summer and autumn. The impact on temperature was strongest during winter, when NDVI was negatively correlated with snow extent and weakly correlated with vegetation. Liu et al. (2006) estimated the magnitude of observed global vegetation feedbacks on temperature and precipitation. And results showed that in the northern mid and high latitudes, vegetation variability is predominantly driven by temperature, while vegetation also exerts a strong positive feedback on temperature. They also concluded that, while most tropical and subtropical vegetation is driven by precipitation, the influence of vegetation on precipitation is not so strong globally, without any evidence of a dominant positive vegetation–precipitation feedback. Using high-resolution digital data and remote sensing dataset across a broad region with a pronounced climate gradient, Smith et al. (2013) developed empirical relationships between landscape morphology and vegetation cover with rainfall and runoff. In fact, the coupling between vegetation and climate is so strong that it has been utilized by scientists to assess climate change and identify changes in climate patterns (Dunne et al., 2004; Goldblum and Rigg, 2005).

2.2.2. Researches on relationship between human activities and land or vegetation cover

At the same time, human activities have also directly or indirectly affected land/vegetation cover in the world. On the one hand, human interference such as afforestation, deforestation, urbanization or farming activities will modify vegetation cover pattern. On the other hand, humans have greatly impacted the rates of supply of the major nutrients that constrain the productivity, composition, and diversity of terrestrial ecosystems (Taub, 2010). For instance, atmospheric CO_2 concentrations have been increased to about 40% above preindustrial levels (IPCC, 2007). Since 1700, land cover changes have been reported as being human-induced changes. Recently, David and Clarence (2001) concluded that anthropogenic changes in environmental limiting factors are likely to cause significant loss of plant diversity. Vescovi et al. (2002) proposed a new method combined Principal Component Analysis (PCA) and the vector analysis methods to identify and quantify the type of human-induced changes in savannah landscapes, which showed that human activities are important factors to lead to land cover changes. Chaudhry et al. (2008) analyzed that there is remarkable increase in urban area due to increasing population and Industrial/Infrastructural development pressure of National Capital.

2.2.3. Researches on separation impacts from climate change and human activities on land or vegetation cover change

Since land/vegetation cover change is caused by complex climate change and human activities, a major challenge hinges on how to distinguish between vegetation changes due to climatic variations and those caused by human land use activities on broad spatial scales. In particular, the impacts of human activities on vegetation dynamics can be extremely difficult to be separated out in the area where precipitation and vegetation cover show large variability (Buyantuyev and Wu 2009).

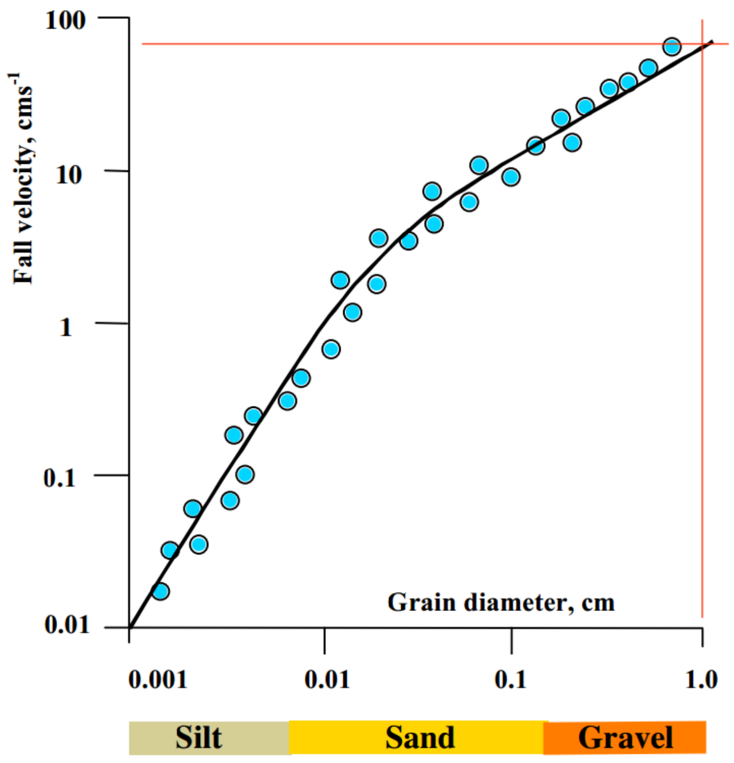
Faced to this challenge, researchers have already tried to conduct some studies based one satellite data like long time series of NDVI. Evans and Geerken (2004) presented a technique to discriminate between climate or human-induced dryland degradation. In this research, the climate influence was firstly removed based on evaluations the relation between AVHRR NDVI data and rainfall data, then remaining changes in NDVI signal were attributed to human influence and those areas displaying a negative trend over time were considered degrading. Geerken and Ilaiwi (2004) also separated the different effects from climate change and human activities caused rangeland degradation in the Syrian Steppe. Wessels et al. (2007) applied Rain-Use Efficiency method and Residual Trends method to try to distinguish human-induced land degradation from the effects of rainfall variability. However, results showed that Rain-Use Efficiency method was not a reliable indicator of degradation, and the Residual Trends method also can only identify potential problem areas at a regional scale, while the cause of negative trends has to be determined by local investigations. Li et al. (2012) also demonstrated the Residual Trends method provided an effective tool to distinguish between the effects of climatic factors and human activities on vegetation changes when plant cover and production are highly coupled with precipitation, which indicated that land use policies played the main role to affect vegetation changes. Specifically, results showed that the grassland vegetation in the Xilingol region of Inner Mongolia deteriorated from the early 1980s to 2000 primarily because of increased livestock grazing, while the degrading trend in vegetation was reversed between 2000 and 2006 due to decreased stocking rates, which was attributable to several new land use policies geared toward grassland conservation and restoration.

As a conclusion, satellite data like long time series of NDVI plays an important role for separation impacts from climate change and human activities on land or vegetation cover change. Even though increasing efforts are being carried out to separate impacts from climate change and human activities on land or vegetation cover change, the applicability and effectiveness of above research method still need to be evaluated and, especially when used in different vegetation zones.

2.3. Relationship between streamflow and sediment yield

2.3.1. Researches on relationship between streamflow and sediment yield

Steamflow is a function of water volume and velocity, which could affect water quality including suspended sediment in the stream. Stream velocity, which increases as the volume of the water in the stream increases, affects the amount of silt and sediment carried by the stream. Suspended sediment load is the particulate material that moves through the channel in the water column. These materials, mainly silt and sand, are kept in suspension by the upward flux of turbulence generated at the bed of the channel. Sediment particles could be physically carried by the stream current. Stronger the stream current, greater is the particle size (or mass) of the particle that can be carried, as well as the bedload. The upward stream currents must equal or exceed the particle fall-velocity (Figure 2.1) for suspended-sediment load to be sustained. The upward stream currents velocity which is dependence of sediment flux on the force of flowing water is expressed as shear stress driving the turbulent flux supporting the suspension. As a result, sediment introduced to quiet, slow-flowing streams will settle quickly to the stream bottom. Fast moving streams will keep sediment suspended longer in the water column.



(http://www.sfu.ca/~hickin/RIVERS/Rivers4(Sediment%20transport).pdf)

Figure 2.1. Fall velocity in relation to diameter of a spherical grain of quartz

A sediment rating curve is always used to describe the average relation between streamflow and suspended sediment concentration (SSC) or sediment load for a certain location. Although there are some other methods for developing sediment rating curves (Phillips et al., 1999) and some other type of equations may also perform well (Walling, 1984; Hickin, 1989; Asselman, 2000; Horowitz, 2003; Schmidt and Morche, 2006), but the most common is a power function (regression) that relates SSC to Q (e.g. Walling, 1977; Crawford, 1996; Phillips et al., 1999; Asselman, 2000). Linear or second-order polynomial sediment rating curves, with and without a ‘smearing’ correction could also calculate very good results for the annual or longer term suspended sediment fluxes (Horowitz et al., 2001). The most common sediment rating curve covers both the effect of increased stream power at higher discharge and the extent to which new sources of sediment become available in weather conditions that cause high discharge. Despite its general use several problems are recognized that regard the accuracy of the fitted curve as well as the physical meaning of its regression coefficients. Unfortunately, the most common sediment rating curve is recognized that the common sediment rating curve method tends to under-predict high, and over-predict low suspended sediment concentrations (Asselman, 2000; Horowitz, 2003). In addition, it does not consider temporal dynamic changes of vegetation cover. However, different vegetation cover should have different effect on soil erosion production and transport capacity by slowing flow through friction losses (Howe et al., 2005). Consequently, one new sediment rating curve considering the effect of land/vegetation cover should be developed to calculate vegetation cover change effect on the sediment load.

Table 2.1. Sediment rating curves

Format	Reference
$TSL = \sum_{i=1}^{n}(Q_{mi}.C_{mi}.P_{ci})$	Walling, 1984
$Log(SSC) = a + blogQ + d(logQ)^2$	Hickin, 1989
$SSC = c + aQ^b$	Asselman, 2000
$SSC = a + bQ^c + dQ^e$	Horowitz, 2003; Schmidt and Morche, 2006
$SSC = aQ^b$	Walling, 1977; De Vries and Klavers, 1994; Gergov, 1996; Phillips et al., 1999; Asselman, 2000

Q_{mi}: the median value of streamflow for the particular discharge class interval

C_{mi}: the concentration associated with Q_{mi} estimated using the common rating relationship

P_{ci}: the percentage of the high frequency discharge record associated with the particular flow class interval

TSL: total sediment load; Q: instantaneous streamflow

SSC: suspended sediment concentration

a,b,c,d,e: different coefficients in equations

Even though the format of relationship could not be agreement with each other, the strong relationship does presents between streamflow and sediment flux.

2.3.2. Researches on models to estimate sediment yield of a basin

In general, all these models fall into three main categories: empirical or statistical, conceptual and physical-based models. The distinction between models is not sharp and therefore can be somewhat subjective. Merritt et al. (2003) summarized these models in terms of their classification, scales of application and input data requirements, and concluded that model components generally contain a mix of empirical, conceptual and physics-based algorithms. It is difficult to sort these models exactly according to physical processes and model algorithms. They are likely to contain a mix of modules from each of these categories (Merritt et al., 2003). Because of this, we would like to classify all into models with more parameters and models with less parameter by amount of model parameters or input requirements.

Among models with more parameters, physical-based models accounts for the main part. This kind of model could be universally used to predict sediment yield of a watershed and to provide an indication of the qualitative and quantitative effects of land use changes or climate change. However, it is always very difficult to determine value of parameters especially at describing the complex process of erosion and sediment yield. Due to the requirement that parameter values are determined through calibration against observed data, these models tend to suffer from problems associated with the identifiability of their parameter values and non-uniqueness of 'best fit' solutions (Jakeman and Hornberger, 1993; Beck et al., 1995; Merritt et al., 2003). In addition, models with more parameters generally require a lot of detailed information including hydrological, hydraulic and geological characteristics of the river basin, and as well as sediment characteristics itself. Preparation of such dataset will be difficult and costly.

As for models with less parameter, sediment rating curves (Asselman, 2000) represents a linear or nonlinear functional relationship relates suspended sediment concentration/load to streamflow are one main type. Among all sediment rating curves, one power functional relationship is most common one (Horowitz, 2003). Due to measuring the sediment flux on a river is a time-consuming and expensive operation, the sediment rating curve provide one considerable way to estimate sediment flux in the routine measurement of the flow in our rivers. As you might imagine, measuring the average suspended-sediment concentration in streamflow is no less time-consuming and expensive and for these same reasons we make considerable use of the suspended sediment rating curve. Unfortunately, it is recognized that the common sediment rating curve method tends to over-predict high, and under-predict low suspended sediment concentrations (Asselman, 2000; Horowitz, 2003). In addition, it is too simple without considering temporal dynamic changes of vegetation cover. However, different vegetation cover should have different effect on soil erosion production by modifying soil erodibility and transport capacity by slowing flow through friction losses (Howe et al., 2005).

Summarily, for basins without enough input data or no data, sediment rating curve provide one opportunity to evaluate sediment load. And on purpose of calculating land cover change effect on the sediment load, new sediment rating curve with few parameters considering the effect of vegetation cover should be developed (Wang and Ishidaira, 2013).

Table 2.2. Erosion/sediment transport models (Modified from Merritt et al., 2003)

Model	Type	Scale	Input/output	Reference
AGNPS	Conceptual	Small catchment	Input requirements: High Output: runoff volume; peak rate, SS, N, P, and COD concentrations	Young et al. (1987)
ANSWERS	Physical	Small catchment	Input requirements: High Output: sediment, nutrients	Beasley et al. (1980)
CREAMS	Physical	field 40–400 ha	Input requirements: High Output: erosion; deposition	Knisel (1980)
EMSS	Conceptual	Catchment	Input requirements: Low Output: runoff, sediment loads, nitrogen loads and phosphorus loads	Vertessey et al. (2001);Watson et al. (2001)
HSPF	Conceptual	Catchment	Input requirements: High Output: runoff, flow rate, sediment load, nutrient concentration	Johanson et al. (1980)
IHACRES-WQ	Empirical/Conceptual	Catchment	Input requirements: Low Output: runoff, sediment and nutrients	Jakeman et al., 1990, Jakeman et al., 1994a and Jakeman et al., 1994b,Dietrich et al. (1999)
IQQM	Conceptual	Catchment	Input requirements: Moderate Output: many pollutants including nutrients, sediments, algae.	DLWC (1995)
LASCAM	Conceptual	Catchment	Input requirements: High Output: runoff, sediment, salt fluxes	Viney and Sivalapan (1999)
SWRRB	Conceptual	Catchment	Input requirements: High Output: streamflow, sediment, nutrient and pesticide yields	USEPA (1994)
GUEST	Physical	Plot	Input: High Output: runoff; sediment concentration	Yu et al. (1997); Rose et al. (1997)
LISEM	Physical	Small catchment	Input: High Output: runoff; sediment yield	Takken et al. (1999); De Roo and Jetten (1999)
PERFECT	Physical	Field	Input: High Output: runoff, erosion, crop yield	Littleboy et al. (1992b)
SEDNET	Empirical/Conceptual	Catchment	Input requirements: Moderate Output: suspended sediment, relative contributions from overland flow, gully and bank erosion processes	Prosser et al. (2001c)
TOPOG	Physical	Hillslope	Input: High Output: water logging, erosion hazard, solute transport	Gutteridge Haskins and Davey (1991)
USLE	Empirical	Hillslope	Input: High Output: erosion	Wischmeier and Smith (1978)
WEPP	Physical	Hillslope/ catchment	Input: High Output: runoff; sediment characteristics; form of sediment loss	Laflen et al. (1991)
MIKE-11	Physical	Catchment	Input: High Output: sediment yield, runoff	Hanley et al. (1998)

2.4. Studies on impacts of land/vegetation cover change and climate change on streamflow and sediment yield

Generally, impact assessment of land/vegetation cover change and climate change on streamflow and sediment flow should be studied from two perspectives, historical evaluation and future prediction. Historical insight into these effects can not only improve the knowledge of river processes, but also is precondition and foundation for analysis of future environmental changes impacts on streamflow and sediment load. Quantitative assessment impacts of future land use/cover and climate change on streamflow and sediment flow is continuation and further extension of historical changes analysis.

2.4.1. Studies on separation of integrated impacts on historical streamflow and sediment yield

The climate change factor and the human activities factor are interacted with each other to affect changes of streamflow and sediment yield. Since both climate change and human activities are the major controls of water balance and sediment yield in a catchment, research towards separation of their effects on streamflow and sediment yield has become one of the widespread issues of scientific concern. It is important to determine the main factors and their contributions to affect the changes of the streamflow and sediment yield to improve the sustainable development of water resources and provide ecological conservation measures.

Many studies have been conducted for this purpose in different ways. One traditional way is paired catchments experiment. Change of streamflow and sediment load among paired catchments are monitored to quantify sediment dynamics response to land cover change or climate change (Garcia-Ruiz et al., 2008). Although this approach is very useful in quantifying the impacts, it is quite costly, time-consuming, and it is difficult to find one reasonable paired catchment for most studies. In addition, most of these are carried out either based on statistical methods or hydrological models. However, their limitations are obvious: statistical methods lack a physical basis and studies based on hydrological models require considerable amount of information which, in many cases, may not be available. This is especially important in distributed hydrological models used to improve the accuracy of the separation. Among all exsited methods, one “fixing–changing” method combined with the hydrological modelling was most popular one (Wang et al., 2009; Tang et al., 2011). For instance, a lumped hydrologic model (CHARM) and a distributed hydrologic model (SWAT) were used to model the impacts of both land-cover change and climate variation on river runoff during the past four decades in the upper reaches of the Yangtze River (Chen et al., 2005). The results showed that the contribution of climate variation to the change of runoff regime makes up 60%–80%, while that of land cover changes only 20%. Wang et al. (2009) applied distributed time-variant gain model (DTVGM) at the watershed scale to quantitatively identify the impacts of climate changes and human activities on runoff in the Chaobai River Basin in North China. Comparing the annual precipitation means over 13 years (before 1980), the means of the second period (1980-2001) decreased by 5.4% and 4.9% in the Chao River and Bai River basins, respectively. However, the related annual runoff decreased by 40.3% and 52.8%, respectively, a much greater decline than exhibited by precipitation. Through the monthly model simulation and the fixing-changing method, it is determined that decreases in runoff between the two periods can be attributed to 35% (31%) from climate variations and 68% (70%) from human activities in the Chao River (Bai River). Thus, human impact exerted a dominant influence upon runoff decline in the Chaobai River basin compared to climate. Li et al. (2009) indicated that SWAT proved to be a powerful tool to simulate the effect of environmental change on surface hydrology. Results showed that both land use change and climate variability decreased runoff by 9.6% and 95.8%, respectively, and decreased soil water contents by 18.8% and 77.1%. Land use change increased evapotranspiration by 8.0% while climate variability decreased it by 103.0%. The climate variability influenced the surface hydrology more significantly than the land use change in the Heihe catchment during 1981–2000; therefore, the influence of climate variability should be considered and assessed separately when quantifying the hydrological effect of vegetation restoration in the Loess Plateau. Tang et al. (2011) presented a geomorphology-based non-point source pollution (GBNP) model for separation of land cover change and climate variability effects on streamflow and water quality, including sediment yield. On the basis of long-term simulation of the GBNP model, annual runoff presented a decreasing trend from 1980 to 2005, where precipitation and increase in air temperature were the dominant factors in runoff decrease. Afforestation, a water–soil conservation practice, positively affected the reduction of non-point source pollution; however, it also caused a reduction of streamflow. A comparison between 1980–1998 and 1999–2005 showed that land-use changes accounted for 6.6% and 9.2% of the decrease in streamflow and sediment load, respectively, while climate variability accounted for 93.1% and 91.3%. Khoi and Suetsugi (2012) also used SWAT model to separate impacts of climate and land-use changes on streamflow, sediment load, and water balance components in Be river basin of Vietnam. The hydrologic and sediment yield responses to land-use and climate changes were simulated based on the calibrated model. The results indicated that a 16.3% decrease in forest land was likely to increase streamflow (1.2%), sediment load (11.3 %). Climate change in the catchment leaded to decreases in streamflow (26.3%) and sediment load (31.7%). Furthermore, the results emphasized water scarcity during the dry season and increased soil erosion during the wet season. Gao et al. (2013) used double mass curve to detect impact of precipitation and human activity on streamflow and sediment discharge. Trends and change-points for streamflow and sediment discharge in the flood season in two major sub-catchments were firstly identified, and then based on the changing point the impacts of precipitation and human activities on the changes were analyzed. Results showed the average human activities contribution rate for the entire area was 83 %, which is significantly higher than the average contribution rate of precipitation (17 %) for streamflow. The average human activities contribution rate to reductions in sediment discharge was 95 % in the Wei River basin, which was very significantly higher than the contribution rate of precipitation (4.44 %). Results indicated that human activities played a major role in both streamflow and sediment discharge reduction in the Wei River basin.

Actually, this “fixing–changing” method has a potential assumption that the total changes of streamflow or sediment load is caused by i) climate variability and human activities or ii) climate variability and land cover change. Under the first assumption, human activities effects could be evaluated, which maybe include combined impacts from land cover change and dam construction, and so on. Among the part of human activities effects, it is difficult to separate them in details. In the case of second assumption, it is not so reasonable because the total change of streamflow or sediment load may be not only caused by climate variability and land cover change. Consequently, more research should be proposed to determine their contributions of environmental changes to affect the changes of the streamflow and sediment yield.

2.4.2. Studies future climate change and its impact on streamflow and sediment yield

Changes in climate have been observed in the past decades, and more changes have been projected for the coming decades (IPCC, 2007). Climate models estimate that the global mean air temperature is likely to increase by 1.8 to 4.0◦C by the end of the 21st century, depending on various greenhouse gas emissions scenarios (GHGES) and general circulation models (GCMs) (IPCC, 2007). An increase in global temperature is expected to increase evapotranspiration and to cause precipitation changes (Hu et al., 2012), which will significantly affect the streamflow and sediment load of many river systems (Lu, 2005) As a result, Climate change emerged as one of the major forces that will affect hydrological processes in the future.

In recent years, the impact of future climate change on streamflow and sediment yield has gained considerable attention through numerous studies in many regions around the world. For instance, Arnell (1999) analyzed that there would be substantial changes in regional hydrology in snow-affected areas under global warming, due to changes in the month of maximum runoff and early snowmelt. Middelkoop et al. (2001) and Chang et al. (2002) also got similar results in the Rhine basin and southwestern Bulgaria respectively. A change in sediment flux from −0.7 to 13.7 % as a result of changes in rainfall ranging from −0.7 to 17.8 % and temperature fluctuation of 0.03–2.4◦C (Zhu et al., 2008) were found in the Longchuanjiang catchment of the Upper Yangtze River, China. In addition, Phan et al. (2011) have also estimated that 1 to 3 %, 3.9 to 11.4 % and −1.1 to −5.3 % changes in mean annual, wet season and dry season streamflows respectively and 1.2 to 4.7 %, 3.6 to 15.3 % and −1.3 to −7.7 % changes in mean annual, wet season and dry season sediment yields respectively maybe happened in the Song Cau watershed in northern Vietnam due to the changes in precipitation and temperature under B1, B2, and A2 climate change scenarios.

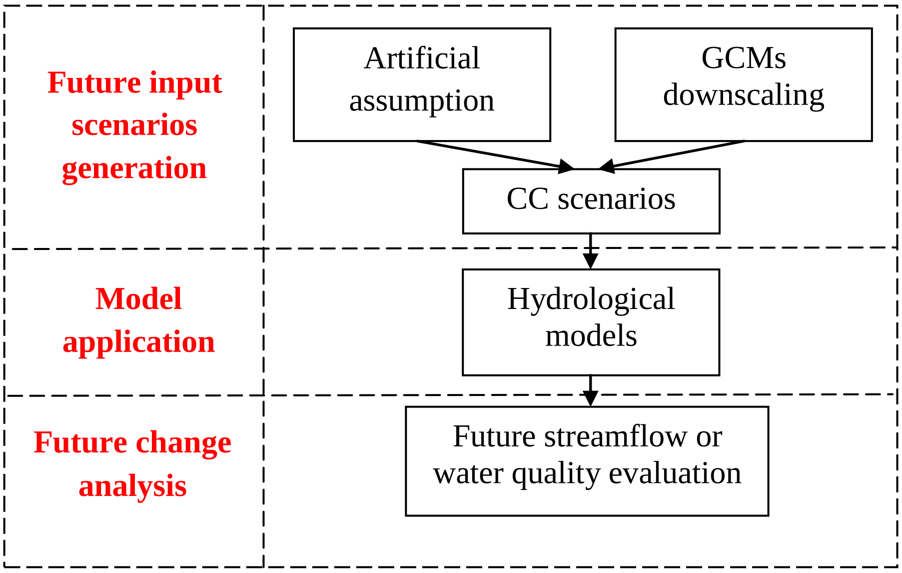


Figure 2.2. General approach for evaluation of future climate change impact on streamflow and water quality

Based on recent studies on future climate change impact on streamflow and water quality, as well as sediment yield, one general approach (Figure 2.2) could be concluded easily, including input (future scenarios generation), model application and output (future change analysis). To investigate the future changes impacts, future climate change scenarios should be first generated. The future scenarios presented in the Special Report on Emission Scenarios (Figure 2.3) in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007) have been widely applied to investigate hydrological responses to climate change (Moradkhani et al., 2010; Praskievicz and Chang, 2011; Yoshimura et al., 2009). However, the spatial resolution mismatch between GCMs outputs and the data requirements of hydrology is a major obstacle (Xu, 1999). It is therefore necessary to perform some post-processing to downscale these global-scale models for impact studies. There are already some downscaling methods, such as delta method, dynamical downscaling (regional climate models, RCMs) and statistical downscaling of GCMs models (Chen et al., 2011). Delta method involves adjusting the observed time series by adding the difference (for temperatures) or multiplying the ratio (for precipitation) between future and present climates as simulated by the RCMs or GCMs. The most significant drawbacks are that the temporal sequencing of wet and dry days, and that the variances of temperatures are unchanged (Minville et al., 2008; Chen et al., 2011). And RCMs are developed based on dynamic formulations using initial and time-dependent lateral boundary conditions of GCMs to achieve a higher spatial resolution at the expense of limited area modeling (Caya and Laprise, 1999). The main problem of RCMs is the time consuming and computational cost (Solman and Nunez, 1999; Chen et al., 2011).

Statistical downscaling techniques have been developed to overcome these challenges, which are computationally cheap and relatively easy to implement. They involve linking the state of some variables representing a large scale (GCM or RCM grid scale, the predictors) and the state of other variables representing a much smaller scale (catchment or site scale, the predictands). Several Statistical downscaling models have already been developed for GCMs output downscaling, such as SDSM (Wilby et al., 2002) and ASD (Hessami et al., 2008). Therefore, statistical downscaling techniques were the most often used and powerful downscaling tools for future climate change scenarios generation.

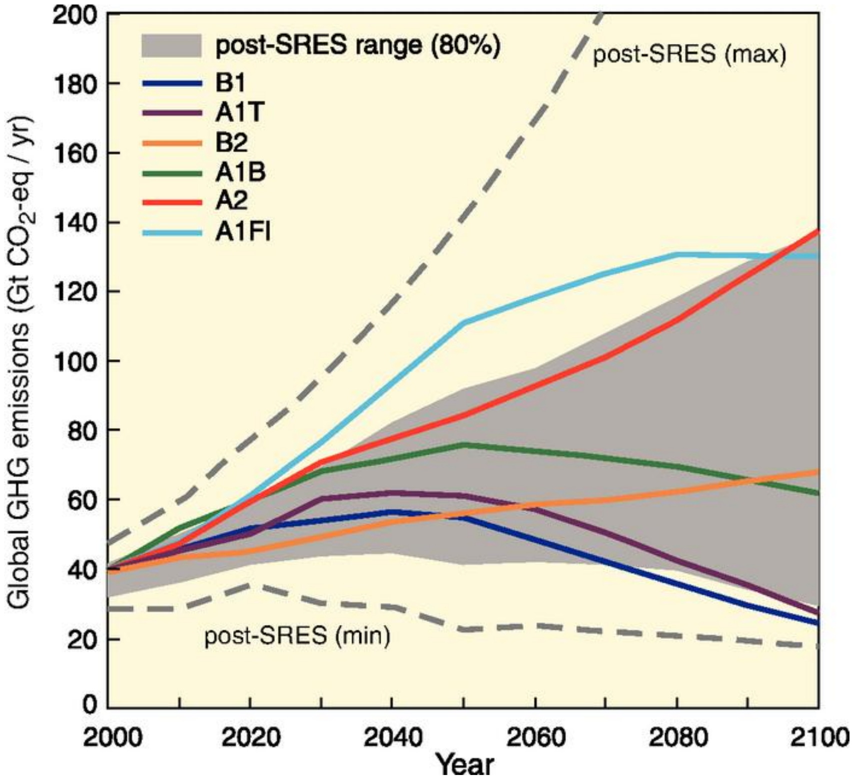


Figure 2.3. Scenarios for GHG emissions from 2000 to 2100 in the absence of additional climate policies (IPCC,2007)

With the help of downscaling process, future climate change scenarios mach with hydrological simulation scale could be generated, which will be used to feed hydrological models to simulate hydrological impacts of climate change. Hydrological modeling is useful to better understand and explain hydrological processes, such as runoff and transport of sediment and pollutants in a catchment. At present, there are many hydrological models, such as Soil and Water Assessment Tool (SWAT), the Agricultural Non-point Source Pollution Model (AGNPS), Hydrologic Simulation Program Fortran (HSPF), MIKE SHE, and Block-wise use of TOPMODEL (BTOPMC). Of these, SWAT model has been employed widely to evaluate the impact of climate change on streamflow and sediment yields. For instance, Githui et al. (2009) evaluated how the potential future climatic changes would affect streamflow on the

Nzoia catchment in the Lake Victoria basin by simulation model SWAT. Results showed that the range of change in mean annual rainfall of 2.4–23.2% corresponded to a change in streamflow of about 6–115%. The analysis revealed important rainfall–runoff linear relationships for certain months that could be extrapolated to estimate amounts of streamflow under various scenarios of change in rainfall. Shrestha et al. (2013) applied swat model to evaluate the impact of climate change on sediment yield in the Nam Ou basin located in northern Laos, combined with four general circulation models (GCMs). The simulation results showed that the changes in annual stream discharges are likely to range from a 17% decrease to 66% increase in the future, which would lead to predicted changes in annual sediment yield ranging from a 27% decrease to about 160% increase. Changes in intra-annual (monthly) discharge as well as sediment yield are even greater (−62 to 105% in discharge and −88 to 243% in sediment yield). A higher discharge and sediment flux were expected during the wet seasons, although the highest relative changes are observed during the dry months. Chien et al. (2013) also applied SWAT model to evaluate assess the potential impacts of climate change on future streamflow in the Rock River (RRW), Illinois River (IRW), Kaskaskia River (KRW), and Wabash River (WRW) watersheds in the Midwestern United States. In his research, the potential impacts of climate change on future water resources are assessed using SWAT streamflow simulations driven by projections from nine global climate models (GCMs) under a maximum of three SRES scenarios (A1B, A2, and B1). Results showed that predicted future streamflow based on climate change scenarios would tend to increase in the winter but decrease in the summer. According to 26 GCM projections, annual streamflows from 2051-2060 (2086-2095) were projected to decrease up to 45.2% (61.3%), 48.7% (49.8%), 48.7% (56.6%), and 41.1% (44.6%) in the RRW, IRW, KRW, and WRW, respectively. In addition, under the projected changes in climate, intra- and inter-annual streamflow variability generally did not increase over time. And there are still a huge mass of simular research (Ficklin et al., 2009; Setegn et al., 2010; Li et al., 2011; Mengistu and Sorteberg, 2012). Because SWAT model need too much inputs and parameters, some other hydrological models such as BTOP model were also applied to evaluate the impact of climate change on streamflow and sediment yield for catchments with limited data. Phan et al. (2011) used BTOPMC model to predict future (2011–2034) river discharge in the Kone River basin located in Central Vietnam. Results showed that discharge volume would slightly increase by 3% under the A1B scenario in the Kone River basin in the future, while discharge during the flood season would tend to decrease by about 18.6% relative to the period 1980–1999. Bastola et al. (2011) also attempted to assess the hydrological impacts of future climate change using a multi-model approach combining multiple emission scenarios, GCMs and four hydrological models (including BTOPMC model) at the catchment scale.

To date, a number of hydrological applications to study hydrology and sediment transport response to climate change in different scale catchments have been undertaken in different regions of the world. The previous studies of hydrological model application and the acceptable results could provide us more experiences support to research of climate change impact on streamflow and sediment yield.

2.4.3. Studies on land use/cover change prediction and its impact on streamflow and sediment yield

Climate change has been affecting hydrological processes worldwide. Land cover changes at local scale may exacerbate or alleviate climate change effects. Thus it is important to evaluate impact of future land cover change on streamflow and sediment yield. Assessing impacts of land cover changes on hydrology and sediment yield is the basis for watershed management and ecological restoration.

In order to evaluate impact of future land cover change on streamflow and sediment yield, future land cover change scenarios should be first investigated. Take a wide view of recent studies, two main approaches ware carried out. The first method is very simple. Future land cover scenarios could be developed according to historical land cover change trend within the catchment (Qi et al., 2009), just like assuming one land use type into another. To obtain potential or future land cover change, land use/cover change models is another more complex and reasonable way. Several land use/cover change models (Table 2.3) have been developed for predicting land use change, such as CLUE-S (Verburg et al., 2002), Dinamica EGO (Soares et al., 2002), GEOMOD (Pontius et al., 2001) and Land Change Modeler (LCM) (Kim, 2010). However, the empirical models (Verburg and Veldkamp, 2004) have frequently been used to study the change in land use/cover because they provide a mechanism for analyzing detailed case studies and can help in identifying the key driving factors for land use/cover changes (Aspinall, 2004). In the first step, these programs compute a “changing trend” by comparing land cover maps at two different dates. In the second step, they derive a transition potential map (per-pixel probabilities of shifting from a one land cover type to another type) using different statistical methods and spatial factors (Figure 2.4).

