博士論文

Study of future soil erosion and sediment yield considering land use and climate changes in northern Thailand

(タイ北部における土地利用変化と気候変動を考慮した将来の土壌浸食と土砂生産量に関する研究)

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Summary

Soil erosion and sediment are important global problems, which are influenced by natural factors and human activities, such as climate change and land use change. The interactions among land use change, climate change, soil erosion, and sedimentation will continue to be a major issue for decades. Many researchers are interested in the factors that affect soil erosion, which generates sediment in rivers, and the impact of soil erosion on the environment. However, few studies have examined the impact of climate and land use changes on soil erosion, and no research has focused on the impacts of climate and land use changes on sediment because the measurement data are scarce.

Therefore, this dissertation 1) developed an R-factor equation for estimating soil erosion on a daily scale, 2) analyzed the impact of climate and land use changes on soil erosion and sediments in the Nan river basin which has observation data and the potential for soil erosion and sediment yield become obvious recently, and 3) estimated the impact of climate and land use changes on sediment inflow into reservoirs. This goal is attained using Revised Universal Soil Loss Equation (RUSLE), sediment delivery ratio (SDR) and sediment transportation model to estimate the change of soil erosion and sediment under the conditions of climate and land use changes.

Typically, RUSLE is used to estimate soil erosion on an annual scale with an R-factor equation due to a lack of rainfall data at fine temporal resolutions. The results using the daily R-factor equation in this study were similar to the observed data from the Royal Irrigation Department (RID) and the standard error of the estimates was low. Therefore, the daily R-factor equation is useful for estimating soil erosion.

The sediment yield simulated by the model using climate data for 1985-2004, and land use data for 2000 was used to calibrate the model with observation data from the RID. Finally, the Nash-Sutcliffe efficiency (NSE) was used to check the accuracy of the simulation. The results showed that the model was well calibrated and could be used to simulate future scenarios, given that the NSE from the calibration and validation runs exceeded 0.5.

The combined analysis of the impacts of climate and land use changes on soil erosion and sediment suggested that the changes in both have significant impacts on both soil erosion and sediment in the river. Rainfall will likely increase in the near future, which directly affects surface runoff, an important factor related to soil erosion and river discharge that controls the sediment flow in a river. Land use change from forest to agriculture has a greater effect on soil erosion and sediment than that from one type of agriculture to another due to the reduction in plant cover. Furthermore, the severe scenarios illustrate how land use changes tend to affect soil erosion more than climate change, while climate change has a greater impact on sediment than land use change.

To this end, the annual average sediment inflow into reservoirs showed that heavy rainfall could accelerate the increment in sediment in the reservoirs twice as much as land use change from forest to agriculture. Appropriate land management can slow the sediment increase in rivers during extreme precipitation. Therefore, land use planning for catchment areas is a good way to protect and extend the lifespan of reservoirs.

This study should help to determine the optimal land use types for reducing soil erosion and decreasing sediment accumulation in rivers, including planning to mitigate the future impact of climate change.

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Chapter 1

Introduction

1.1) Soil erosion and sediment

Soil erosion is one of the main factors that cause deterioration of water quality. It may affect the chemical properties of soil, reduce soil productivity and increase sediment in the river. (Ovuka, 2000, Lu *et al*., 2016, Chen *et al*., 2017) (Figure 1.1).

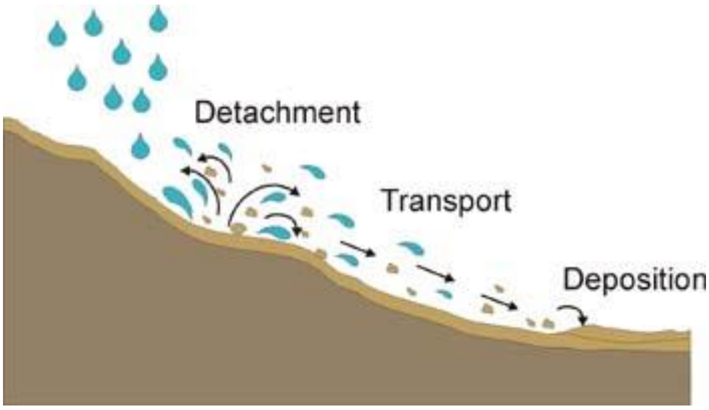


Figure 1.1 Soil erosion process (*Source:http://wiki.ubc.ca/LFS:SoilWeb/Soil_Management/Soil_Erosion*)

Soil erosion contributes to several environmental problems, including the removal of topsoil, loss of soil nutrients, and flooding (Wang *et al*., 2016). Water pollution is also a consequence of soil erosion, as soil particles, fertilizers, pesticides, and other harmful chemicals contained in the eroded soil may flow with the surface water from the eroded area into rivers, thus contributing to the degradation of water quality (Tucker, 2018).

Soil erosion is the origins of the sediment in the river (Shit *et al*., 2012) which is the main factors contributing to river shallowness. Sedimentation is the process by which suspended particles settle due to gravity (Figure 1.2). Amount of sediment in the river depends on eroded soil particle and sediment delivery ratio (SDR) that transport the soil particles from the site of origin to the river (Morgan, 2005) and water flow which is the factor that transports the sediment in the river (Jain and Kothyari, 2009).

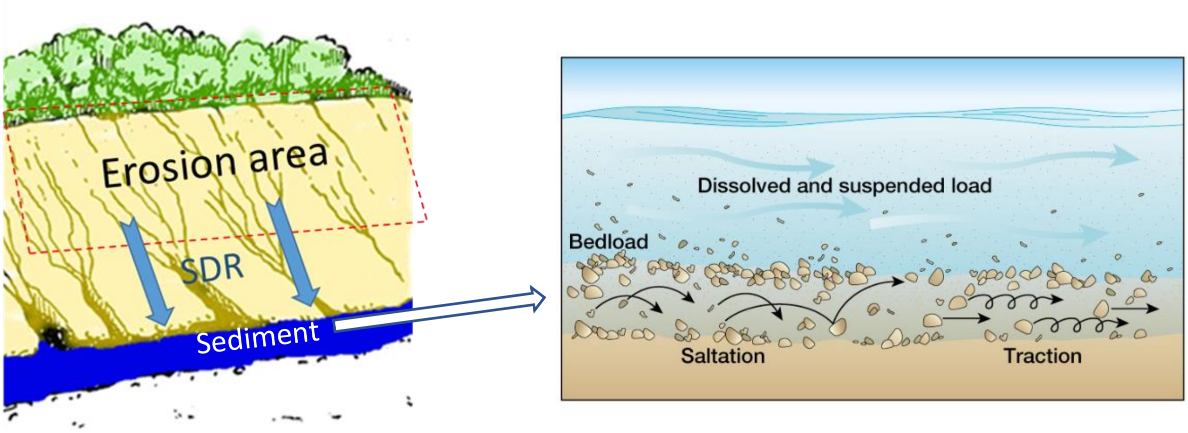


Figure 1.2 The process of sedimentation (Source: *http://getdrawings.com/erosion-drawing and http://www.geologyin.com/2016/01/how-do-streams-transport-and-deposit.html*)

Increased sediment decreases the storage capacity of streams, resulting in flooding and heightened risk of flash floods (Daniel *et al*., 2015). It also causes further corrosion by deflecting the flow into the adjacent stream bank or even toward neighboring land (The Department of Water and Environmental Regulation, 2017).

Sediment flow can be particularly problematic for reservoirs, as reservoir sediment may result in diminished reservoir storage capacity and a reduction in the reservoir's lifespan. Climate change and land use change have a positive impact on the variation of sediment inflow to the reservoir. However, studies investigating the effects of sediment inflow to reservoirs are scarce, owing to the limited availability of measurement data and its having been overlooked by the people (Palmieri *et al*., 2001 Tigrek and Aras, 2011).

The key factors determining soil erosion rates and sediment levels are the climate and land use. Climate change and land use change are currently important global issues (Branes, 2017). Land use changes are anthropogenic, which are changes in land cover that result from the way in which the land has been utilized, have a significant impact on natural resources, including water, soil, and vegetation (Lawlera *et al*., 2013, Paul and Rashid, 2017, NOAA, 2018). Land use changes are strongly influenced by population growth and economic expansion (Elmhagen *et al*., 2015).

Climate change is the long-term alteration of global weather patterns. The climate system comprises the atmosphere, land surface, oceans and other water bodies, and living things, and is often described in terms of the mean and variability of temperature and precipitation over a period that may range from months to millions of years (The Classic period is 30 years) (Treut *et al*., 2007). Climate change may cause flood or drought, owing to its many associated factors, including higher temperatures and increased evaporation variability (Kundzewicz *et al*., 2007).

As observed above, soil erosion and sediment issues are closely associated with human activities and have significant implications for society. Furthermore, successful estimation of the impact of climate and land use changes impact is crucial to sustaining human life and the security of human settlements, in line with the Sustainable Development Goals (SDGs) issued by the United Nations (UN) (United Nations, 2018).

1.2) Impact of climate and land use changes

Climate change affects the environmental wellbeing and livelihood of all living things (FAO, 2017). The Intergovernmental Panel on Climate Change (IPCC, 2007) forecast that average surface temperature is likely to increase by around 1^{o}C by the 2020s, and will have increased by 3-4 ^{o}C at the end of the 21st century, with evaporation and precipitation also likely to increase in most areas (Meehl *et al*., 2007). These changes will exacerbate the risk of both flood and drought, and the extent of soil erosion and sediment yield, in addition to affecting vegetation growth (Nelson *et al*., 2009). Changes of this nature will have negative impacts on human life and the economy, giving rise to further extreme weather events, land degradation, water scarcity, and rising sea levels (FAO, 2017). Furthermore, altered rainfall patterns, including increased or decreased heavy rainfall events and high rainfall variability, will contribute to variations in soil erosion (Ritter, 2012, Li and Fang, 2016, National Geographic, 2018). This could directly affect surface runoff, which is a key factor in soil erosion in terms of the detachment and movement processes from which river sediment originates (Coit, 2014, Roudier *et al*, 2014, Chang *et al*., 2017). Climate change reduces surface runoff in the Mediterranean and in Central and Southern America, while increasing surface runoff in South and East Asia (Arnell, 2004, Nohara *et al*., 2006, Estrela *et al*., 2012, Zhang *et al*., 2014). These phenomena are significant issues that make it increasingly imperative that soil erosion be regulated (Lslam *et al*., 2015).

Land use change affects soil, water resources, and hydrology. Several countries worldwide have begun to pay greater attention to the impact of land use change in response to the continuous decline of forest cover. Population increases exert considerable demand on agricultural areas, resulting in increased deforestation aimed at expanding agricultural terrain to meet public demand (Elmhagen *et al*., 2015). This problem has resulted in the continuous decline of forest cover, which has a significant impact on water resources, soil, wildlife, and vegetation (Lawlera *et al*., 2013). Deforestation leads to the destruction of wildlife habitats, affects hydrological cycles, and increases soil erosion, flooding, and landslides (Wu, 2008). The expansion of agricultural terrain in Asia is ongoing and, consequently, forested areas have sharply declined (Zhao *et al*., 2006). Forested areas generate surface litter, which provides protection for the soil surface and reduces the impact of rainfall. However, when forested areas are converted to agricultural terrain, surface litter decreases, leading to increased surface runoff and erosion, among the consequences of which is increased sediment in the river (Elliot, 2010). Deep soil desiccation may also ensue (Huang and Pang, 2011). Therefore, climate change and land use changes exert considerable influence on soil erosion and river sediment levels (FAO, 2011). The interplay between land use change, climate change, and hydrologic processes is set to be a major global issue in coming decades (Palmer *et al*., 2008). Assiduous planning and management of land use changes can therefore serve to regulate soil erosion rates and moderate sediment levels in rivers.

Several studies have suggested that the consequences of climate change and land use change are significant factors that should be afforded due consideration (Defries and Eshleman, 2004, Rogger *et al*., 2017, Branes, 2017, Grothmann *et al*., 2017). Moreover, soil erosion and sediment are currently particularly important environmental issues in developing countries (Lslam *et al*., 2015). However, the effects of climate change and land use changes on soil erosion and sediment are still not fully appreciated for the following reasons:

1) The sediment measurement data required for estimation are limited.

Hitherto, research concerning sediment and the effects of climate change and land use change on sedimentation are scarce, and the topic has not been afforded sufficient scholarly attention owing to the limited availability of measurement data (Karaburun, 2010). It is particularly difficult to access sediment measurement data in developing countries, where there is insufficient continuous data collection to calibrate and validate models. The results obtained through prediction may be unreliable and invalid if the data are inadequate to check the accuracy of the model or validation of the results.

2) Previous studies have tended to focus only on a single factor: climate change or land use change

Previous studies on the effects of climate change and land use change are widespread (Table 1.1 and Figure 1.3). For example, Vanwalleghem *et al*. (2017) reviewed existing research into the effects of historical land use and soil management on soil erosion and agricultural sustainability during the Anthropocene and found that changes in land use from natural vegetation to agriculture, and poor management of agricultural areas were associated with increased soil erosion. Jose and Ruiz (2010) reviewed research concerning the effects of land use on soil erosion in Spain and observed that farmland abandonment in mountainous regions can potentially reduce soil erosion due to vegetation recolonization. Regarding the impact of climate change more generally, research has found that soil erosion tend to correlate directly with rainfall levels (Li and Fang, 2016): Mullan *et al.* (2012) studied the key limitations associated with modelling soil erosion under the impact of future climate change; Routschek *et al.* (2014) simulated the impact of climate change on soil erosion; and Correa *et al.* (2016) estimated the risk of soil erosion associated with climate change at the Mantaro river basin. All predicted that future risk of soil loss will increase or decrease according to variations in rainfall. However, most previous studies have focused only on a single factor, climate change or land use change, and thus provide insufficient insight for optimal management of the environment and integrated water resources that would contribute to a sustainable drainage system (Kaushal *et al.*, 2017).

1.3) Objective and significance of this study

As noted above, three issues have hitherto been overlooked:

1) The extent of sediment inflow to the reservoir

Sedimentation is a key issue for older or small reservoirs that lack the capacity to counteract or clear sediment build-up. However, this issue has been overlooked by the people and researcher since sediment accumulates very gradually in reservoirs (Palmieri *et al.*, 2001 Tigrek and Aras, 2011), and also because the measurement data available are limited. Therefore, research concerning sediment inflow to reservoirs is lacking.

2) Limitations of the rainfall-runoff erosivity equation (R-factor)

Mathematical models are currently an important tool for studying soil erosion and sedimentation processes. The best-known models are the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE), which form the basis for several models used worldwide and have been demonstrated as the most reliable equations for estimating future results (Millward and Mersey, 1999, Yang *et al.*, 2003, Nearing *et al.*, 2005, Pholkerd *et al.*,2012, Alexakis *et al.*, 2013, Sun *et al.*, 2014, Biswas and Pani, 2015, Ganasri and Ramesh, 2016). USLE and RUSLE can be applied to large-scale catchment areas, taking into account land cover type to estimate rill and interrill erosion rates and incorporating several factors, including rain erosivity, soil erodibility, slope length and steepness, land cover and the support practice factor (Renard *et al*., 1997). Nonetheless, the 15-minute rainfall intensity data required to calculate the daily rainfall- runoff erosivity factor (R-factor) using USLE and RUSLE are difficult to access. Consequently, most earlier studies calculated soil erosion on an annual scale.

3) Limitations of the research concerning soil erosion

Most researchers have focused on factors related to soil erosion as the origin of river sediment, and on the environmental impact of soil erosion. For example, Novara *et al*. (2018) estimated the impact of soil erosion on soil fertility and vine vigor using remote sensing and field studies. Bakker *et al*. (2005) studied the relationship between soil erosion and land use change, while Erkossa *et al*. (2015) investigated the connection between soil erosion and on-site financial cost in the Blue Nile basin. Comino *et al*. (2016) studied the high variability of soil erosion and hydrological processes, including the factors that can potentially regulate soil erosion in Mediterranean hillslope vineyards, using an experimental plot. Prosdocimi *et al*. (2016) reviewed research into mulching practices aimed at reducing soil water erosion, and concluded that appropriate soil management practices and mulching can help to reduce soil and water loss (Table 1.1 and Figure 1.3). However, little research has focused on the impact of climate change and land use change on soil erosion.

Therefore, this dissertation is aimed at developing a daily R-factor equation for use with the soil erosion model to evaluate the impact of climate change and land use change on both the soil erosion and sedimentation processes in Nan river basin, Thailand, for which some observational data are available. The full extent of soil erosion and sediment yield in this river basin have recently become evident.

The objectives of this study are:

1) To create a daily R-factor equation for use with RUSLE, and apply the soil erosion and sediment model to estimate future soil erosion and sediment yield on local scales.
2) To examine and assess land use management and the effects of climate change on soil erosion and sediment yield, to estimate the future impact of climate change and land use change on soil erosion and sediment yield.
3) To estimate the impact of climate change and land use change on sediment inflow to reservoirs.

To realize these goals, Revised Universal Soil Loss Equation (RUSLE) is applied, which determines the R-factor from hourly and daily rainfall intensity, sediment delivery ratio (SDR), and the sediment transportation model to estimate changes in soil erosion and sediment yield that result from climate change and land use changes in the Nan river basin, where increased soil surface loss due to erosion is likely and there is an increased risk of river shallowness as a result of sedimentation, caused by climate change and the rapid decline of forestation.

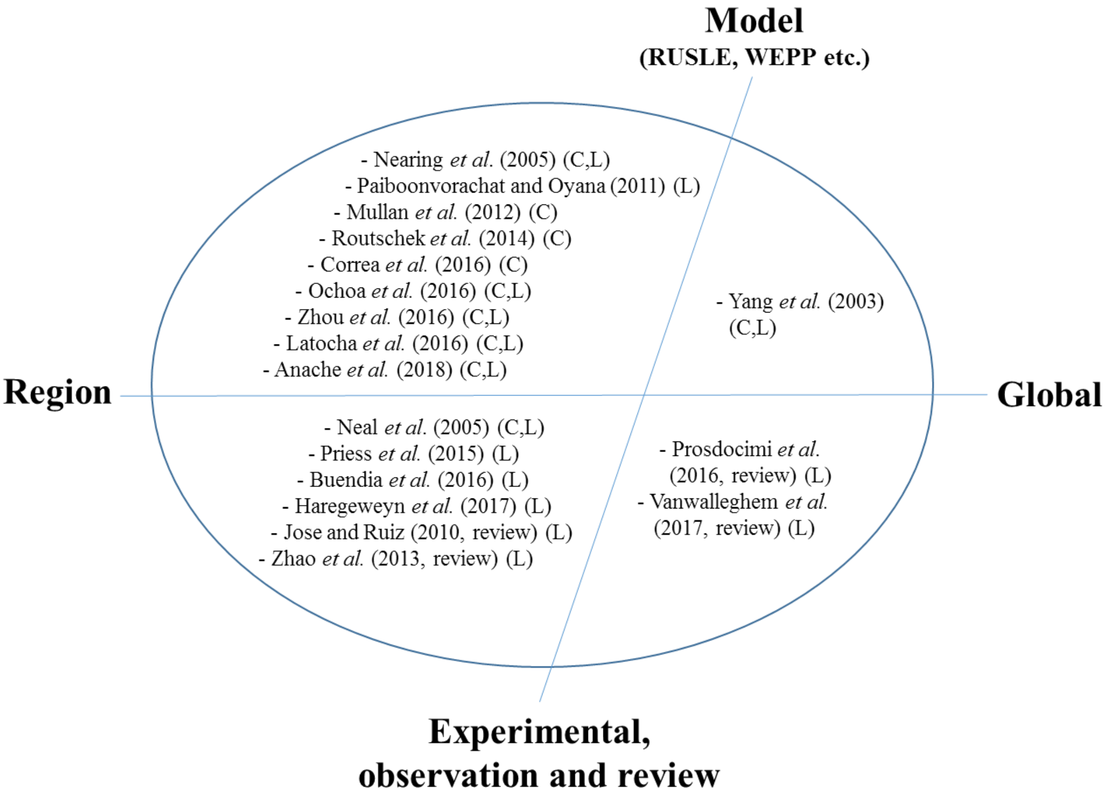


Figure 1.3 The sample of an academic papers about the impact of climate and land use changes on soil erosion and sediment (This figure based on the academic paper in Table 1.1) *(C means that the academic paper is related to climate change, L is land use change, and C,L mean that the academic paper is related to both of climate and land use change)*

Table 1.1 The sample of an academic paper (This table created from the previous academic paper that related to the impact of climate and land use changes on soil erosion and sediment)

Title	**Author**	**Year**	**Result**
Global potential soil erosion with reference to land use and climate changes	Yang *et al.*	2003	In the world, southeast Asia is the most seriously affected region from the soil erosion. The global warming, the development of cropland, and increasing of population are the significant impact to soil erosion in both current and future.
Climate change impacts on soil erosion in Midwest United States with changes in crop management	Neal *et al.*	2005	The increase in precipitation might affect soil erosion in the future but future crop management change might affect the erosion beyond that predicted from climate change.
Modeling response of soil erosion and runoff to changes in precipitation and cover	Nearing *et al.*	2005	The incremental in both of precipitation amount and precipitation intensity might lead to increase erosion. On the other hand, the increasing in both of ground cover and canopy cover could help to decrease erosion.
The effects of land uses on soil erosion in Spain: A review	Jose and Ruiz	2010	The farmland abandonment in the mountain can lead to the reduction of soil erosion due to the vegetation recolonization.
Land-cover changes and potential impacts on soil erosion in the Nan watershed, Thailand	Paiboonvorachat and Oyana	2011	The conversion of forests to agricultural lands such as paddy field and croplands could explain the increase in soil erosion especially in the high mountainous area.
Addressing key limitations associated with modelling soil erosion under the impacts of future climate change	Mullan *et al.*	2012	Soil erosion got the direct impact of climate change and indirect impact from land use change. In addition, the risk of soil erosion varies following the variation of rainfall.
Soil erosion, conservation and eco-environment changes in the Loess Plateau of China	Zhao *et al.*	2013	The population growth, deforestation, and soil and water conservation could control the change of soil erosion. Furthermore, decreasing of rainfall, and large-scale soil and water conservation could help to decrease sediment yield.
Impact of climate change on soil erosion — A high-resolution projection on catchment scale until 2100 in Saxony/Germany	Routschek *et al.*	2014	In the near future of Germany, the rainfall intensity will increase but the total amount of annual rainfall is decreasing. Climate change can lead to increase of soil erosion in 2050 but the impact of land use change is likely to effect on soil erosion than climate change.

Figure 1.1 Continue

Topic	**Author**	**Year**	**Result**
Impacts of agricultural land-use dynamics on erosion risks and options for land and water management in Northern Mongolia	Priess *et al.*	2015	The land use management and climate factors could reduce or aggravate erosion risks approximate 30%. In the near future, the combining of the climate change and land use management seem to pose a greater risk of soil erosion more than decline.
Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment	Buendia *et al.*	2016	The expansion of forest area was the main driver that helps to reduced streamflow and the peak floods, resulting in decrease of sediment loads but it was less significant in an upland Mediterranean catchment.
Soil erosion risk associated with climate change at Mantaro river basin, Peruvian Andes	Correa *et al.*	2016	Soil erosion rate by the end of this century might increase in moderate to severe rates due to the increase in rainfall.
Effects of land abandonment and climate change on soil erosion—An example from depopulated agricultural lands in the Sudetes Mts., SW Poland	Latocha *et al.*	2016	The extension of forest area and grassland in Sudetes mountain from the past to the present caused the decrease of average soil erosion. Additionally, the change of land use had a large impact on soil erosion than climate change.
Effects of climate, land cover and topography on soil erosion risk in a semiarid basin of the Andes	Ochoa *et al.*	2016	The soil erosion in the evergreen forest was very low although the slope and rainfall were high. The land cover and soil erodibility are the most important factors to estimate soil erosion but in the dry season, in the agricultural areas and where the land cover is dilute, the soil erodibility is the higher important factor.
Mulching practices for reducing soil water erosion: A review	Prosdocimi *et al.*	2016	The suitability of soil management practices and mulching can help to reduce soil and water loss as much as possible.
Effects of precipitation and restoration vegetation on soil erosion in a semi-arid environment in the Loess Plateau, China	Zhou *et al.*	2016	The shrub cover is the very good land cover to protect the surface soil, and decrease runoff and soil erosion while the grassland has a significant impact on runoff and soil erosion more than other land cover types. In addition, rainfall and average thickness of the litter layer had a positive and negative influence on soil erosion, respectively.

Figure 1.1 Continue

Topic	Author	Year	Result
Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River	Haregeweyn *et al.*	2017	Soil erosion is strongly influenced by population density which is related to the land use change, and soil conservation practices. The suitability of soil and conservation practices could help to reduce the total soil loss in Upper Blue Nile River around 52 %.
Impact of historical land use and soil management change on soil erosion and agricultural sustainability during the Anthropocene	Vanwalleghem *et al.*	2017	The land used change from natural vegetation to agriculture and unsuitable management in agricultural area were involved with increased rates of soil erosion.
Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado	Anache *et al.*	2018	Land use and rainfall could influence runoff and soil loss rate, and the increase of rainfall intensity might increase the variation of runoff and soil erosion. Moreover, they conclude that the land use management following conservation principles can contribute to the soil sustainability.

1.4) Study area

The area selected for study in this dissertation is the Nan river basin, located in northern Thailand. The Nan river basin has nine sub-basins and a total catchment area of approximately 12,000 km^2. The topography of the study area ranges from flat terrain to mountains, with an elevation from 160 to 2,008 meters above mean sea level (Figure 1.4). The Nan river basin is currently experiencing severe land use change, including inappropriate land use in the highlands. Most of the river's catchment area is mountainous and a considerable area of the mountainous terrain was encroached upon and deforested to make way for crop fields. This has reduced the soil surface's level of protection against rainfall. Problems of this nature negatively affect water quality in the Nan river basin and increase the risk of flash floods, with greater likelihood of soil erosion and sedimentation. Soil erosion has a negative impact on agricultural productivity, associated with a reduction of nutrients in the surface soil due to surface runoff. Moreover, loss of soil surface as a result of soil erosion in the Nan river basin can reduce the soil's water retention capacity and may thus result in water shortages during the dry season (Wangpimool *et al.*, 2013).

Some sedimentation data required to calibrate and validate the model are available for the Nan river basin. These data were measured continuously over a 4-year period by the Royal Irrigation Department (RID). The data are sufficient, serviceable, and necessary for estimating the soil erosion rate and sedimentation levels in the river.

Consequently, this river basin was selected as the study area due to the availability of the measurement data and the several environmental problems in the area that stem from climate and land use changes.

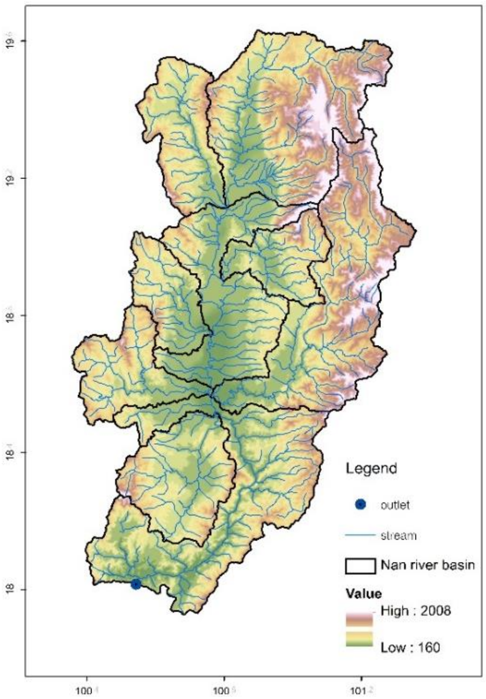


Figure 1.4 The topographic map of Nan river basin

1.5) Dissertation outline

Chapter 2 details the method used to develop the new daily R-factor equation and the results of the sediment yield comparison based on the daily, monthly, and annual R-factor equation, using the observational data from the RID.