Table 2.3. Algorithm of land use/cover change models

MODEL	Principium & algorithm	Scale
CLUE-S	Deriving a transition potential map using empirically quantified relations between land-use and its driving factors	Regional
Dinamica EGO	Deriving a transition potential map based on a set of explanatory variables and past trends involving some degree of expert knowledge	Regional
GEOMOD	Deriving a transition potential map based on a statistical deduction approach (maximum power principle)	Regional
LCM	Deriving a transition potential map based upon neural networks algorithm	Global/Regional

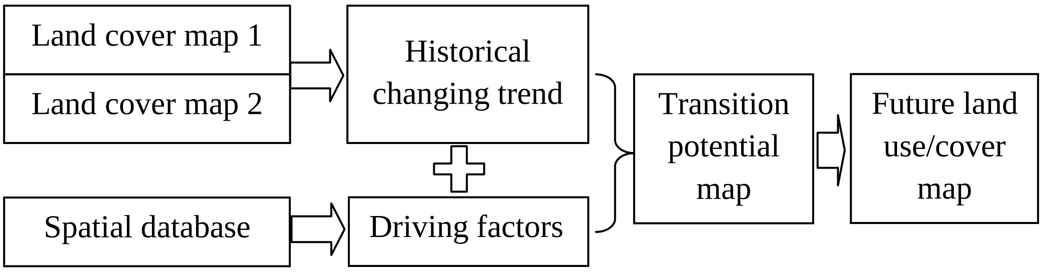


Figure 2.4. Overview of the general land use/cover change modeling procedure

Different LUCC models have their strong point and weak point. Follador et al. (2008) evaluated four land use/cover change models based on satellite dataset and concluded that it is difficult to compare the performances of numerous LUCC models because we have to consider many different aspects during the LUCC modelling. Many studies have been carried out to predict land use/cover change. Kim (2010) applied GEOMOD Modeling and Land Change Modeler (LCM) to predict future land cover in Chiquitanía, Bolivia. Results showed GEOMOD lacked the potential to model multiple transitions, and the LCM's logistic regression seemed the most suitable LUCC module to construct a Reducing Emissions from Deforestation and Forest Degradation (REDD) baseline in this case. Azucena et al. (2011) evaluated maps of change potential produced by two spatially explicit models (LCM and Dinamica EGO) and then applied to a Tropical Deciduous Forest in western Mexico. Results indicated that the potential transition map generated using LCM was more accurate because neural networks outputs are able to express the simultaneous change potential to various land cover types more adequately than individual probabilities obtained through the weights of evidence method. As a result, we could not speak which model is the best and model selection should depend on our research purpose.

Many studies have been carried out to predict land use/cover change based on LUCC models (McRae et al., 2008; Alcamo et al., 2011; Guan et al., 2011). And, it is also started to link LUCC model with hydrological model to evaluate LUCC effect on hydrology and water quality, as well as SSC. Recently, several studies have already been proposed. Yu-Pin Lin et al. (2007) developed an approach for simulating and assessing land use changes and their effects on land use patterns and hydrological processes at the watershed level. This study provided a novel approach that combines a land use change model, landscape metrics and a watershed hydrological model with an analysis of impacts of future land use scenarios on land use pattern and hydrology in the Wu-Tu watershed in northern Taiwan. The results show that the variability and magnitude of future hydrological components were significantly and cumulatively influenced by land use changes during the simulation period, particularly runoff and groundwater discharge. Ying Chen et al. (2009) combined an empirical land use change (CLUE-S) and an event-scale rainfall-runoff model (HEC–HMS) to quantify the impacts of potential land use change on the storm runoff generation in the Xitiaoxi basin, upstream of Taihu Lake watershed. The results indicated that the future land use scenarios were projected to increase the total runoff as well as the peak discharge, and that the magnitude of increment relates to the expansion rate of built-up area. Oñate-Valdivieso and Sendra (2010) applied LCM model to predict future land use map using logistic regression (Reg-Log) and Multi-layer perceptron Neural Networks (MPL) in a binational hydrographic basin in South America. resultas showed biophysical variables had the most explicative power with a better performance of the model based on logistic regression than the one made by using neural networks, which could be further feed hydrological model. Leh et al. (2011) evaluated the impact of rapidly changing land use on erosion and sedimentation in a mixed land use watershed in the Ozark Highlands of the USA, which combined a geographic information system-based soil erosion modeling approach with LCM model to quantify the influence of changing land use on erosion risk. Results supported previous reports of increased urbanization leading to increased soil erosion risk and highlighted the interaction of changes in land use with soil erosion potential. Based on LCM model and SWAT model, Wilson and Weng (2011) predicted the future total SSC under different future land use scenarios between 2010 and 2030 within Des Plaines River watershed, Illinois. The analysis results denoted that middle and high density residential development can reduce excess TSS concentration, while the establishment of dense commercial and industrial development might help ameliorate high phosphorus levels.

More studies were focused on linking land use/cover change model with streamflow, which could support more experience for our future research. However, only few studies were extended to sediment yield or water quality, so it is necessary to pay more attention to combining LUCC model with water quality, as well as sediment yield.

2.4.4. Combine impact of future climate and land use/cover change on streamflow and sediment yield

The previous SRES scenarios for the Fourth Assessment Report (AR4) of the IPCC are only forced by greenhouse gas and aerosol from artificial climate change factors. However, the Fifth Assessment Report (AR5) of the IPCC which will be published in 2014 will include new scenarios based on various technical developments. These new scenarios, called representative concentration pathways (RCPs), are a set of greenhouse gas concentration and emissions pathways designed to support research on the impacts of and potential policy responses to climate change, which also considered to include impacts caused by LUCC (Riahi et al., 2011; Van Vuuren et al., 2011).

Although studies of the combined impact of future climate and land use/cover changes on hydrology and sediment yield are desirable, most published studies consider only one type of change (climate change or land-use change) or one type of impact (hydrology or sediment yield). Few studies have analyzed the effect of future climate and land use/cover changes on streamflow and sediment yield as well as water quality. For instance, Tu (2009) investigated the combined impact of climate and land use changes on streamflow and water quality by using AVGWLF model (Generalized Watershed Loading Function with an ArcView geographic information system interface) to simulate the future changes in streamflow and nitrogen load under different climate change and land use change scenarios in Eastern Massachusetts, USA. Result showed that climate change and land development had more impact on changing the seasonal distributions of the streamflow and nitrogen load than on altering average annual amounts of the streamflow and nitrogen load. Khoi and Suetsugi (2012) investigated the responses of hydrology and sediment yield with impacts of land-use and climate change scenarios in the Be River Catchment, Vietnam, using the SWAT hydrological model. The results indicated that a 16.3% decrease in forest land was likely to increase streamflow (0.2 to 0.4%), sediment load (1.8 to 3.0%). Climate change in the catchment leaded to decreases in streamflow (0.7 to 6.9%) and changes in sediment load (-5.3 to 4.4%). The combined impacts of land-use and climate changes decreased streamflow (2.0 to 3.9%) and sediment load (2.0 to 7.9%).

It is becoming necessary to quantitatively assess combined impacts of land use/cover and climate changes on streamflow and sediment load of past and future, which is a complex and difficult task that requires many aspects to be considered, including environmental, socioeconomic and institutional issues.

CHAPTER Ⅲ

STUDY AREA AND GENERAL RESEARCH FRAMEWORK

3. 1. Study Area Description

3.1.1 General description

Red river, with its overall sediment load previously classed 9th in the world, has received increasing attention with many eco-hydrological problems, such as hydrological changes in the upper reaches and lower reaches, sediment changes and biodiversity disappear (He et al., 2005). The Da River Basin (Figure 3.1) located in humid region is the biggest branch of the Red River which gets its name from the reddish-brown color caused by its high sediment load rich in iron dioxide, with the basin area of 55000 km^2. The Red River originates from the mountainous region in Yunnan Province of China, at an elevation of nearly 2500 m. The river cross sections are narrow, with a steep slope of 0.37. Then, it runs through Vietnamese provinces and flows into the South China Sea. The Red River basin is located in the tropical monsoon region, with the latitude from 20 °N to 26 °N and the longitude from 100 °E to 106.5 °E. The total area of the Red River basin is about 169000 km^2, including 48% in China, 1% in Laos, and 51% in Vietnam. In Vietnam territory, the Red River basin covers surface lands of 26 provinces and cities including the Hanoi capital and Red River delta. The Red River comprises of three main upstream tributaries Da, Thao, and Lo River, and its delta forms near the capital Hanoi (Dang, 2000). The river delta has a triangular form with the apex near to Viet Tri, which is the junction of three main tributaries (Nguyen et al, 2001).

The population in the Red River basin is about 24 million people of which 15 percent live in urban areas. With almost 17 million people living in the delta, the Red River delta is one of the most densely populated rural areas in the World – about more than 1000 persons/km^2 (Tinh, 2001). The delta comprises two big cities of Vietnam: the national capital Hanoi and a big seaport city Hai Phong. It is an important area for the socio-economic development of Vietnam.

The altitude varies from 3620 m to 10 m with the direction from northwest to southeast in Da River Basin (Figure 3.2). The slope of the basin can be divided into three levels. A slope from 0 to 10% accounts for 30% of the total area, one from 10 to 20% accounts for 46% of the area, and one greater than 20% accounts for 24% of the area. Most of the slope is more than 10%, which shows the study basin is located in the steep area. The area with the slope more than 20% are mainly distributed in the center of the basin and the areas with a slope less than 10% are located in the downstream and edge of the basin (Figure 3.2).

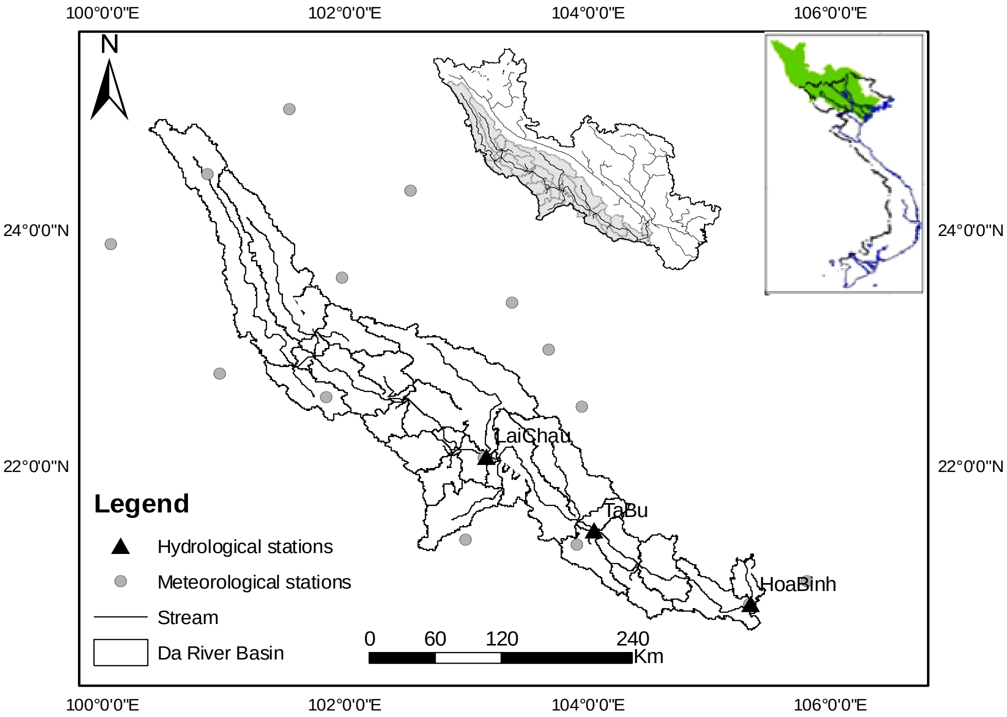


Figure 3.1. Location of the study area and the meteorological stations

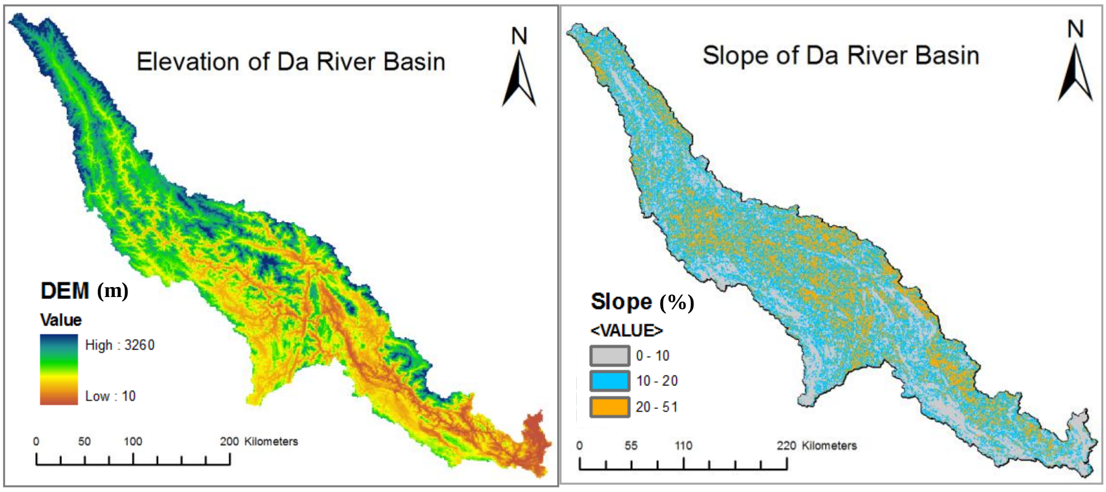


Figure 3.2. (a) DEM and (b) Slope maps of the Da River Basin

It is an important area for the socio-economic development of Vietnam. Moreover, the biggest reservoir in Vietnam (HoaBinh reservoir) is also located on the downstream of Da River Basin. It is one of the largest (V=9.5 km^3) dams in South-East Asia, which was completely finished in 1993. The reservoir is designed to keep the peak flood level of the most extreme historical flood that occurred in 1971 at Hanoi below 13.3 m. Besides flood control, the reservoir is expected to produce on average 7.8 billion kWh per year corresponding to 40 percent of Vietnam's electricity (Tinh, 2001).

3.1.2 hydro-meteorological condition

Generally, the climate of the Red River basin is subtropical, and it is mainly affected by the eastern Asia monsoon wind. It is necessary to point out that the seasonal variation of rainfall is significant in the Red River basin (Figure 3.4). Only 10% to 20% of the annual rainfall occurs in the dry season (November to March), while the other 80% to 90% of total annual rainfall concentrates in the rainy season (April to October). The mean annual rainfall in the upper basin (China territory) is approximately 1200 mm per year, while about 1900 mm per year in the Vietnam territory. The amount of precipitation during storms can reach to more than 300 mm/day. The annual mean rainfall is about 1320 mm for the Da River basin, 85% of which falls during wet rainy season. In addition, the delta region is affected by typhoons from June to October, especially in July and August with a maximum wind speed recorded to about 180 km/h (Binnie et al., 1995). In terms of spatial distribution of rainfall, the highest precipitation is distributed in the center of the basin (Figure 3.3).

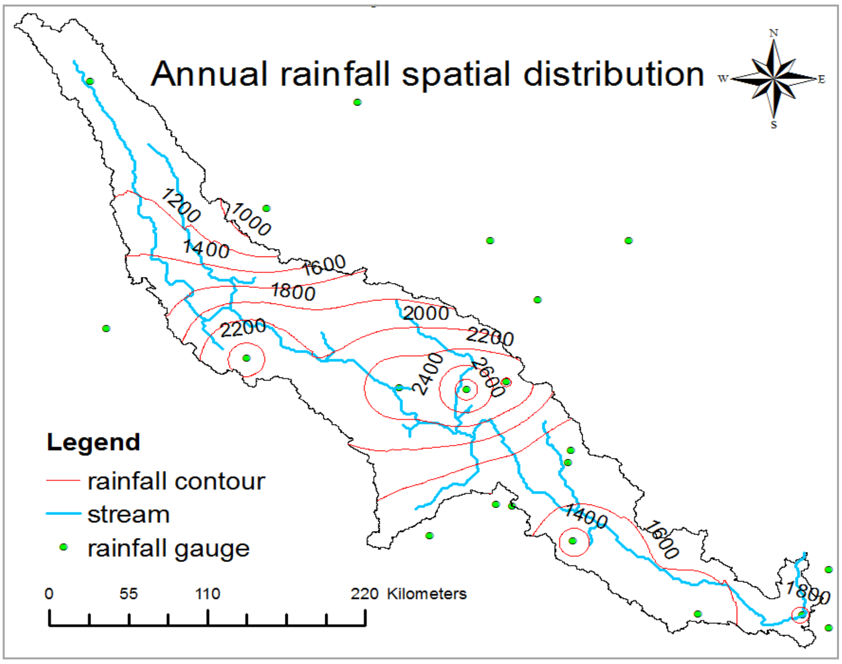


Figure 3.3. Spatial distribution of annual rainfall in the Da River Basin

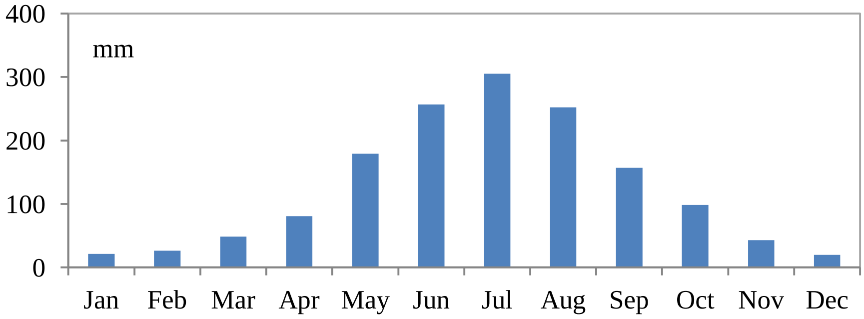


Figure 3.4. Monthly mean rainfall in the Da River Basin

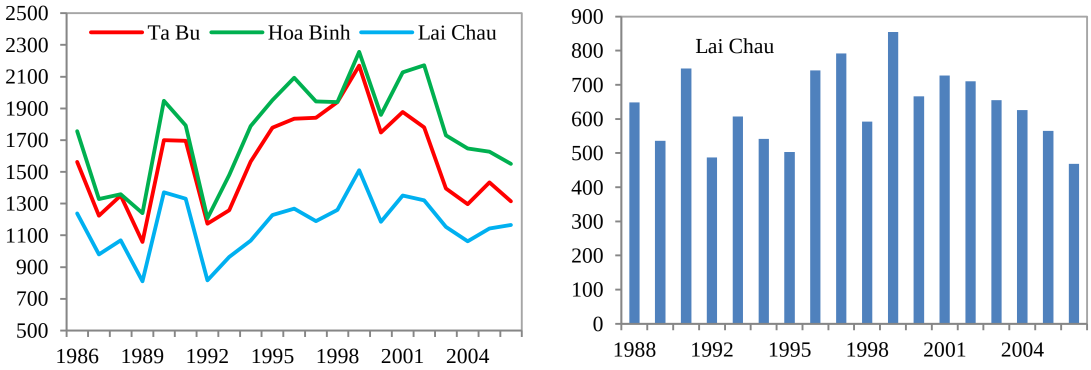


Figure 3.5. Annual runoff (left) and SSC (right) in the Da River Basin

The annual river runoff of the Red River basin is around 130 billion m^3, representing an average discharge of about 3700 m^3/s. As for the Da River Basin, the annual mean runoff is about 1168 m^3/s from 1988 to 2004 at Laichau station, associated with the total annual sediment load about 40.1×10^6 t/yr. In terms of annual trend of runoff in the Da River Basin, it shows one increasing trend from 1986 to 2004. And the sediment concentration also shows one increasing trend in the past in Da River Basin. The variations of streamflow in the upstream affected the utilization of water resources and sediment flow into the Hoa Binh reservoir. Furthermore, changes of sediment inflow induced reservoir siltation and increase or decrease the flood risk of the downstream region.

3.1.3 Land use/cover and soil condition

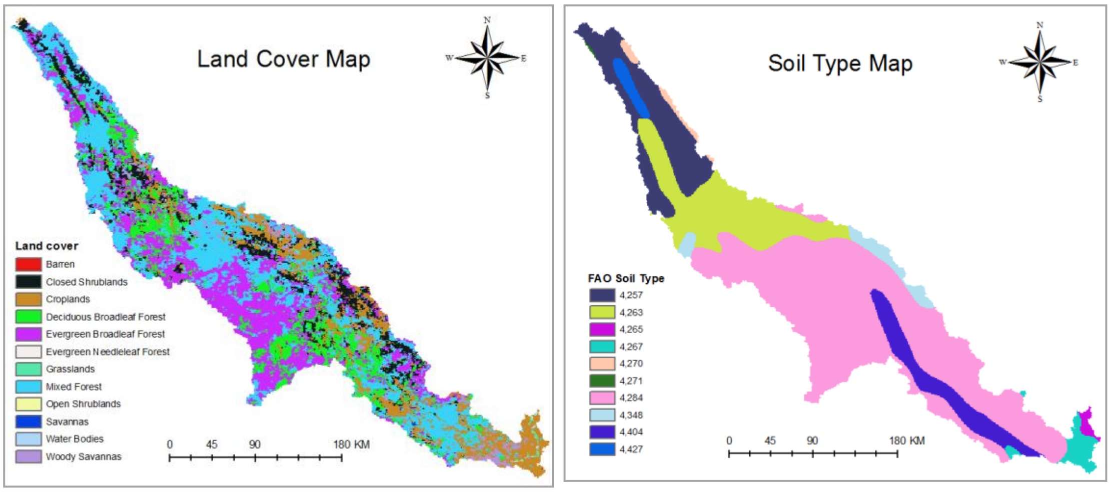


Figure 3.6. Land cover map (left) and soil map (right) in the Da River Basin

As shown in Figure 3.6, forest cover spread over almost half of the total Da River Basin, in which evergreen broadleaf forest and mixed forest are dominant vegetation types. In addition, cropland is also important land cover type in both upstream (Chinese part) and downstream (Viennese part). The soil map shown in Figure 3.6 is extracted from SOIL-FAO databases from the Food and Agriculture Organization of the United Nations (FAO, 1995). According to the survey report (Khiem and Poel, 1993), the soils in the Da River Basin have experienced strong ferralitic processes, which decrease with increasing altitudes. Above 2,000 m altitude there is almost no ferralitic process. The majority of the soils is acid and has low nutrient contents. Their fertility depends mainly on the humus content and vegetation cover. Humus content increases with increasing altitude. In the Russian soil system, soils over 900m altitude are called humic soils. Based on the Russian system, red yellow soils, red humic soils and brown red soils are major soil types in the Da River Basin, which lead to red color of the river.

Deforestation has become an issue of increasing concern in Red River Basin. According to UNEP and World Bank, deforestation has been intense in Red River Basin especially in the mountainous area, where the percentage of forest cover decreased from 95% in 1943 to 17% in 1991. Since 1995, the forest area of Vietnam has increased thanks to forest plantation programs. However, due to poor accessibility in DRB, plantation forests are limited in the Northwest areas (Forest Science Institute of Vietnam, 2009). In addition, deforestation reached its peak in the beginning of 1990s for the Chinese part of DRB, and Chinese government called off the felling of nature economic forest and launched forest plantation program from 1998. However, compared with original nature forest, young man-made forest has lower canopy density, shallower root depth, so cannot play the equal role of soil conservation. Deforestation had intensified soil erosion (Ren et al., 2007) and increased the sediment load in the Red River Basin.

3. 2. General research framework

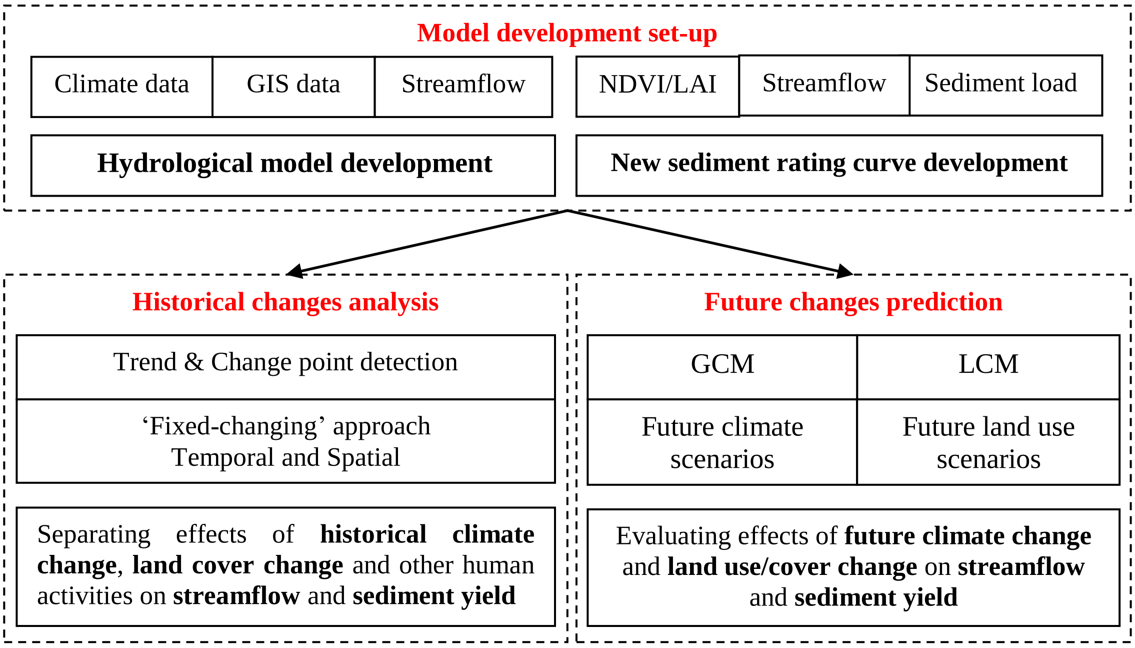


Figure 3.7. The general framework of the thesis

The overall framework of the study is presented in Figure 3.7, including following components:

The hydrological model was first set up, calibrated, and validated to model the rainfall-runoff process in the study basin and then used to simulate the streamlow. In addition, one new sediment rating curve considering temporal dynamic changes of vegetation cover was also attempted to be developed for our study area, which was used to simulate sediment yield. The simulation outputs from these two models were then used to evaluate the effects of climate change and land use/cover change on streamflow and sediment yield in the past and future.

For the historical changes analysis in streamflow and sediment yield, we firstly developed the ‘fixed-changing’ approach to separate the effects of historical climate change, land use/cover change and other human activities on streamflow and sediment yield. On the one hand, Pettitt mutation method was employed to detect changing point in annual streamflow, which divided our research period into two periods: pre-change and post-change period. SWAT model was then applied to separate different effects from climate change and human activities on streamflow in these two periods. Based on new sediment rating curve, impacts from climate change and human activities on sediment yield were also separated. On the other hand, the satellite Normalized Difference Vegetation Index (NDVI) and Potential leaf area index (LAI) from ecosystem model (Biome-BGC) were inputted into the new sediment rating curve to evaluate human-induced vegetation cover change effect on sediment yield.

For the future changes prediction in streamflow and sediment yield, future climate change scenarios were firstly generated based on different GCMs and downscaling methods, and future land cover/use scenarios were also obtained with the help of land change model and past land use/cover maps. All these scenarios were used to drive hydrological model and new sediment rating curve. Finally, future streamflow and sediment yield would be predicted under different future climate change and land use/cover scenarios.

As for the details methodology, we will introduce in the following chapters.

CHAPTER VI

NEW SEDIMENT RATING CURVES DEVELOPMENT AND ITS VALIDATION IN OTHER ASIAN RIVER BASINS

Suspended sediment concentration of a river can provide very important perspective on erosion or soil loss of one river basin ecosystem. The changes of land use and land cover, such as deforestation or afforestation, affect sediment yield process of a catchment through changing the hydrological cycle of the area. A sediment rating curve can describe the average relation between discharge and suspended sediment concentration for a certain location. However, the sediment load of a river is likely to be undersimulated from water discharge using least squares regression of log-transformed variables and the sediment rating curve doesn't consider changes of vegetation cover monthly or yearly. The Normalized Difference Vegetation Index (NDVI) can well be used to analyze the status of the vegetation coverage well. Thus long time monthly NDVI data was used to detect vegetation change in the past 19 years in this study. And monthly suspended sediment concentration and discharge from 1988 to 2006 in Laichau station were used to develop and interpret one new sediment rating curve. Compared with the common sediment rating curve, the new curve can simulate and predict the suspended sediment concentration much better in the Da river basin. In addition, we also applied new sediment rating in another two basins and got promising results. The new curve can describe the relationship among sediment yield, streamflow and vegetation cover, which can be the basis for soil conservation and sustainable ecosystem management.

4.1. Introduction

The issue of soil erosion of the watershed is one of the hot spots, which currently causes the global widespread attention. River sediment load is affected by climate change and land cover change within its drainage basin in an integrated way (Maria et al., 2007; Rustomji et al., 2008). With the increase of population and rapid development of economics and society, human activities have been seriously affecting the watershed land cover, which in turn affect sediment yield response of a catchment through modifying the surface gradient, surface roughness and soil erodibility (Wardrop and Brooks, 1998). In addition, sediment load also responds to climate variability and effect of climate change in assessing sediment load changes could not be negligible. In the face of intricate impacts from land cover change and climate change, it is necessary to make it clear that how much land cover change could affect sediment loads.

To evaluate how much land cover change could affect sediment loads, useful sediment yield model is needed. Physical based models based on erosion processes and transport mechanisms, and conceptual models are two main categories for estimating sediment yield. In practice, physical models need more parameters that are often very difficult to determine especially at describing the complex process of erosion and sediment yield. Therefore, they must be integrated with experience means to execute parameter calibration. Problems with a lack of identifiability of model parameters can be expected (Beck et al., 1995; Merritt et al., 2003).Among all conceptual models, sediment rating curve(Asselman, 2000) represents a power functional relationship relates suspended sediment concentration/load to streamflow is most common one (Horowitz, 2003). Unfortunately, it is recognized that the common sediment rating curve method tends to over-predict for high, and under-predict for low suspended sediment concentrations (Asselman, 2000; Horowitz, 2003). In addition, it is too simple without considering temporal dynamic changes of vegetation cover. However, different vegetation cover should have different effect on soil erosion production by modifying soil erodibility and transport capacity by slowing flow through friction losses (Howe et al., 2005). For that reason, one new sediment rating curve with few parameters considering the effect of vegetation cover with limitation information will be firstly developed to calculate land cover change effect on the sediment load in this study.

4.2. Dataset and methodology

4.2.1. Data Description and validation basins

In addition to Da River Basin, another two target basins in East-south Asian were selected to develop news sediment rating curves: Chiang Sean basin in the upper part of Mekong River basin and Nam muc basin in Red river basin (Figure 4.1). The basic characters of basins are showed in Table 4.1.

Table 4.1. Basic characters of our selected basins

Basins	R and SSC time span	Area (km^2)	Characters
Da River Basin	1988-2004 monthly	55000	No big dam in the upstream before 2004 Main vegetation cover: forest
Chiang Sean basin	1986-1991 monthly	185,000	No big dam before 1992 Main vegetation cover: Grass and forest
Nam muc basin	1997-2006 monthly	2,200	No big dam existed Main vegetation cover: Forest

In addition to the basic hydrological data showed in Table 4.1, other spatial dataed were also used for our research. SRTM 90m DEM data was provided by the CIAT-CSI (http://srtm.csi.cgiar.org). Global 1km Land Cover data in the year of 1992 obtained from the U.S. Geological Survey's National Center for Earth Resources Observation Science was also employed in the study. The GIMMS NDVI data set including a 25 years period from 1981 to 2006 was used to analyze the vegetation changes in a long time period for the study area.

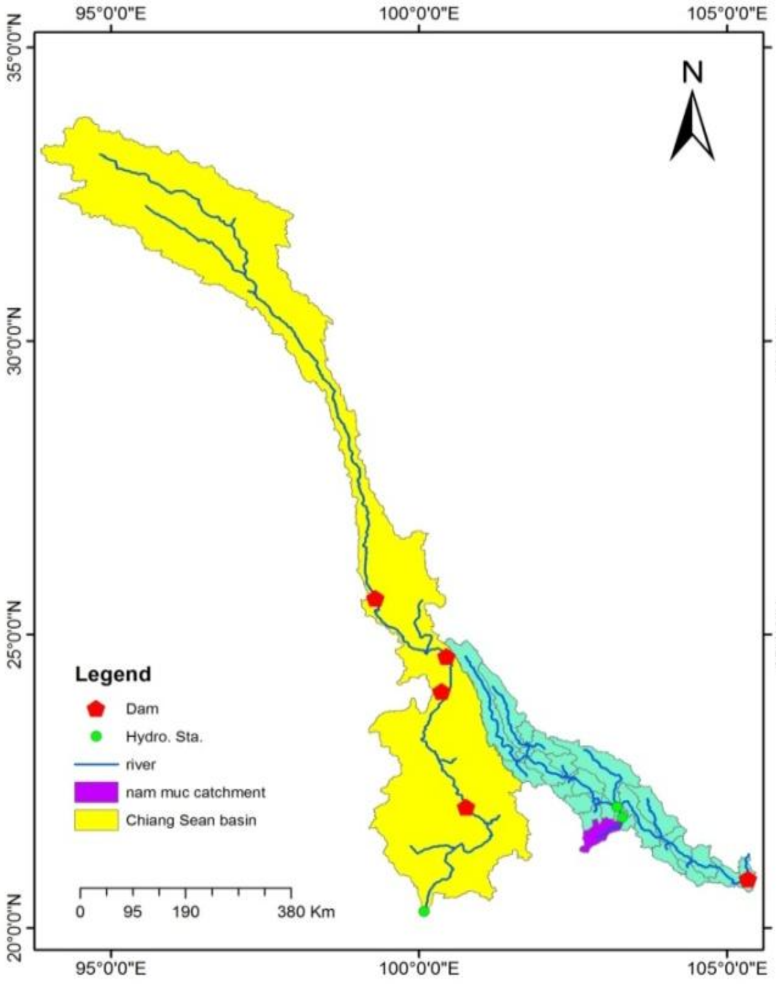


Figure 4.1. Location of another two validation basins

4.2.2. Methodology

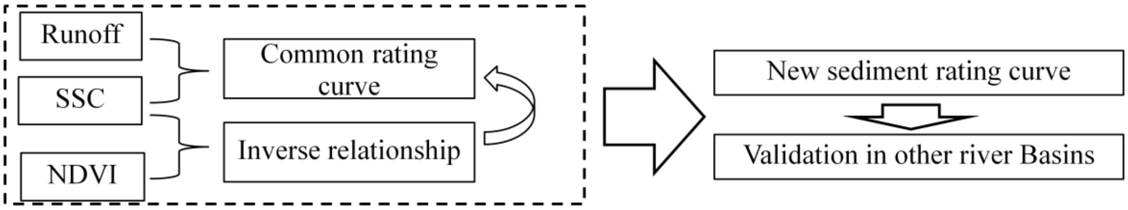


Figure 4.2. The research framework for developing new sediment rating curve

As reviewed before, we have already known that common sediment rating curve without considering temporal dynamic changes of vegetation cover is not so reasonable and generally could not get agreement simulation results. In addition, the physical-based sediment yield calculation model can give better results. However, these kinds of models have more parameters to identify and need more input dataset.