In Chapter 3, the results of the model calibration and validation, including the accuracy of the Conversion of Land use change and its Effects (CLUE) model used to create the projected land use map, are presented. Additionally, the impact of climate change and land use change, including extreme scenarios, on soil erosion and sediment yield will be examined before the percentage differences of each scenario are presented.

Chapter 4 investigates the probability of increased sediment in the Nan river basin reservoir and the impact of climate change and land use change on sediment inflow to the reservoirs.

Chapter 5 summarizes the key findings of the dissertation and, in the Conclusion, the impact of climate change and land use changes on soil erosion and sediment yield, and the probability of increased reservoir sedimentation are discussed.

All models used in this study, including the H08 model, the soil erosion model, the sediment and sediment transportation model, and the land use model, are detailed in Appendix A.

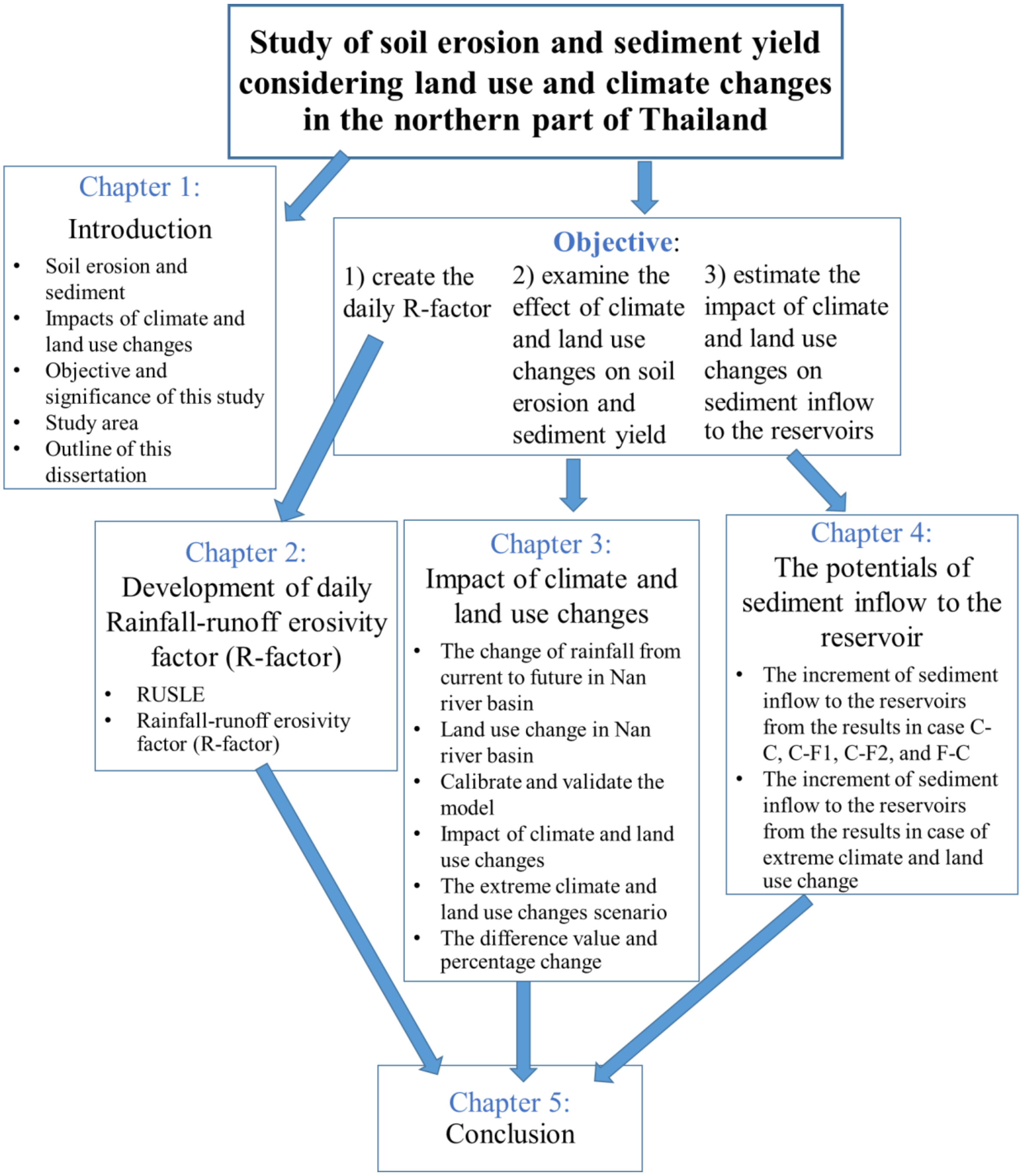


Figure 1.5 The outline of thesis

Chapter 2

Development of the daily rainfall-runoff erosivity factor (R-factor)

As previous studies have indicated, use of the daily R-factor equation for calculating soil erosion is scarce, due to the limited availability of 15-minute rainfall data. The maximum 30-minute rainfall intensity (I_{30}) must use 15-minute rainfall data to calculate, but data of this nature in developing countries, including Thailand, are very rarely available or accessible, since Thailand collects hourly rainfall data at a minimum. Previous studies have calculated soil erosion on the annual scale, which is inadequate to explain soil erosion tendencies on a daily or monthly scale. Consequently, this chapter aims to develop a daily R-factor equation based on the relationship between daily rainfall and the daily R-factor calculated from the maximum 60-minute rainfall intensity (I_{60}).

2.1) Revised Universal Soil Loss Equation (RUSLE)

This study uses RUSLE as the optimal equation for estimating the relationship between soil erosion and land use, due to the land cover management factor (C-factor) in this equation related to land use type (Leh *et al.*, 2013). RUSLE is the best known equation used to model erosion potential for the purpose of soil conservation planning worldwide (Zhang *et al.*, 2013). It is the most reliable model and yields results that align most closely with the measurement data (Tiwari *et al.*, 2000, Cecilio *et al.*, 2004, Stolpe, 2005, Wade *et al.*, 2012, Mondal *et al.*, 2018). Moreover, RUSLE can be used in conjunction with the SDR model to effectively evaluate sediment in the river. RUSLE constitutes the updated version of USLE, developed by Renard and others in conjunction with the US Department of Agriculture (USDA) (Renard *et al.*, 1997, Merritt *et al.*, 2003). RUSLE's formula is identical to that of USLE, but with improvements in each factor. For example, the developers improve the rainfall factor by adding a factor related to runoff, a new equation to reflect slope length and steepness, and a new conservation practice value (Renard *et al.*, 1997). RUSLE's formula is as follows:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (1)$$

Where A is the computed soil loss per unit of area, expressed in the units selected of K-*factor* and period selected of R-*factor*. In this study, the unit of A is ton/ha/day, R-*factor* is rainfall-runoff erosivity factor, *K-factor* is soil erodibility factor, *L-factor* is slope length factor, *S-factor* is slope steepness factor, *C-factor* is land cover management factor, and *P-factor* is conservation practice factor.

2.2) Rainfall-runoff erosivity factor (R-factor)

R-factor is associated with rainfall, which is the most significant factor affecting soil erosion, being capable of breaking down soil aggregates and dispersing the aggregate material (National Geographic, 2018). Very fine sand, silt, and clay are easily displaced by raindrop splashes and runoff water (Ritter, 2012). The R-factor may be determined from 15-minute rainfall data using the equation developed by Renard *et al.* (1997), as follows:

$$R\text{-}factor = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m} E_k (I_{30})_k\right] \tag{2}$$

Where E is the total storm kinetic energy (MJ/ha),

I_{30} is the maximum 30-minute rainfall intensity (mm/hr),

j is an index of the number of years used to produce the average,

k is an index of the number of storms in each year,

n is the number of years used to obtain the average *R-factor*, and

m is the number of storms in each year.

This study create daily R-factor equation for calculate soil erosion in the step as follows:

1) Select a day with rainfall greater than 5 mm over 6 consecutive hours, based on hourly and daily rainfall data from the IMPAC-T project between 1985 and 2004. Days with less than 5 mm rainfall were excluded since rainfall below 5 mm has a significantly weaker relationship with soil erosion (Bullock *et al*., 1989).

2) Calculate the maximum hourly rainfall intensity (mm/h) from the selected day.

3) Calculate the daily R-factor from the daily rainfall data, I_{60}, and average rainfall intensity (mm/h) on that day using the equation as follows (Foster *et al*., 1981):

$$R\text{-}factor = E \cdot I_{60} \tag{3}$$

$$E = \sum_j e_j \cdot P_j \tag{4}$$

Where E is the total storm kinetic energy (MJ/ha),

I_{60} is the maximum 60-minute rainfall intensity (mm/hr),

e_j is the kinetic energy per mm rainfall for time interval j (MJ/ha/mm),

$$e_j = 0.119+0.0873\log10(i_j), \quad i_j \leq 76 \text{ mm/hr} \tag{5}$$

$$e_j = 0.283, \quad i_j > 76 \text{ mm/hr}$$

P_j is rainfall in time period j (mm), and

i_j is rainfall intensity in the time interval j (mm/hr), respectively.

4) Assess the relationship between daily R-factor value, which is calculated using the I_{60}, and daily rainfall data using an exponential formula from a scatter plot, to create a new daily R-factor equation.

The new daily R-factor equation is:

$$\textit{Daily R-factor} = 0.01 \cdot X^{2.31} \tag{6}$$

Where X is daily rainfall (mm)

The coefficient of determination (R^2) of daily R-factor and daily rainfall is 0.930 (Figure 2.1).

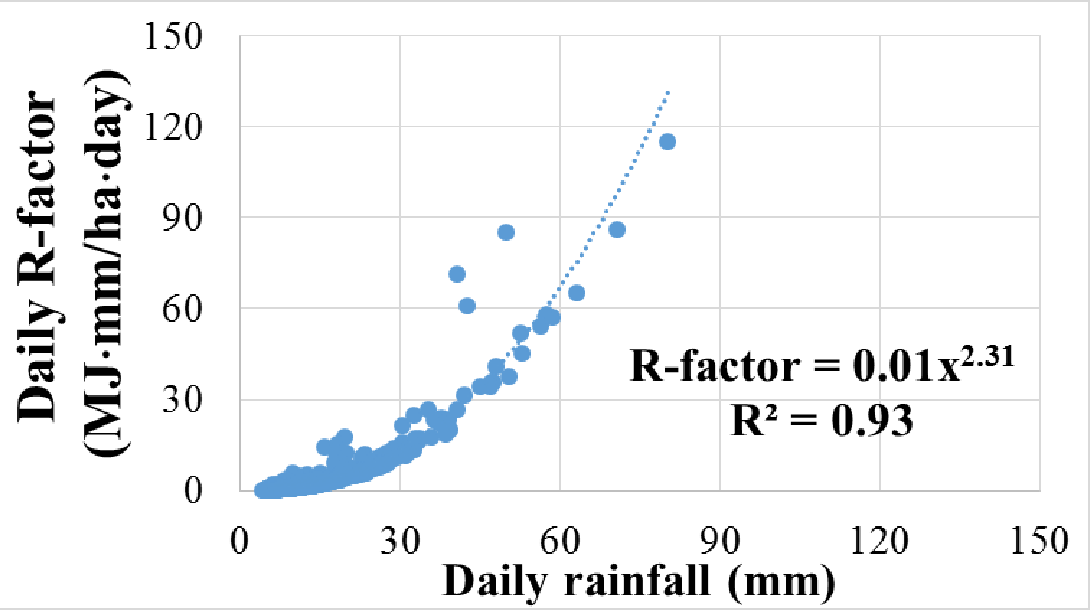


Figure 2.1 The relationship among daily R-factor value and daily rainfall including R^2

Prior to calculating the soil erosion and sediment yield in the Nan river basin using the new daily R-factor equation, the sediment yield that was calculated from the daily R-factor equation was compared with RID observational data from four sediment stations (Figure 2.2), the results from the monthly R-factor equation, and the annual R-factor equation.

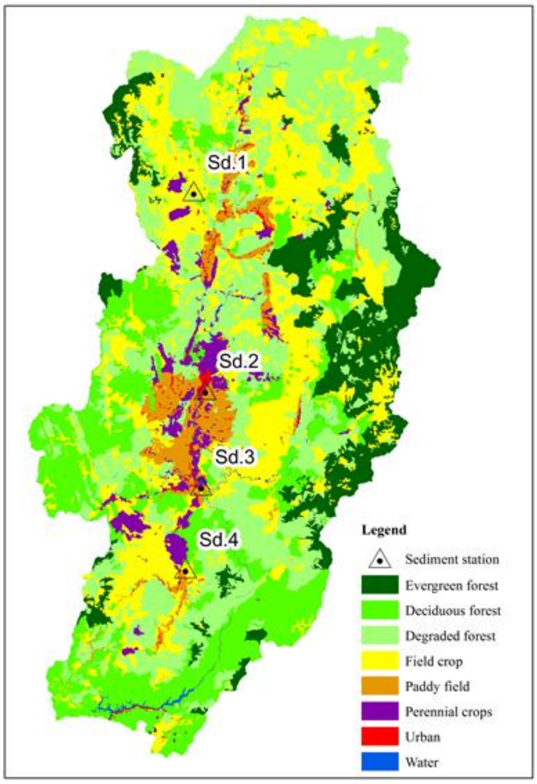


Figure 2.2 The location of sediment station in Nan river basin from RID

Sekachon *et al.*’s (1984) now-familiar annual R-factor equation was used to calculate annual rainfall erosivity in Thailand, as follows:

$$R\text{-}factor = 0.4669x - 12.1415 \qquad (7)$$

Where x is average annual rainfall.