The common sediment rating curve3),16) generally represents a power functional relationship, relating suspended sediment concentration to streamflow:

$$SSC = aQ^{b} \tag{4.1}$$

$$SL = Q \times SSC \tag{4.2}$$

in which Q (m^3/s) is discharge, SSC (g/m^3) is suspended sediment concentration, SL (g/s) is sediment load.

According to Figure 4.3, we will firstly check the shortage of common rating curve and find out the relationship between vegetation cover change and SSC in this study. Then new sediment rating curves will be developed and evaluated in several East-south Asian basins. Two statistics are introduced to evaluate new sediment rating curves: coefficient of determination (R^2) and the mean absolute error (*MAE*). The use of these statistics is to provide a more comprehensive evaluation of the model performance. Finally, more suitable sediment rating curve will be developed for our river basin.

4.3. Results

4.3.1. Limitation of common sediment rating curve

In order to check out the limitation of common sediment rating curve, common sediment rating curve was first developed in Da River Basin (Figure 4.3). The mean absolute error (*MAE*) between simulated and observed SSC was also calculated for high and low values, as shown in Table 4.2. Results showed that the common sediment rating curve method under-predicted low and whole SSC, and over-predict high SSC values in Da River Basin, which kept agreement with previous research.

Table 4.2. Statistics analysis between monthly observed SSC and simulated SSC from common sediment rating curve

SSC(g/m^3)	Obs	Simu	MAE	
High value	1265	1313	48	overpredict
Low value	416	296	-120	underpredict
Average	629	551	-78	underpredict

Obs: monthly observed SSC; Simu: simulated SSC from common sediment rating curve

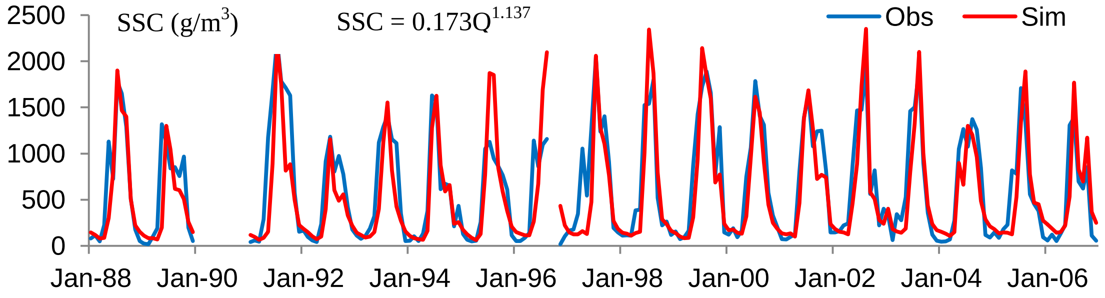


Figure 4.3. Comparison of monthly observed SSC and simulated SSC from common sediment rating curve

4.3.2. Relationship between NDVI and SSC

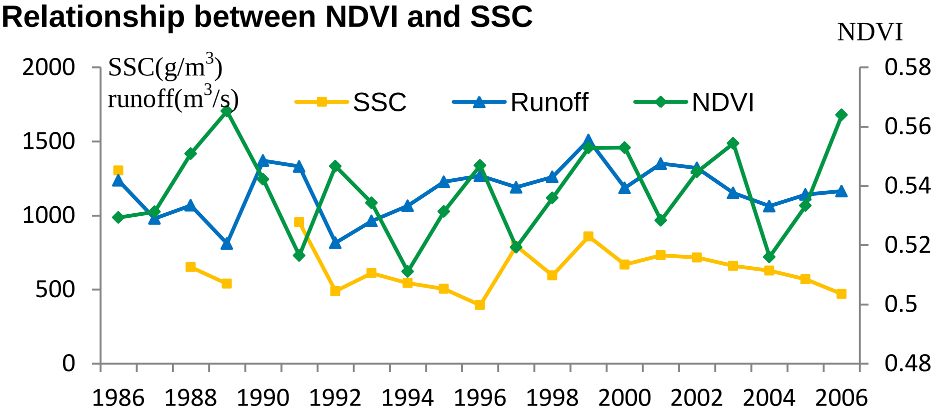


Figure 4.4. Comparison among annual SSC, runoff and NDVI in Da River Basin

As shown in Figure 4.4, the similar change trend between SSC and runoff indicates that SSC is mainly controlled by runoff. However, some years shows inverse trend, such as 1996, 2005 and 2006. In these three years, SSC shows lower values even though runoff become higher because the higher NDVI could reduce the soil erosion production and transport capacity. In addition, the negative correlation coefficient between SSC and NDVI (-0.31) also make the inverse relation more clear between NDVI and SSC. This inverse relationship between NDVI and SSC could also explain the reason of the limitation of common rating curve simulation. Different vegetation cover should have different effect on soil erosion production and transport capacity by slowing flow through friction losses. In the wet season and wet year, vegetation cover is better and the soil erosion production and transport capacity should be lower. The facts in the dry season are just the opposite.

4.3.3. New sediment rating curve development

Previous studies combining results from different watersheds provided physical interpretations of the two parameters in the common sediment rating curve (Walling and Webb, 1985; Asselman, 2000; Horowitz, 2003). The common sediment rating curve coefficient ‘a’ may give information on the soil erodibility and transport capacity for the whole basin; and ‘b’ may represent the erosive power of the river and its sediment transport capacity. As a result, vegetation cover should only affect coefficient ‘a’ in a river basin. Based on the inverse relationship between NDVI and SSC, we tried to add vegetation cover information (NDVI) into coefficient ‘a’ and carried out three following types of new sediment rating curves. All these three kinds of new sediment rating curves could reflect the inverse relationship between SSC and vegetation cover.

$$SSC = a\ (c\text{-}NDVI)\ Q^b \qquad 4.3$$

$$SSC = a/(c+NDVI^d)\ Q^b \qquad 4.4$$

$$SSC = a\ (1\text{-}NDVI^c)\ Q^b \qquad 4.5$$

in which Q (m^3/s) is discharge, SSC (g/m^3) is suspended sediment concentration and Parameter of a, b, c and d for are determined from data via least squares method.

Then three calibrated new sediment rating curves were developed for Da River Basin as following:

$$B:\ SSC = 0.17(1.75\text{-}NDVI)Q^{1.137} \qquad 4.6$$

$$C:\ SSC = 0.28/(1.3+NDVI^{4.5})Q^{1.137} \qquad 4.7$$

$$A:\ SSC = 0.234(1\text{-}NDVI^{5.3})Q^{1.137} \qquad 4.8$$

Table 4.3. Comparison of simulation results from three new sediment rating curves and common sediment rating curve in Da River Basin

SSC(g/m^3)	Obs	Common		Trial A		Trial B		Trial C	
		Sim	**MAE**	**Sim**	**MAE**	**Sim**	**MAE**	**Sim**	**MAE**
High value	1265	1313	48	1283	18	1306	41	1274	9
Low value	416	296	-120	325	-91	328	-88	343	-73
Total average	629	551	-78	564	-65	572	-57	580	-49
R^2	no	0.821		0.845		0.847		0.852	

High value: SSC from July to September; Low value: SSC from remaining months.

As shown in Table 4.3, three new sediment rating curves also under-predicted low and average SSC, and over-predict high SSC, however, all these new rating curves reduced the mean difference between simulated SSC and observed SSC in various degrees. In addition, all the coefficient of determination of three new sediment rating curves are also higher than common one, which indicates that vegetation cover information could improve the common sediment rating curve in Da River Basin. Among three new sediment rating curves, type c could improve common one most and get best simulation results. Consequently, type c is considered as the most agreement sediment rating curve in Da River Basin.

Moreover, we compared new sediment rating curve simulation result with SWAT model simulation result, as showed in Figure 4.5. The coefficient of determination of SWAT model simulation is lower than new sediment rating curve results. In addition, SWAT model trends to over-predict SSC very much in the DRB. Based on above, Figure 4.5 indicated that new sediment rating could simulate SSC better than SWAT model in DRB.

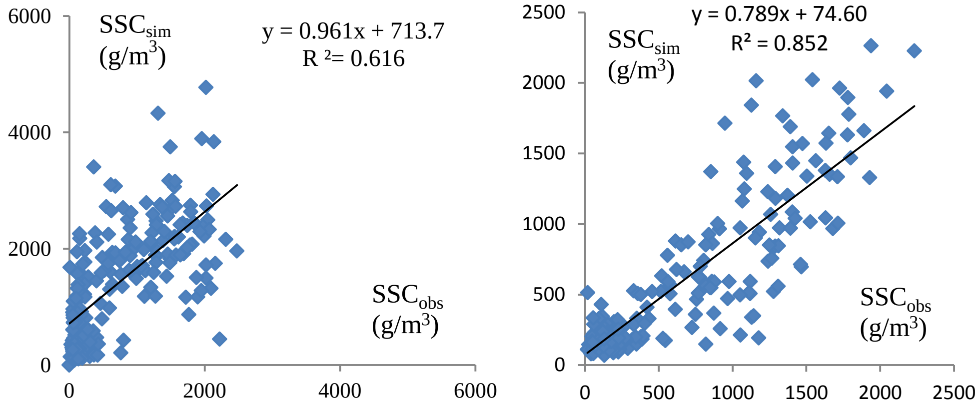


Figure 4.5. Scatterplot of observed and simulated monthly SSC from SWAT (left) and new sediment rating curve (right) in the Laichau station

4.3.4. Validation in other river basins

To further confirm the performance of the best new sediment rating curve, we select another two basins to validate it. Similarly, inverse relationship between NDVI and SSC are also found out in other basins even though the correlation coefficient between SSC and NDVI is different (Figure 4.6).

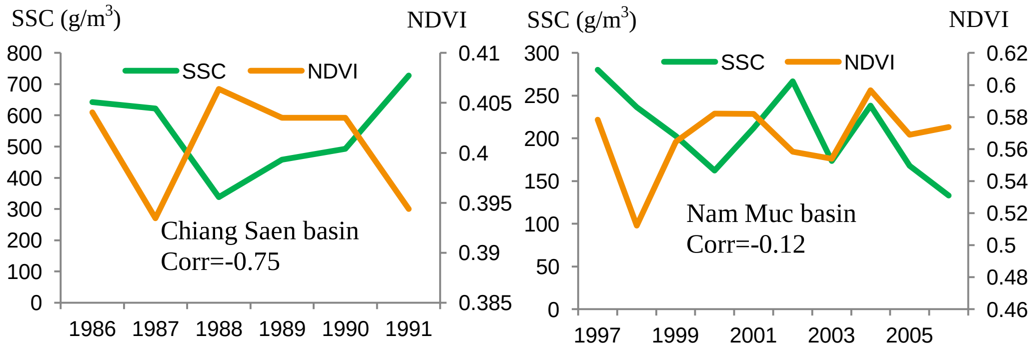


Figure 4.6. Relationship between annual SSC and NDVI

Simulation results comparison from new sediment rating curve and common sediment rating curve in another two basins are listed in Table 4.4 & 4.5. Not only the coefficient of determination of new sediment rating curve is higher than common one, but also MAE is lower than common one, which showed that new sediment rating curve also performed better than common one in these two basins. All simulation results further confirmed that vegetation cover information (NDVI) can improve the sediment rating curve and new sediment rating curve could simulate better in these East-South Asian basins.

Table 4.4. Comparison of simulation results from new sediment rating curve and common sediment rating curve in Chiang Saen basin

SSC(g/m^3) (Chiang Saen)	**Obs**	**Common**		**New One (Trial c)**	
		Sim	**MAE**	**Sim**	**MAE**
High value	927	1030	103	1011	84
Low value	312	244	-68	252	-60
Average	517	506	-11	508	-9
R^2		0.80		0.86	

High value: SSC from July to September; Low value: SSC from remaining months.

Table 4.5. Comparison of simulation results from new sediment rating curve and common sediment rating curve in Nam Muc basin

SSC(g/m^3) (Nam Muc)	**Obs**	**Common**		**New One (Trial c)**	
		Sim	**MAE**	**Sim**	**MAE**
High value	401	410	9	405	4
Low value	110	76	-68	102	-8
Average	207	190	-17	204	-3
R^2		0.74		0.75	

High value: SSC from July to September; Low value: SSC from remaining months.

4.3.5. Discussions

Results above showed that vegetation cover information could improve simulation results. However, the improvement is different in different basins. Summary of improvement was listed in Table 4.6, which showed that improvement of correlation coefficient in basin with large area was higher than small catchment. For large basins, more vegetation cover information could be obtained, which maybe improve the simulation results better. As a result, more accurate and high precision vegetation cover information seems more useful to improve simulation result. Actually, several previous studies have already been carried out to calculate the sediment load in terms of vegetation cover change. Guzman et al (2013) tried to develop different sediment rating curves based on normalization of fractional cropland for each part of the rainy season (early, middle, late) in three watersheds, which indicated that vegetation cover in different seasons have different effects.

Because the new sediment rating curve only has few parameters and inputs which could be applied to simulate sediment yield for basins without enough dataset. The most point of this new sediment rating curve is not only to improve the common sediment rating curve, but to describe the relationship among vegetation cover, runoff and sediment load. Hence the new sediment rating curve has its potential application related to vegetation cover change. For example, in order to evaluate reservoir sediment trapping, we have to know actual reservoir sediment outflow and potential sediment outflow without considering dam effect. According to many researches, the common sediment rating curve was used to predict the potential sediment flow. Unfortunately, the potential sediment flow from common sediment rating curve does not consider vegetation cover change effects because the common curve does not consider vegetation cover change effect. As a result, the reservoir sediment trapping result looks like not so reasonable. Another potential application is to evaluate vegetation cover change impacts on sediment yield change, which would be discussed in Chapter 6.

Table 4.6. Summary of improvement compared with common rating curve in three basins

Basin	**Area (10^3 km^2)**	***R^2***		
		common	***new***	**improvement**
Chiang Saen	185	0.80	0.86	6%
Laichau	52	0.82	0.85	3%
Nam muc	2.2	0.74	0.75	1%

Although our new sediment rating curve has already been proved better than common one, we still could not conclude that it is universal for all the basins worldwide. More validation should be carried out in basins with different area, vegetation cover types and climate conditions in the future.

4.4. Conclusions

In this study, we successfully considered vegetation cover information in sediment simulation and developed new sediment rating curve in Da River Basin. Main conclusions are as follows.

1) The common sediment rating curve tends to over predict the high, and under predict the low SSC in all the three basins.

2) Vegetation cover (NDVI) can improve the sediment rating curve. Among the three new sediment rating curves, the third one is the better sediment rating curve for our research basin.

3) The new sediment rating curve can simulate better in these three Asian basins, but for different scale basin, vegetation cover (NDVI) improved the sediment rating curve differently.

4) The most point of this new equation is not only to improve the common sediment rating curve, but describe the relationship among vegetation cover, runoff and sediment load.

CHAPTER V

DEVELOPING MODEL SIMULATION METHOD TO SEPARATE IMPACTS FROM CLIMATE CHANGE AND HUMAN ACTIVITIES ON STREAMFLOW AND SEDIMENT FLOW

Impacts of human activities and climate variability on streamflow and sediment have long been an issue for concern. It is critical to quantify the contribution of climate change and human activities on the change of streamflow and sediment flow, which can provide a scientific basis for future land conservation and river ecological conservation. In this study, Pettitt mutation method was employed to detect trends and changes in annual streamflow. SWAT model simulation method was then applied to separate different effects from climate change and human activities. Based on new sediment rating curve, one well fitted curve between sediment and runoff was introduced to simulate the suspend sediment. Results indicated that effects of human activities on streamflow accounted for more than 50% both in the Laichau and Tabu catchments. Human activities are the main factor to affect the changes of streamflow and sediment flow into the Hoa Binh reservoir.

5.1. Introduction

It has been generally accepted that climate change has brought great impacts on the hydrological process in river basins (Schulze, 2000). With the increase of population and rapid development of economics and society, human activities have been seriously affecting the watershed land use and water cycle. The changes of land use and land cover affect runoff response of a catchment through changing the balance between rainfall and evaporation (Costa et al., 2003). In addition, the sediment yield of one catchment is intimately related to the geology, topography, climate, vegetation cover and land use within the basin. The geologic and topographic variables are fixed, but long-term changes in climatic conditions, vegetation cover and land use will produce abrupt alterations in erosion processes and sediment yields. It is necessary to investigate main factors affecting the changes of streamflow and sediment yield.

Red river, with its overall sediment load previously classed 9th in the world, has received increasing attention with many eco-hydrological problems, such as hydrological changes in the upper reaches and lower reaches, sediment changes and biodiversity disappear (He et al., 2005). Hoa Binh reservoir, the largest reservoir in Vietnam, established on the Red River, with an important role for flood control, hydropower generation, and irrigation, has caused a significant decrease of sediment loads in the downstream of reservoir (Le et al., 2007). The variations of runoff in the upstream affect the utilization of water resources and sediment flow into the Hoa Binh reservoir. Furthermore, changes of sediment inflow can induce reservoir siltation and increase or decrease the flood risk of the downstream region. Therefore, analyzing on the effect of climate change and human activities on streamflow and sediment flow into the Hoa Binh Reservoir and determining the main factors and their contributions to the total changes are critical for the appropriate utilization of water resources, flood control, soil conservation and ecological protection.

The change of streamflow in the Red River basin has been paid much attention in the past years and some results had been raised. For the Vietnamese part of Red River basin, Tuan (1993) concluded that the peak discharge and the total of runoff volume increased clearly as the forest cover area decreased in the past in the Hoa Binh Reservoir basin. For the upstream of the basin, Mann-Kendall method and cluster technique method were used to analyze the variability of the 45-year runoff series at Manhao station in the Red River, and got an increasing trend for annual runoff in the past years (Ye et al., 2008). Therefore, they concluded that the jump of runoff was mainly influenced by vegetation cover change. On the other hand, the changed discharge and vegetation cover change will further affect the sediment load in the basin. Some researchers had got some similar results of changing sediment load in the Red River basin. Ren et al (2007) analyzed annual sediment load of different periods in Yuan Jiang, the main branch of red river. Results showed that annual sediment load in the 1980s was less than it in the 1990s and forest cover and sediment load showed the inverse relationship. In addition, Dang et al (2010) simulated sediment load and a significant decrease of sediment load after 1990 was detected in the downstream of reservoir, which indicated that the Hoa Binh dam reduced annual sediment by half.

Increasing efforts are being made to quantify the consequences of environmental change for the hydrological cycle in the Red river basin. However, contribution of climate change and human activities on changes in both water and sediment flux are still not well evaluated. In this study, quantification of climate change and human activities contributions to changes of streamflow and sediment load was partitioned and evaluated. Firstly, Pettitt mutation method was employed to detect the abrupt year in annual streamflow. Then, SWAT model was applied and evaluated in the Da River basin. Lastly, the validated SWAT model and well fitted sediment rating curve were proposed to calculate the individual effects of climate change and human activities on streamflow and sediment.

5.2. Dataset and methodology

5.2.1. Data Description

Da River Basin was also selected as the target basin of this study. Streamflow data at Laichau (LC) and Tabu (TB) stations were selected in the Da River basin, which were available from 1960 to 2008. Suspend sediment concentration data at Laichau station is available from 1988 to 2004. There are 16 rainfall or meteorological stations located in or around the basin. These stations are spatially well distributed, which can reflect the characteristics of regional climate. Hydrologic data is from the China Meteorological Data Sharing Service and Vietnam Academy of Science and Technology, which has been checked by the primary quality control. SRTM 90m DEM data was provided by the CIAT-CSI (http://srtm.csi.cgiar.org). Global 1km Land Cover data in the year of 1992 obtained from the U.S. Geological Survey's National Center for Earth Resources Observation Science was also employed in the study. The GIMMS data set including a 25 years period spanning NDVI data from 1981 to 2006 was used to analyze the vegetation changes in a long time period for the study area (Tucker et al., 2005).

5.2.2. Analysis of change point in annual series

A change in observed mean annual streamflow ΔQ^{tot} can be resulted from climate variability ΔQ^{clim} and human activities ΔQ^{hum}. However, it is difficult to identify the timing of change by manual judgment in streamflow for a catchment (Li et al, 2007; Zhao et al., 2009).

$$\Delta Q^{tot} = \Delta Q^{clim} + \Delta Q^{hum} \qquad 5.1$$

In the study, nonparametric Pettitt method, which was firstly proposed to detect change point for a long time series in 1979 (Pettitt, 1979), was widely-used to detect the time of the change in time series (Pettitt, 1979; Zhao et al., 2009). This approach can detect a significant change in the mean of annual streamflow when the exact time of the change is unknown. Based on an adaptation of the rank-based Mann-Whitney test, it considers one time series as two samples represented by $x_{1,}...x_t$ and $x_{t+1,}...x_N$, and define one statistical index $U_{t,N}$:

$$U_{t,N} = U_{t-1,N} + \Sigma_{j=1}^{N} sgn(x_t - x_j) \quad (t = 2,.....N) \qquad 5.2$$

in which $sgn(x)=1$, for $x>0$; $sgn(x)=0$, for $x=0$; $sgn(x)= -1$, for $x<0$.

A time series with no change point would result in a continually increasing value of $\left|U_{t,N}\right|$. Otherwise, if there is a change point then $\left|U_{t,N}\right|$ would increase up to the change point and then begin to decrease. This change point may occur several times in a time series, the most significant change point t where the value of $\left|U_{t,N}\right|$ is maximum. The probability of a change point being at the year where $|U_{t,N}|$ is maximum is approximated by

$$P \cong 1 - \exp\{-6(U_N)^2/(N^3 + N^2)\} \qquad 5.3$$

Since a significant change point was found, the total streamflow series can be divided into two periods (Figure 5.1). The first period is pre-change period, representing the baseline with no significant human activities, and the second period is post-change period associated with significant human activities.

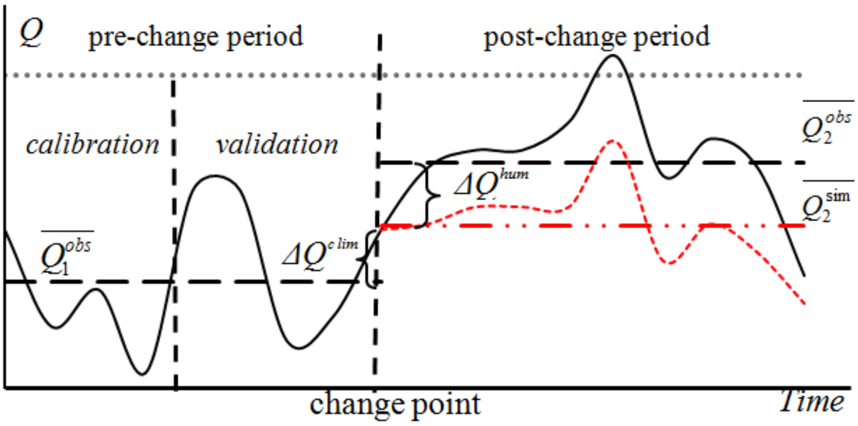


Figure 5.1. Schematic diagram of ΔQ and different period separation

5.2.3. Model simulation method

The SWAT model is considered as one of the most suitable models for predicting long-term impacts of land management measures on water, sediment, and agricultural chemical yield (nutrient loss) in large complex watersheds with varying soils, land use, and management conditions.

SWAT is a continuous, long-term, and distributed parameter model based on water balance (Figure 5.2), designed to evaluate the impact of climate and land use change on the hydrology, sediment transport in watersheds. The relationship between input and output variables is described by regression equations. The SWAT model integrates all relevant eco-hydrological processes including water flow, nutrient transport and turn-over, vegetation growth, and land use and water management at the sub-basin scale. Consequently, the watershed is subdivided into sub-basins based on the number of tributaries. Size and number of sub-basins is variable, depending on stream network and size of the entire watershed. Sub-basins are further disaggregated into classes of Hydrological Response Units (HRU), whereby each unique combination of the underlying geographical maps (soils, land use, etc.) forms one class. HRU are the spatial unit where the vertical flows of water and nutrients are calculated, which are then aggregated and summed for each sub-basin. Water and material from HRU in subwatersheds are routed to the sub-watershed outlet. The HRU in SWAT are spatially implicit, their exact position in the landscape is unknown, and it might be that the same HRU covers different locations in a sub-basin. The water balance for each HRU is represented by the four storages snow, soil profile, shallow aquifer and deep aquifer. The soil profile can be subdivided in up to ten soil layers. Soil water processes include evaporation, surface runoff, infiltration, plant uptake, lateral flow and percolation to lower layers (Neitsch et al., 2005). The model predicts the hydrology at each HRU using the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day,i} - Q_{surf,i} - E_{a,i} - W_{seep,i} - Q_{gw,i}) \tag{5.4}$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

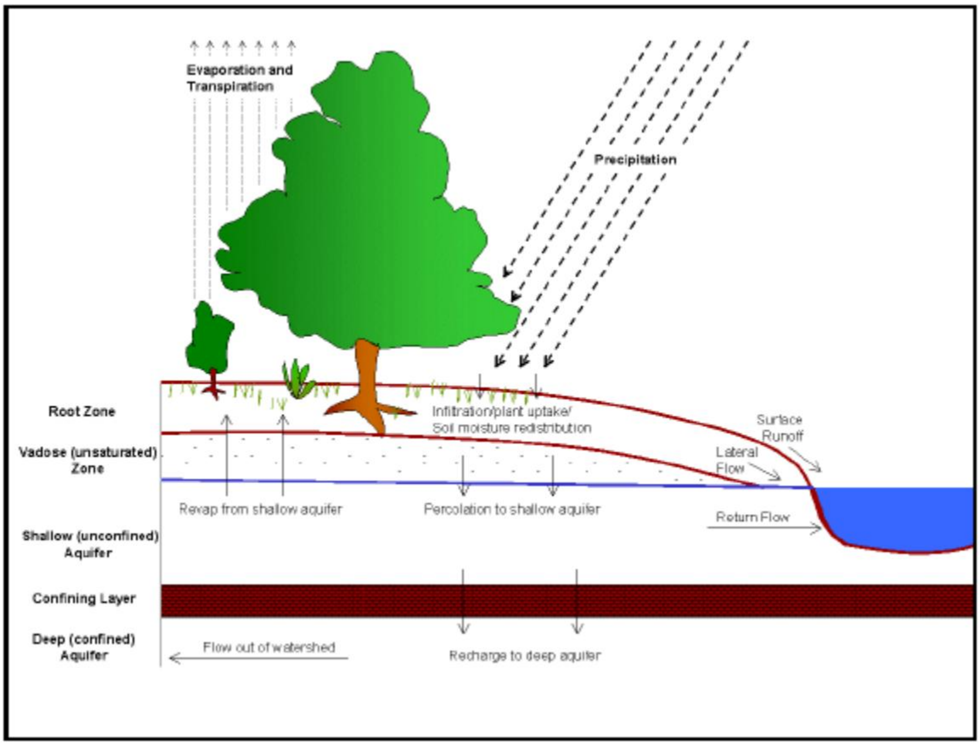


Figure 5.2. Hydrologic cycle considered by SWAT model (from Neitsch et al., 2001)

The soil water processes include infiltration, percolation, evaporation, plant uptake, and lateral flow. Percolation is modeled with a layered storage routing technique combined with a crack flow model. Potential evaporation can be calculated using Hargreaves, Priestly-Taylor or Penman-Monteith method (Arnold et al., 1998). The surface runoff from daily rainfall is estimated with a modification of the SCS curve number method from United States Department of Agriculture-Soil Conservation Service (USDA SCS) and Green & Ampt infiltration method (Neitsch et al., 2001). Peak runoff rate is estimated using a modification of the Rational Method (Chow et al., 1998). Flow is routed through the channel using a variable storage coefficient method (Williams, 1969) or the Muskingum routing method (Cunge, 1969).

The sediment from sheet erosion for each HRU is calculated using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). Details of the USLE equation factors can be found in Neitsch et al. (2005). The sediment concentration is obtained from the sediment yield, which corresponds to flow volume within the channel on a given day. The transport of sediment in the channel is controlled by simultaneous operation of two processes: deposition and degradation. Whether channel deposition or channel degradation occurs depends on the sediment loads from the upland areas and the transport capacity of the channel network. If the sediment load in a channel segment is larger than its sediment transport capacity, channel deposition will be the dominant process. Otherwise, channel degradation occurs over the channel segment. Theory and details of hydrological and sediment transport processes integrated in SWAT model are available online in SWAT documentation (http://swatmodel.tamu.edu/).

Generally, the SWAT model set-up involved the following five steps: (1) data preparation; (2) sub-basin discretization; (3) HRU definition; (4) parameter sensitivity analysis; and (5) calibration and validation. Sensitivity analysis was carried out to identify the most sensitive parameters for the model calibration using Latin Hypercube One-factor-At-a-Time (LH-OAT), an automatic sensitivity analysis tool implemented in SWAT (Van Griensven et al, 2006). These sensitive parameters were calibrated using the auto-calibration tool that is currently available in the SWAT Interface (Van Liew et al. 2005). In addition, SWAT-cup also supported another three automatic calibration methods (SUFI2, GLUE, and ParaSol), specially designed for SWAT model.

In this part, SWAT model was applied to evaluate the effects of climate change and human activities on streamflow. Following recommendations (Moriasi, 2007), four statistics are used to indicate the accuracy of SWAT model: coefficient of determination (R^2), Nash- Sutcliffe efficiency (*NSE*), percent bias (*PBIAS*) and the mean absolute error (*MAE*). The use of these statistics is to provide a more comprehensive evaluation of the model performance.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Qobs_i - Qsim_i)^2}{\sum_{i=1}^{n}(Qobs_i - \overline{Qobs})^2} \qquad 5.5$$

$$R^2 = \frac{\sum_{i=1}^{n}\left(Qobs_i - \overline{Qobs}\right)\left(Qsim_i - \overline{Qsim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Qobs_i - \overline{Qobs}\right)}\sqrt{\sum_{i=1}^{n}\left(Qsim_i - \overline{Qsim}\right)}} \qquad 5.6$$

$$PBIAS = \frac{\left|\overline{Qsim} - \overline{Qobs}\right|}{\overline{Qobs}} * 100\% \qquad 5.7$$

$$MAE = \left|\overline{Qsim} - \overline{Qobs}\right| \qquad 5.8$$

where $Qsim$ is simulated discharge, $Qobs$ is observed discharge, $\overline{Qsim}$ is average simulated discharge, $\overline{Qobs}$ is average observed discharge

SWAT model was firstly calibrated and validated for the pre-change period and then applied the calibrated model to the post-change period with changed underlying surface conditions to model streamflow that would occur if there were no human activities. The effect of human activities on streamflow is calculated by the differences between simulated and observed streamflow for the post-change period, and the effect of climate change is the remaining (Figure 5.1).

$$\Delta Q^{hum} = \overline{Q}_2^{obs} - \overline{Q}_2^{sim} \qquad 5.9$$

$$\Delta Q^{clim} = \overline{Q}_2^{sim} - \overline{Q}_1^{obs} \qquad 5.10$$

Moreover, based on the new well fitted sediment rating curve, the effect of human activities on sediment load can be calculated by the differences between simulated and observed value for the post-change period and the effect of climate variability is the remaining part of the total change.

$$\Delta SL^{hum} = \overline{SL_2}^{obs} - \overline{SL_2}^{sim} \qquad 5.11$$

$$\Delta SL^{clim} = \overline{SL_2}^{sim} - \overline{SL_1}^{obs} \qquad 5.12$$

in which ΔSL^{hum} and ΔSL^{clim} are the change of sediment load by human activities and climate change respectively. SL_1^{obs} is the observed sediment load in the first period, SL_2^{obs} and SL_2^{sim} are the observed and simulated sediment load in the second period, respectively.

5.3. Results

5.3.1. Determination of research period

Pettitt mutation detection method was employed to detect the approximate time of the change in discharge at Laichau and Tabu stations over the period from 1960 to

2008. Figure 5.3 shows graphically the result of Pettitt mutation test. The curves indicate a change point in annual discharge occurring in 1993 at the 10% of significance level for Laichau and Tabu hydrologic stations, which shows a significant upward trend from 1993. Based on the Pettitt test, the period of the discharge record is divided into two parts: a pre-change period (1960–1993), representing discharge under natural conditions, and a post-change period (1994–2008), representing discharge under human activities control. However, limited by the short precipitation series (1988-2004), the pre-change point period from 1988 to 1993 is used as the calibration and validation periods in SWAT model and the period from 1994 to 2004 is used as post-change period.