Moreover, the monthly R-factor equation was developed based on the relationship between the Modified Fournier Index (MFI) and the annual R-factor calculated using Sekachon *et al.*’s (1984) annual R-factor equation, using an exponential formula from a scatter plot. The climate data from the IMPAC-T project, collected between 1985 and 2004, were used to calculate the MFI and to determine the relationship between the annual R-factor and the MFI.

First, MFI was calculate from monthly rainfall by equation as follows:

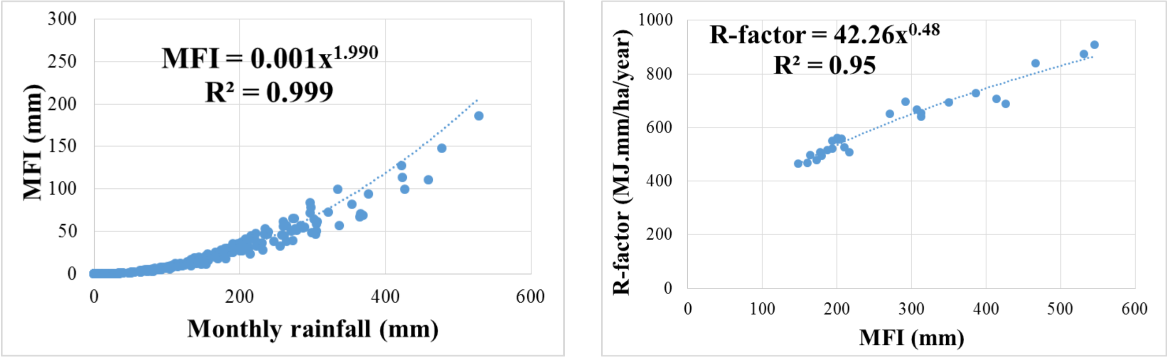
$$MFI = \sum_{i=1}^{i=12} \frac{p_i^2}{P} \tag{8}$$

Subsequently, the relationship between MFI and monthly rainfall using an exponential formula from a scatter plot was determined, and then the new MFI equation from the scatter plot was used to calculate the MFI on monthly and annual time scales before finding the relationship between the annual R-factor value, calculated using the equation developed by Sekachon *et al*. (1984), and the annual MFI to develop the monthly R-factor equation. The new MFI and monthly R-factor equations are:

$$MFI = 0.001x^{1.990} \tag{9}$$

$$Monthly\ R\text{-}factor = 42.26MFI^{0.48} \tag{10}$$

The coefficient determinant (R^2) of MFI and monthly rainfall is 0.999 (Figure 2.3a) and the annual R-factor with MFI is 0.95 (Figure 2.3b).

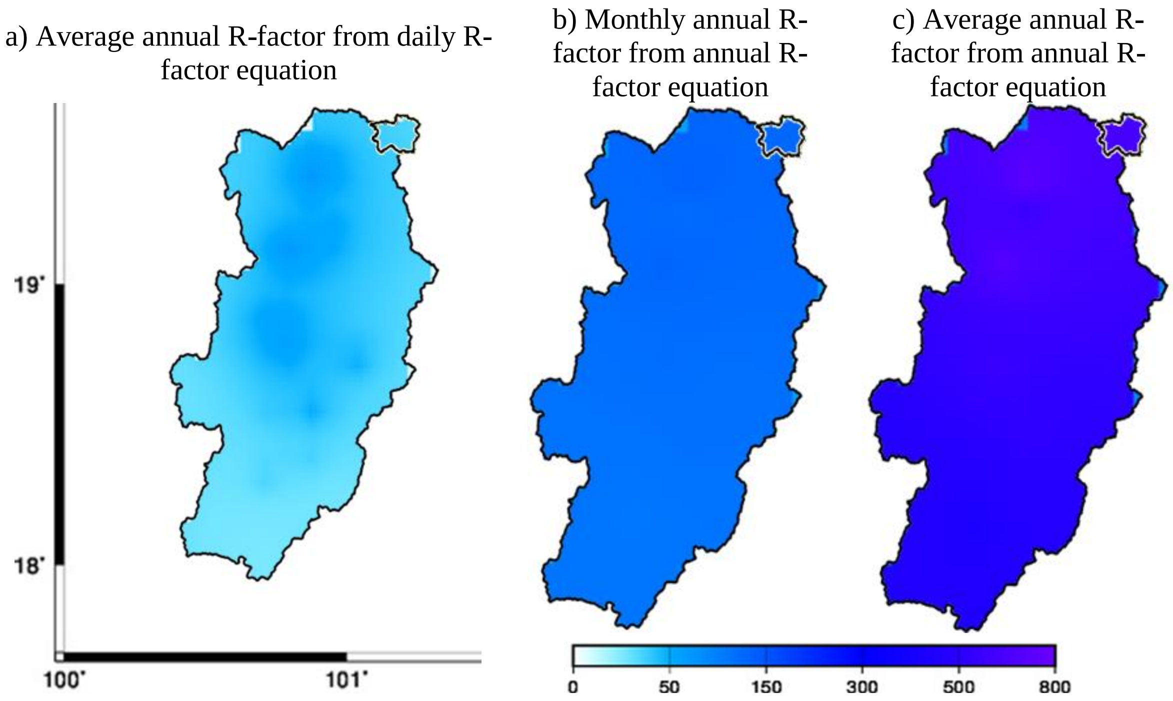


a) The relationship among monthly MFI and monthly rainfall

b) The relationship among annual MFI and annual R-factor

Figure 2.3 The relationship among monthly MFI and monthly rainfall (a), and the relationship among annual MFI and annual R-factor value (b)

The comparison results determined that the annual sediment yield, as calculated using the daily R-factor equation, are closer to the RID observation data than are the results yielded by the annual R-factor equation. Most results (with the exception of those from sediment station 2; Sd2) yielded by the annual R-factor equation constitute overestimations, due to the high R-factor value, which is higher than that obtained using the daily R-factor equation, at more than 500 MJ·mm/ha·day. Moreover, the standard error of estimate (SEE) value indicates that the results from the daily R-factor equation are more accurate than those from the annual R-factor equation. SEE value and the result from comparison are shown in Table 2.1 and Figure 2.5, respectively.


a) Average annual R-factor from daily R-factor equation

b) Monthly annual R-factor from annual R-factor equation

c) Average annual R-factor from annual R-factor equation

Figure 2.4 Average annual R-factor from daily rainfall data in 1985-2004 from daily, monthly, and annual R-factor equation

Table 2.1 The Standard Error of Estimate (SEE) of the annual sediment yield from daily, monthly, and annual R-factor equation

Sediment station	Standard Error of Estimate (SEE)		
	From daily R-factor	From monthly R-factor	From annual R-factor
1	0.29	0.30	7.45
2	0.25	0.21	0.36
3	1.13	0.96	2.14
4	0.31	0.19	0.67

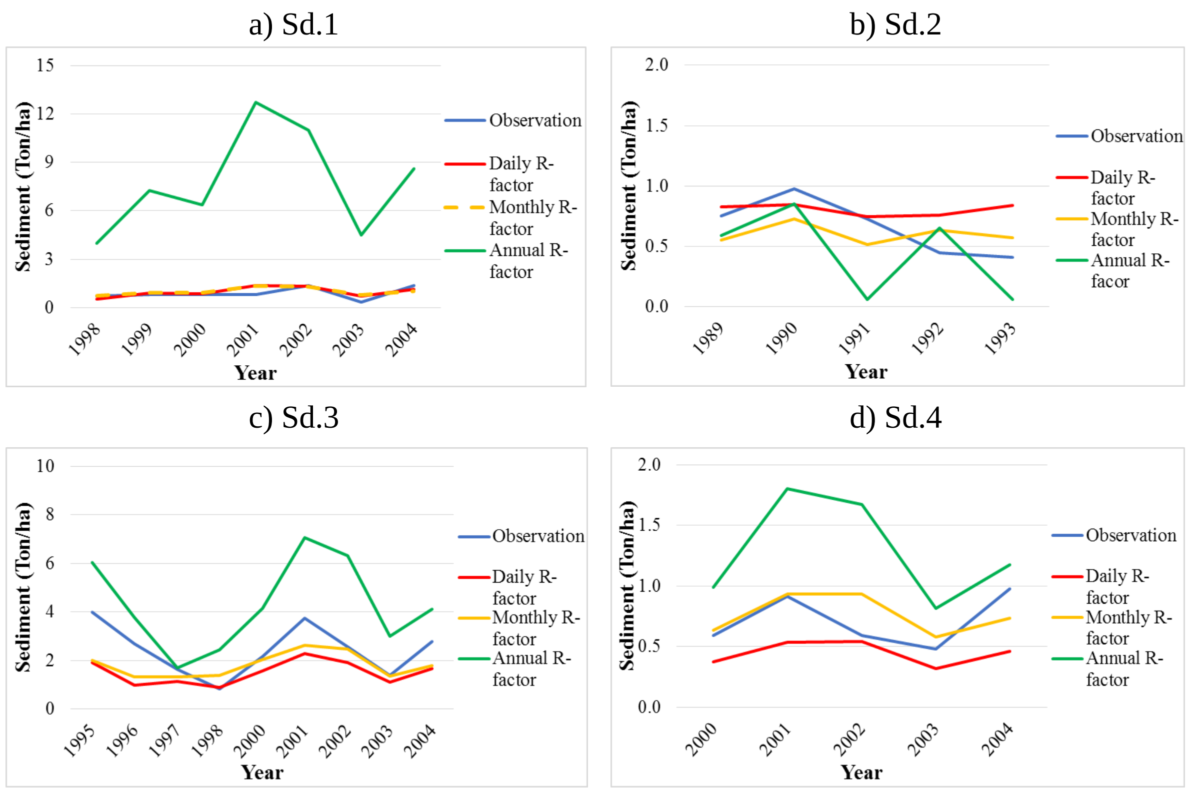


Figure 2.5 The results from comparison among sediment from daily and annual R-factor equation

Furthermore, the SEE value suggests that the accuracy levels of the daily and monthly R-factor equations are equivalent, but that the results from the monthly R-factor equation exceed those from daily R-factor equation due to the difference in the R-factor value. However, if the monthly sediment yield is considered, the results from the daily R-factor equation are superior to those from the monthly R-factor equation, due to the lower SEE value.

Table 2.2 The Standard Error of Estimate (SEE) of the monthly sediment yield from daily and monthly R-factor equation

Sediment station	Standard Error of Estimate (SEE)	
	From daily R-factor	From monthly R-factor
1	0.08	0.09
2	0.05	0.06
3	0.21	0.24
4	0.09	0.09

In view of the above, the daily R-factor equation was selected for this study, due to its precision and suitability for calculating soil erosion and sediment. While soil erosion and sedimentation processes may occur on a daily basis, the monthly R-factor equation can calculate only a single result per month. Therefore, the daily R-factor equation was deemed to be more suitable, and to yield more accurate sediment yield results compared with other equations.

Chapter 3

Impact of climate and land use changes

Soil erosion and sedimentation are currently significant global problems that are exacerbated both by natural influences and human activities, such as climate change and land use change. Climate change influences surface runoff by directly affecting rainfall intensity. Rainfall intensity and surface runoff are, in turn, important factors in soil erosion, particularly with regard to the detachment and transportation of material. In addition to problems related to climate change, land use change poses its own set of challenges, having an impact on natural resources including water, soil, and plants. Population increase has resulted in deforestation on a larger scale, for the purpose of agricultural expansion. These land use activities have had a substantial impact on soil erosion and sedimentation. Assiduous planning and management of changes in land use can help to regulate the soil erosion rate and amount of river sediment (Palmer *et al*., 2008, FAO, 2011). Therefore, interactions between land use change, climate change, and hydrologic processes are expected to be of major global interest in the coming decades.

However, most research has focused on the factors associated with soil erosion that cause river sedimentation, and on the impact of soil erosion on the environment. Little research has focused on the impact of climate change and land use change on soil erosion. There is also a dearth of research concerning the impact of climate change and land use change on sediment, owing to the limited availability of measurement data.

Therefore, a key objective of this dissertation is to analyze the impact of climate and land use changes on soil erosion and sediment in the Nan river basin using RUSLE, SDR, and the sediment transportation model. Detail of the model is shown in Appendix A.

This chapter explores the impact of climate change and land use changes on soil erosion and sediment yield in the entire Nan river basin area, including the upstream and downstream regions, to demonstrate the consequences of climate and land use changes. The upstream area is located in upper area of Nan river basin and downstream area was analyzed by the whole area of the study area; the total areas of these regions are 170 km^2 and 12,000 km^2, respectively. The average soil erosion and sediment yield from the entire upstream and downstream areas are presented in this study. The location of upstream and downstream area are shown in Figure 3.1.

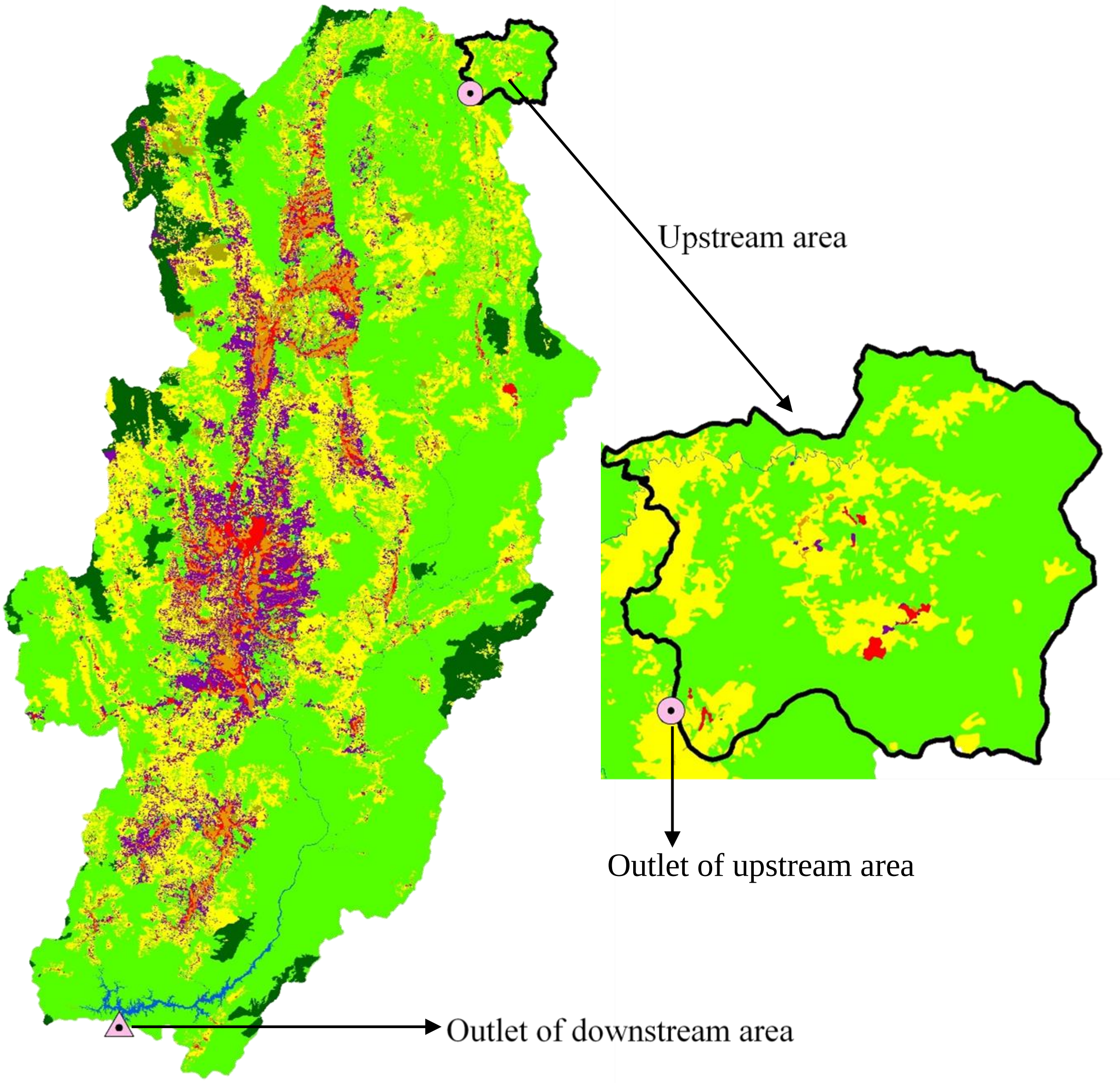


Figure 3.1 Location of upstream and downstream area of Nan river basin, which present by land use in 2016

This study examined eight specific cases (Table 3.1) to compare the impacts of land use change and climate change; past (hereafter, P; land use in 2000), current (hereafter, C; climate in 1985-2004 and land use in 2016), and future (hereafter F; climate in 2080–2099 and land use in the future (2036)) climate and land use data were considered. To estimate the impact of climate change on soil erosion and sediment, the results using climate data for different periods and land use data for the same periods were compared; to estimate the impact of land use change on soil erosion and sediment, the results using climate data for the same period and land use data for different periods were compared. For example, the results obtained using climate data for the period 1985–2004 (case C-P) were compared with those obtained using projected climate data for 2080-2099 (case F-P), based on land use in 2000. By contrast, the results obtained using land use data for 2000 (case C-P) were compared with those obtained using land use data for 2016 (case C-C) and projected future land use data (2036) (case C-F), based on climate data for the period 1985-2004. The severe climate and land use scenarios were also analyzed to demonstrate the extreme effects of climate change and land use change.

Table 3.1 List of case studies

Climate **Land use**	Current (1985-2004)	Future (2080-2099 from 3 GCM; IPSL, GFDL-ESM2M, and CNRM-CM5)
2000 (Past)	Case C-P (Used to calibrated)	Case F-P
2016 (Current)	Case C-C	Case F-C
2036 (Future; increase forest area)	Case C-F (1)	Case F-F (1)
2036 (Future; decrease forest area)	Case C-F (2)	Case F-F (2)

After the daily R-factor equation had been devised, the data for the H08 model, the soil erosion model, and the sediment model were prepared using a geographic information system (GIS). These data were then used to estimate soil erosion and sediment yield over several steps, as follows:

The first step used flow direction data and climate data to estimate runoff using a land-surface process module. Subsequently, the runoff result was used to estimate river discharge using a river module, while the SDR was calculated using the SDR model. The river module was calibrated and validated prior to being used for estimating the storage change of sediment in the third step.

In the second step, the soil erosion rate was calculated using RUSLE, prior to being multiplied by the SDR (obtained during the previous step) to calculate sediment yield in ton/ha and calibrated with observational data from 1992. Subsequently, the sediment yield from RUSLE and SDR (model 1) was compared with that calculated based on the precipitation and slope (model 2), to determine the most appropriate formula for estimating sediment yield; the first model was deemed most suitable.

During the third step, the change in river sediment storage was calculated using the river discharge value obtained in the first step, the sediment yield calculated in the second step, and sediment size and flow velocity using the sediment transportation model.

The final step involved calibration and validation of the soil erosion and sediment models prior to their use for estimating the impact of land use change and climate change on soil erosion and sediment yield. The methodology of this study is shown in Figure 3.2.

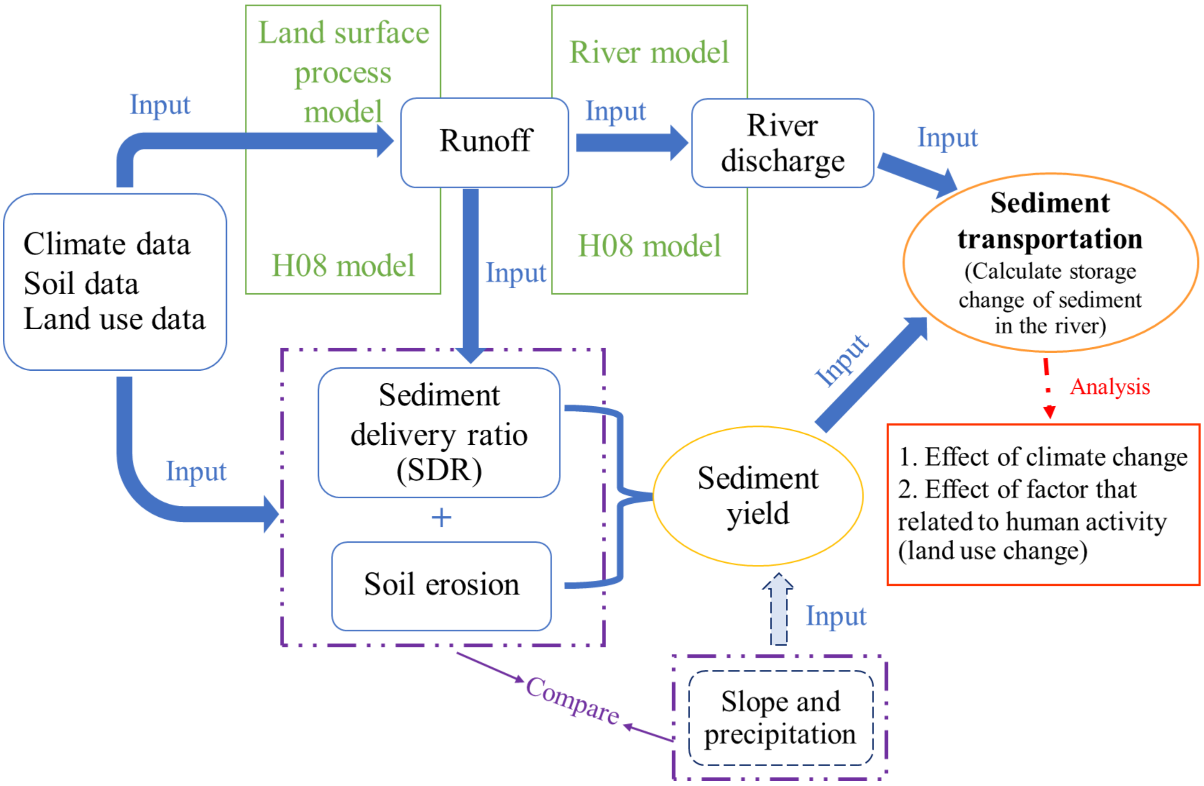


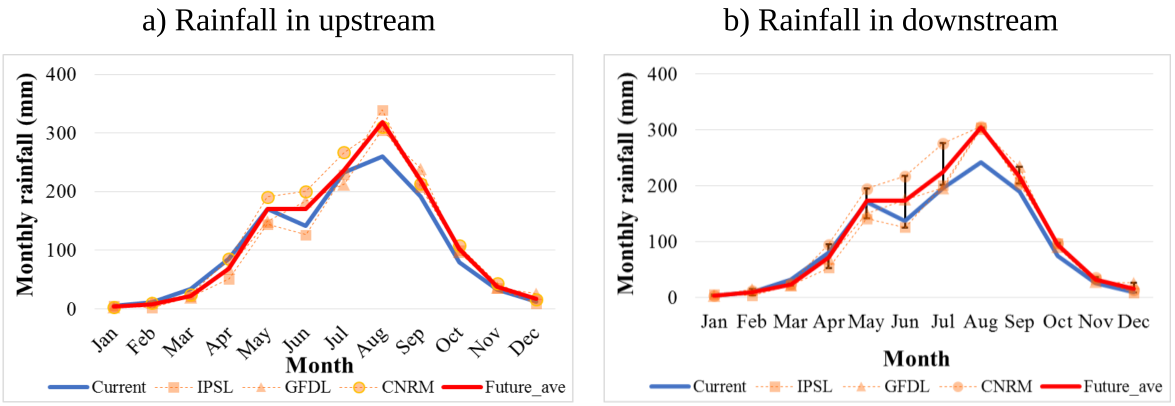
Figure 3.2 Methodology

3.1) Projected future rainfall changes based on current data from the Nan river basin

The estimation was conducted at the daily time scale at 1 arc-minute spatial resolution, or approximately 2 × 2 kilometers by the climate data from the IMPAC-T project for the periods 1985–2004 and 2080–2099, to estimate soil erosion and sediment yield in the Nan river basin. The monthly average rainfall values were from three datasets, CNRM-CM5, GFDL-ESM2M, and IPSL-CM5A-LR in 2080–2099. The monthly average rainfall data for the period 1985–2004 show that the rainfall data in the downstream area of the Nan river basin (2080–2099) is projected to decrease from March to April and increase during other months. It increases and decreases by an average of approximately 19 mm, or 18%, and 9 mm, or 16% of the current rainfall, respectively. Upstream, monthly rainfall tends to increase by approximately 22 mm, or 16% of the current rainfall from June to December, decreasing from January to May by approximately 7 mm, or 11%. Moreover, considering rainfall changes across the entire year, the average annual rainfall both downstream and upstream was found to increase by approximately 14.2 mm, or 14.5%, and 9.8 mm, or 9.4% of current average rainfall, respectively (Table 3.2, Figure 3.3, and 3.4).

Table 3.2 Difference value and % difference between average rainfall data in current and future (mm)

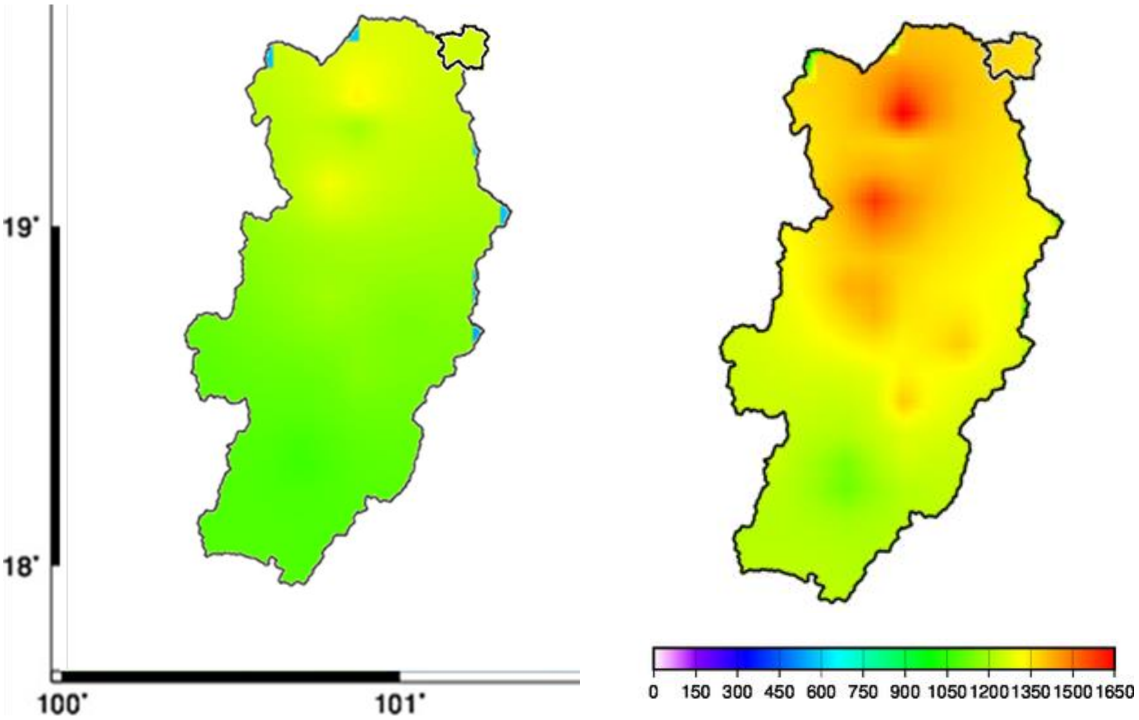
Month	**Difference value (mm)**		**% Difference**	
	Upstream	Downstream	Upstream	Downstream
Jan	-1.1	0.1	-20.9	1.7
Feb	-2.9	0.9	-25.9	9.8
Mar	-12.2	-9.8	-35.8	-29.8
Apr	-17.4	-8.2	-20.2	-10.1
May	-0.5	2.6	-0.3	1.5
June	28.5	35.2	20.1	25.5
July	3.3	28.6	1.4	14.6
Aug	58.5	62.1	22.5	25.6
Sep	28.6	25.8	14.9	13.6
Oct	22.8	20.4	28.8	27.2
Nov	5.8	6.2	18.0	23.7
Dec	4.2	6.6	32.8	67.8
Annual	9.8	14.2	9.4	14.5


a) Rainfall in upstream

b) Rainfall in downstream

Figure 3.3 difference value of rainfall in upstream (a) and downstream (b)