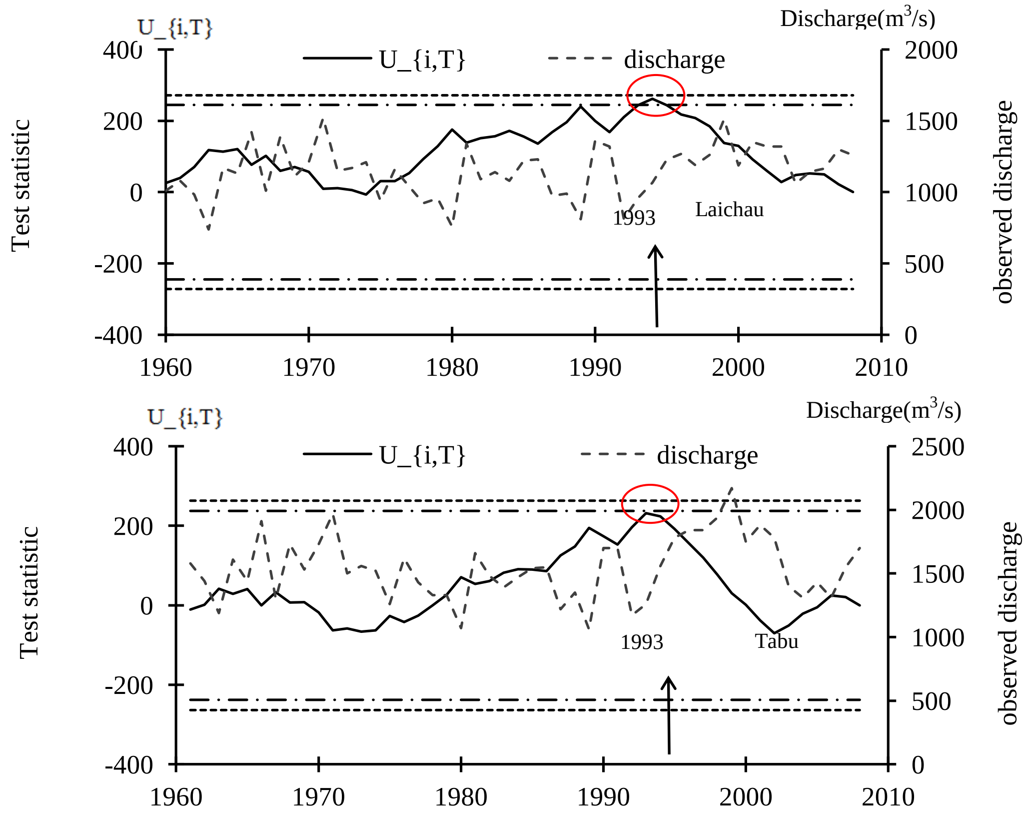


Figure 5.3. Pettitt mutation test of annual streamflow. The horizontal dotted and solid lines represent the critical values of the 5% and 10% significance level respectively.

5.3.2. Effects of human activities and climate variability on streamflow

In order to evaluate human activities and climate change effects on streamflow, SWAT model should firstly be calibrated and validated to prove its applicability in the DRB. As shown in Table 5.1, four statistics to evaluate the SWAT model mentioned above give agreement results. For example, the high NSE presents better results with the value of greater than 0.85 which indicate that SWAT model is reasonable in this basin. In addition, from the viewpoint of comparison between the simulated and observed monthly streamflow during the pre-change period, results indicate that the simulated streamflow by using SWAT model has a good match with the observed values, and are satisfactory at Laichau and Tabu stations, as showed in Figure 5.4. The results shown in Table 5.1 and Figure 5.4 can comprehensively explain that the SWAT model can predict streamflow accurately during the pre-change period.

Table 5.1. Evaluation of model simulation during the pre-change period for the catchments controlled by Laichau and Tabu stations in the DRB

	Laichau		Tabu	
	Calibration	Validation	Calibration	Validation
R^2	*0.91*	*0.87*	*0.95*	*0.88*
NSE	*0.89*	*0.85*	*0.88*	*0.85*
MAE(mm)	*3.56*	*4.29*	*2.83*	*3.91*
PBIAS (%)	*0.331*	*0.398*	*0.203*	*0.283*

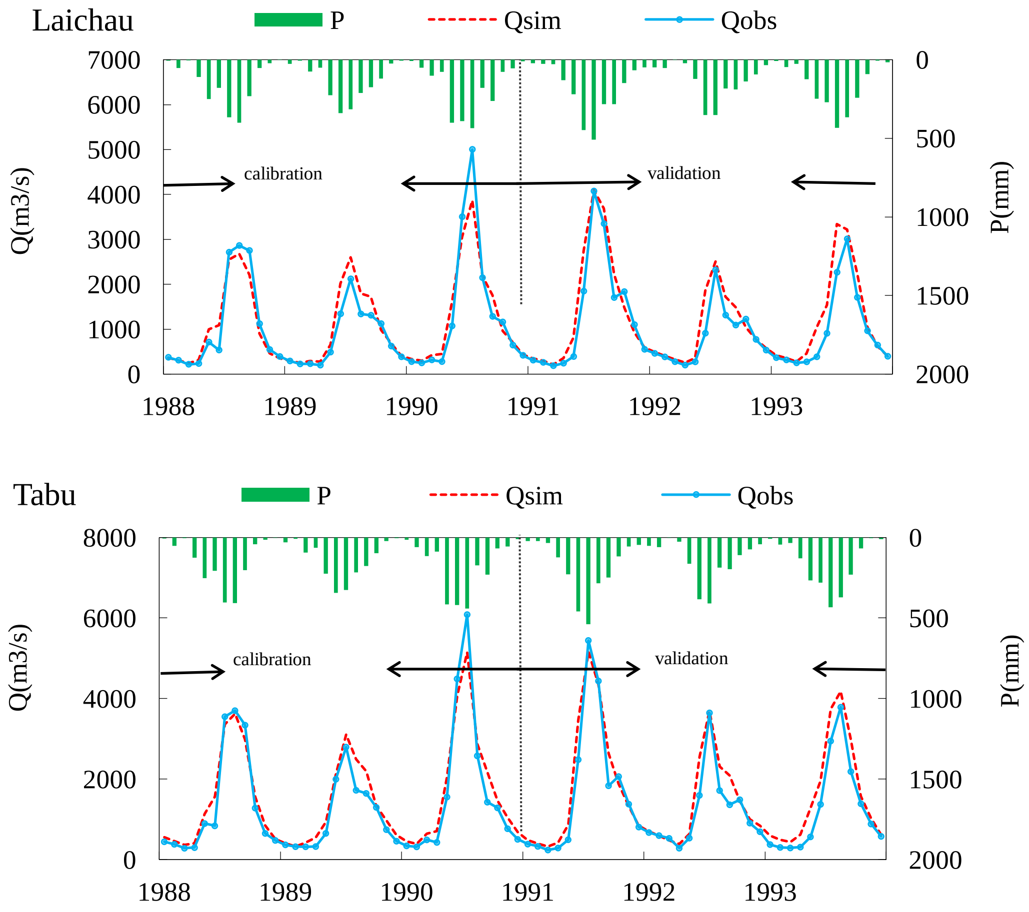


Figure 5.4. Comparison of observed and simulated monthly streamflow in the DRB

Table 5.2. Effects of human activities and climate change on the annual streamflow (mm) across catchments controlled by hydrological stations in the DRB (subscript 1: 1988-1993; subscript 2:1994-2004)

	$\overline{Q_1^{obs}}$	$\overline{Q_2^{obs}}$	$\overline{Q_2^{sim}}$	ΔQ^{tot}	ΔQ^{hum}	*Hum*	*Clim*
						%	%
LC	*1054.2*	*1231.1*	*1135.5*	*176.9*	*95.6*	*54*	*46*
TB	*1364.6*	*1738.0*	*1513.4*	*373.4*	*223.6*	*60*	*40*

The total difference in streamflow between the two periods was calculated and The SWAT model built during the pre-change period was then applied to quantify the effect of human activities on streamflow and the results are listed in Table 5.2. The effect of human activities on streamflow is represented by the difference between simulated and observed streamflow for the post-change period, and the proportion of this difference to changes of streamflow (%). The results show that total increase of streamflow in the Tabu catchment is larger than Laichau catchment and the proportions of human activities effect to changes of streamflow across two catchments are a little different. Human activities contribution rate are 54% in the Laichau catchment, 60% in the Tabu catchment, at the same time, climate change only accounts for 46% and 40% of the total effects on streamflow in Laichau and Tabu catchments respectively.

5.3.3. Effects of human activities and climate change on sediment load

The increased streamflow will further change the sediment load for the DRB. To evaluate human activities and climate change effects on sediment load, one well fitted new sediment rating curve (Figure 5.5) for Laichau station was firstly proposed based on the monthly SSC data in pre-change period, as Equation 5.13.

$$SSC = 0.234(1-NDVI^{5.3})Q^{1.137} \qquad 5.13$$

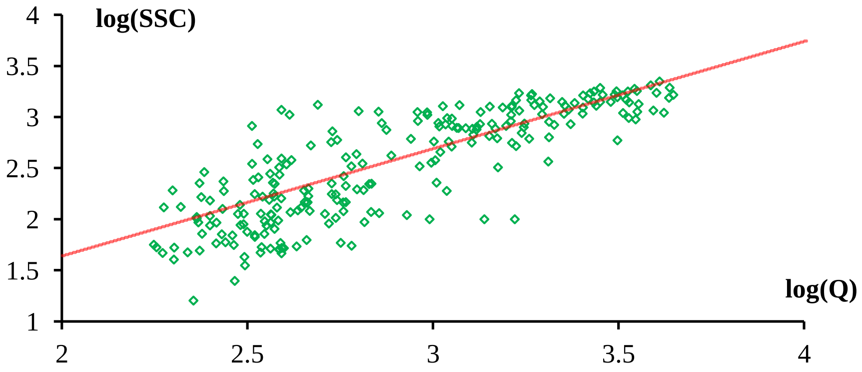


Figure 5.5. Relation between observed Q and SSC in the DRB

Table 5.3. Performance of New sediment rating curve for Laichau

Catchment	R^2	$MAE(g/m^3)$	$PBIAS$ (%)
Laichau	*0.83*	*6.67*	*1.03*

Table 5.4. Effects of human activities and climate change on the annual sediment load (10^6 ton/yr) of Laichau station

	$\overline{SL}_1^{obs}$	$\overline{SL}_2^{obs}$	$\overline{SL}_2^{sim}$	ΔSL^{tot}	ΔSL^{hum}	*Hum* %	*Clim* %
LC	*35.1*	*42.9*	*37.9*	*7.8*	*5.0*	*64*	*36*

As shown in Table 5.3, three statistics to evaluate the sediment rating curve mentioned above give the agreement results. A high R^2 (0.83), low *PBIAS* and *MAE* in Table 5.3 indicate that this sediment rating curve can evaluate SSC accurately in Laichau station. According to Equation 5.13, simulated SSC from 1994 to 2004 was then calculated where the simulated discharge by SWAT model in the same period was as the input. Finally, $\overline{SL_1^{obs}}$, $\overline{SL_2^{obs}}$ and $\overline{SL_2^{sim}}$ can be gotten based on Equation 4.2. The total difference in sediment load between the two periods was then calculated, which showed an increase after 1993. As a result, effects of human activities and climate change on the annual sediment load of Laichau was estimated and listed in Table 5.4. The results show that the proportions of human activities effect to total change of sediment load accounts for 64% and climate change is 36% in Laichau.

5.3.4. Discussions

Quantification of individual impacts of climate change and human activities is difficult. In this study, streamflow of Tabu station close to Hoa Binh reservoir can stand for the inflow into the reservoir. As for sediment load data, it was not available at Tabu station, so sediment load at Laichau station which drains 2/3 area of the DRB was considered as most of the sediment load into the reservoir. The results indicate both the streamflow and sediment load into the Hoa Binh reservoir increased. Human activities effects on sediment load are stronger than streamflow. Therefore, human activities effects on sediment load were more sensitive than on streamflow and human activities were largely responsible for the upward trends of streamflow and sediment load into the Hoa Binh reservoir after the transition year in the DRB.

During the study period, there was no big reservoir built in the upstream of Hoa Bin reservoir. As a result, the vegetation cover changes, such as deforestation may be the main human activities, which produced abrupt increase in streamflow and sediment yield. Annual accumulated values of NDVI can be used as an indicator for detecting inter-annual of vegetation activities (Box et al., 1990). In order to detect changes of vegetation cover, the GIMMS data set including 25-year period NDVI data from 1982 to 2006 was introduced to analyze the changes of the vegetation cover. Two kinds of changes were used to evaluate the temporal and spatial vegetation changes in the study area (up to Tabu station), one is the difference of average annual accumulated NDVI between two periods, the other is the linear slope of annual accumulated NDVI from 1982 to 2006, as showed in Figure 5.6. Both maps indicate similar spatial changes that NDVI of most area shows a downward trend, and part of north area displays upward trend, which reflects that vegetation cover have changed and decreased from 1982 to 2006. Some researchers got similar result in the study area. Ye et al (2008) analyzed the relationship between total sum of squares of deviations and breakpoint of annual NDVI which indicated that vegetation in the Chinese part of Red River basin was destroyed so severely in 1993. In the other hand, from data of UNEP (1990) and Review of World Bank (1996), deforestation has been intense in Red River Basin especially in the mountainous area in 1990s. As a result, forest cover was degraded very severely in the past and became the worst situation in about 1993, which keeps agreement with the detected changing point of streamflow in 1993 and vegetation cover change is one main factor for the changes of streamflow and sediment load into the Hoa Binh reservoir.

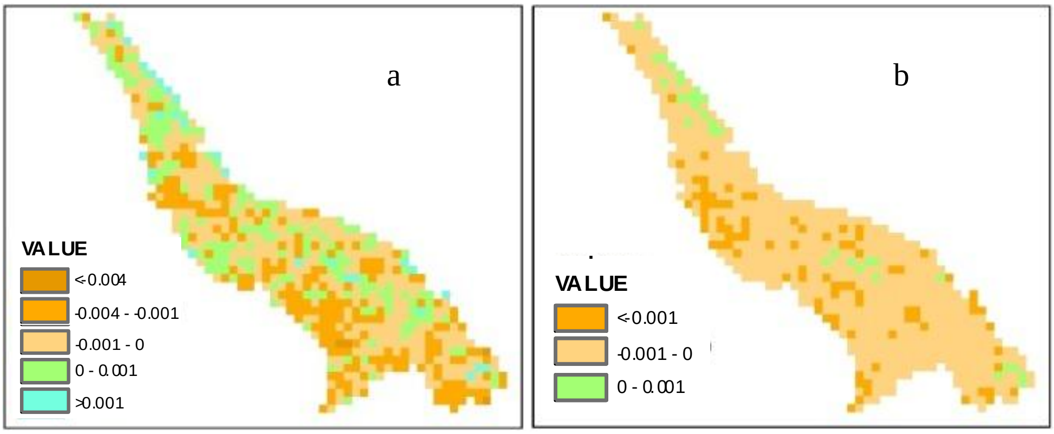


Figure 5.6. (a) Difference between annual accumulated NDVI from 1982 to 1993 and from 1994 to 2006; (b) Linear slope of annual accumulated NDVI from 1982 to 2006

As a result, due to the reservoir siltation and increasing sediment flow into reservoir, the useful lifetime of the Hoa Binh reservoir would be shorten quickly, which would cause the flood risk increasing, hydropower generation reduction in the Red River region.

From the results above in this paper, vegetation cover change can change the streamflow and sediment load and human activities are the key factor for the changes in the Da River basin.

5.4. Conclusions

In conclusion, an upward trend has been found for annual streamflow into Hoa Binh reservoir, with an abrupt change identified in 1993. It is also found out that NDVI changed very much before and after 1993. Effects of climate change and human activities on the increase of streamflow and sediment flow into Hoa Binh dam were estimated in DRB. The separation of climate change and human activities effects were also investigated.

Main conclusions are as follows. Firstly, an increase of streamflow and sediment load from 1988 to 2004 was detected. Secondly, effect of human activities on streamflow was stronger in the Tabu station of downstream than Laichau station of upstream. Effect of human activities on streamflow accounted for about 60% both in Laichau and Tabu catchments which is higher than effect of climate change. And human activities contribution rate on sediment increase was also stronger than climate change. Thirdly, vegetation change was the main human activities, which was more sensitive to sediment yield than streamflow. Summarily, human activities are the main factor to affect the changes of streamflow and sediment flow into the Hoa Binh Reservoir.

CHAPTER VI

COUPLING NEW SEDIMENT RATING CURVE AND ECOLOGICAL MODEL TO EVALUATE HUMAN-INDUCED VEGETATION COVER CHANGE EFFECT ON SEDIMENT FLOW

Sediment load can provide very important perspective on erosion of river basin. The changes of human-induced vegetation cover, such as deforestation or afforestation, affect sediment yield process of a catchment. In this study, a new sediment rating curve considering vegetation cover was developed to evaluate the impact of vegetation cover changes on sediment yield in Da River Basin. The Normalized Difference Vegetation Index (NDVI) and leaf area index (LAI) can be used to analyze the status of the vegetation cover well. Thus long time series NDVI from satellite was applied to represent vegetation cover in the past years. Potential LAI from ecosystem model (Biome-BGC) was used to explain the vegetation cover without human activities. Finally, standardized NDVI and LAI were inputted into the new sediment rating curve to evaluate human-induced vegetation cover change effect on sediment load.

6.1. Introduction

The issue of soil erosion of the watershed is one of the hot spots, which currently causes the global widespread attention, especially for Red River with its overall sediment load previously classed 9th in the world. Red River has received increasing attention with many eco-hydrological problems, such as sediment changes and biodiversity disappear. It has been generally accepted that vegetation cover change has brought great impacts on the sediment yield process in river basins. As concluded in Chapter 5, many researchers have already carried out to investigate the sediment load changes in Red River Basin (Ren et al, 2007; Dang et al., 2010; Wang and Ishidaira, 2012). In Chapter 5, we used model simulation method to conclude that human activities are the main factor to affect the changes of sediment flow and vegetation cover change is the main human activities in Red River Basin. However, it is not clarified yet that how much human-induced vegetation cover change could affect sediment loads. This study provides a different research view on effects of vegetation cover change on sediment loads.

The calculation of sediment loads requires both discharge and concentration data in river basins. The discharge data can be relative easier to obtain than sediment in situ measurement. On the other hand, sediment concentration data typically result from manually collected individual samples taken at fixed temporal intervals and was still absent at most hydrological stations especially for developing country. In the absence of actual sediment concentration measurements, researchers have used different models to estimate suspended sediment concentration (SSC). In Chapter 4, one new sediment rating curve considering the effect of vegetation cover has already been developed to calculate vegetation cover change effect on the sediment load (Wang and Ishidaira, 2012). In addition, it could consider impact of temporal dynamic changes of vegetation cover on sediment load, which is really suitable for the objective of this chapter.

For one fixed catchment, the sediment load is intimately related to the geology, topography, climate, vegetation cover within the basin. The geologic and topographic variables are fixed in the short term, but long-term changes in climatic conditions or vegetation cover will produce abrupt alterations in erosion processes and sediment loads (Maria et al., 2007). Vegetation cover change plays an important role in altering surface flow and sediment yield. To evaluate the effect of vegetation cover change on sediment load, vegetation cover temporal dynamic should firstly be investigated. Nevertheless, vegetation cover over longer time periods is difficult to obtain directly. NDVI and Leaf area index (LAI) are two of the most widely used vegetation indexes, due to the good performance of explaining the status of vegetation coverage. Time series of observed vegetation index derived from remote sensing data provides an opportunity to study vegetation cover. However, NDVI or LAI obtained from remote sensing data only can explain the current vegetation cover with dual influence of climate change and human activities. To investigate potential vegetation cover (e.g., potential LAI) under assumed or future climate scenarios without human activities, ecosystem simulation models are required. In addition, ecosystem models have the advantage of considering effects of not only climatic condition but also carbon dioxide concentrations.

The objective of this study is ultimately to design one new approach to analyze effect of human-induced vegetation cover change on the sediment load. On purpose of this, time series NDVI from Global Inventory Modeling and Mapping Studies (GIMMS) was introduced to analyze the changing trend of vegetation cover in the past years. In addition, potential LAI was simulated by one ecosystem model to describe the potential vegetation cover condition without human activities effects. Based on the relationship between NDVI and LAI, they were then converted into standardized values. Finally, standardized NDVI and LAI were inputted into new sediment rating curve to evaluate vegetation cover change effect on sediment load.

6.2. Dataset and methodology

6.2.1. Data Description

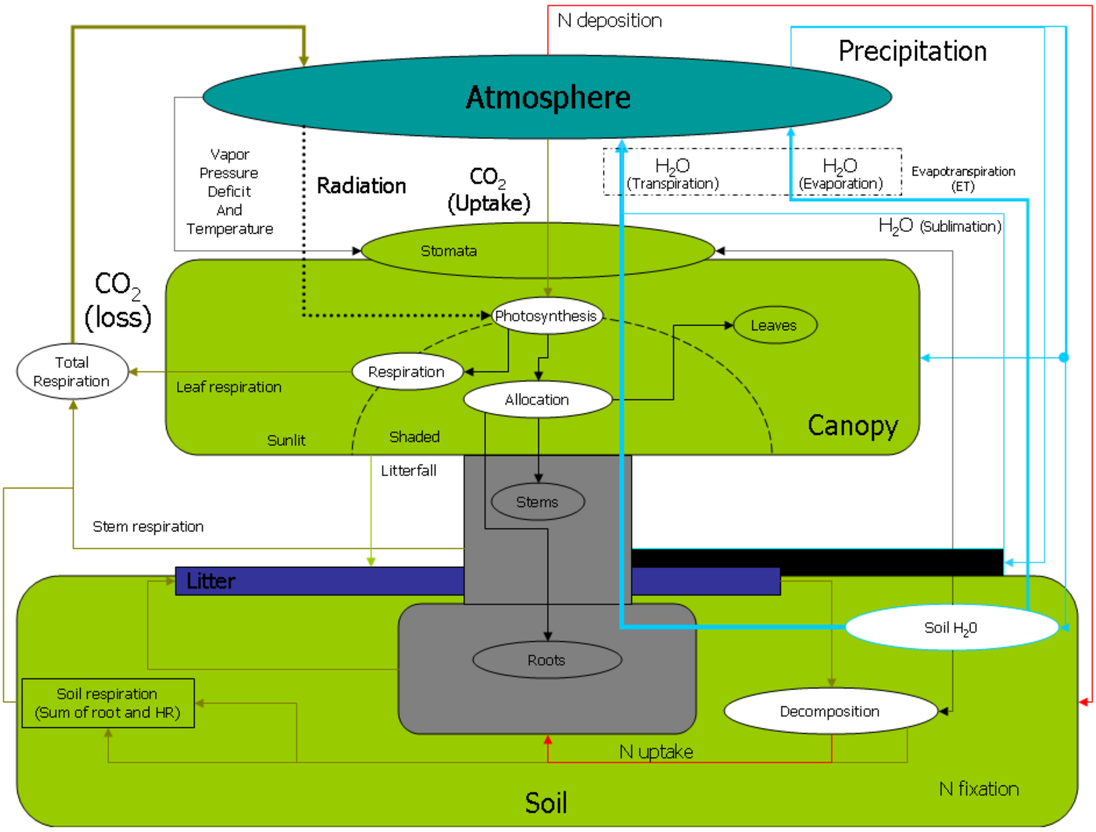
Da River Basin was also selected as the target basin of this study. Streamflow data and suspend sediment concentration data at Laichau station is available from 1988 to 2004, which is from Vietnam Academy of Science and Technology. We used 0.25 degree gridded daily precipitation and average temperature data from APHRODITE's Water Resources Project (Yasutomi et al., 2011). 0.5 degree gridded monthly average daily maximum and minimum temperature data from Climatic Research Unit (CRU) was introduced to calculate the diurnal temperature range (DTR), which was applied to transform daily average temperature from APHRODITE into daily maximum and minimum temperature.

1km elevation data was provided by GTOPO30 from U.S. Geological Survey (USGS). Global Digitized Soil Map and effective Soil Depth of FAO-UNESCO with a spatial resolution of 5*5 arc minutes were used to obtain the soil properties. Global 1km Land Cover data obtained from the USGS National Center for Earth Resources Observation Science was employed and the land cover was reclassified into the following seven types: evergreen needle-leaf forest, evergreen broadleaf forest, deciduous broadleaf forest, deciduous needle-leaf forest, evergreen shrubs, C3 and C4 (photosynthesis type) grassland in the study. The GIMMS data (Tucker et al., 2005) set including a 25 years period spanning NDVI data from 1982 to 2006 was used to analyze the vegetation cover and develop the new sediment rating curve in our study area. All the geographic data were re-gridded into the same spatial resolution of 0.25 degree.

In addition, a 30+ year long global data sets of vegetation leaf area index (LAI3g) which derived from the third generation GIMMS NDVI3g data set was applied to validate Biome-BGC model. The dataset is at 1/12 degree resolution, 15-day composites and span the period July 1981 to December 2012. A set of neural networks were first trained on best-quality and significantly post-processed MODIS LAI products and AVHRR GIMMS NDVI data for the overlapping period (2000 to 2009). The trained neural networks were then used to produce the LAI data sets (Zhu et al., 2013).

6.2.2. Ecological model (Biome-BGC)

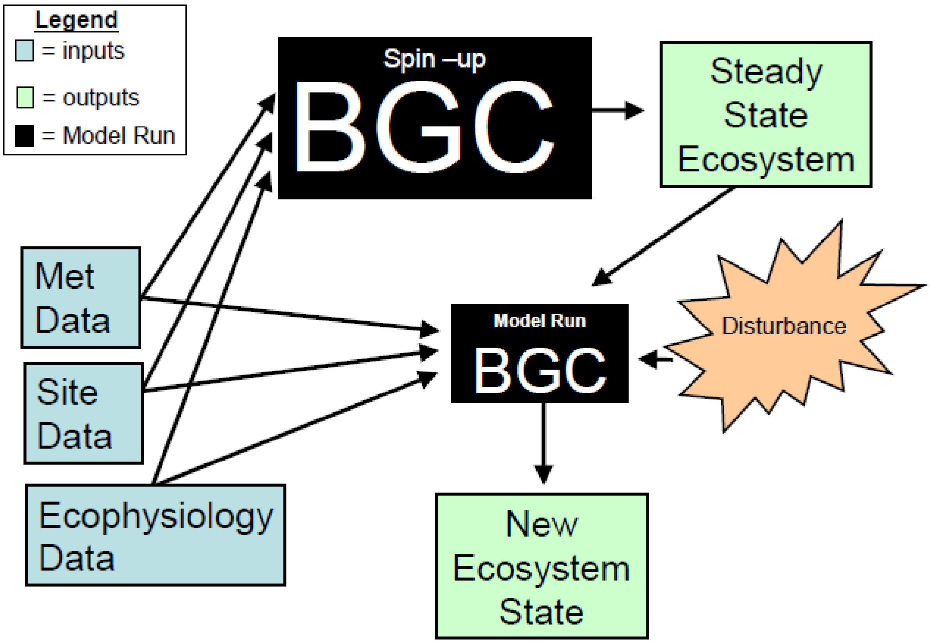
Biome-BGC is a biogeochemical point simulation model developed by the University of Montana (Running and Gower, 1991) to estimate the storage and fluxes of carbon, nitrogen and water within terrestrial ecosystems, which was applied to calculate the potential LAI under present climate conditions without human activities effects. Biome-BGC is a computer program that estimates fluxes and storage of energy, water, carbon, and nitrogen for the vegetation and soil components of terrestrial ecosystems. As mentioned above, the primary biogeochemical cycles represented in Biome-BGC are the C, N, and H_2O cycle (Figure 6.1). In conjunction with these cycles, Biome-BGC models the physical processes of radiation and water disposition. Biome-BGC partitions incoming radiation and precipitation and treats the excess/unused portions as outflows. The primary physiological processes modeled by Biome-BGC are photosynthesis, evapotranspiration, respiration (autotrophic and heterotrophic), decomposition, the final allocation of photosynthetic assimilate, and mortality. To model these processes, Biome-BGC first models the phenology of the systems based on the input meteorological data.



(http://www.ntsg.umt.edu/project/biome-bgc)

Figure 6.1. Conceptual Diagrams of Biome-BGC model

The model uses a daily time-step. This means that each flux is estimated for a one-day period. Between days, the program updates its memory of the mass stored in different components of the vegetation, litter, and soil. Weather is the most important control on vegetation processes. Flux estimates in Biome-BGC depend strongly on daily weather conditions. Model behavior over time depends on the history of these weather conditions, the climate. It requires: daily climate data, information of the general environment (i.e. soil, vegetation type and site conditions) and parameters describing the eco-physiological characteristics of vegetation. As is usual for such models, Biome-BGC needs “spin-up” simulations (Figure 6.2) to achieve equilibrium conditions where the initial soil and plant compartment pools actually match the mass balance equations. Biome-BGC emphasizes leaf area index (LAI) as a key structural output, calculated by multiplying carbon allocated to leaves times the specific leaf area.



(http://www.ntsg.umt.edu/project/biome-bgc)

Figure 6.2. Conceptual diagram showing Biome-BGC general model structure

In this study, Biome-BGC was applied to calculate the potential LAI under present climate conditions without human activities effects. It requires: daily climate data, information of the general environment (i.e. soil, vegetation type and site conditions) and parameters describing the eco-physiological characteristics of vegetation. The missing daily meteorological data, not available from APHRODITE or CRU dataset, were estimated by the MTCLIM model (Thornton et al., 2000). As is usual for such models, Biome-BGC needs "spin-up" simulations to achieve equilibrium conditions where the initial soil and plant compartment pools actually match the mass balance equations. Biome-BGC emphasizes leaf area index (LAI) as a key structural output, calculated by multiplying carbon allocated to leaves times the specific leaf area. Ichii et al (Ichii et al., 2005) applied this model to simulate the carbon fluxes and gross primary productivity in Amazonian, African and Asian area and got reasonable estimates of these parameters. As a result, we also used the model to simulate potential LAI since our study basin is one part of Asian area. In order to obtain LAI values for all grids, we developed the grid-based Biome-BGC model instead of previous point simulation vision for DRB, with the spatial resolution of 0.25 degree.

6.2.3. Standardization of LAI and NDVI

The NDVI is one of the most extensively used as vegetation proxy for LAI. NDVI increases almost linearly with increasing LAI especially for not so large range of LAI and NDVI (Fan et al., 2009). For the purpose of comparison LAI with NDVI equally, LAI and NDVI were transformed to standardized value using this linear relationship in our research.

$$M_{NDVI} = (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min}) \qquad 6.1$$

$$M_{LAI} = (LAI - LAI_{min}) / (LAI_{max} - LAI_{min}) = M_{NDVI} \qquad 6.2$$

where $M_{NDVI}/_{LAI}$ is the standardized value for NDVI or LAI. $NDVI_{min/max}$ and $LAI_{min/max}$ are the minimum and maximum NDVI or LAI value respectively. Then NDVI or LAI can be changed into $M_{NDVI/LAI}$ to develop the new sediment rating curve.

6.2.4. New modified sediment rating curve

Based on our new sediment curve, time series of $M_{NDVI/LAI}$ instead of NDVI/LAI were applied to develop the new sediment rating curve and to estimate sediment loads from the streamflow and vegetation cover in this study. The new modified sediment rating curve represents as follows:

$$SSC = a\ (1-M_{NDVI/LAI}{}^{c})\ Q^{b} \qquad 6.3$$

in which Q (m^3/s) is discharge, SSC (g/m^3) is suspended sediment concentration and $M_{NDVI/LAI}$ is standardized NDVI or LAI. Parameter of a, b and c for are determined from data via least squares method. Then, sediment load can be calculated by:

$$SL = Q \times SSC \qquad 6.4$$

in which SL (g/s) is sediment load.

To provide a more comprehensive evaluation of the model performance, three statistics are used to indicate the accuracy of this curve: coefficient of determination (R^2), percent bias (*PBIAS*) and the mean absolute error (*MAE*). Based on the well fitted sediment rating curve, the effect of human-induced vegetation cover change on sediment load can be calculated by the difference value (ΔSL^{veg}) between observed SL (SL^{obs}) and simulated SL from potential LAI (SL_{LAI}^{sim}).

6.3. Results

6.3.1. Determination of research period

In order to evaluate human-induced vegetation cover change effects on sediment load, we should first determine which period was the period of most strong human activities. According to the previous study, the period after 1993 was recognized as the most serious period of human activities effect in DRB compared with the period before 1993. And we also analyzed the change of NDVI from 1982 to 2006 and detected one obvious downward shift. Additionally, the average NDVI before and after 1993 also indicate vegetation cover affected by human activities was more serious after 1993 (Figure 6.3). As a result, the same period from 1994 to 2004 is selected as the target period to evaluate human-induced vegetation cover change effects in this research and it is also more convenient to compare results with the previous study.