Remark: Current is the name of climate dataset in the current (1985-2004). IPSL, GFDL, and CNRM are the climate dataset in the future (2080-2099) and Future_ave mean the average rainfall from 3 climate dataset in the future (IPSL, GFDL, and CNRM).


a) Average annual rainfall from climate data in 1985-2004 (current)

b) Average annual rainfall from climate data in 2080-2099 (future)

Figure 3.4 Average annual rainfall from rainfall data in current, 1985-2004 (a) and rainfall data in future, 2080-2099 (b)

3.2) Land use change in Nan river basin

Land use data for Nan river basin in 2000 and 2016 were provided by the Land Development Department (LDD). The data indicate that, in 2000, the land was covered with degraded forest and field crops covering approximately 3,794.4 km^2, or 31.6 %, and 3,224.2 km^2, or 26.9 % of the total area, respectively. In 2016, field crop covered 2,752.8 km^2, or 22.9%, of the total area and deciduous forest covered 6,853.2 km^2, or 57.1%, of the total area. Future land use was projected using the CLUE model, which was developed to simulate land-use change using empirically quantified relationships between land use and its driving factors (Verburg, 2010). In this study, the 2016 land use data were used as the baseline data for simulation of two future land use scenarios, and land use data from 2009 were used to verify the accuracy of the model. In the first scenario, the forest area was converted into other land use types by increasing the forested area in accordance with the RID’s strategy for watershed management of the Nan river basin (HAII, 2012), which is aimed at increasing the forested area by approximately 5% of the total area within 20 years. In the second scenario, the forested area was decreased by around 5% of the total area and given over to other land use types, such as field crops (Figure 3.5).

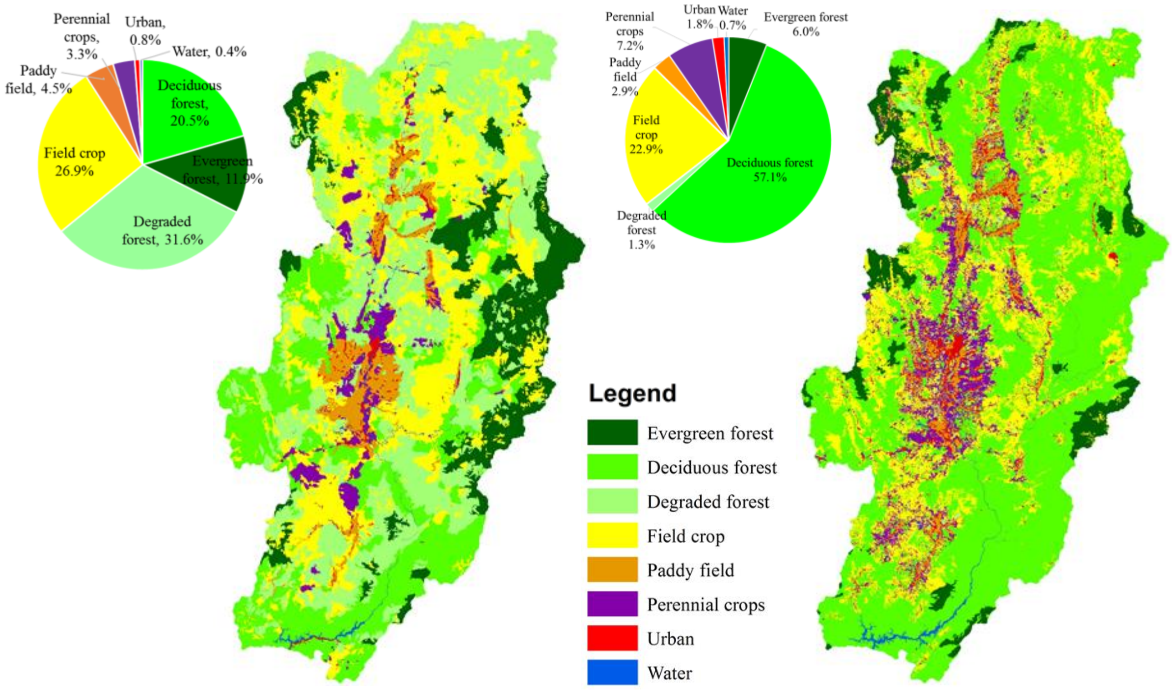
The impact of land use change on soil erosion and sedimentation in the downstream area was analyzed based on land use in the entire Nan river basin area. Land use change was projected for approximately 5% of its total area, of 12,000 km^2 (Table 3.3 and Figure 3.6). Moreover, the soil erosion and sediment yield of the upstream area were calculated from the upper area of the Nan river basin, the total area of which is 170 km^2. Future land use change in the upstream area is expected to exceed 5% of the total area. Compared with land use data from 2016, the deciduous forest in future scenario 1 (F1) is increased by approximately 20% of the total area, and deciduous forest in future scenario 2 (F2) is decreased by approximately 6% of the total area (Table 3.4).

Table 3.3 Land use in downstream area of Nan river basin

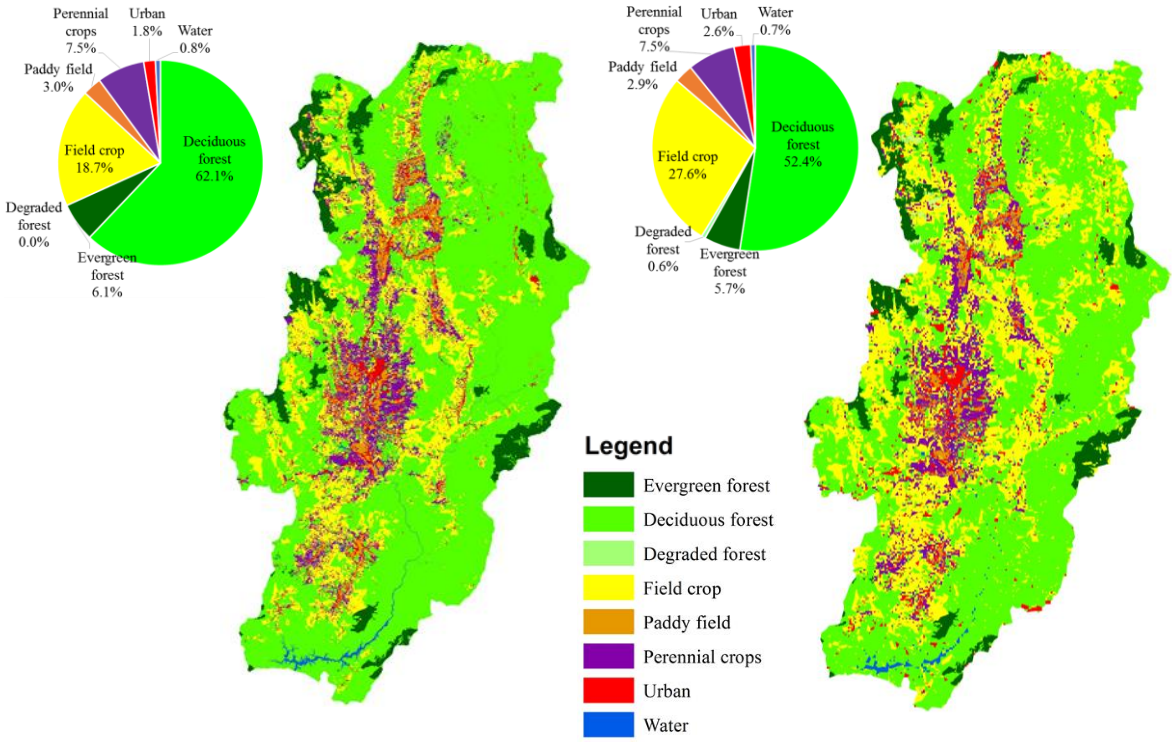
Year	Area (Km^2)			
Land use type	2000	2016	2036 (1)	2036 (2)
Evergreen forest	1429.8	721.5	734.3	681.9
Deciduous forest	2465.2	6853.2	7453.2 (↑ 5%)	6289.7 (↓ 5%)
Degraded forest	3794.5	160.4	0	71.7
Field crop	3224.1	2752.8	2242	3310.2
Paddy field	540	348.2	355.2	351.7
Perennial crops	400.1	862.1	900.5	894.5
Urban	95	214.3	220.4	315.1
Water	51.2	87.4	94.4	85.2
Total	12000	12000	12000	12000

Table 3.4 Land use in upstream area of Nan river basin

Year	Area (Km^2)			
Land use type	2000	2016	2036 (1)	2036 (2)
Evergreen forest	0	0	0	0
Deciduous forest	0.9	128.2	162.8 (↑ 20.4%)	117.6 (↓ 6.3%)
Degraded forest	149.5	0	0	0
Field crop	19.7	39.8	5.5 (↓ 20.2%)	50.5 (↑ 6.3%)
Paddy field	0	0.3	0.03	0
Perennial crops	0	0.3	0.31	0
Urban	0	1.1	1.13	1.5
Water	0	0.2	0.25	0.5
Total	170	170	170	170


a) Land use in 2000

b) Land use in 2016


c) Land use in 2036 (scenario 1)

d) Land use in 2036 (scenario 2)

Figure 3.5 Land use in Nan river basin

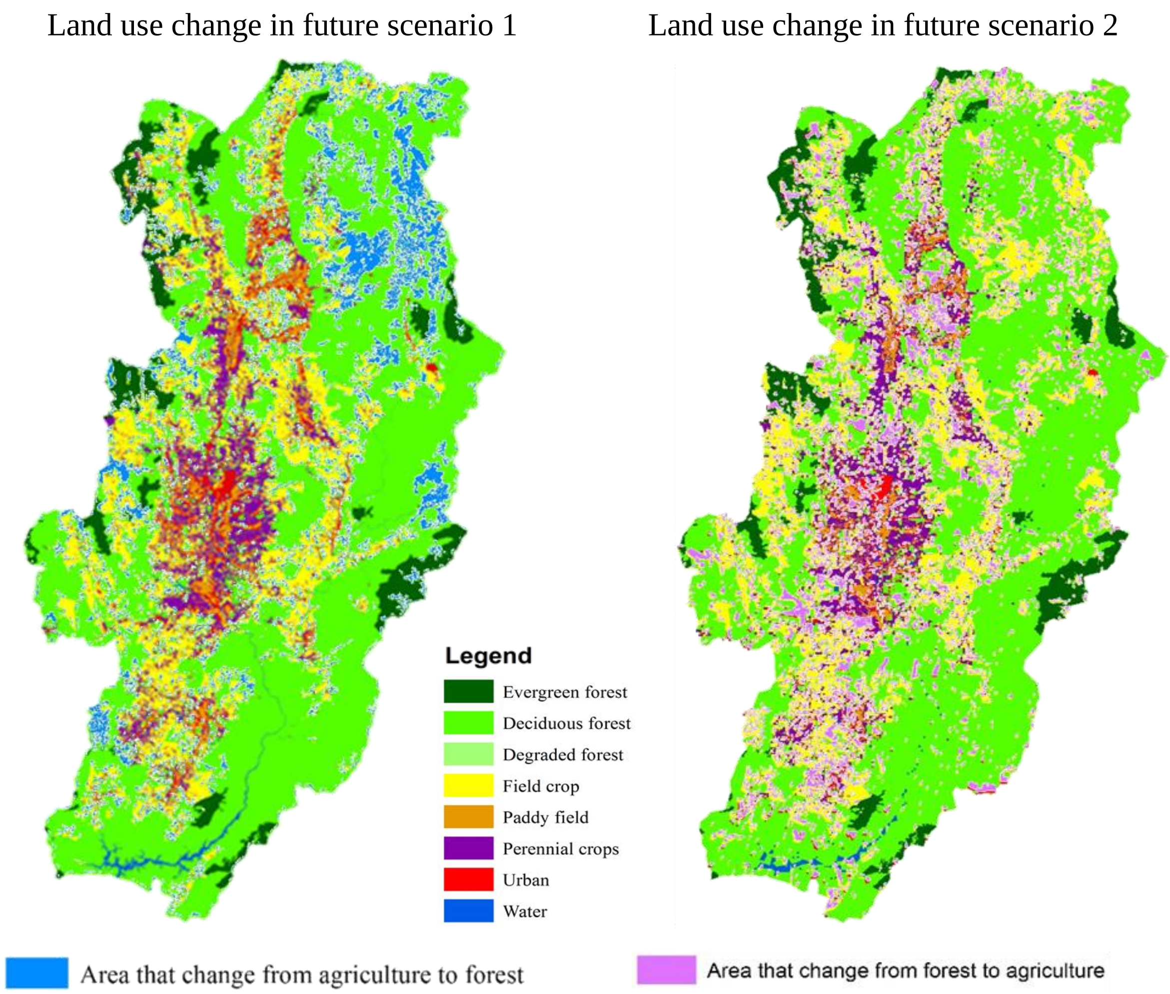
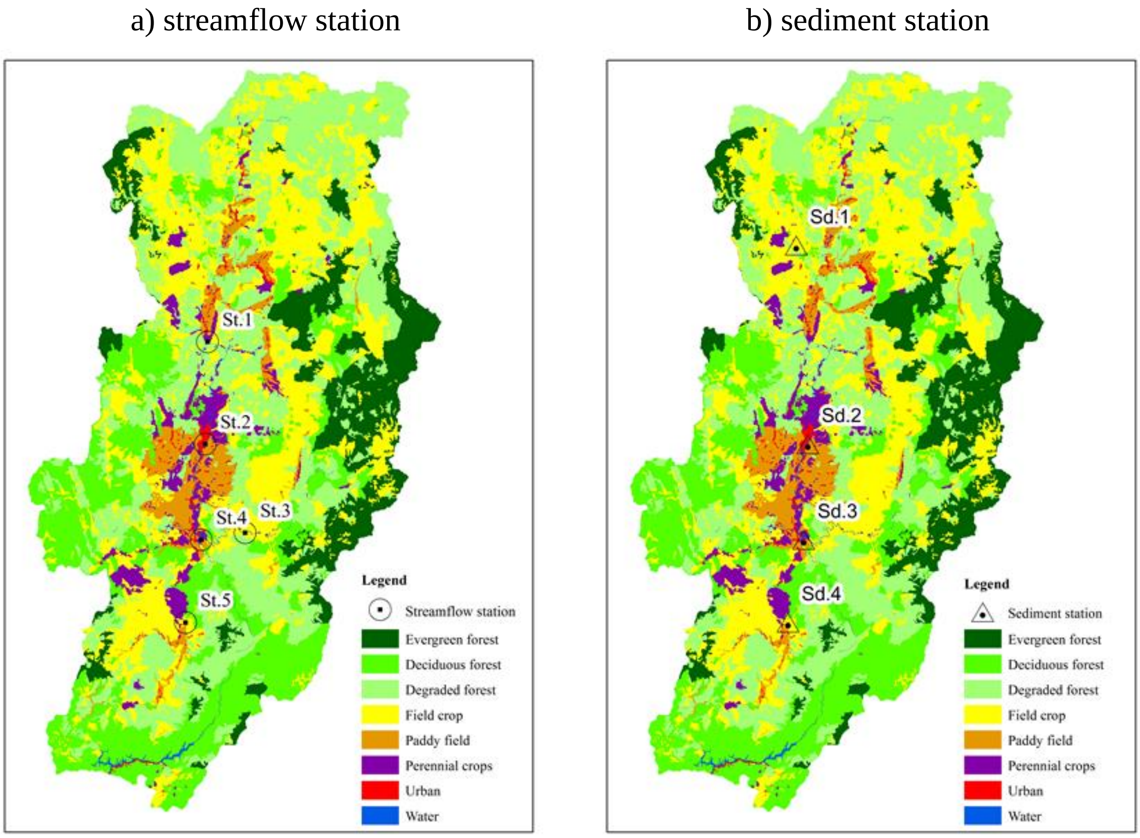


Figure 3.6 Land use change in the future in whole area of Nan river basin; a) Land use change in future scenario 1, and b) Land use change in future scenario 2

3.3) Calibration and validation of the model

3.3.1) Data used for calibration and validation of the model

River discharge data for the period 1985-2004 from five observation stations in the Nan river basin of the Royal Irrigation Department (RID, 2017) (Figure 3.7a), and inflow data for the Sirikit reservoir for the period 1985-2004, obtained from the Electricity Generating Authority of Thailand (EGAT), were used to calibrate and validate the river model. Sediment data for the period 1989-2004 from four observation stations of RID (Figure 3.7b) were used to calibrate and validate the sediment model. Additionally, soil erosion data collected between April and October 1992 at the Nan watershed research station were used to calibrate the soil erosion model.



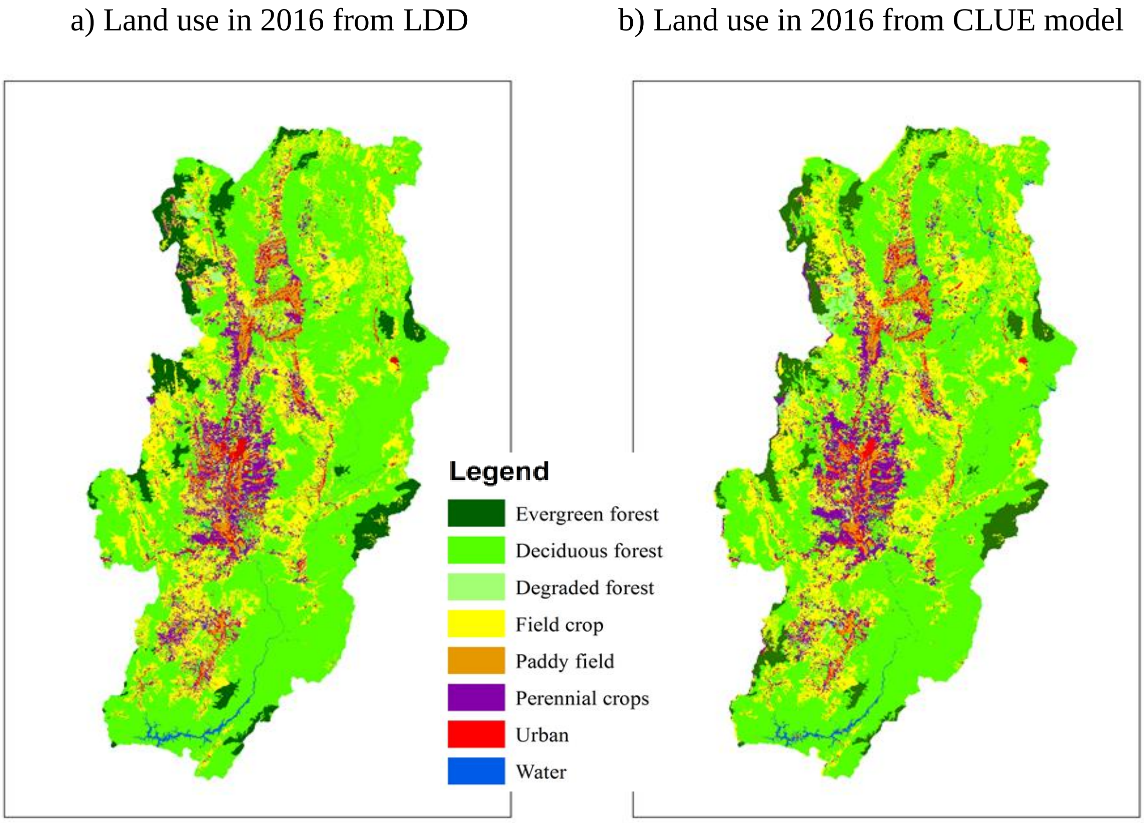
a) streamflow station

b) sediment station

Figure 3.7 Location of streamflow and sediment station in Nan river basin

3.3.2) Accuracy of the CLUE model

The accuracy of the CLUE model was verified prior to use to generate the future land-use map. This study verified the accuracy of the model by mapping the land use for 2016 based on land use data for 2009, obtained from Thailand’s Land Development Department (LDD) and corroborating the similarity between the result for 2016 yielded by the CLUE model and the data provided by the LDD. The results from the CLUE model corroborated the land use data from the LDD for over 82% of the total area (Figure 3.9). Furthermore, the results revealed that the changes in primary land use, such as evergreen forest, deciduous forest, and field crop, visible in the CLUE model simulation closely corroborate the land use changes evident from the data provided by the LDD (Table 3.5 and Figure 3.8). However, there was an error in the CLUE model’s simulation of small land use areas, such as water bodies. Land use in 2016 from LDD and CLUE model are shown in Figure 3.8a and 3.8b, respectively.



a) Land use in 2016 from LDD

b) Land use in 2016 from CLUE model

Figure 3.8 Land use in 2016 from a) LDD and b) CLUE model

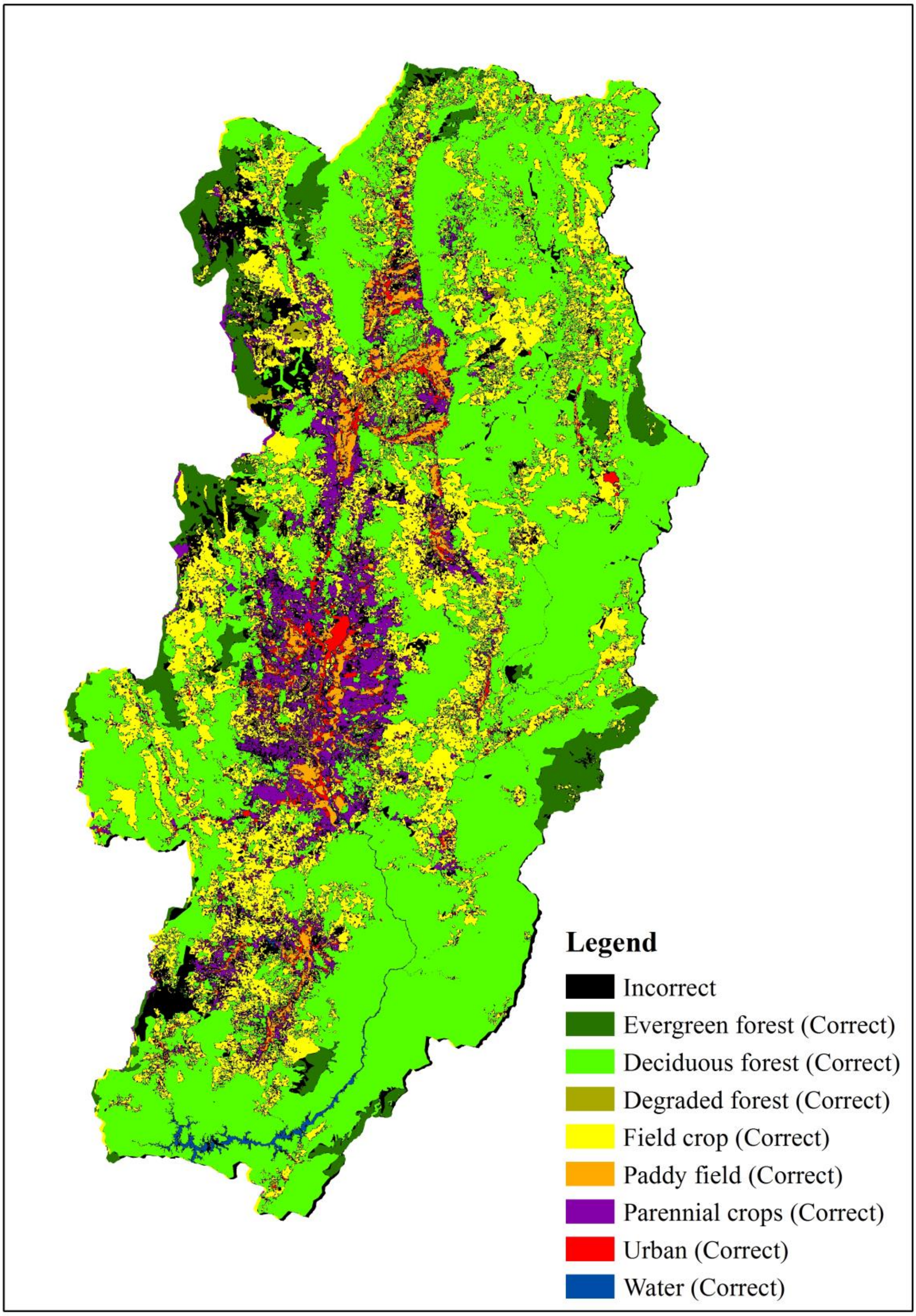


Figure 3.9 The comparison of Land use in 2016 from LDD and CLUE model. Incorrect means that the land use change from 2009 to 2016 by CLUE model is different from the land use change data of LDD.