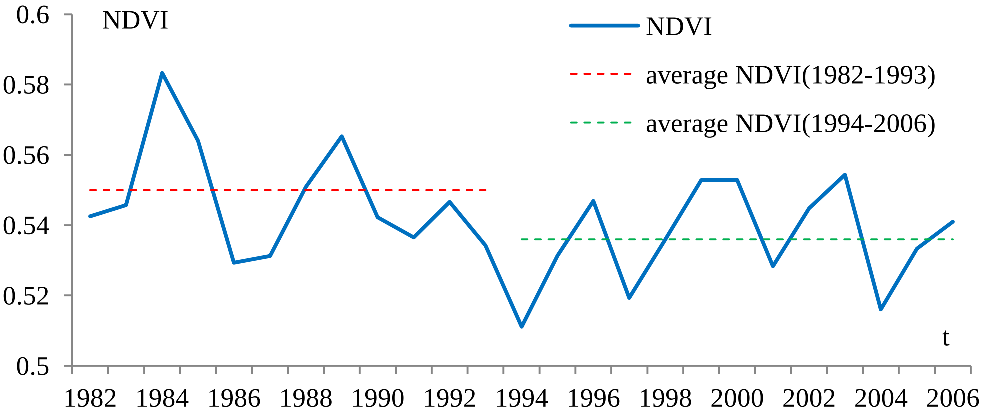


Figure 6.3. Change of annual maximum NDVI in the upstream of laichau station (1982-2006)

6.3.2. Biome-BGC simulation results

Since post-change period from 1994 to 2004 is considered as more human activities effects. So we assume pre-change period from 1982 to 1993 without serious human activities and select this period for this ecological model calibration period. Even though, it is still difficult to calibrate ecological because human activities maybe also affect vegetation cover change in the pre-change period.

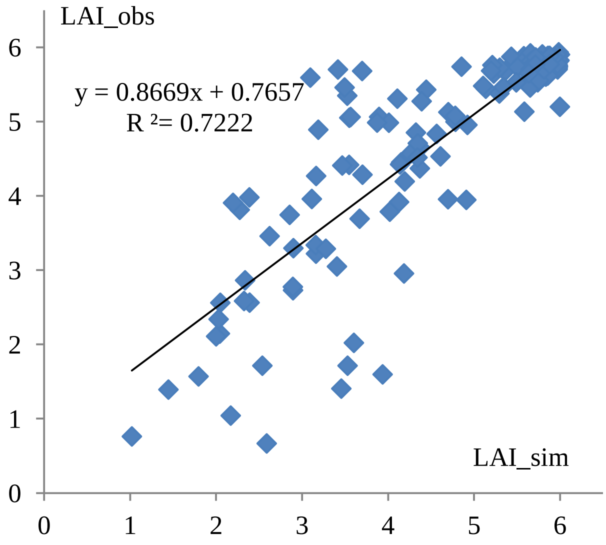


Figure 6.4. Scatterplot of satellite and simulated monthly basin average LAI

As mentioned before, the point Biome-BGC model was first developed into grid-based model for the basin scale to evaluate vegetation cover change effects on sediment load. From the viewpoint of comparison between the simulated and observed monthly basin average LAI from 1982 to 1993, results display that the simulated LAI from ecological model has a good match with the satellite observed values, as showed in Figure 6.4. In addition, the high R^2 value (0.772) also suggests that this ecological model can simulate LAI reasonably.

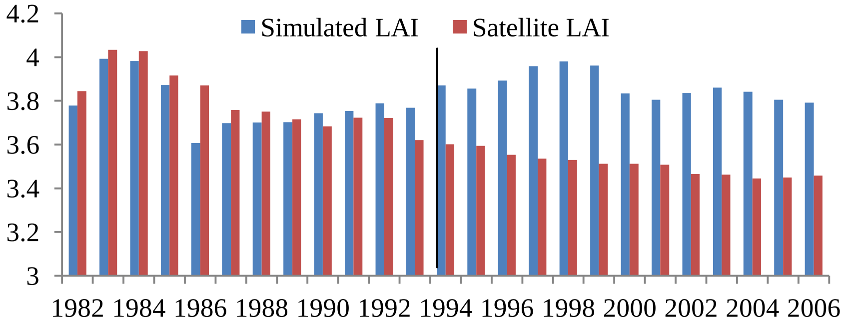


Figure 6.5. Comparison between simulated and satellite annual maximum LAI

Moreover, we compared simulated and satellite annual maximum LAI from 1982 to 2006 (Figure 6.5). It is obvious that the annual simulated LAI has a good match with the satellite observed values before 1994 and there is some partial difference in the post-change period.

Based on results above, biome-BGC ecological model was successfully applied in our river basin and could be used for potential LAI simulation without human activities effects in this research.

6.3.3. NDVI and potential LAI analysis

Grid maximum monthly and annual potential LAI were generated from the model to analyze the potential vegetation cover conditions. The linear trend of annual NDVI from GIMMS and potential LAI from Biome-BGC forced by real climate data alone were calculated with significance level of 0.05 (Figure 6.6 & 6.7), which express some inverse trend between NDVI and potential LAI from 1982 to 2006. Almost all the area in the basin shows one obvious decreasing trend for the NDVI whereas most grids had one increasing slope for potential LAI. On the other hand, the maximum decreasing trend of NDVI is 0.12/year, much higher than the increasing slope of 0.01/year. And the maximum increasing trend of LAI is 0.13/year, much higher than the decreasing slope of 0.05/year. This unsymmetrical result above also shows that human actives aversely changed trend of vegetation cover.

After the process of potential LAI and NDVI standardization, standardized potential LAI and NDVI were compared to explain human-induced vegetation cover change. From the standpoint of comparison between the average M_{LAI} and M_{NDVI} during our study period, results show that M_{LAI} is larger than M_{NDVI} not only for almost all the months but also for wet and dry season (Figure 6.8). As shown in Table

6.1, two statistics are used to evaluate the changes of vegetation cover without human actives effect. The changes between M_{LAI} and M_{NDVI} for wet season, dry season and annual average are different, which indicate vegetation cover changed most serious and human activities affected the vegetation cover stronger in the dry season. Results showed in Table 6.1, Figure 6.6 and Figure 6.7 can comprehensively explain that human activities affected a lot to the vegetation cover from 1994 to 2004 in DRB.

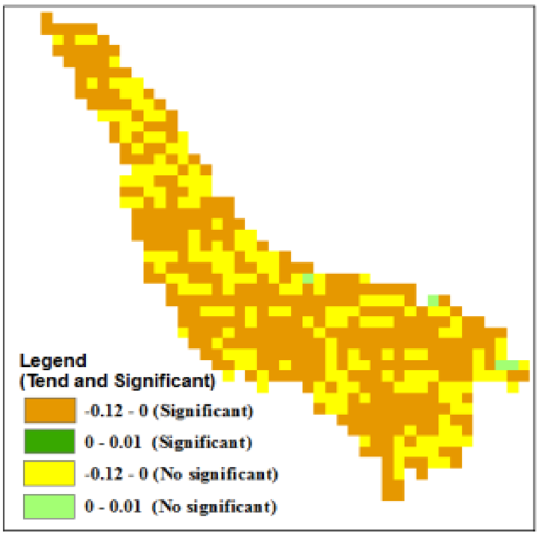


Figure 6.6. Linear slope of actual annual maximum NDVI from GIMMS (1982-2006) (Significant: passed significance level of 0.05)

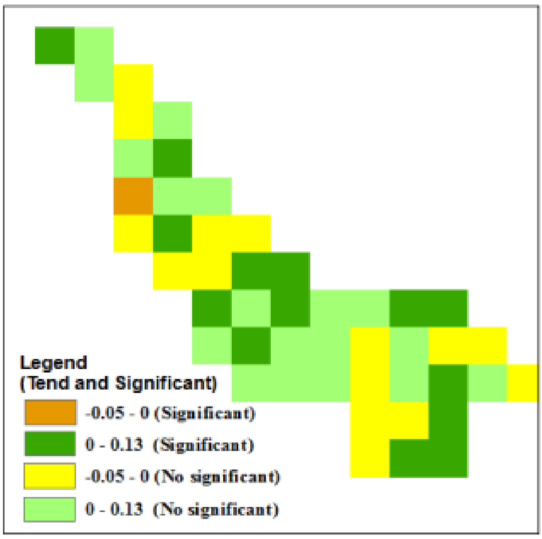


Figure 6.7. Linear slope of potential annual maximum LAI from Biome-BGC model (1982-2006) (Significant: passed significance level of 0.05)

6.3.4. New modified sediment rating curve development

To apply the M_{LAI} and M_{NDVI} to evaluate human-induced vegetation cover change effects on sediment load, according to Eq.6.4, one well fitted new sediment rating curve for Laichau station was firstly proposed based on the monthly SSC data from 1994 to 2004, as Eq.6.5.

$$SSC = 0.4(1-M_{NDVI}{}^{6.7})Q^{1.04} \tag{6.5}$$

From the viewpoint of comparison between the simulated and observed monthly SSC, results display that the simulated SSC from the new sediment rating curve has a good match with the observed values, as showed in Figure 6.9. In addition, as shown in Table 6.2, three statistics to evaluate the sediment rating curve mentioned above give the agreement results. The high R^2 (0.894), low PBIAS and MAE better than the common sediment rating curve result suggest that this new sediment rating curve can evaluate SSC more accurately in Laichau station and can be further used to evaluate human-induced vegetation cover change effects on sediment load.

Table 6.1. Statistic results of MLAI and MNDVI from 1994 to 2004

	Wet season	Dry season	Annual average
M_{LAI}	*0.783*	*0.635*	*0.696*
M_{NDVI}	*0.756*	*0.548*	*0.636*
MAE	*0.027*	*0.087*	*0.06*
PBIAS(%)	*3.57*	*15.88*	*9.43*

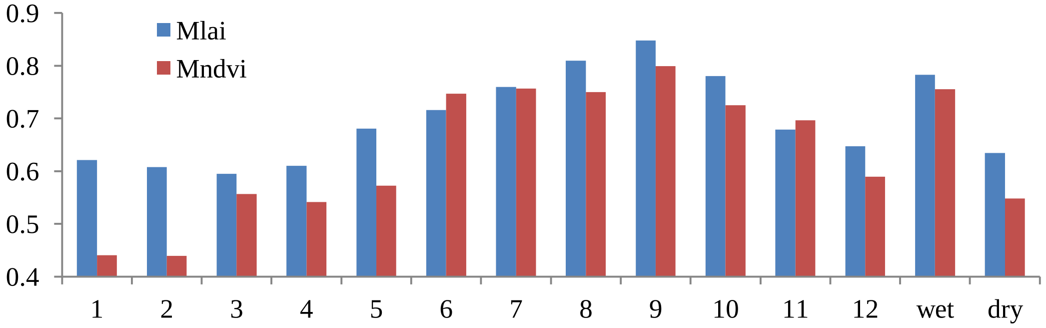


Figure 6.8. Comparison of season and month average standardized potential LAI and NDVI from 1994 to 2004

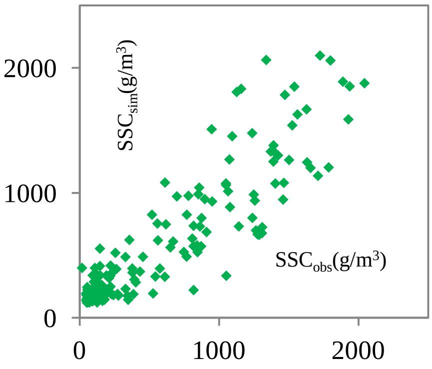


Figure 6.9. Scatterplot of observed and simulated monthly SSC in the Laichau station

Table 6.2. Effects of human-induced vegetation cover change on month average sediment load (10^6ton/month) at Laichau station

Laichau	SL^{obs}	SL_{LAI}^{sim}	ΔSL^{veg}	*PBIAS* (%)
Wet season	*7.95*	*6.81*	*1.14*	*14.3*
Dry season	*0.49*	*0.43*	*0.05*	*10.2*
Annual	*3.57*	*3.08*	*0.49*	*13.7*

6.3.5. Effects of human-induced vegetation cover change on sediment load

As well known, the calculation of sediment loads requires both discharge and concentration data. According to Eq. 6.5, simulated SSC_{LAI}^{sim} from 1994 to 2004 was calculated from time series of M_{LAI} and the simulated discharge without human activities effect from our previous study. Finally, SL_{LAI}^{sim} and SL^{obs} can be gotten based on Eq.6.4. The total difference between SL^{obs} and SL_{LAI}^{sim} was then calculated. As a result, effects of human-induced vegetation cover change on the sediment load of Laichau was estimated and listed in Table 6.3. The results showed that the proportions of vegetation cover change effect on annual sediment load accounted for 13.7% in Laichau station. Besides that, the increase in sediment load for wet season, dry season and annual average were different, which indicated human-induced vegetation cover change affected the sediment load stronger in the wet season.

6.3.6. Discussions

The interaction and feedback between sediment load and vegetation cover is not so easy to diagnose and quantify. On purpose of this, one new approach was first proposed in our research, which may support guide for some other similar research.

Two vegetation parameters were introduced to explain the temporal and spatial of vegetation cover in this study. The potential LAI from Biome-BGC ecological model expressed one inverse trend compared with realistic vegetation cover change, as showed in Figure 6.6 and Figure 6.7, which illustrated a situation that human activities affected the vegetation cover very much and even reversed the changing trend in the last 25 years. Some research also got similar result in our study area.

Considering the results from Table 6.1 and Table 6.3, we could find vegetation cover changed stronger in the dry season than wet season whereas sediment load changed more in the wet season, which implied that changes of vegetation cover are more sensitive to SSC in wet season. Compared with the previous results, human activities caused 11.7% changes of sediment load lower than 13.7% of this research. Previous research used the common sediment rating curve without considering the effect of vegetation cover change; however, this study considered dual effects from changed discharge and human-induced vegetation cover change. Besides, cross-validation of the results from these two studies could further explain that vegetation cover change truly induced the increasing sediment load in DRB in the past.

Laichau station draining 2/3 area of the DRB was considered its sediment load as most of the sediment flow into HoaBinh reservoir the biggest reservoir in Vietnam. So changes of sediment in the upstream of this reservoir play a key role for reservoir operation. Therefore, due to increasing sediment flow into reservoir and the reservoir siltation itself, the useful lifetime of the HoaBinh reservoir would be shorten quickly, which would cause the flood risk increasing, hydropower generation reduction in the Red River area.

From the results above, quantify of human-induced vegetation cover change impact on sediment load was successfully carried out and analyzed for the Da River basin based on one new research review.

6.4. Conclusions

In our research, one new method to quantify of human-induced vegetation cover change impact on sediment load was proposed and successfully applied in the Da River Basin. In conclusion, the NDVI and potential LAI from ecological model were investigated and effect of human-induced vegetation cover change on the increase of sediment flow into HoaBinh dam was estimated in DRB.

Main conclusions are as follows. Firstly, an obvious downward trend of NDVI and upward trend of potential LAI were detected. Secondly, one new sediment rating curve considering changes of vegetation cover was used to estimate sediment loads from the streamflow and vegetation cover. Thirdly, vegetation cover changed stronger in the dry season than wet season whereas sediment load changed more in the wet season, which implied that changes of vegetation cover are more sensitive to wet season. Effect of human-induced vegetation cover changed 13.7% of sediment load in the Laichau station.

The present paper presented one new method to quantify of human-induced vegetation cover change impact on sediment load, which may provide guidance for future similar studies. In addition, evaluation of human-induced vegetation cover effect on sediment load is critically important in directing efforts in managing land use, in improving agricultural practices, and in protecting soil erosion in the Da River.

CHAPTER Ⅶ

ANALYZING THE POTENTIAL EFFECT OF FUTURE LAND COVER AND CLIMATE CHANGE ON STREAMFLOW AND SEDIMENT FLOW BASED ON LAND USE CHANGE MODEL AND GCMS DOWNSCALING MODEL

We have already evaluated that climate change and land cover change changed the historical streamflow and sediment yield, and land cover change is the main factor. But future streamflow and sediment yield changes under different future climatic change scenarios and potential future land cover change scenarios still have not been evaluated For this purpose, future scenario of land cover change is developed based on historical land cover changes and land change model (LCM). At the same time, climate change scenarios are built based on downscaling outputs of GCMs from the IPCC Fourth Assessment Report (2007). In addition, future leaf area index (LAI) is simulated by ecological model (Biome-BGC model) based on future land cover scenario. Then future scenarios of land cover change, climate change and LAI are used to drive hydrological model and new sediment rating curve. The results of this research provide information that decision-makers need in order to promote water resources planning efforts. Besides that, this study also contributes a basic framework for assessing climate change impacts on streamflow and sediment yield that can be applied in the other basins around the world.

7.1. Introduction

Studies on hydrological processes in a changing environment have been the focus of hydrological science in the 21st century. Red river, with its overall sediment load previously classed 9th in the world, has received increasing attention with many eco-hydrological problems, such as hydrological changes, sediment changes and biodiversity disappear. The variations of runoff in the upstream affect the utilization of water resources and sediment flow into the Hoa Binh reservoir. Furthermore, changes of sediment inflow can induce reservoir siltation and increase or decrease the flood risk of the downstream region. Therefore, analyzing on the effect of future climate change and land use/cover change on streamflow and sediment flow into the Hoa Binh Reservoir is critical for the appropriate utilization of water resources, flood control, soil conservation and ecological protection.

Recently, a variety of studies have been performed on the impact of climate change or land use/cover change on streamflow (Chang et al., 2002; Githui et al., 2009; Bauwens et al., 2011) and sediment yield (Li et al., 2011; Phan et al., 2011; Shrestha et al., 2013). In addition, few researches were related to double impacts of climate change and land use change on both streamflow and sediment yield (Tu, 2009). As for Red River Basin, several studies related to impacts of climate change and land cover change on streamflow or sediment yield have also been carried out. For example, Tuan (1993) analyzed the variability of annual runoff changing trend in the past years by Mann-Kendall method and cluster technique method in the Red River and concluded that the jump of runoff was mainly influenced by vegetation cover change. Dang et al (2010) simulated sediment load and detected a significant decrease of sediment load after 1990 in the downstream of reservoir, which indicated that the Hoa Binh dam reduced annual sediment by half. Wang et al. (2012) applied model simulation method to separate different impacts of climate change and human activities on streamflow and sediment flow in Da River Basin and concluded that human activities are major factors to modify the streamflow and seiment flow into Hoa Binh reservoir. Wang et al. (2013) also quantitatively evaluated effects of human-induced vegetation cover change on sediment flow using satellite observations and terrestrial ecosystem model and found historical vegetation cover decrease raised sediment yield by 13.7% in Da River Basin. However, most researchers focused on historical changes analysis of streamflow or sediment yield in Red river basin, rare studies about future land use change and climate change on hydrology and sediment load were conducted. Consequently, quantitative assessment of future land use/cover and climate changes on streamflow and sediment load of is necessary to carry out not only for red river basin, but also for other basins in the world.

The overall objective of this study is to investigate changes in streamflow and sediment load response to land cover change and climatic change in the Da River Basin. The specific objectives are: (1) to simulate responses of streamflow and sediment yield to future climate change; (2) to simulate responses of streamflow and sediment yield to future land cover change; and (3) to investigate the combined impact of future climate and land cover changes on streamflow and sediment yield. For this purpose, future scenario of land cover change is developed based on historical land cover changes and land change model (LCM). At the same time, climate change scenarios are built based on downscaling outputs of GCMs from the IPCC Fourth Assessment Report (2007). In addition, future leaf area index (LAI) is simulated by ecological model (Biome-BGC model) based on future land cover scenario. Then future scenarios of land cover change, climate change and LAI are used to drive hydrological model and new sediment rating curve. The results of this research provide information that decision-makers need in order to promote water resources planning efforts. Besides that, this study also contributes a basic framework for assessing climate change impacts on streamflow and sediment yield that can be applied in the other basins around the world.

7.2. Dataset and methodology

7.2.1. Data Description

Da River Basin was also selected as the target basin of this study. Streamflow data at Laichau (LC) and Tabu (TB) stations were selected in the Da River basin, which were available from 1990 to 2000. Suspended sediment concentration data at Laichau station is available from 1990 to 2000. There are 16 rainfall stations located in or around the basin. These stations are spatially well distributed, which can reflect the characteristics of regional climate. Hydrologic data is from the China Meteorological Data Sharing Service and Vietnam Academy of Science and Technology, which has been checked by the primary quality control. In addition, the baseline period was defined as 1991 to 2000 and the future period was assumed as 2046 to 2066 in this study.

To feed with hydrological model (BTOPMC), GTOPO30 1km elevation data from U.S. Geological Survey (USGS), global Digitized Soil Map and effective Soil Depth from FAO-UNESCO with a spatial resolution of 5*5 arc minutes and global 1km Land Cover data in the year of 2001 obtained from MODIS annual land cover data (MCD12Q1) was also employed in this study.

In order to drive land change model (LCM), a series of spatial drivers were selected, which include the following dataset: GTOPO30 elevation data, global gridded population density in 2000 produced by the Columbia University Center for International Earth Science Information Network (CIESIN) and Centro International of Agricultural Tropical (CIAT), global roads open access data Set (gROADS) provided by Center for International Earth Science Information Network (CIESIN)/Columbia University and Information Technology Outreach Services (ITOS)/University of Georgia, basin river network from Vietnam Academy of Science and Technology, global human footprint from Wildlife Conservation Society (WCS) and Center for International Earth Science Information Network (CIESIN)/Columbia University, basin slope calculated from elevation data, basin rainfall trend calculated from TRMM satellite product. In addition, the MCD12Q1 land cover data from 2001 to 2011 were used to estimate historical land cover change map by LCM model.

The GIMMS data set including a 25 years period spanning NDVI data from 1981 to 2006 was used to analyze the current vegetation changes for the study area. At the same time, future LAI was simulated from the validated ecological model (Biome-BGC) driven by future climate change scenario and future land cover change.

Table 7.1. Dataset summary for different models

Models	Spatial dataset	Point dataset
Hydrological model	Elevation, land cover, soil map, NDVI	Rainfall, streamflow
Land change model	Elevation, land cover, population density, road, river network, slope, human footprint, rainfall trend	
Ecological model	Elevation, land cover, soil map	Rainfall, maximum and minimum temperature

7.2.2. Research framework

Based on previous research experience, research framework was presented as Figure 7.1. Firstly, future land cover change scenario was prepared based on LCM model and future climate change scenario was obtained by downscaling GCMs. Then, future land cover change and climate change scenarios were used to drive Biome-BGC model to predict future LAI. After this, all kinds of scenarios were applied for driving BTOPMC model and new sediment rating curve to assess future streamflow and sediment yield in the Da River Basin.

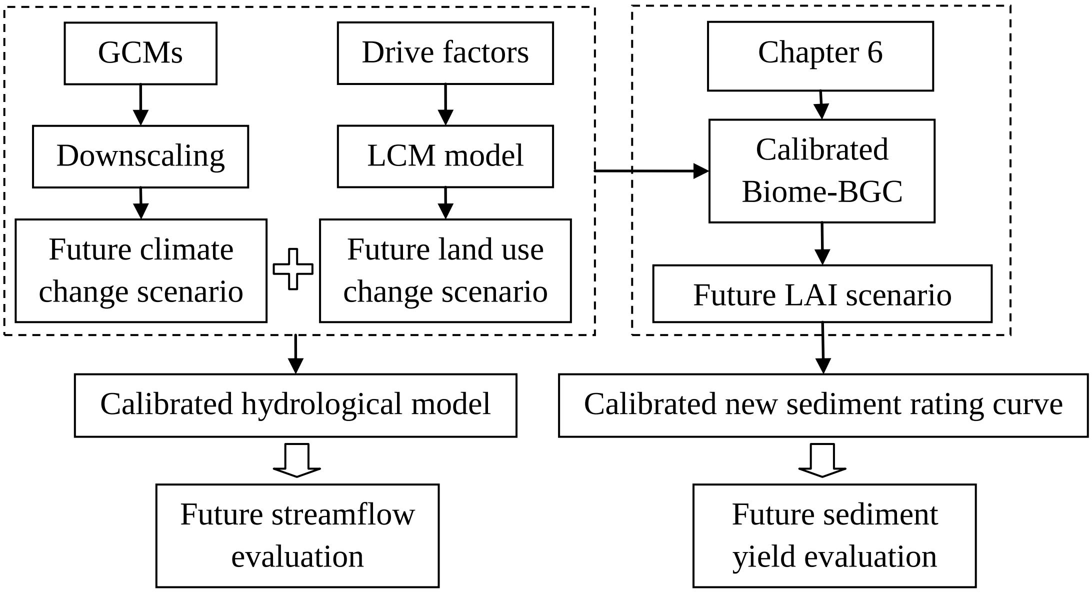


Figure 7.1. The research framework of Chapter 7

7.2.3. BTOPMC model

The BTOPMC model is a grid-based distributed hydrological model developed by the University of Yamanashi (Japan) for hydrological simulations in large river basins since 1999 (Takeuchi *et al.*, 1999; Ishidaira *et al.*, 2000; Ao *et al.*, 2003a,b). In this paper, this model is applied to predict future streamflow under future land cover change and climate change scenarios. The runoff generation module is based on extended TOPMODEL concepts (Takeuchi et al., 1999; Zhou et al., 2006a, 2006b).

BTOPMC model divided the whole basin into a number of blocks/sub-basins, each blocks/sub-basins may consist of several hill slopes. Water shared between hill slopes in each block, no water exchange between blocks. The topographic index γ is redefined, which is effective in the grid based applications, especially for large basin analysis:

$$q_{bi} = [a_i f(a_i) r_k]/a_{0i} \tag{7.1}$$

$$\gamma_i = ln \frac{a_i f(a_i)/a_{0i}}{tan\beta_i} \tag{7.2}$$

where $f(a_i)$ ($0 \leq f(a_i) \leq 1$) is the effective contributing area ratio, which is the ratio of the net upstream catchment area that contributes to the discharge from the grid cell *i* to the total upstream area a_i. q_{bi} (m day^{-1}) is the specific base flow of the grid cell *i* to the local stream segment per unit grid cell area (rather than per unit contour line), r_k (m day^{-1}) is the spatially homogeneous recharge rate over the block *k*, $a_i f(a_i) r_k$ (m^2) is the effective contributing area of the grid cell (a fraction of its drainage area), and a_{0i} (m^2) is the area of the grid cell *i*. Similar with the infiltration excess overland flow or saturation excess overland flow, ground water discharge occurs not only from the hillslope outlet but also from any grid cell in the sub-basin, ground water discharge ability D is also redefined:

$$q_{bi} = D_i tan\beta_i exp\,(-\frac{SD_i}{m}) \tag{7.3}$$

where q_{bi} is the discharge generated at the grid cell outlet, *Di* (m day^{-1}) is the groundwater discharge ability, the subscript *i* refers to the grid cell *i* and a block-average value is used for *m*, the discharge decay factor.

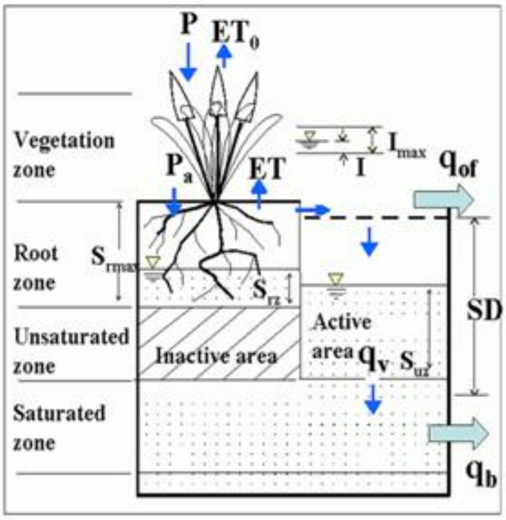


Figure 7.2. BTOPMC Runoff Generation Structure

The runoff routing is using the Muskingum-Cunge method in BTOPMC model. The vertical column includes vegetation zone, root zone, unsaturated zone and saturation zone. The runoff generation in each grid cell is shown by Figure 7.2, where P is the gross rainfall, ET_0 is the interception evaporation, I_{max} is the interception storage capacity, I is the interception state, In_{fmax} is the infiltration capacity, P_a is the net rainfall on the land surface, ET is the actual evapotranspiration, S_{rmax} is the storage capacity of the root zone, S_{rz} is the soil moisture state in root zone, *SD* is soil moisture deficit in unsaturated zone, S_{uz} is the soil moisture state in unsaturated zone, q_{of} is the overland runoff, q_{if} is the saturation excess runoff, q_v is the groundwater recharge, and q_b is groundwater release. θ_{wilt}, θ_{fc}, θ_s are soil water content at wilting point, field capacity and saturation respectively. The Shuttleworth-Wallace (S-W) model is developed for potential evapotranspiration from the interception and the soil water of root zone. The spatial resolution of grid cell is 2 minutes and the computation time step is daily.

As for model calibration and validation, coefficient of determination (R^2), percent bias (*PBIAS*) and the mean absolute error (*MAE*) are also applied to indicate the accuracy of BTOPMC model. The use of these statistics is to provide a more comprehensive evaluation of the model performance.

7.2.4. Land use/cover change prediction

The Land Change Modeler (LCM) for Ecological Sustainability available in Idrisi Andes software (Clark Labs, Worcester, MA) was used to predict future land use/cover change scenarios in this study. The LCM is a useful tool that can be used to rapidly assess gains and losses in land cover classes, land cover persistence, transitions between categories, and to make LULC change predictions. LCM uses a three-stage (change assessment, transition potential modeling and change prediction) process to model land cover change between two time periods and to predict the future land cover.

Key features of Land Change Modeler that we will use in this study are listed as following.

1) Land Change Analysis

Quickly generate graphs and maps of land change, including gains and losses, net change, persistence and specific transitions; Uncover underlying trends of complex land change with a change abstraction tool.

2) Land Transition Potential Modeling

Model land cover transition potentials that express the likelihood that land will transition in the future using one of three methodologies—a multi-layer perceptron neural network with full reporting on the explanatory power of driver variables, logistic regression, and SimWeight, a modified machine-learning procedure; Incorporate into the prediction model dynamic or static environmental variable maps that might drive or explain change.

3) Land Change Prediction

Incorporate planning interventions, incentives and constraints, such as reserve areas and infrastructural changes that may alter the course of development in the change prediction process; Conduct scenario mapping by creating either a hard prediction map based on a multi-objective land competition model with a single realization or a soft prediction map that is a continuous map of vulnerability to change; Validate the quality of the prediction land cover map in relation to a map of reality. Through a 3-way cross tabulation, hits, misses, and false alarms are reported.

In this study, setting the 2001 and 2008 land use layers as inputs, we modeled the LULC change within that time period. We computed the contribution of each of the land use classes to net change and assessed gains and losses of land use classes. In the transition potential stage, the variables that influence the transitions of interest are identified and how they influence future change is modeled. In the final stage, the relative amount of transition to a future date is calculated (Clark Labs, 2009). This was done by modeling each transition potential using a multi-layer perception (MLP) neural network. The transition potential modeling helped to determine the transition potential of each land cover class. The model was built by exploring the potential power of a set of drive variables that potentially contributed to land cover change. The land cover likelihood was a map that showed how likely a particular LULC would occur if that area experienced transition. The strength of the model was evaluated by kappa index and mean error between simulated and observed land cover map of 2011.

7.2.5. Climate change scenarios generation

According to one result from CREST project (Development of well-balanced urban water use system adapted to climate change), CCCMA47 from Canadian Centre for Climatic Modelling & Analysis and ECHAM5 from Max Planck Institute for Meteorology, Germany, were evaluated as most suitable models for our research area. As a result, we introduced these two GCM models to generate future climate change scenarios in our research. And based on scenarios for GHG emissions of IPCC, A1B is a balance scenario where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies. Then A1B is selected in this case.

While GCMs demonstrate significant skill at the continental and hemispheric spatial scales and incorporate a large proportion of the complexity of the global system, they are inherently unable to represent local subgrid-scale features and dynamics (Carter et al., 1994). The conflict between GCM coarse spatial scales and the needs of high-resolution meteorological inputs required for modelling hydrological processes could be solved by downscaling techniques. In this study, Statistical Downscaling Model (SDSM) and Automatic Statistical Downscaling model (ASD) were applied to generate high-resolution meteorological inputs required for hydrological model.

1) SDSM

SDSM (Statistical DownScaling Model) is a decision support tool for assessing local climate change impacts using a robust statistical downscaling technique. SDSM facilitates the rapid development of multiple, low-cost, single-site scenarios of daily surface weather variables under current and future regional climate forcing. Additionally, the software performs ancillary tasks of predictor variable pre-screening, model calibration, basic diagnostic testing, statistical analyses and graphing of climate data. SDSM permits the spatial downscaling of daily predictor-predictand relationships using multiple linear regression techniques. The predictor variables provide daily information concerning the large-scale state of the atmosphere, while the predictand describes conditions at the site scale. For a more detailed introduction to SDSM, see the SDSM User Guide (Wilby et al., 2004; Dawson and Wilby, 2007) for all details. The SDSM software reduces the task of statistically downscaling daily weather series into five key steps

Quality control and data transformation: Few meteorological stations have 100% complete and/or full accurate data sets. Handling of missing and imperfect data is necessary for most practical situations. Simple Quality control checks enable the identification of the gross data error, specification of missing data codes and outliers prior to model calibration.

Screening of the predictor variables: Identifying empirical relationships between gridded predictors (such as mean sea level pressure) and single site predictands (such as station precipitation) is central to all the statistical downscaling methods. The main purpose of Screen Variables operation is to assist the user in the selection of appropriate downscaling predictor variables.

Model calibration: The Calibrate Model operation takes a user-specified predictand along with a set of predictor variables, and computes the parameters of multiple regression equation.

Weather generator: The weather generator operation generates ensembles of synthetic daily weather series given observed (or NCEP re-analysis) atmospheric predictor variables. The procedure enables the verification of calibrated models (using independent data) and the synthesis of artificial time series for present climate conditions.

Scenario generations: The Scenario Generator operation produces ensembles of synthetic daily weather series given atmospheric variables supplied by a climate model.

2) ASD

The Automated Statistical Downscaling (ASD) tool is an easy to use graphical user interface for the statistical downscaling of GCM outputs to regional or local variables (Hessami et al., 2008). This tool has been developed by the team of the Canada Research Chair on the Estimation of Hydro-meteorological variables (Pr. T. Ouarda) at INRS-ÉTÉ, in collaboration with the Adaptation and Impacts Research Division (Environment Canada, i.e. Dr. Philippe Gachon). ASD runs on all platforms that support MATLAB. ASD is a hybrid of a stochastic weather generator and regression-based downscaling methods and facilitates the rapid development of multiple, low-cost, single-site scenarios of daily surface weather variables under current and future climate forcing. ASD is designed to help the user identify those large-scale climate variables (the predictors) which explain most of the variability in the climate (the predictand) at a particular site and statistical models are then built based on this information. Statistical models are built using daily observed data – local climate data for a specific location for the predictand and larger-scale NCEP data for the predictors – and these models are then used with GCM-derived predictors to obtain daily weather data at the site in question for a future time period.

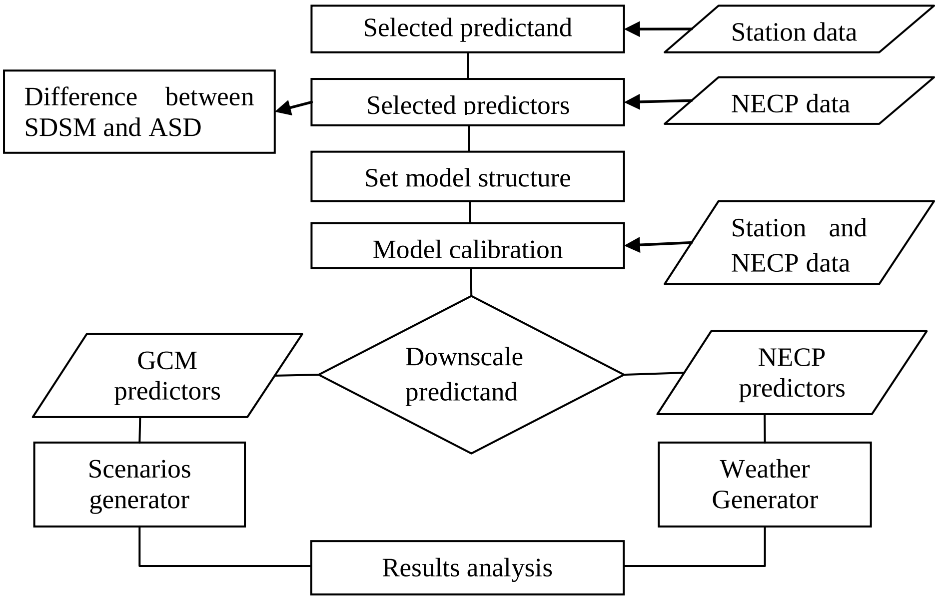


Figure 7.3. Technological process of SDSM and ASD model

ASD also needs the same five key steps with SDSM to generate future climate change scenarios. However, the difference between SDSM and ASD is methods for selection of predictors. In SDSM (Wilby et al., 2004), selection of predictors is an iterative process, partly based on the user’s subjective judgment. In the ASD tool, two automated methods based on backward stepwise regression and on partial correlation coefficients are implemented to select the predictors. Backward stepwise regression starts with all the terms in the model and removes the least significant terms until all the remaining terms are statistically significant. The partial F-test is used for either adding a predictor to the F-test equation or removing a predictor from the equation. For a more detailed introduction to the software, see the ASD Brief Introduction Document and the User Guide (Hessami et al., 2008) for all details on this model.

7.3. Results

7.3.1. Land cover change scenarios generation

In order to predict future land cover change, the historical land change was firstly investigated based on land cover map 2001 and 2008. Figure 7.4 presents that gains and losses of land cover between 2001 and 2008, which shows that croplands, forest, shrublands and grasslands changed more than others in the past. The net land cover changes between 2001 and 2008 are showed in Figure 7.5, which indicates that croplands have an obvious increase by 4%, grasslands and forest had a decrease by -1.2% and -3.0%. In addition, other kinds of land cover only have very slight changes. So gains of croplands should come from forest and grasslands losses.

Based on land cover changes above and our selected drive factors (Figure 7.6), potential land cover transition maps will be generated by multi-layer perceptron neural network method, which present land cover transition possibilities between different land cover types. For example, transition possibilities map from forest to shrublands in Figure 7.7 shows that there is a high possibility in the bottom and center of our basin and Figure 7.8 presents transition possibilities from shrublands to croplands and shows that there is a high possibility in the up part of our basin.

In order to validate the accuracy of LCM model, land cover map in 2011 obtained through neural networks is presented in Figure 7.9. The map forecasted changes, observed between 2001 and 2008, for 2011. The map obtained can be visually compared to the land cover map of the 2011 image in Figure 7.9, which shows an agreement spatial simulation.

Comparing the map obtained through neural network with the map extracted from the 2011 image, we can observe a great similitude in the areas with water, forest, croplands and urban; however, there is an overestimation (14.8%) of the areas covered by shrublands and a certain underestimation (-15%) of the areas of grasslands (Table 7.2). In addition, the high kappa index of 0.94 (Table 7.2) also indicates that simulated map has a good match with the reference map. These values reach acceptable levels that guarantee the adjustment between the calculated model and the reference map. All these facts make us assume that the neural networks may show agreement results if it is applied in creating the map of land cover by 2050.

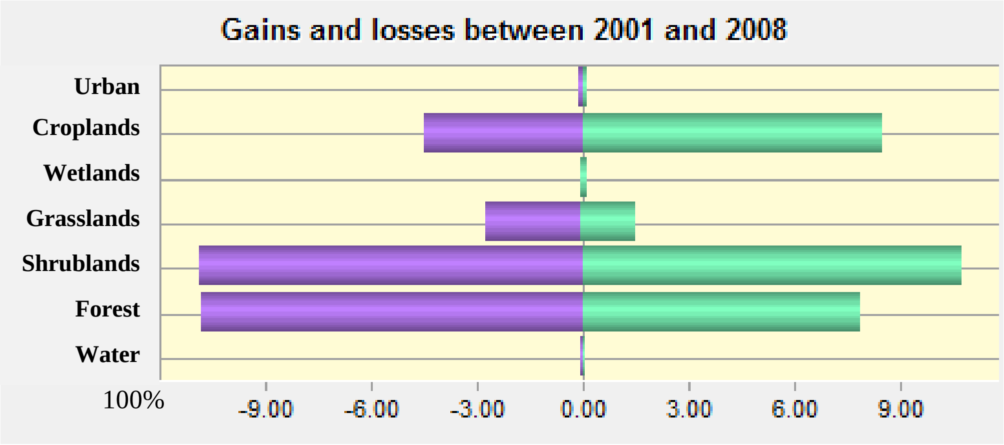


Figure 7.4. Gains and losses of land cover between 2001 and 2008

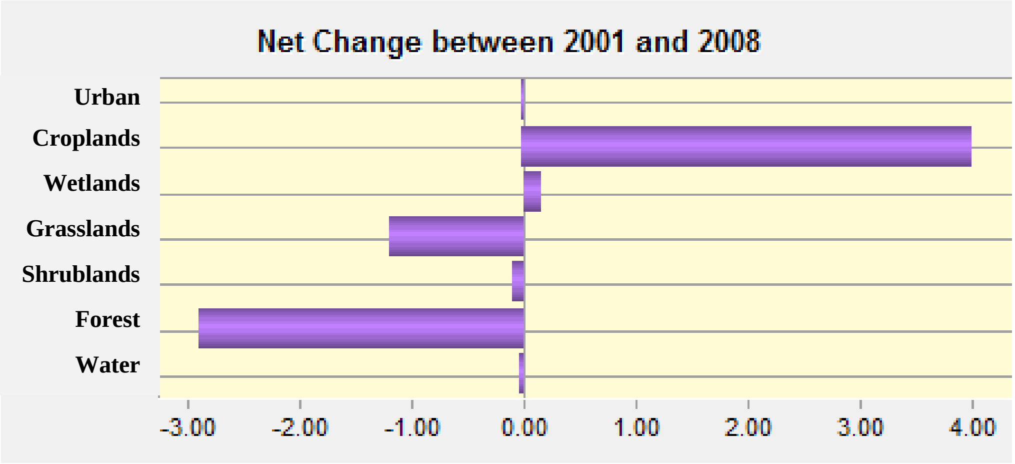
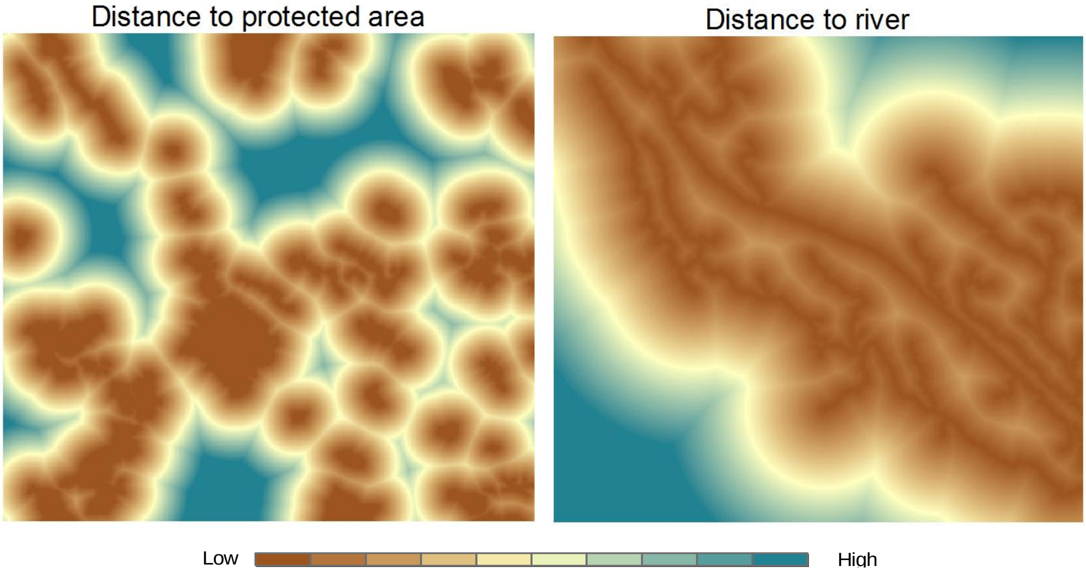


Figure 7.5. Net land cover change between 2001 and 2008



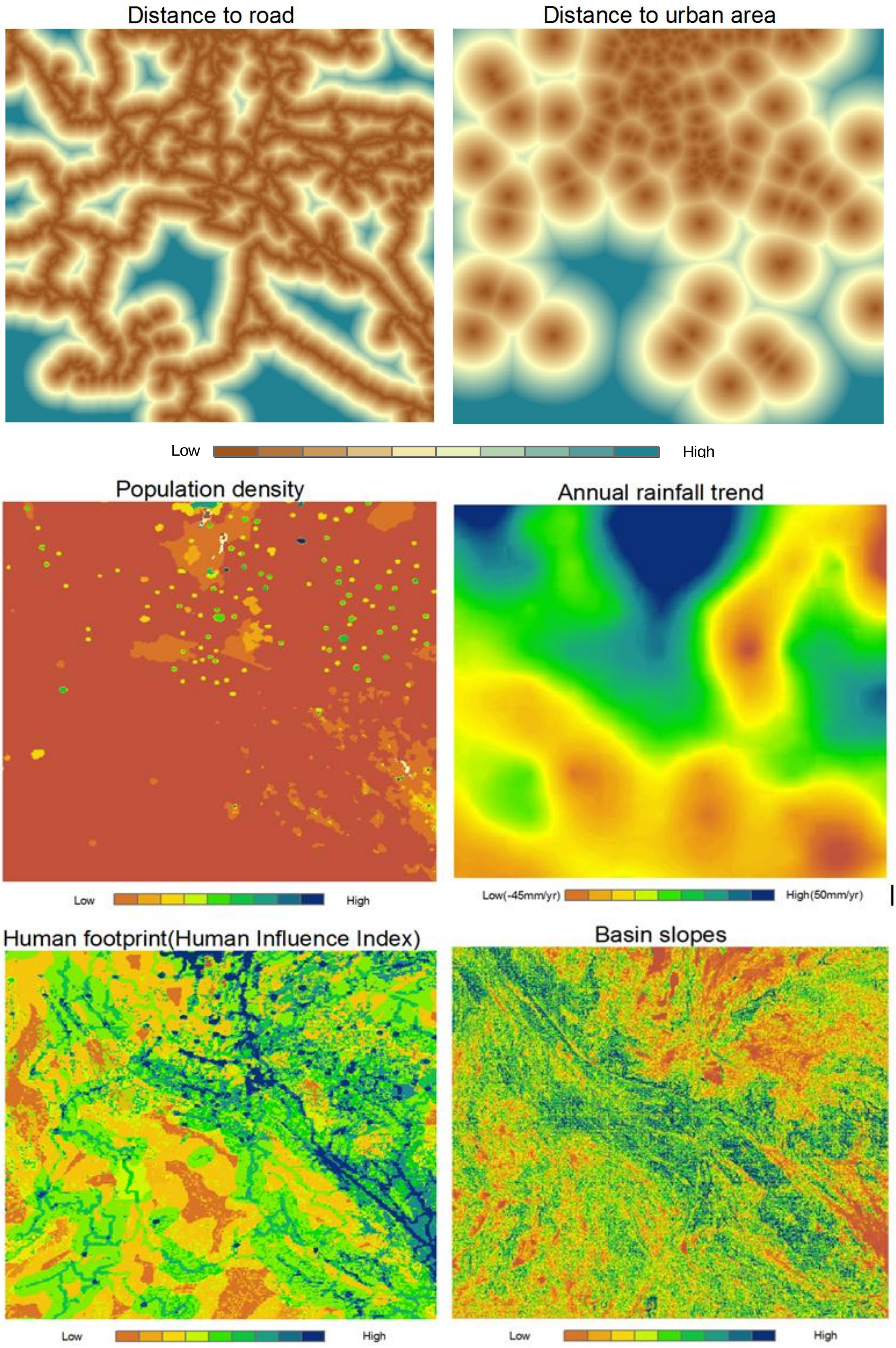


Figure 7.6. Selected drive factors for LCM

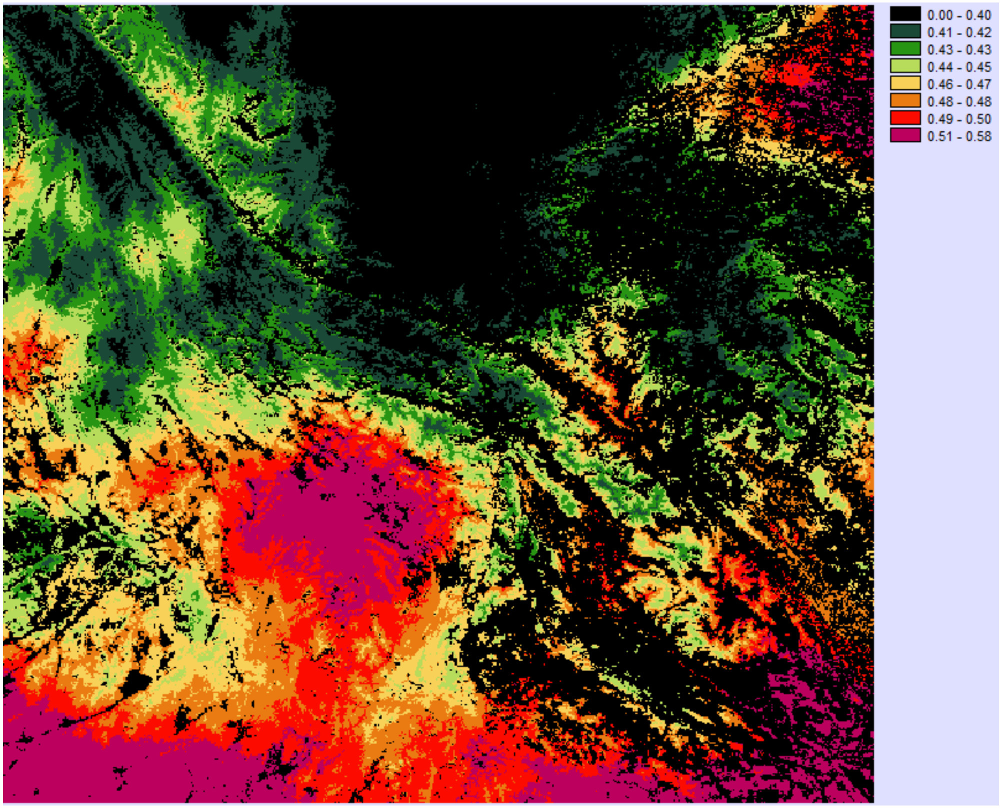


Figure 7.7. Potential map for transition from forest to shrublands

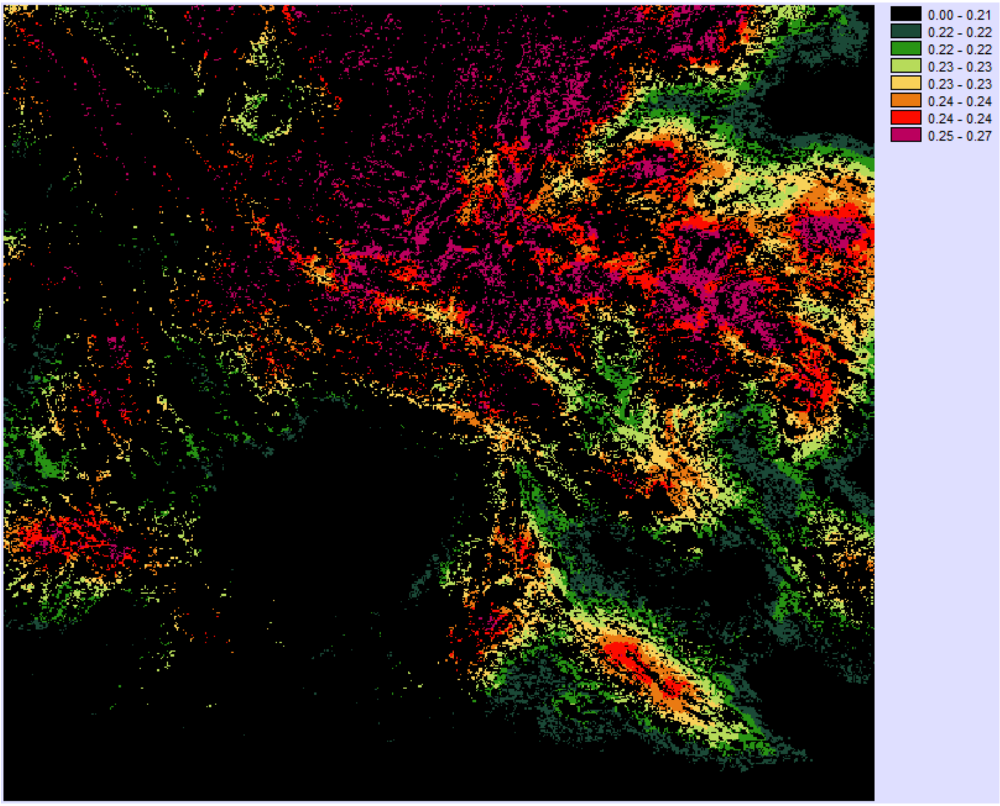


Figure 7.8. Potential map for transition from shrublands to croplands

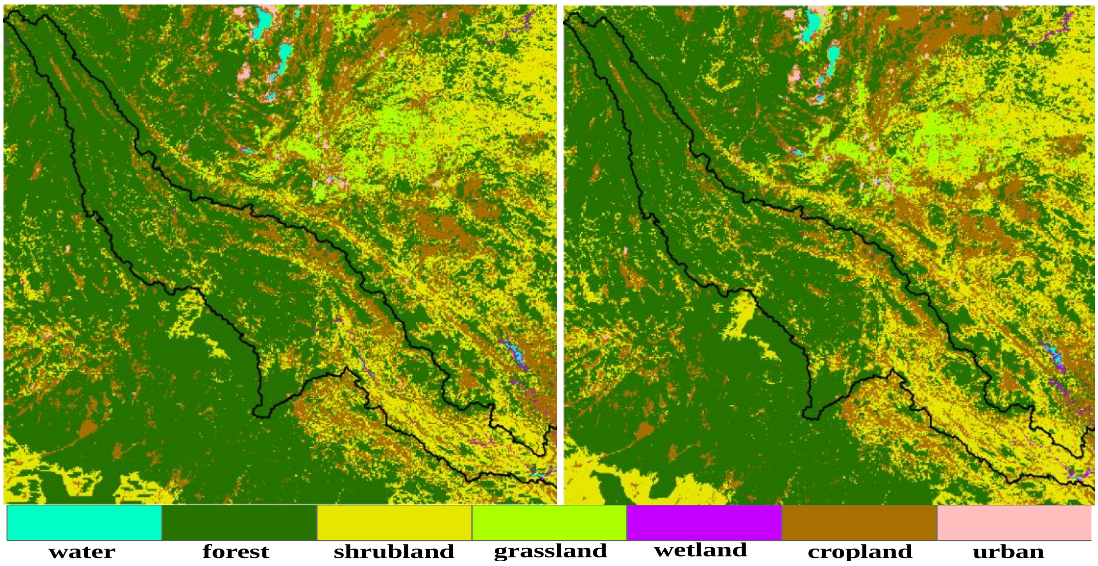


Figure 7.9. Reference (left) and simulated (right) land cover map of 2011

Table 7.2. Difference between the reference map of 2011 and the simulated map 2011

Land cover	Reference 2011(pix)	Simulated 2011(pix)	Mean error	Percent (%)	Kappa index
Water	869	842	-27	-3.1	0.94
Forest	184701	177657	-7044	-3.8	
Shrublands	60433	69411	8978	14.8	
Grasslands	10743	9126	-1617	-15.0	
Wetlands	825	896	71	8.6	
Croplands	58871	58403	-468	-0.8	
Urban	1618	1725	107	6.6	

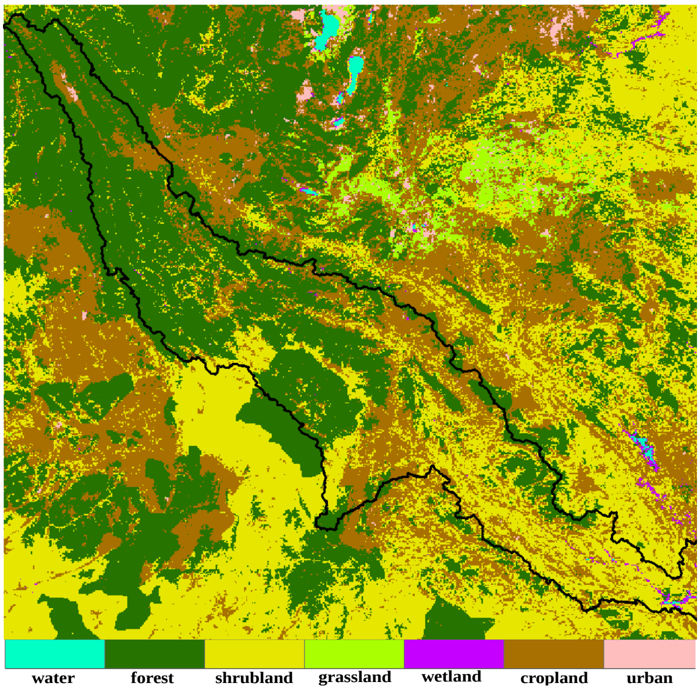


Figure 7.10. Predicted future land cover map of 2050

Table 7.3. Future land cover changes of 2050 created through neural networks compared with the baseline map of 2001 image in DRB (area percent: %)

Land cover	Baseline 2001(%)	Predicted 2050(%)	Changes (%)
Water	0.06	0.05	-0.01
Forest	70.91	49.57	**-21.34**
Shrublands	15.5	25.47	**9.97**
Grasslands	0.72	0.16	-0.56
Wetlands	0.19	0.34	0.15
Croplands	12.57	24.27	**11.7**
Urban	0.06	0.14	0.08

Finally, the scenery of land use projected for 2050 is carried out by applying neural network; it can be observed in Figure 7.10. The land cover changes between 2001 and 2050 are summarized in Table 7.3. Results indicate that forest area would have an obvious decrease of about 26% of the total area in 2050, and shrublands, croplands and urban area would have some obvious increase, especially for croplands which increased about 19% of total area.

7.3.2. Climate change scenarios generation

CCCMA47 and ECHAM5 were downscaled to station scale by SDSM and ASD respectively. Followed downscaling process of SDSM and ASD model (Figure 7.3), predictors were firstly selected for all the rainfall stations through different methods. Then statistical models between rainfall and selected predictors were calibrated and validated in the period from 1961 to 1980 and from 1981 to 2000, respectively. The range of explained variances for all rainfall stations is from 0.10 to 0.18, which shows that a reasonable result for rainfall according to acceptable range from 0.1 to 0.15 (Wilby and Wigley, 1997). At the same time, the low explained variance is very typical for precipitation and is most likely due to the fact that we have to transform the data and the resulting distribution, while normal, is not as statistically "elegant" as the temperature distribution (http://www.cccsn.ec.gc.ca/?page=faq). The explained variance of ASD model is higher than it of SDSM model for most stations, which indicate that results from ASD model may be better than SDSM model.

Finally, daily time series of future rainfall scenarios were constructed from CCCMA47 and ECHAM5 based SDSM and ASD model. Basin average monthly rainfall changes from 2046 to 2055 (2050s) compared with baseline period from 1991 to 2000 is presented in Figure 7.11. As shown in Figure 7.11, the rainfall change in different month is different, for example, rainfall of most months generated from CCCMA47 for would increase and rainfall of all the months from ECHAM5 would increase in the period of 2050s. Although the basin average annual precipitation will increase about 8% for CCCMA47 and 38% for ECHAM5 in the 2050s under A1b scenario, we still could not get the agreement increase in rainfall for considering the spatial distribution (Figure 7.12). In addition, although different downscaling models give various changes for different stations, however future rainfall for most stations show shift trend (Figure 7.12). Compared the two downscaling method, although the changing amplitude of rainfall was different, the changing trend of basin average monthly rainfall was the same.

Table 7.4. Explained variances (R^2) of rainfall stations in calibration of ASD and SDSM

Station	CCCMA47		Station	ECHAM5	
	SDSM	ASD		SDSM	ASD
Baoshan	0.162	0.166	Baoshan	0.140	0.146
Chuxiong	0.126	0.135	Chuxiong	0.11	0.1
Dali	0.174	0.18	Dali	0.163	0.172
Jiangcheng	0.143	0.153	Jiangcheng	0.120	0.136
Jiongd	0.151	0.150	Jiongd	0.140	0.143
Kunming	0.121	0.130	Kunming	0.112	0.111
Lincang	0.123	0.125	Lincang	0.145	0.149
Baoshan	0.162	0.171	Baoshan	0.11	0.115
Simao	0.11	0.12	Simao	0.10	0.11
Yuanj	0.10	0.011	Yuanj	0.10	0.11
Yuanmou	0.10	0.10	Yuanmou	0.11	0.114
Yuxi	0.11	0.11	Yuxi	0.114	0.116
Mengz	0.125	0.128	Mengz	0.157	0.167
Pingb	0.173	0.172	Pingb	0.159	0.161
Wensz	0.148	0.158	Wensz	0.143	0.146
Sinho	0.151	0.159	Sinho	0.149	0.160

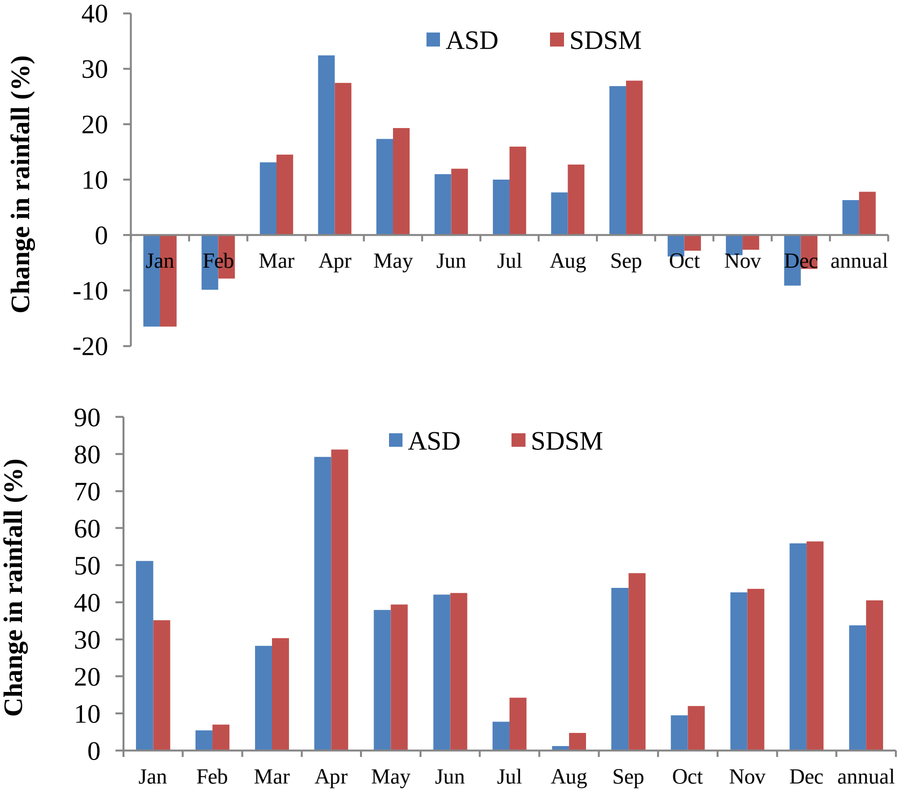


Figure 7.11. Basin average monthly rainfall changes from 2046 to 2055 compared with baseline from 1991 to 2000(up: CCCMA47 model; bottom: ECHAM5)

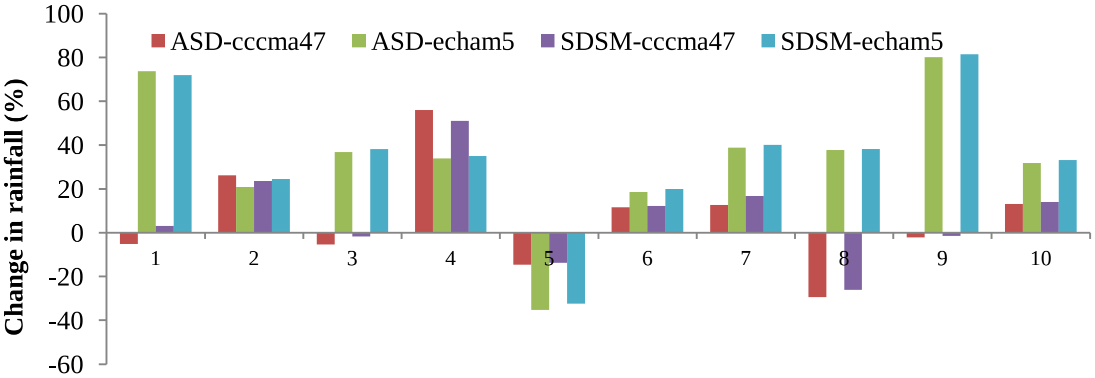


Figure 7.12. Average annual rainfall changes from 2046 to 2055 compared with baseline from 1991 to 2000 for different stations (up: CCCMA47 model; bottom: ECHAM5)

Even though results from different months, different stations, different GCM models and downscale models show some uncertainty, however the overall results indicate one increase trend for rainfall in the red river basin in the period of 2050s.

7.3.3. Future LAI prediction

In Chapter 6, Biome-BGC ecological model has already been validated as suitable for our research basin. So this model driven by future climate change and land cover scenarios is directly applied to predict future LAI in the period of 2046 to 2055. Compared future standardized LAI with current standardized NDVI, results show that future LAI would decrease especially for dry season due to deforestation.

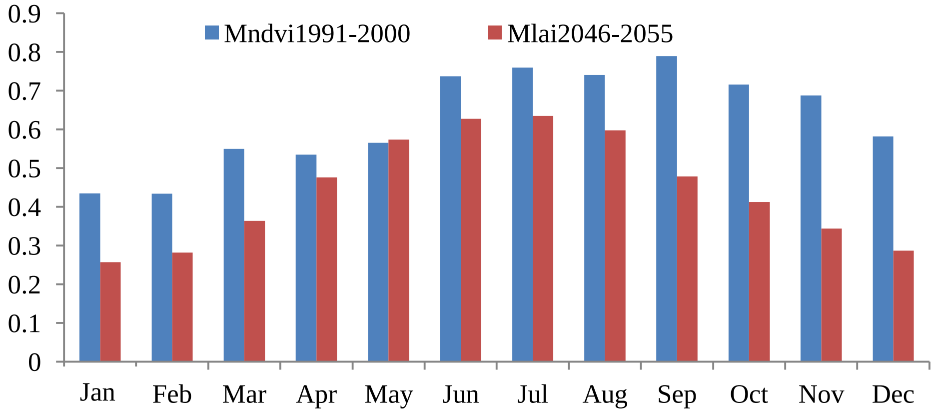


Figure 7.13. Comparison between current basin average vegetation cover ($M_{ndvi1991-2000}$) and future basin average vegetation cover ($M_{lai2046-2055}$)

7.3.4. BTOPMC model simulation (1991-2000)

As shown in Table 7.5, four statistics to evaluate the BTOPMC model mentioned above give agreement results. For example, the NSE presents better results with the value of greater than 0.60 which indicated that BTOPMC model is reasonable in this basin. In addition, from the viewpoint of comparison between the simulated and observed monthly streamflow during the baseline period, results indicate that the simulated streamflow by using BTOPMC model has a good match with the observed values, and are satisfactory at Laichau and Tabu stations, as showed in Figure 7.14. The results shown in Table 7.5 and Figure 7.14 can comprehensively explain that the BTOPMC model can predict streamflow accurately during the baseline period.

Table 7.5. Evaluation of model simulation during the baseline period for the catchments controlled by Laichau and Tabu stations in the DRB

	Laichau		Tabu	
	Calibration	Validation	Calibration	Validation
NSE	*0.75*	*0.70*	*0.70*	*0.60*
R^2	*0.83*	*0.77*	*0.76*	*0.72*
MAE(mm)	*0.74*	*0.80*	*0.77*	*0.91*
PBIAS (%)	*6.2*	*7.2*	*7.0*	*7.8*

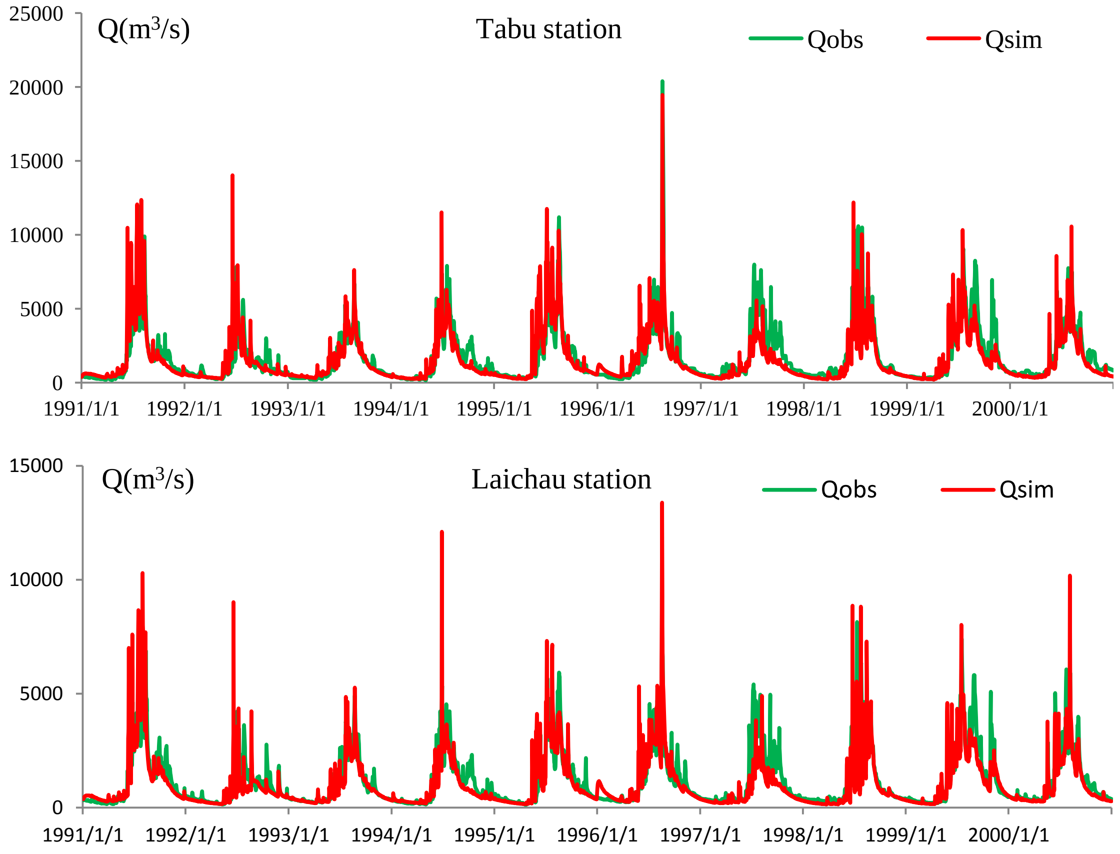


Figure 7.14. Comparison of observed and simulated daily streamflow in the DRB (calibration period: 1991-1995, validation period: 1996-2000)

7.3.5. New sediment rating curve (1991-2000)

Based on previous study, new sediment rating curve was applied in the period from 1991 to 2000. Here, we will not show the calibration and validation process since the detailed process had already been presented in Chapter 4 and Chapter 6. Finally, new sediment rating curve in this Chapter is showed as the following equation:

$$SSC = 0.41(1-M_{LAI}{}^{6.5})Q^{1.05} \qquad 6.5$$

7.3.6. Future climate change impacts on streamflow and sediment yield

Considering the uncertainties of GCMs and downscaling method, we took the average rainfall scenarios of results from two GCMs and two downscaling models, and then applied the averaged rainfall scenarios to evaluate the future rainfall impacts on streamflow and sediment yield.

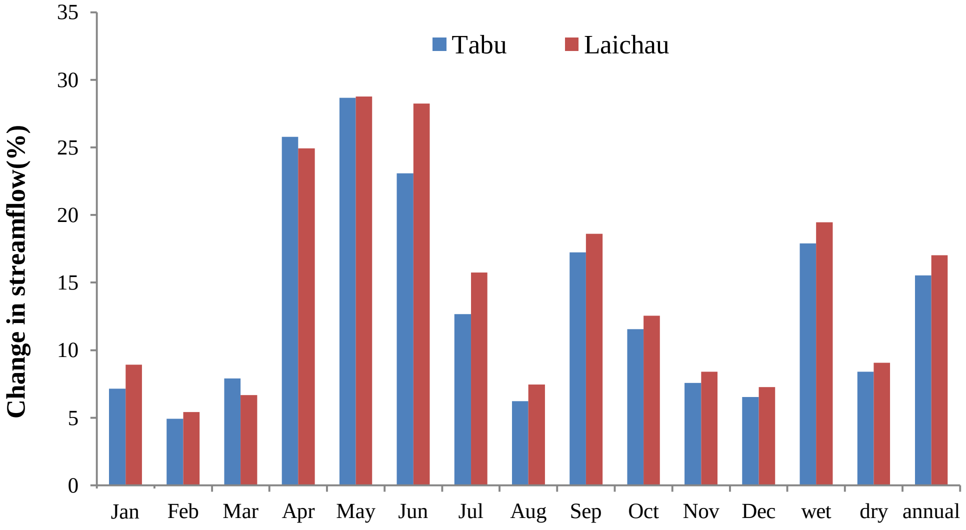


Figure 7.15. Changes in future monthly, seasonal annual streamflow under the A1B scenario for Laichau station and Tabu station

Figure 7.15 illustrates the effects of projected climate change on monthly, seasonal and annual streamflow of different stations under the A1B scenario. Compared with the baseline period, the predicted annual streamflow is expected to increase, with changes of 15.5% in the Tabu catchment (downstream), 17.1% in the Laichau catchment (upstream). Regarding seasonal change, it also shows obvious increase for both wet season and dry season even though the magnitude of change in wet season was higher than in dry season. The predicted annual streamflow change varies from 4.9% to 28.2% in different months, where it shows very high changes in April, May, June and September. Compared streamflow changes in the upstream with downstream of DRB, changes in the upstream are slightly higher due to higher rainfall increase in the up part of DRB. As for the streamflow changes under different downscaling models, the increase under SDSM model is stronger than under ASD model which indicate that uncertainties existed in different downscaling methods.

Figure 7.16 shows the effects of projected climate change on monthly, seasonal and annual sediment load under the A1B scenario. Compared with the baseline period, the predicted annual sediment load is expected to increase, with changes of 29.7% in the Laichau catchment. As for seasonal change, it also shows obvious increase for both wet season and dry season with different magnitude of change, 33.7% in wet season and 15.8% in dry season. The future annual sediment load changes varies from 9.5% to 49.5% in different months, where it also shows very high changes in the same months with sediment load. Compared sediment changes with streamflow changes, changes of sediment load are obvious higher than changes of streamflow, which indicate that sediment load is more sensitive to climate change in the future. Generally, the responses of streamflow and sediment yield to climate change occur in the same direction clearly.

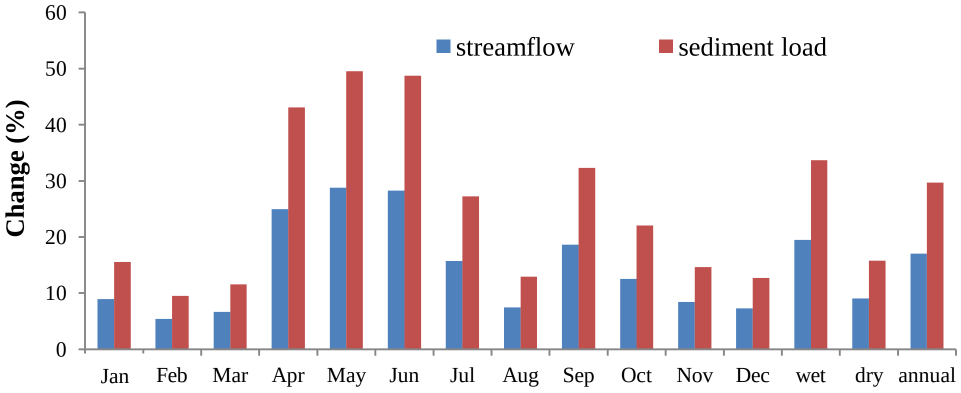


Figure 7.16. Changes in future monthly, seasonal annual streamflow and sediment load under the A1B scenario for Laichau station

7.3.7. Future land cover change impacts on streamflow and sediment yield

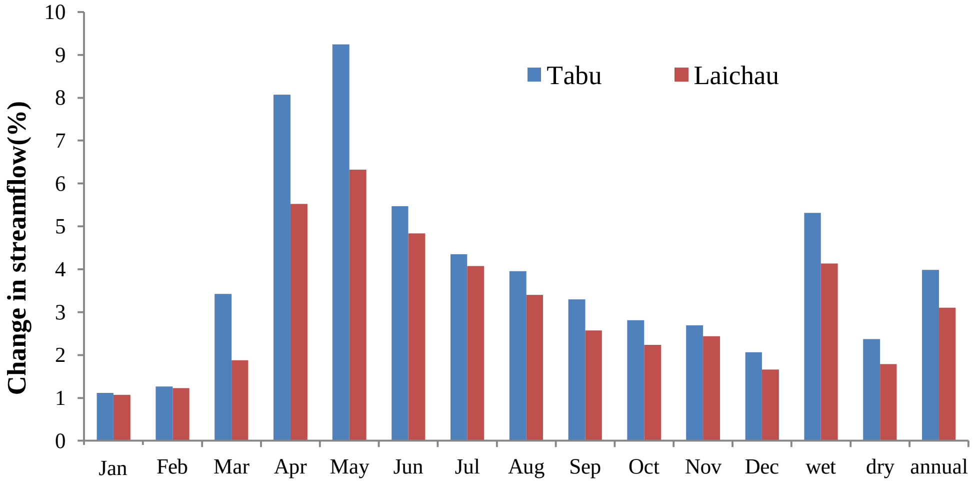


Figure 7.17. Changes in monthly, seasonal annual streamflow under land cover changes in 2050 for Laichau station and Tabu station

The land cover map in 2050 obtained by Land Change Model is applied to evaluate the future land cover change impacts on streamflow and sediment yield. Changes in monthly, seasonal annual streamflow under land cover changes in 2050 for Laichau station and Tabu station are showed in Figure 7.17. Compared with the baseline period, the predicted annual streamflow is expected to increase, with changes of 3.1% in the Laichau catchment and 4.0% in the Tabu catchment. As for seasonal change, it also shows increase for both wet season and dry season with different magnitude of change. The future annual streamflow changes vary from 1.1% to 9.5% in different months, where it also shows special high changes in April and May. Compared streamflow changes in the upstream with downstream of DRB, changes in the downstream are slightly higher than in upstream of DRB, which indicates that land cover change impacts in the downstream is stronger than in the upstream.

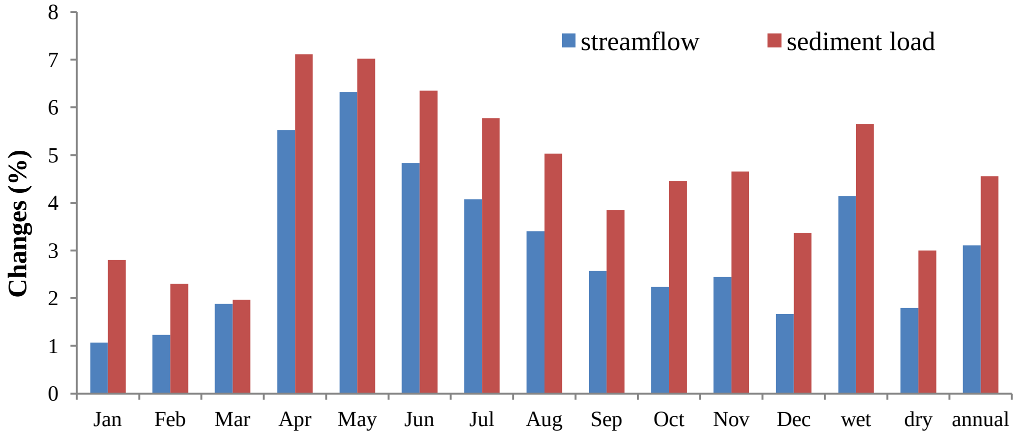


Figure 7.18. Changes in future monthly, seasonal annual streamflow and sediment load under land cover change scenario in 2050 for Laichau station

Figure 7.18 shows the effects of projected climate change on monthly, seasonal and annual sediment load under future land cover change. Compared with the baseline period, the predicted annual sediment load is expected to increase, with changes of 4.6% in the Laichau catchment. As for seasonal change, it also shows obvious increase both for wet season and for dry season with different magnitude of change, 5.7% in wet season and 3.0% in dry season. The future annual sediment load changes varies from 2.0% to 7.1% in different months, where it also shows very high changes in April, May and June. Compared sediment load changes with streamflow change, changes of sediment load are obvious higher than changes of streamflow, which indicates that sediment load is more sensitive to land cover change in the future. Generally, the responses of streamflow and sediment yield to land cover change also occur in the same direction obviously, which keep agreement with impact direction of climate change.

7.3.8. Combined impacts of future climate and land cover change impacts on streamflow and sediment yield

In order to investigate the combined impacts of land cover and climate changes, the streamflow and sediment yield under land cover change in 2050 and under the A1B climate change scenario for the 2050s period are compared to the corresponding current conditions in the baseline period (1991 to 2000). The results are presented in Figure 7.19 and 7.20.

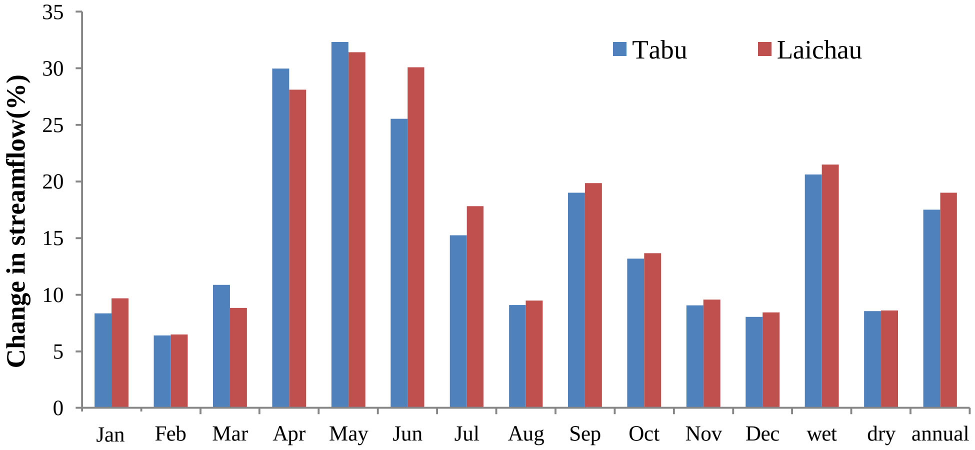


Figure 7.19. Changes in monthly, seasonal annual streamflow under land cover changes and climate changes in 2050s for Laichau station and Tabu station

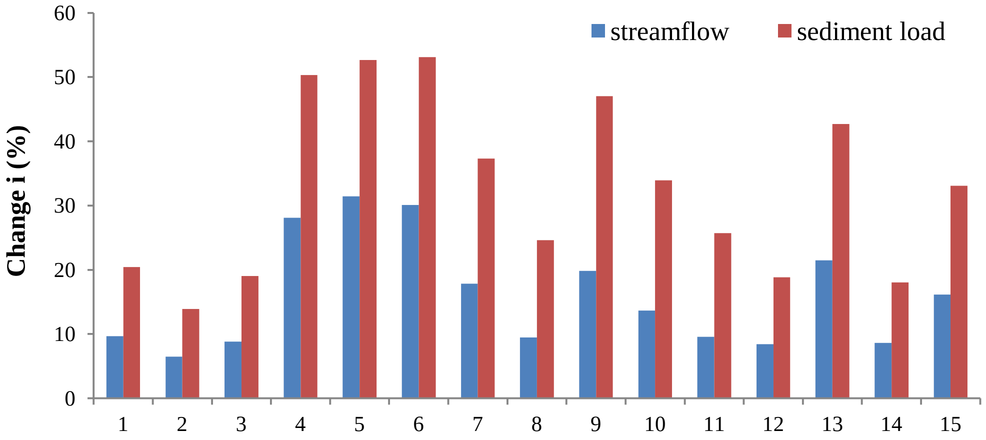


Figure 7.20. Changes in monthly, seasonal annual streamflow and sediment load under land cover changes and climate changes in 2050s for Laichau station

Changes in monthly, seasonal annual streamflow and sediment load under land cover changes and climate changes in 2050s for Laichau station and Tabu station is showed in Figure 7.19 and 7.20. The annual streamflow increases by 17.5% in Tabu catchment and 19% in Laichau catchment. And the annual sediment load increases significantly by 33% in Laichau catchment. In general, the separate impacts of climate and land cover change complement each other. Therefore, when climate and land cover changes occur concurrently, the streamflow will increase and sediment load will be intensified more seriously. In terms of monthly change, increases in streamflow (by 6.5 to 30%) and increases in sediment load (by 13 to 52%) are predicted. As for seasonal change, it shows obvious increase both for wet season and for dry season with different magnitude of change, 21% in wet season and 8% in dry season for streamflow, 42% in wet season and 18% in dry season for sediment load. Considering the upstream and downstream changes in streamflow, changes of several months in the upstream are higher than in the downstream and some months perform inversely. However, changes of wet season, dry season and annual streamflow in the upstream always higher than in the downstream.

7.4. Conclusions

The BTOPMC model was successfully applied to the Da River Basin in order to investigate the effects of climate change and land cover change on streamflow, sediment load.

In order to predict future land cover change, LCM model was successfully applied in the Da River Basin. Based on land cover changes above and our selected drive factors, the scenery of land use projected for 2050 was carried out by applying neural network. Results showed that forest area would have an obvious decrease of about 26% of the total area in 2050, and shrublands, croplands and urban area would have some obvious increase, especially for croplands which increased about 19% of total area. Compared with the baseline period, the predicted annual streamflow under land cover change in 2050 is expected to increase, with changes of 3.1% in the Laichau catchment and 4.0% in the Tabu catchment. And the predicted annual sediment load is expected to increase, with changes of 4.6% in the Laichau catchment.

To generate future climate change scenarios, ASD and SDSM downscaling models were applied to downscale the GCMs output to station scale. The explained variance of ASD model was higher than it of SDSM model for most stations, which indicated that results from ASD model may be better than SDSM model. Compared the two downscaling method, although the changing amplitude of rainfall was different, the increasing trend of basin average monthly rainfall was the same. Even though results from different months, different stations, different GCM models and downscale models showed some uncertainty, however the overall results indicated one increase trend for rainfall in the Da River Basin in the period of 2050s. Climate change under A1B scenario in 2050s in the DRB leads to increase streamflow and sediment load. The future annual streamflow is expected to increase, with changes of 15.5% in the downstream, 17.1% in the upstream compared with the baseline period. And the predicted annual sediment load is expected to increase, with changes of 29.7% in the Laichau catchment.

Analyses of the combined impacts of climate and land cover change indicate that the impacts of climate change and land cover change on streamflow, sediment yield, were also carried out. The annual streamflow increases by 17.5% in Tabu catchment and 19% in Laichau catchment. And the annual sediment load increases significantly by 33% in Laichau catchment. In general, the separate impacts of climate and land cover change complement each other.

Generally, the streamflow and sediment yield will increase in 2050s in both wet season and dry season under future climate change and land cover change. Streamflow change in wet season is higher than in dry season, which indicated that flood would become more severe. In addition, sediment load increase in 2050s in wet season emphasize the importance of building adaptation to climate and land cover changes to avoid soil erosion in the wet season. The results obtained in this study could be useful for managing water resources and ecological protection in this region by enhancing the understanding of the impact of various climate and land cover change scenarios on streamflow and sediment yield.

CHAPTER Ⅷ

SUMMARY OF THE STUDY

8.1. Conclusions

In this thesis, a comprehensive framework was developed for quantitative assessment of environmental changes on both historical and future streamflow and sediment flow, which was successfully applied in Da River Basin. In addition, this study is expected to provide information that decision-makers need for appropriate utilization of water resources, flood control, soil conservation and ecological protection. Besides that, this framework will also provide guidance for other potential applications the other basins around the world. The main conclusions of this thesis are as following:

1) New sediment rating curve considering vegetation cover change information in sediment simulation was developed for several Asian Basins. The Normalized Difference Vegetation Index (NDVI) can well be used to analyze the status of the vegetation coverage well. Thus Long time monthly NDVI data was used to detect vegetation change in the past 19 years in this study. And monthly suspended sediment concentration and discharge from 1988 to 2006 in Laichau station were used to develop and interpret one new sediment rating curve. Results showed that vegetation cover (NDVI) can improve the sediment rating curve. Among the three new sediment rating curves, the third one was the better sediment rating curve for our research basin. And the new sediment rating curve can simulate better in three selected Asian basins, but for different scale basin, vegetation cover (NDVI) improved the sediment rating curve differently. In addition, new sediment rating curve could simulate better than SWAT model in Da River Basin. The most point of this new equation is not only to improve the common sediment rating curve, but to describe the relationship among vegetation cover, runoff and sediment load, which can be the basis for soil conservation and sustainable ecosystem management.

2) Quantifying the contribution of climate change and human activities on the change of historical streamflow and sediment flow was carried out, which can provide a scientific basis for future land conservation and river ecological conservation. An upward trend has been found for annual streamflow into Hoa Binh reservoir, with an abrupt change identified in 1993. SWAT model simulation method was sucessfully applied to separate different effects from climate change and human activities. Based on new sediment rating curve, one well fitted curve between sediment and runoff was introduced to simulate the suspend sediment. Effect of human activities on streamflow accounted for about 60% both in Laichau and Tabu catchments which is higher than effect of climate change. And human activities contribution rate on sediment increase

was also stronger than climate change. In addition, vegetation change was the main human activities, which was more sensitive to sediment yield than streamflow. Summarily, human activities are the main factor to affect the changes of streamflow and sediment flow into the Hoa Binh Reservoir.

3) One new approach to quantify of human-induced vegetation cover change impact on sediment load was proposed and successfully applied in the Da River Basin. The NDVI and potential LAI from ecological model were investigated and effect of human-induced vegetation cover change on the increase of sediment flow into HoaBinh dam was estimated in DRB. Main conclusions are as follows. Firstly, Biome-BGC model was successfully applied in our river basin, and then potential LAI from the model was used to explain the vegetation cover without human activities. Results presented an obvious downward trend of NDVI and upward trend of potential LAI. Secondly, one new sediment rating curve considering changes of vegetation cover was used to estimate sediment loads from the streamflow and vegetation cover. Thirdly, vegetation cover changed stronger in the dry season than wet season whereas sediment load changed more in the wet season, which implied that changes of vegetation cover are more sensitive to wet season. Effect of human-induced vegetation cover changed 13.7% of sediment load in the Laichau station. In conclusion, the new method presented to quantify of human-induced vegetation cover change impact on sediment load may provide guidance for future similar studies. In addition, evaluation of human-induced vegetation cover effect on sediment load is critically important in directing efforts in managing land use, in improving agricultural practices, and in protecting soil erosion in the Da River.

4) Future streamflow and sediment yield changes under different future climate change scenarios and potential future land cover change scenarios were evaluated in this step. Future scenario of land cover change was developed based on historical land cover changes and land change model (LCM). At the same time, climate change scenarios were built based on downscaling outputs of GCMs from the IPCC Fourth Assessment Report (2007). And future leaf area index (LAI) was predicted by ecological model (Biome-BGC model) based on future land cover scenario. Then future scenarios of land cover change, climate change and LAI are used to drive hydrological model and new sediment rating curve. Results showed that the streamflow and sediment yield will increase in 2050s in both wet season and dry season under future climate change and land cover change. Streamflow change in wet season is higher than in dry season, which indicated that flood would become more severe. In addition, sediment load increase in 2050s in wet season emphasize the importance of building adaptation to climate and land cover changes to avoid soil erosion in the wet season. The results obtained in this study could be useful for managing water resources and ecological protection in this region by enhancing the

understanding of the impact of various climate and land cover change scenarios on streamflow and sediment yield.

The results of this research provide information that decision-makers need in order to promote water resources planning efforts. Besides that, this study also contributes a basic framework for assessing climate change impacts on streamflow and sediment yield that can be applied in the other basins around the world.

8.2. Contributions

1) New sediment rating curve considering vegetation cover change was developed for some Asian basins, which showed better results than common rating curve. The important point of this new sediment rating curve is not only to improve the common sediment rating curve, but describe the relationship among vegetation cover, runoff and sediment load.

2) One new approach to quantify of human-induced vegetation cover change impact on sediment load was firstly proposed and successfully applied in the Da River Basin. This method solved out the limitation of traditional model simulation method and improved it.

3) A comprehensive framework was developed for quantitative assessment of environmental changes on both historical and future streamflow and sediment flow. In this framework, we firstly developed the ‘fixed-changing’ approach to separate the effects of historical climate change, land use/cover change and other human activities on historical streamflow and sediment yield. Based on historical changes, we further evaluated future potential land cover change and climate change impacts on streamflow and sediment yield. This framework was successfully applied in Da River Basin, which is expected to provide information that decision-makers need for appropriate utilization of water resources, flood control, soil conservation and ecological protection. In addition, this framework will also provide guidance for other potential applications the other basins around the world.

8.3. Recommendations for future research

From the present study, a comprehensive framework was developed for quantitative assessment of environmental changes on both historical and future streamflow and sediment flow. However, some limitations are also existed. Consequently, followings are recommended for further research:

1) One limitation in this study is the unavailability of many kinds of data. Due to the lack of sediment load data, the sediment simulation is calibrated and validated at a

monthly time step, whereas hydrological modeling is better to be calibrated and validated at a daily time step. In addition, the few number of rainfall gauges also contributes to decreased accuracy of the simulation. Therefore, in order to improve the simulated results, more rainfall data and daily sediment load data should be prepared in the future work in order to improve model performance in simulations of streamflow and sediment yield.

2) It is necessary to make new sediment rating curve more generalization. The new sediment rating curve considering vegetation cover change was developed in this study for several Asian Basins, which could describe the relationship among sediment yield, streamflow and vegetation cover. But it is still not clear of its performance in other basins worldwide, so more target basins should be selected to validate this new sediment rating curve and check the range of the parameters. In addition, many factors could affect sediment yield, but we only consider vegetation cover in this case. In order to make this new sediment rating curve more generalization, many other factors should be taken into account. So field experiment is necessary to define the meaning of the parameters for future research.

3) In this study, we only used two GCMs to generate future scenarios, which maybe exists uncertainties in climate change scenarios. As for our future research, more GCMs should be evaluated and generated ensemble future scenarios to evaluate future climate change impacts. Moreover, we only considered rainfall scenarios in this study. Then more meteorological scenarios should be considered in the future research.

4) A comprehensive framework was developed for quantitative assessment of environmental changes on both historical and future streamflow and sediment flow. However, it is only applied in Da River Basin; as a result, we could not claim that this framework could work for all the basins in the world. It is necessary to further validate this framework in other basins in the future research. Another research challenge is how to apply this framework to evaluate other water quality factors, such as total nitrogen and water temperature.

REFERENCES

Ao, T, Yoshitani J, Takeuchi K, Fukami K, Mutsuura T, Ishidaira H. 2003a. Effects of sub-basin scale on runoff simulation in distributed hydrological model: BTOPMC. Weather Radar Information and Distributed Hydrological Modeling. IAHS Publ. 282: 227–234.

Ao T, Takeuchi T, Ishidaira H, Yoshitani J, Fukami K, Matsuura T. 2003b. Development and application of a new algorithm for automated pits removal for grid DEMs. Hydrological Sciences Journal 48(6): 985–997.

Alcamo J, Schaldach R, Koch J, Kölking C, Lapola D, Priess J. 2011. Evaluation of an integrated land use change model including a scenario analysis of land use change for continental Africa. Environmental Modelling and Software 26: 1017-1027

Arnell NW. 1999. The effect of climate change on hydrological regimes in Europe: a continental perspective. Global Environment Change 9: 5–23.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large Area Hydrologic Modeling and Assessment Part I: Model Development. Journal of the American Water Resources Association 34: 73-89.

Aspinall R. 2004. Modeling land use change with generalized linear models – a multi-model analysis of change between 1860 and 2000 in Gallatin Valley, Montana. Journal of Environment Management 72: 91–103.

Asselman NEM. 2000. Fitting and interpretation of sediment rating curves. Journal of Hydrology 234: 228–248.

Azucena PV, Mas JF, Arika LZ. 2011. Comparing two approaches to land use/cover change modeling and their implications for the assessment of biodiversity loss in a deciduous tropical forest, Environmental Modelling & Software 29(1): 11-23, doi: 10.1016/j.evsoft.2011.09.011.

Bastola S, Murphy C, Sweeney J. 2011. The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. Advances in Water Resources 34(5): 562-576, doi:10.1016/j.advwatres.2011.01.008.

Bauwens A, Sohier C, Degré A. 2011. Hydrological response to climate change in the Lesse and the Vesdre catchments: contribution of a physically based model (Wallonia Belgium). Hydrology and Earth System Sciences 15: 1745-1756.

Beck MB, Jakeman AJ, McAleer MJ. 1995. Construction and evaluation of models of environmental systems. In: Beck, M.B., McAleer, M.J. (Eds.), Modelling Change in Environmental Systems. John Wiley and Sons, pp. 3-35.

Binnie & Partners, Snowy Mountains Engineering Corporation Ltd, AACM International Ply Ltd, Delft Hydraulics, 1995, Red River Delta Master Plan – Vol 1 and Vol 2 - The present situation (VIE/89/034). Ministry of Science, Technology and Environment, Hanoi, Vietnam

Box EO, Holben BN. 1990. Nations Environment Programme. China Conservation Strategy, UNEP & China Environmental Science Press, Beijing, China.

Brad HM, Nathan HS, Robert BM, Richard TB, Allen MS, Connie AB. 2008. A multi-model framework for simulating wildlife population response to land-use and climate change, Ecological Modelling 219(1–2): 77-91, doi: 10.1016/j.ecolmodel.2008.08.001.

Buyantuyev A, Wu J. 2009. Urbanization alters spatiotemporal patterns of ecosystem primary production: a case study of the Phoenix metropolitan region, USA. Journal of Arid Environment 73(4–5):512–520.

Carter TR, Parry ML, Harasawa H, Nishioka S. 1994: IPCC technical guidelines for assessing climate change impacts and adaptions. IPCC special report to Working Group II of IPCC. London: University College London, and Tsukuba, Japan: Centre for Global Environmental Research.

Caya D, Laprise R. 1999. A semi-implicit semi-lagrangian regional climate model: the Canadian RCM. Monthly Weather Review 127: 341–362.

Chang H, Knight CG, Staneva MP, Kostov D. 2002. Water resource impacts of climate change in southwestern Bulgaria. GeoJournal 57: 159–168

Chaudhry GP, Saroha BS, Yadav M. 2008. Human Induced Land Use/Land Cover Changes in Northern Part of Gurgaon District, Haryana, India: Natural Resources Census Concept. Journal of Human Ecology 23(3): 243-52.

Chen J, Brissette FP, Leconte R. 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. Journal of Hydrology 401(3): 190-202.

Chen JF, Li XB, Zhang M. 2005. Simulating the impacts of climate variation and land-cover changes on basin hydrology: a case study of the Suomo basin. Science of. China Ser. D: Earth Science 48 (9): 1501–1509.

Chen Y, Lee SYM, Huang CR. 2009. PolyUHK: A Robust Information Extraction System for Web Personal Names. In 2nd Web People Search Evaluation Workshop (WePS 2009), 18th WWW Conference.

Chien HC, Yeh PJF, Knouft JH. 2013. Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. Journal of Hydrology 491: 73-88, 10.1016/j.jhydrol.2013.03.026.

Chomitz KM, Kumari K. 1998. The domestic benefits of tropical forests: a critical review. The World Bank Research Observe 13: 13–35.

Chow, V.T., Maidment, D.R., Mays, L.W. (Eds.), 1998. Applied Hydrology. McGrawHill, New York, USA.

Clark Labs. 2009. The Land Change Modeler for Ecological Sustainability. IDRISI Focus Paper. Clark University, Worcester, MA.

Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins Rivers, Southeastern Amazonia. Journal of Hydrology, 283(1-4): 206-217.

Crawford CG. 1996. Estimating mean constituent loads in rivers by the rating curve and flow duration rating-curve methods. PhD dissertation, Indiana University: Bloomington. URL: http://books.google.co.jp/books?id=KoFQOAAACAAJ.

Cunge JA. 1969. On the subject of a flood propagation method (Muskingum method). Journal of Hydraulics Research, 7 (2): 205–230

Dang AT. 2000. The Red River Delta – The Cradle of the Nation. Hanoi National University Publisher, Hanoi.

Dang TH, Coynel A, Orange D, Blanc G, Etcheber H, Le LA. 2010. Long-term monitoring (1960-2008) of the river-sediment transport in the Red River Watershed (Vietnam): temporal variability and dam-reservoir impact. The Science of Total Environment 408(20): 4654-4664.

David T, Clarence L. 2001. Human-caused environmental change: Impacts on plant diversity and evolution. Proceedings of the National Academy of Sciences of the United States of America 98(10): 5433–5440.

Dawson CW, Wilby RL. 2007. Statistical Downscaling Model SDSM, version 4.1. Department of Geography, Lancaster University, UK.

De VA, Klavers HC. 1994. Riverine fluxes of pollutants: monitoring strategy first, calculation methods second. European Journal of Water Pollution Control 4: 12–17.

Dunne JA, Saleska SR, Fischer ML, Harte J. 2004. Integrating experimental and gradient methods in ecological climate change research. Ecology 85(4): 904–916

Evans J, Geerken R. 2004. Discrimination between climate and human-induced dryland degradation. Journal of Arid Environment 57(4):535–554.

Fan L, Gao Y, Brück H, Bernhofer C. 2009. Investigating the relationship between NDVI and LAI in semi-arid grassland in Inner Mongolia using in-situ measurements, Theoretical and applied climatology 95(1-2): 151-156.

FAO. 1995. Digital Soil Map of the World and Derived Soil Properties. Food and Agriculture Organization of the United Nation, Rome.

Ficklin DL, Luo Y, Luedeling E, Zhang M. 2009. Climate Change sensitivity assessment of a highly agricultural watershed using SWAT. Journal of Hydrology, 374(1-2): 16-29.

Fitzjarrald DR, Acevedo OC, Moore KE. 2001. Climatic consequences of leaf presence in the eastern United States. Journal of Climate 14: 598–614.

Follador FM, Villa N, Paegelow M, Renno F, Bruno R. 2008. Tropical deforestation modelling: comparative analysis of different predictive approaches. The case study of Peten, Guatemala. Modelling Environmental Dynamics, 77-107. doi:10.1007/978-3-540-68498-5_3.

Forest Science Institute of Vietnam (FSIV). 2009. Vietnam Forestry Outlook Study, Asia-Pacific Forestry Sector Outlook Study II. Working paper series.

Gallimore R, Jacob R, Kutzbach J. 2005. Coupled atmosphere-ocean-vegetation simulations for modern and mid Holocene climates: Role of extratropical vegetation cover feedbacks. Climate Dynamic 25, doi: 10.1007/s00382-005-0054-z.

Gao P, Geissen V, Ritsema CJ, Mu, X M, Wang F. 2013. Impact of climate change and anthropogenic activities on stream flow and sediment discharge in the Wei River basin, China. Hydrology and Earth System 17: 961-972, doi: 10.5194/hess-17-961-2013, 2013.

García-Ruiz, JM, Regüés D, Alvera B., Lana-Renault N, Serrano-Muela P, Nadal-Romero E, Navas A, Latron J, Martí-Bono C, Arnáez J. 2008. Flood generation and sediment transport in experimental catchments affected by land use changes in the Central Pyrenees. Journal of Hydrology 356: 245-260.

Gergov G. 1996. Suspended Sediment Load of Bulgarian Rivers. Geojournal, Kluwer Acad. Publisher 40(4): 387-396.

Geerken R, Ilaiwi M. 2004. Assessment of rangeland degradation and development of a strategy for rehabilitation. Remote Sensing of Environment 90:490–504.

Githui F, Gitau W, Mutua F, Bauwens W. 2009. Climate change impact on SWAT simulated streamflow in western Kenya. International Journal of Climatology 29: 1823-1834. DOI:10.1002/ioc.1828.

Goldblum D, Rigg LS. 2005. Tree growth response to climate change at the deciduous–boreal forest ecotone, Ontario, Canada. Can. Journal of Forest Research 35: 2709–2718.

Guan DJ, Li HF, Inohae T, Su WC, Tadashi N, Kazunori H. 2011. Modeling urban land use change by the integration of cellular automaton and Markov model, Ecological Modelling 222(20–22): 3761-3772.

He DM., Wu SH., Peng H, Yang ZF., Ou XK, Cui BS. 2005. A study of ecosystem changes in Longitudinal Range-Gorge Region and transboundary eco-security in southwest China. Advances in Earth Science 20(3): 338-344.

Hessami M, Gachon P, Ouarda T, St-Hilaire A. 2008: Automated regression-based Statistical Downscaling Tool. Environmental Modelling & Software 23: 813-834.

Hewlett JD, Lull HW, Reinhart KG. 1969. In defense of experimental watersheds. Water Resources Research 5(1): 306-316.

Hickin, Edward J. 1989. Contemporary Squamish River sediment flux to Howe Sound, British Columbia. Canadian Journal of Earth Sciences 26(10): 1953-1963.

Horowitz AJ, Elrick KA, Smith JJ. 2001. Estimating suspended sediment and trace element fluxes in large river basins: methodological considerations as applied to the NASQAN programme. Hydrological Processes 15: 1107–1132.

Horowitz AJ. 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. Hydrological Processes 17: 3387–3409.

Howe A, Rodriguez J, MacFarlane G. 2005. Vegetation Sediment Flow Interactions in Estuarine Wetlands. In Zerger, A. and Argent, R.M. (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, pp. 332-338. ISBN: 0-9758400-2-9.

Hu Y, Maskey S, Uhlenbrook S. 2012. Downscaling daily precipitation over the Yellow River source region in China: a comparison of three statistical downscaling methods, Theoretical and Applied Climatology 112(3-4): 447-460, Online ISSN: 1434-4483, doi: 10.1007/s00704-012-0745-4, 2012.

Ichii, K, Hashimoto H, Nemani R, White M. 2005. Modeling the interannual variability and trends in gross and net primary productivity of tropical forests from 1982 to 1999, Global and Planetary Change 48: 274-286.

IPCC. 2007. The Physical Science Basin: Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ishidaira H, Takeuchi K, Ao T. 2000. Hydrological simulation of large river basins in Southeast Asia. Proceedings Fresh Perspectives on Hydrology and Water Resources in

Southeast Asia and the Pacific, Christ Church, 21–24 November 2000, IHP-V Technical Document in Hydrology 7: 53–54.

Jakeman, AJ, Hornberger GM. 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research 29(8), 2637–2649.

Joseph A, Rüdiger S, Jennifer K, Christina K, David L, Jörg P. 2011. Evaluation of an integrated land use change model including a scenario analysis of land use change for continental Africa, Environmental Modelling & Software 26(8): 1017-1027, doi: 10.1016/j.envsoft.2011.03.002.

Kaufmann RK, Myneri RB, Tucker CJ, Slayback D, Shabanov NV, Pinzon J. 2003. The effect of vegetation on surface temperature: A statistical analysis of NDVI and climate data. Geophysical Research Letters 30(22): 2147, doi: 10.1029/2003GL018251.

Khiem ND, van der PP. 1993. Land Use in the Song Da Watershed. Hanoi: Vietnam-German Technical Cooperation in Social Forestry Development Project.

Khoi DN, Suetsugi T. 2012. The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. Hydrological Processes. doi: 10.1002/hyp.9620

Kim OS. 2010a. An assessment of deforestation models for reducing emissions from deforestation and forest degradation (REDD). Transactions In Gis 14: 631–654.

Kim OS. 2010b. Comparison of Two GIS-based Land Change Modules for Constructing REDD Baselines in Bolivia. AAG Annual Meeting, Washington, DC.

Le TQ, Garnier J, Gilles B, Sylvain T, Van MC. 2007. The changing flow regime and sediment load of the Red River, VietNam. Journal of Hydrology 334(1-2): 199-214.

Leh M, Bajwa S, Chaubey I. 2011. Impact of land use change on erosion risk: an integrated remote sensing, geographic information system and modeling methodology. Land Degradation & Development. Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ldr.1137

Levis S. Bonan GB, Bonfils C. 2004. Soil feedback drives the mid-Holocene North African monsoon northward in fully coupled CCSM2 simulations with a dynamic vegetation model. Climate Dynamic 23: 791–802.

Li A, Wu JG, Huang JH. 2012. Distinguishing between human-induced and climate-driven vegetation changes: a critical application of RESTREND in inner Mongolia. Landscape ecology 27(7): 969-982.

Li H, Zhang Y, Vaze J, Wang B. 2012. Separating effects of vegetation change and climate variability using hydrological modeling and sensitivity-based approaches. Journal of Hydrology 420-421(14): 403-418.

Li LJ, Jiang DJ, Li JY. 2007. A summary and perspective of forest vegetation impacts on water yield. Journal of Natural Resources 22(2): 211–224 (in Chinese).

Li LJ, Zhang L, Wang H, Wang J, Yang JW, Jiang DJ, Li JY, Qin DY. 2007. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. Hydrological Processes 21(25): 3485-3491.

Li Y, Chen BM, Wang Z, Peng, S. 2011. Effects of temperature change on water discharge, and sediment and nutrient loading in the lower Pearl River basin based on SWAT modeling. Hydrological Sciences Journal 56(1): 68-83.

Li Z, Liu W, Zhang X, Zheng FL. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. Journal of Hydrology 377: 35–42, doi:10.1016/j.jhydrol.2009.08.007.

Lin YP, Hong NM, Wu PJ, Lin CJ. 2007. Modeling and assessing land-use and hydrological processes to future land-use and climate change scenarios in watershed land-use planning. Environmental Geology 53: 623–634.

Liu Z, Notaro M, Kutzbach J, Liu N. 2006. Assessing global vegetation–climate feedbacks from observations. Journal of Climate 19: 787–814.

Lu XX. 2005. Spatial variability and temporal change of water discharge and sediment flux in the lower Jinsha tributary: impact of environmental changes, River Research and Applications 21: 229–243.

Ma ZG. 2005. Historical regular patterns of the discharge in the Yellow River and the cause of their formation. Chinese Journal of Geophysics 48(6): 1270–1275 (in Chinese).

María JM, Ramón B, Luis J, Raquel P. 2007. Effect of vegetal cover on runoff and soil erosion under light intensity events. Rainfall simulation over USLE, Science of The Total Environment 378:161-165.

McPherson RA, Stensrud DJ, Crawford KC. 2004. The impact of Oklahoma’s winter wheat belt on the mesoscale environment. Monthly Weather Review 132: 405–421.

McRae BH, Dickson BG, Keitt TH, Shah VB. 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology 89: 2712–2724. http://dx.doi.org/10.1890/07-1861.1

Mengistu DT, Sorteberg A. 2012. Sensitivity of SWAT simulated streamflow to climatic changes within the Eastern Nile River basin. Hydrol. Earth Syst. Sci., 16, 391–407, 2012. doi:10.5194/hess-16-391-2012.

Merritt WS, Letcher RA, Jakeman AJ. 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18(8): 761-799.

Middelkoop H, Daamen K, Gellens D, Grabs W, Kwadijk JCJ, Lang H, Parmet BWAH, Schädler B, Schulla J, Wilke K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Climate Change 49: 105–128

Minella JPG, Merten GH, Walling DE, Reichert JM. 2009. Changing sediment yield as an indicator of improved soil management practices in southern Brazil, CATENA 79(3): 228-236, DOI: 10.1016/j.catena.2009.02.020.

Minville M, Brissette F, Leconte R. 2008. Uncertainty of the impact of climate change on the hydrology of a nordic watershed. Journal of Hydrology 358: 70–83.

Moradkhani H, Baird RG, Wherry SA. 2010. Assessment of climate change impact on floodplain and hydrologic ecotones. Journal of Hydrology 395: 264–278

Moriasi DN, Arnold JG, VanLiew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Transactions of the ASAE 50(3): 885-900.

Neitsch SL, Arnold JG, Kiniry JR, Williams J.R, King KW. 2005. Soil and water assessment tool. Theoretical Documentation: Version 2005. TWRI TR-191, College Station, TX.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR. 2001. Soil and Water Assessment Tool theoretical documentation version 2000. Available at online website: http://www.brc.tamus.edu/swat/doc.html. Accessed 10 November 2004.

Nguyen HK, Nguyen VT. 2001. Geography and Hydrology in Vietnam. Vietnam National University publisher, Hanoi, Vietnam, pp: 194.

Oñate-Valdivieso F, Sendra JB. 2010. Application of GIS and remote sensing techniques in generation of land use scenarios for hydrological modeling, Journal of Hydrology 395(3–4): 256-263, doi: 10.1016/j.jhydrol.2010.10.033.

Patrick G, Ronald PN, James ML, Raymond JD. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Global Ecology and Biogeography 19(6): 755–768, DOI: 10.1111/j.1466-8238.2010.00558.x

Pettitt, A. 1979. A nonparametric approach to the change-point problem. Journal of Applied Statistics 28(2):126-135.

Phan DB, Wu CC, Hsieh SC. 2011. Impact of climate change on stream discharge and sediment yield in Northern Viet Nam. Water Research 38: 827–836.

Phan TTH, Sunada K, Oish S, Sakamot Y. 2010. River discharge in the Kone River basin (Central Vietnam) under climate change by applying the BTOPMC distributed hydrological model. Journal of Water and Climate Change 1(4): 269–279. doi:10.2166/wcc.2010.046

Phillips JM, Webb BW, Walling DE, Leeks GJL. 1999. Estimating the suspended sediment loads of rivers in the LOIS study area using infrequent samples. Hydrological Processes 13: 1035–1050.

Pontius RG, Cornell JD, Hall CAS. 2001. Modeling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica. Agriculture Ecosystems & Environment 85: 191–203.

Praskievicz S, Chang H. 2011. Impacts of climate change and urban development on water resources in the Tualatin River Basin, Oregon. Annals of the Association of American Geographers (JournalSeek) 101: 249–271.

Qi S., Sun G., Wang Y., McNulty SG., Myers JAM. 2009. Streamflow response to climate and land use changes in a coastal watershed in North Carolina. Transactions of the ASABE, 52: 739-749.

Ren J, Hen DM, Fu KD, Li YG. 2007. Sediment changes driven by Climate change and human activities in Yuanjiang of the Red River basin, Chinese Science Bulletin 52: 142-147.

Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N, Rafaj P. 2010. The representative concentration pathways: an overview. Climate Change 109: 5–31.

Richard HM, Jae AE, Kathy AH, Martin RM, Steven KR, Detlef PV, Timothy RC, Seita E, Kainuma M, Kram T, Meehl GA, Mitchel JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffe RJ, Thomson AM, Weyant JP, Wilbanks TJ. 2010. The next generation of scenarios for climate change research and assessment. Nature, 463: 747–756.

Running SW, Gower ST. 1991. FOREST-BGC, A general model of forest ecosystem processes for regional applications, Tree Physiology 9: 147-160.

Rustomji P, Wilkinson SN. 2008. Applying bootstrap resampling to quantify uncertainty in fluvial suspended sediment loads estimated using rating curves. Water Resources Research, 44: W09434.

Schmidt KH, Morche D. 2006. Sediment output and effective discharge in two small high mountain catchments in the Bavarian Alps Germany. Geomorphology 80 (1-2): 131–145.

Schulze RE. 2000. Modelling hydrological responses to land use and climate change: a southern African perspective. Ambio 29 (1): 12-22.

Schwartz MD. 1996. Examining the spring discontinuity in daily temperature ranges. Journal of Climate 9: 803–808.

Setegn SG, Srinivasan R, Melesse AM, Dargahi B. 2010. SWAT model application and prediction uncertainty analysis in the Lake Tana basin, Ethiopia. Hydrological Processes 24: 357-367, DOI:10.1002/hyp.7457.

Shrestha B, Babel MS, Maskey S, van Griensven A, Uhlenbrook S, Green A, Akkharath I. 2013. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR, Hydrology and Earth System Science 17: 1-20, doi:10.5194/hess-17-1-2013.

Smith VB, David CH, Cardenas MB, Yang ZL. 2013. Climate, river network, and vegetation cover relationships across a climate gradient and their potential for predicting effects of decadal-scale climate change, Journal of Hydrology 488: 101-109, doi: 10.1016/j.jhydrol.2013.02.050.

Soares BS, Cerqueira GC, Pennachin CL. 2002. DINAMICA - a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecological Modelling 154: 217–235.

Solman S, Nunez M. 1999. Local estimates of global climate change: a statistical downscaling approach. International Journal of Climatology 19: 835–861.

Takeuchi K, Ao T, Ishidaira H. 1999. Introduction of block-wise use of TOPMODEL and Muskingum-Cunge method for the hydroenvironmental simulation of a large ungauged basin. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 44(4): 633–646.

Tang LH, Yang DW, Hu HP, Gao B. 2011. Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation, Journal of Hydrology 409(1–2): 172-182. doi: 10.1016/j.jhydrol.2011.08.015.

Taub D. 2010. Effects of Rising Atmospheric Concentrations of Carbon Dioxide on Plants. Nature Education Knowledge 3(10):21.

Thornton PE, Hasenauer H, White MA. 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria, Agriculture Forest Meteorology 104: 255–271.

Tinh DQ. 2001. Participatory planning and management for flood mitigation and preparedness and trends in the Red River Basin, Vietnam. Available at the website: http://www.unescap.org/esd/water/disaster/2001/vietnam.doc by June 2001

Tu J. 2009. Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA, Journal of Hydrology 379(3–4): 268-283, doi: 10.1016/j.jhydrol.2009.10.009.

Tuan VV. 1993. Evaluation of the impact of deforestation to inflow regime of the Hoa Binh Reservoir in Vietnam. Hydrology of Warm Humid Regions (Proceedings of the Yokohama Symposium, July 1993). IAHS Publ. 216: 135-138.

Tucker CJ, Pinzon JE, Brown ME, Slavback D, Park EW, Mahoney R, Vermote E, Saleous N El. 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. International Journal of Remote Sensing 26(20): 4485-4498.

Van GA, Meixner T, Grunwald S, Bishop T, Diluzio M, Srinivasan R. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. Journal of Hydrology 324: 10-23.

Van Liew MW, Veith TL, Bosch DB, Arnold J. 2005. Problems and potential of auto-calibrating a hydrologic model. Transactions of the ASABE 48 (3): 1025-1040.

Van Vuuren, DP, Riahi K, Moss R, Edmonds J, Thomson A, Nakicenovic N, Kram T, Berkhout F, Swart R, Janetos A, Rose SK, Arnell N. 2011. A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change 22 (1): 21-35. doi: 10.1016/j.gloenvcha.2011.08.002.

Verburg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SS. 2002. Modeling the spatial dynamics of regional land use: The CLUE-S model. Environmental Management 30: 391–405.

Verburg PH, Veldkamp A. 2004. Projecting land use transitions at forest fringes in the Philippines at two spatial scales. Landscape Ecology 19 (1): 77–98.

Vescovi FD, Park SJ, Vlek PLG. 2002. Detection of human-induced land cover changes in a savannah landscape in Ghana: I. Change detection and quantification." Proceedings of the EARSeL SIG Remote Sensing for Developing Countries.

Walling DE. 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Research 12: 1869–1894

Walling DE. 1984. Dissolved loads and their measurement, in Hadley, R. F. and Walling, D. E. (Eds.), Erosion and Sediment Yield: Some Methods of Measurement and Modelling. Geo Books, Norwich, 111-177.

Walling DE, Webb BW. 1985. Estimating the discharge of contaminants to coastal waters by rivers: some cautionary comments. Marine Pollution Bull., 16: 488-92.

Wang G, Xia J, Chen J. 2009. Quantification of the effects of climate variations and human activities on runoff by a monthly water balance model: a case study of the Chaobai River Basin in Northern China. Water Resources Research. 45. W00A11 http://dx.doi.org/10.1029/2007WR006768.

Wang J, Ishidaira H. 2012. Development and interpretation of new sediment rating curves considering the effect of vegetation change in the Da River Basin, Proceeding of Hydro Predict in 2012, pp: 54.

Wang J, Ishidaira H. 2012. Effects of climate change and human activities on streamflow and sediment flow into the hoa binh reservoir, Journal of Japan Society of Civil Engineers, Ser.B1 (Hydraulic Engineering) 68(4): I_91-I_96.

Wang J, Ishidaira H. 2013. Effects of human-induced vegetation cover change on sediment flow using satellite observations and terrestrial ecosystem model, Journal of Japan Society of Civil Engineers, Ser.B1 (Hydraulic Engineering) 69(4): I_205-I_210.

Wardrop DH, Brooks RP. 1998. The Occurrence and impact of sedimentation in central Pennsylvania wetlands. Environmental Monitoring and Restoration 51(1-2): 119–130.

Wessels KJ, Prince SD, Malherbe J, Small J, Frost PE, VanZyl D. 2007. Can human-induced land degradation be distinguished from the effects of rainfall variability? a case study in South Africa. Journal of Arid Environment 68(2):271–297.

Wilby LR, Zorita E, Timbal B, Whetton P, Mearns LO, Charles SP. 2004. Guidelines for use of Climate Scenario Developed from Statistical Downscaling Methods. Environmental Agency of England and Wales, UK.

Wilby RL, Dawson CW, Barrow EM. 2002. SDSM – a decision support tool for the assessment of regional climate change impacts. Environmental and Modelling Software 17: 145-157.

Wilby RL, Wigley TM. 1997. Downscaling general circulation model output: a review of methods and limitations. Progress in Physical Geography 21: 530-548.

Williams JR. 1969. Flood routing with variable travel time or variable storage coefficients. Transactions of the ASAE 12 (1): 100–103

Williams JR. 1975. Sediment-yield prediction with universal equation using runoff energy factor. In: Present and Prospective Technology for Predicting Sediment Yield and Sources: Proceedings of the Sediment Yield Workshop 1975, ARS-S-40. USDA Sedimentation Lab., Oxford, 244–252.

Wilson CO, Weng Q. 2011. Simulating the impacts of future land use and climate changes on surface water quality in the Des Plaines River watershed, Chicago Metropolitan Statistical Area, Illinois. Science of the Total Environment 409(20): 4387-4405.

World Bank. Vietnam Water Resources Sector Review. Selected Working Papers of the World Bank, ADB, FAO/UNP and NGO Water Resources Sectoral Group, Hanoi, 1996, pp:340.

Xu CY. 1999. From GCMs to river flow: a review of downscaling methods and hydrologic modeling approaches. Progress in Physical Geography, 23(2): 229–249. doi:10.1177/030913339902300204.

Ye CQ, Gan S, Wang WL, Deng QY, Chen WH, Li YG. 2008. Analysis on the runoff distribution and the variability in the downstream of Honghe River. Resources and Environment in the Yangtze basin 17(06): 886-891.

Yoshimura C, Zhou MC, Kiem AS, Fukami K, Prasantha HHA, Ishidaira H, Takeuchi K. 2009. 2020s scenario analysis of nutrient load in the Mekong River Basin using a distributed hydrological model. The Science of Total Environment, 407(20): 5356–5366. doi: 10.1016/j.scitotenv.2009.06.026. Epub 2009 Jul 22.

Yasutomi N, Atsushi H, Akiyo Y. 2011. Development of a long-term daily gridded temperature dataset and its application to rain/snow discrimination of daily precipitation. Global Environ. Res 15: 165-172.

Ziegler A, Eshel G, Rees PM, Rothfus T, Rowley D, Sunderlin D. 2003. Tracing the tropics acrossland and sea:Permian to present. Lethaia 36, 227–254.

Zhao FF, Xu ZX, Zhang L, Zuo DP. 2009. Streamflow response to climate variability and human activities in the upper catchment of the Yellow River Basin. Science in China Series E: Technological Sciences 52(11): 1–8, DOI: 10.1007/s11431-009-0354-3.

Zheng HX, Zhang L, Zhu R, Liu CM, Sato Y, Fukushima Y. 2009. Responses of streamflow to climate and land surface change in the Headwaters of the Yellow River Basin. Water Resource Resources 45: DOI: 10.1029/2007WR006665.

Zhou M, Ishidaira H, Hapuarachchi HP, Magome J, Kiem AS, Takeuchi K. 2006a. Estimating potential evapotranspiration using Shuttleworth–Wallace model and NOAA-AVHRR NDVI data to feed a distributed hydrological model over the Mekong River basin. Journal of Hydrology 327(1–2): 151–173.

Zhou M, Ishidaira H, Hapuarachchi HP, Magome J, Kiem AS, Takeuchi K. 2006b. Adaptive Muskingum-Cunge routing method for distributed hydrological modeling in large river basins. 3rd APHW Conference, 16–18 October 2006, Bangkok, Thailand.

Zhu YM, Lu XX, Zhou Y. 2008. Sediment flux sensitivity to climate change: a case study in the Longchuanjiang catchment of the upper Yangtze River, China, Global and Planetary Change 60: 429–442.

Zhu ZC, Bi J, Pan YZ, Ganguly S, Anav Al, Xu L, Samanta A, Piao SL, Nemani RR., Myneni RB. 2013. Global Data Sets of Vegetation Leaf Area Index (LAI) 3g and Fraction of Photosynthetically Active Radiation (FPAR) 3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2011. Remote Sensing 5(2): 927-948.

APPENDICES

Appendix Tables

Table A.1. Available predictors from NECP, CCCMA47 and ECHAM5

Predictor	Predictor description
p_fas	Surface airflow strength
p_uas	Surface zonal velocity
p_vas	Surface meridional velocity
p_zas	Surface vorticity
p_thas	Surface wind direction
p_zhas	Surface divergence
p5_fas	500 hPa airflow strength
p5_uas	500 hPa zonal velocity
p5_vas	500 hPa meridional velocity
p5_zas	500 hPa vorticity
p500as	500 hPa geopotential height
p5thas	500 hPa wind direction
p5zhas	500 hPa divergence
p8_fas	850 hPa airflow strength
p8_uas	850 hPa zonal velocity
p8_vas	850 hPa meridional velocity
p8_zas	850 hPa vorticity
p850as	850 hPa geopotential height
p8thas	850 hPa wind direction
p8zhas	850 hPa divergence
s500as	Specific humidity at 500 hPa
s850as	Specific humidity at 850 hPa
shumas	Surface specific humidity
tempas	Mean temperature at 2 m
mslpas	Mean sea level pressure

Appendix Figures

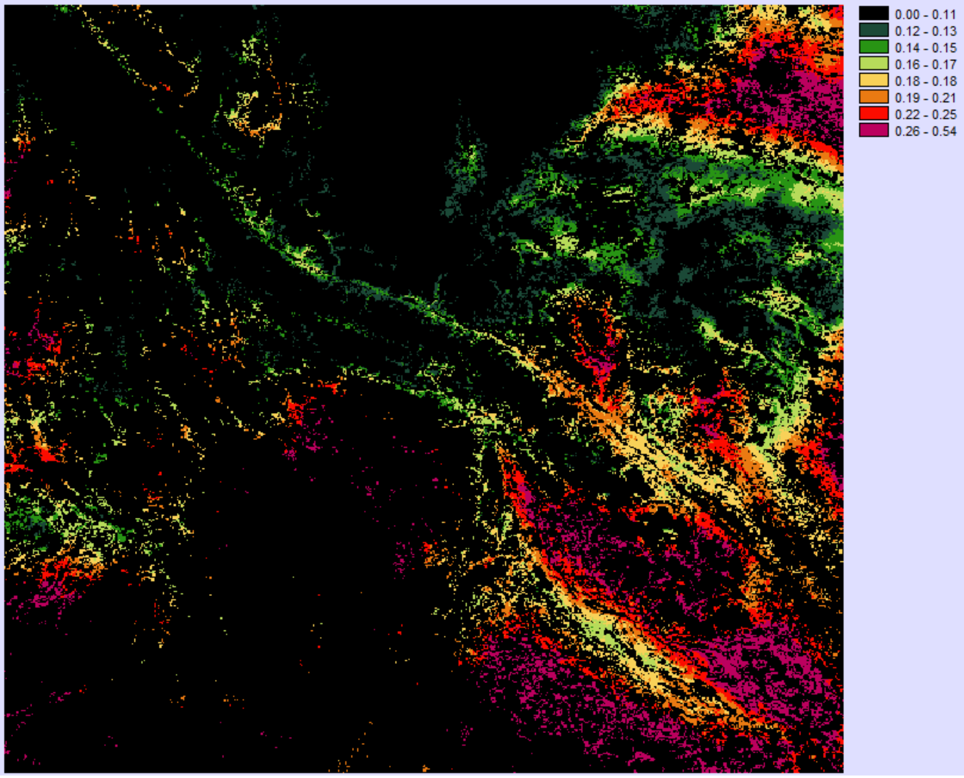


Figure B.1. Potential for transition from shrublands to forest

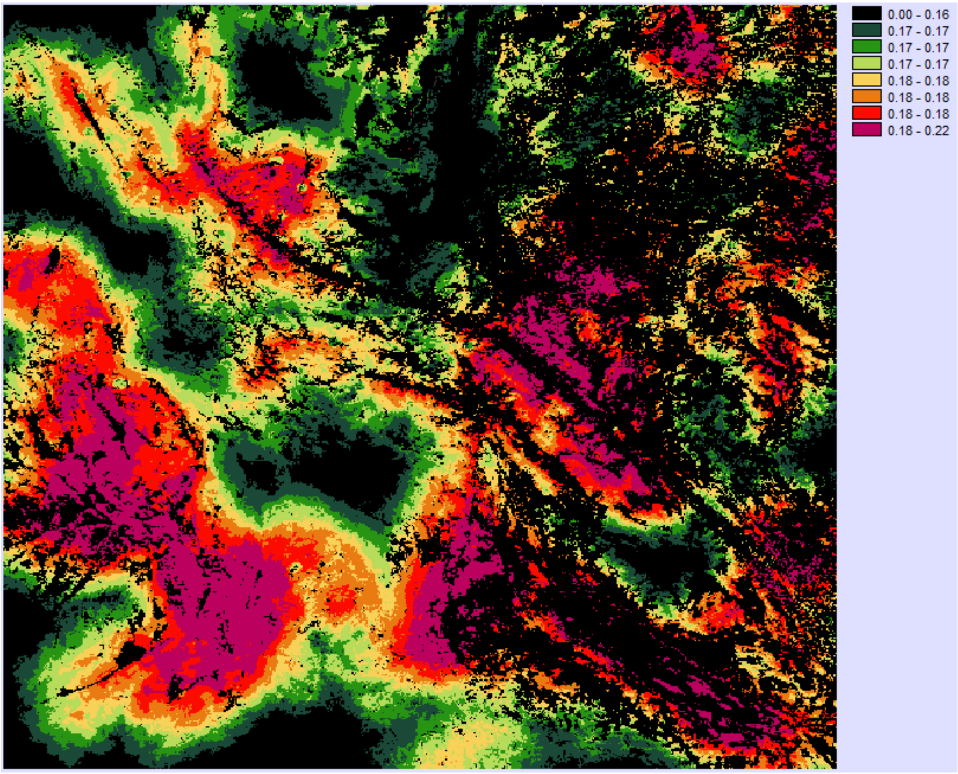


Figure B.2. Potential for transition from forest to croplands

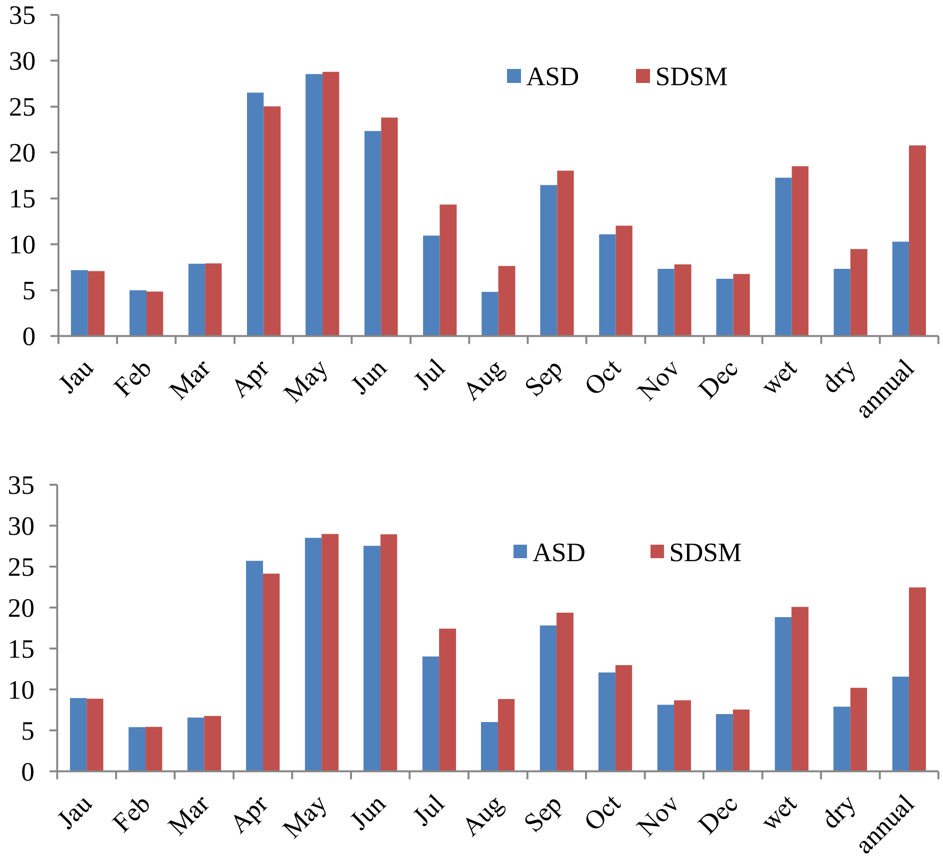


Figure B.3. Changes in monthly, seasonal annual streamflow under the A1B scenario downscaled by SDSM and ASD (up:Laichau station, down: Tabu station)