Table 3.5 The comparison of land use in 2016 from LDD and CLUE model (Km^2)

		Land use in 2016 from LDD (Km^2)							
		Evergreen forest	Deciduous forest	Degraded forest	Field crop	Paddy field	Perennial crops	Urban	Water
Land use in 2016 from CLUE model (Km^2)	Evergreen forest	650.2	125.6	0.4	40.9	0.1	3.1	0.1	0.0
	Deciduous forest	76.6	6003.2	39.6	340.3	15.2	101.7	13.4	21.7
	Degraded forest	0.4	42.9	55.9	48.6	2.6	14.7	1.8	0.5
	Field crop	26.0	352.2	50.6	2234.6	31.3	140.1	16.3	10.6
	Paddy field	0.1	10.2	4.5	25.9	260.7	28.9	25.4	8.3
	Perennial crops	1.8	37.6	14.8	165.0	35.3	597.1	18.8	6.1
	Urban	0.5	11.6	1.7	19.4	17.6	13.9	146.6	4.7
	Water	0.0	29.8	0.4	5.8	1.8	3.0	2.0	39.7
	Total	755.5	6613.1	167.9	2880.5	364.6	902.5	224.4	91.5

Table 3.6 The comparison of land use in 2016 from LDD and CLUE model (%)

		Land use in 2016 from LDD (%)							
		Evergreen forest	Deciduous forest	Degraded forest	Field crop	Paddy field	Perennial crops	Urban	Water
Land use in 2016 from CLUE model (%)	Evergreen forest	86.1	1.9	0.3	1.4	0.0	0.3	0.1	0.0
	Deciduous forest	10.1	90.8	23.6	11.8	4.2	11.3	6.0	23.7
	Degraded forest	0.1	0.6	33.3	1.7	0.7	1.6	0.8	0.5
	Field crop	3.4	5.3	30.1	77.6	8.6	15.5	7.3	11.6
	Paddy field	0.0	0.2	2.7	0.9	71.5	3.2	11.3	9.0
	Perennial crops	0.2	0.6	8.8	5.7	9.7	66.2	8.4	6.7
	Urban	0.1	0.2	1.0	0.7	4.8	1.5	65.3	5.1
	Water	0.0	0.5	0.2	0.2	0.5	0.3	0.9	43.4
	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 3.7 The difference of land use change from 2009 to 2016 from LDD and CLUE model

		Land use in 2016 from LDD (Km^2)								**Total**
		Evergreen forest	Deciduous forest	Degraded forest	Field crop	Paddy field	Perennial crops	Urban	Water	
Land use in 2016 from CLUE model (Km^2)	Evergreen forest	-	13.6	0.7	-10.2	0.0	1.3	0.2	0.0	5.7
	Deciduous forest	59.3	-	12.8	126.9	13.0	27.4	9.7	15.1	264.1
	Degraded forest	0.3	-12.2	-	-26.7	2.2	0.5	0.8	0.4	-34.7
	Field crop	-14.8	193.3	-48.9	-	19.1	-36.2	9.7	7.0	129.2
	Paddy field	0.1	12.3	4.4	13.6	-	14.2	20.7	6.5	71.7
	Perennial crops	0.8	-23.7	-3.8	1.5	23.4	-	10.2	5.3	13.7
	Urban	0.3	9.5	0.0	20.6	13.6	4.5	-	3.6	52.3
	Water	0.0	30.9	0.1	3.4	0.3	2.1	1.0	-	37.8
	Total	46.0	223.8	-34.7	129.2	71.7	13.7	52.3	37.8	

Remark: This table calculate from the land use change data from 2009 to 2016 of LDD and CLUE model in whole area of Nan river basin (It is the difference between table 3.5 and 3.6)

Following verification of the CLUE model's accuracy, the H08 model, soil erosion, sediment, and sediment transportation models were calibrated based on land use type. The procedure was as follows: first, the river discharge simulated by the H08 model using climate data for 1985-1994 was calibrated with observational data, including inflow to the Sirikit reservoir, from five stations. The calibration value was used to validate the model outputs for 1995-2004. Subsequently, the soil erosion and sediment models calculated using climate data for 1989-2004 and land use data from 2000 were calibrated and validated with the soil erosion measurements for 1992 from the Nan watershed research station, and sediment data from four stations of RID, respectively. However, owing to the limitations of the soil erosion measurement data, soil erosion data from the Nan watershed research station was used to calibrate the soil erosion only for deciduous forestation, while other land use types were calibrated and validated via the sediment and sediment transportation models. The procedures of calibration and validation are shown in Figure 3.10.

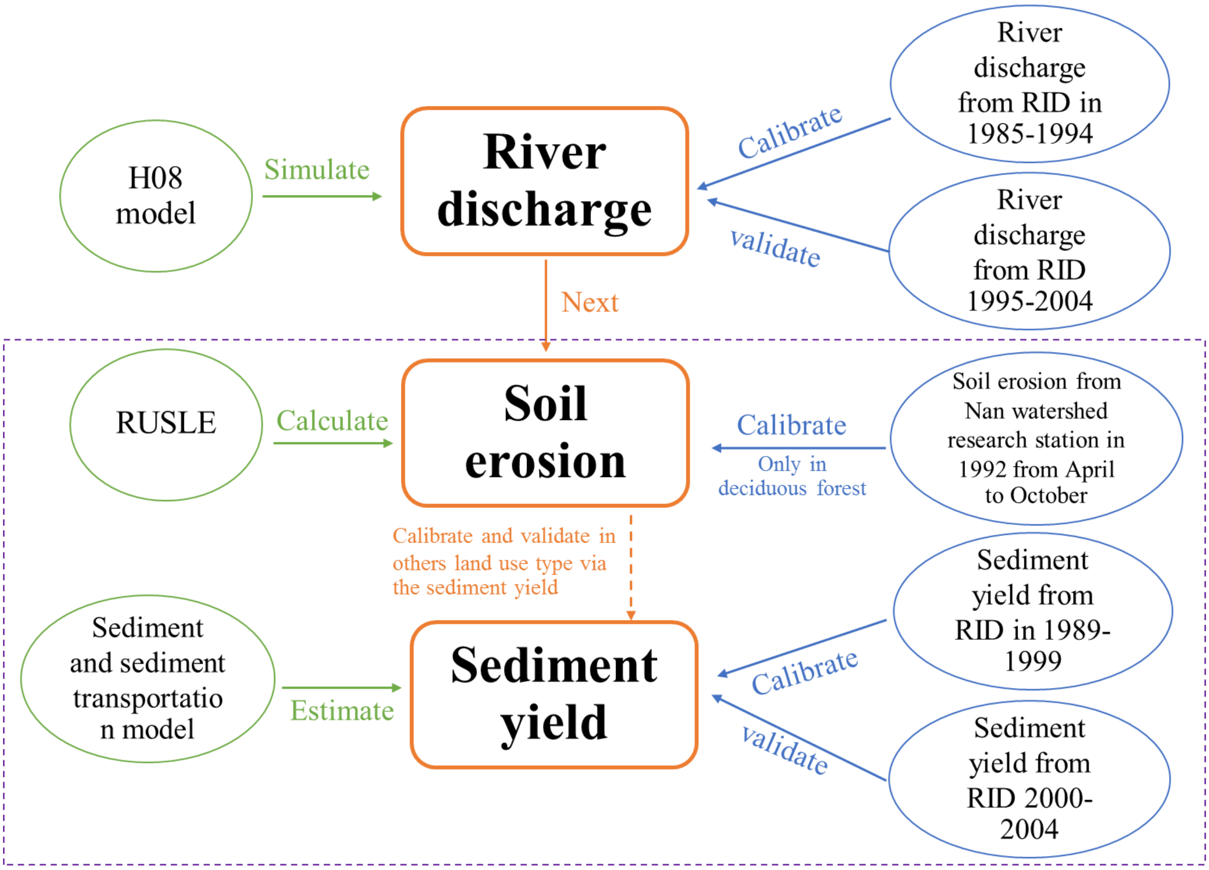


Figure 3.10 The procedures of calibrate and validate the model

3.3.3) Calibration and validation of the H08 model

The parameters of the H08 model that are susceptible to river discharge and associated with land use are soil depth (SD), the bulk transfer coefficient (C_D), the time constant for daily maximum subsurface runoff (TAU (day), τ), and a shape parameter that is related to sub-surface flow (Gamma, γ) (Hanasaki *et al*., 2008, Mateo *et al*., 2012). Gamma, Tau, and SD control the baseflow and C_D directly controls the evapotranspiration (Hanasaki *et al*., 2014). Prior to calibration, the default values of SD, C_D, Gamma and Tau provided by Mateo *et al.* (2012) were used to estimate river discharge in the Nan river basin. The default values of SD, C_D, Gamma and Tau are 1.0. 0.003, 2.0 and 100.0, respectively. Subsequently, this study modified the SD parameter from the soil depth that can sustain plant root growth, based on soil series and soil group data provided by the LDD and forest area soil data provided by Thailand's Royal Forest Department. These data suggest that the soil depths in agricultural areas are very large, at over 150 cm, while the average soil depth of forested areas is between around 79 and 135 cm (TMD, 2000, Murata *et al.*, 2009, Royal Forest Department, 2018). Moreover, this study modified the C_D, which is related to the evapotranspiration generated by the land use type. Shiklomanov and Krestovsky (1988) observed that evapotranspiration in forest areas between 30 and 100 years old exceeded that of agricultural areas, and Verstraeten *et al.* (2005) observed the average annual evapotranspiration of forest areas to be 491 mm, which is higher than that of an agricultural area at around 93 mm.

The model can be calibrated by changing the values of the parameters, based on land-use type and evaluated using the Nash-Sutcliffe Efficiency Coefficient (NSE). When the NSE value is close to 1, both outcomes agree; when the NSE value is close to or lower than 0, the groups do not agree (Suwanlertcharoen, 2011). The optimum parameter set calibrated in each land use is shown in Table 3.8.

Table 3.8 Results of optimum parameter set calibrated in each land use

Land use	Parameter	Value	Land use	Parameter	Value
Paddy field	Soil Depth (m)	1.5	Forest	Soil Depth (m)	1.7
	C_D	0.0005		C_D	0.001
	GAMMA (γ)	1.8		GAMMA (γ)	1.7
	TAU (τ, day)	110		TAU (τ, day)	140
Field crop	Soil Depth (m)	2.0	Urban	Soil Depth (m)	1.5
	C_D	0.00045		C_D	0.0006
	GAMMA (γ)	1.5		GAMMA (γ)	1.7
	TAU (τ, day)	120		TAU (τ, day)	100
Perennial Crops	Soil Depth (m)	2.3			
	C_D	0.0045			
	GAMMA (γ)	1.7			
	TAU (τ, day)	120			

In this study, the discharge from the Nan river basin in case C-P (climate data in 1985-2004 and land use in 2000) from the simulation was used to calibrate and validate the H08 model. For the calibration, evaluation of the accuracy and compatibility of the monthly flow rate using measurements from the Nan river basin and the H08 model yielded NSE values for case C-P at stations 2 and 4, and inflow from Sirikit reservoir, of 0.73, 0.87 and 0.50, respectively. For the validation, NSE values for case C-P at stations 1-5 and inflow from Sirikit reservoir are 0.88, 0.74, 0.64, 0.87, 0.74 and 0.52, respectively (Table 3.9). The NSE values indicate that the model is well calibrated and suitable for simulating cases of land use change. The result before and after calibrate are shown in Figure 3.11 and the result from validation are shown in Figure 3.12.

Table 3.9 Nash-Sutcliffe efficiency value after calibration and validation of the H08 model by observation data.

Calibration		
Station name	NSE value	Data periods
St.2	0.69	1985-1994
St.4	0.81	1988-1994
Inflow of Sirikit reservoir	0.61	1985-1994
Validation		
Station name	NSE value	Data periods
St.1	0.82	1995-2004
St.2	0.67	1995-2004
St.3	0.72	1993-2002
St.4	0.72	1995-2004
St.5	0.79	1997-2004
Inflow of Sirikit reservoir	0.71	1995-2004

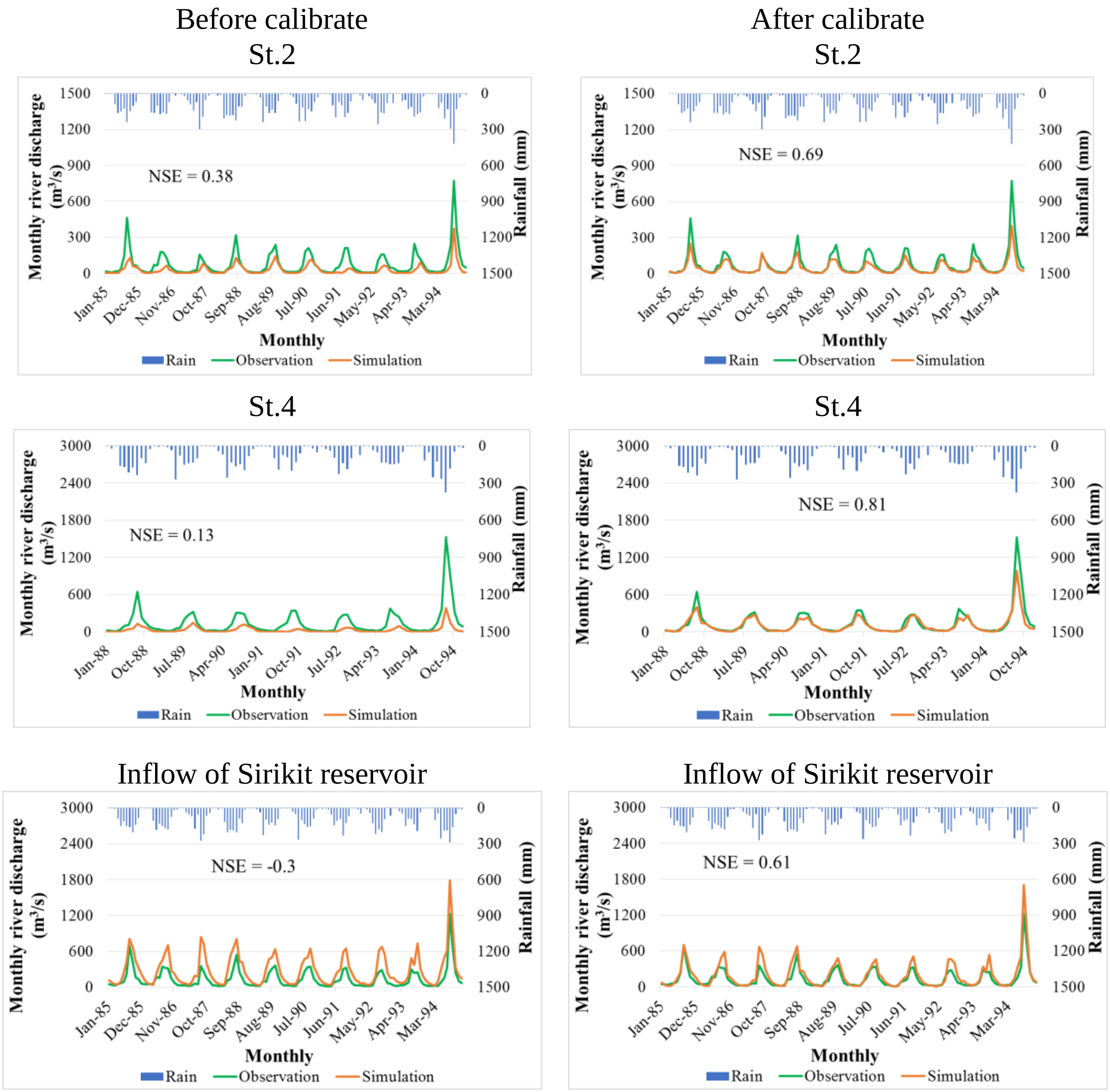


Figure 3.11 The result before and after calibration of H08 model (Sd.2 and Sd.4 are the name of streamflow station)

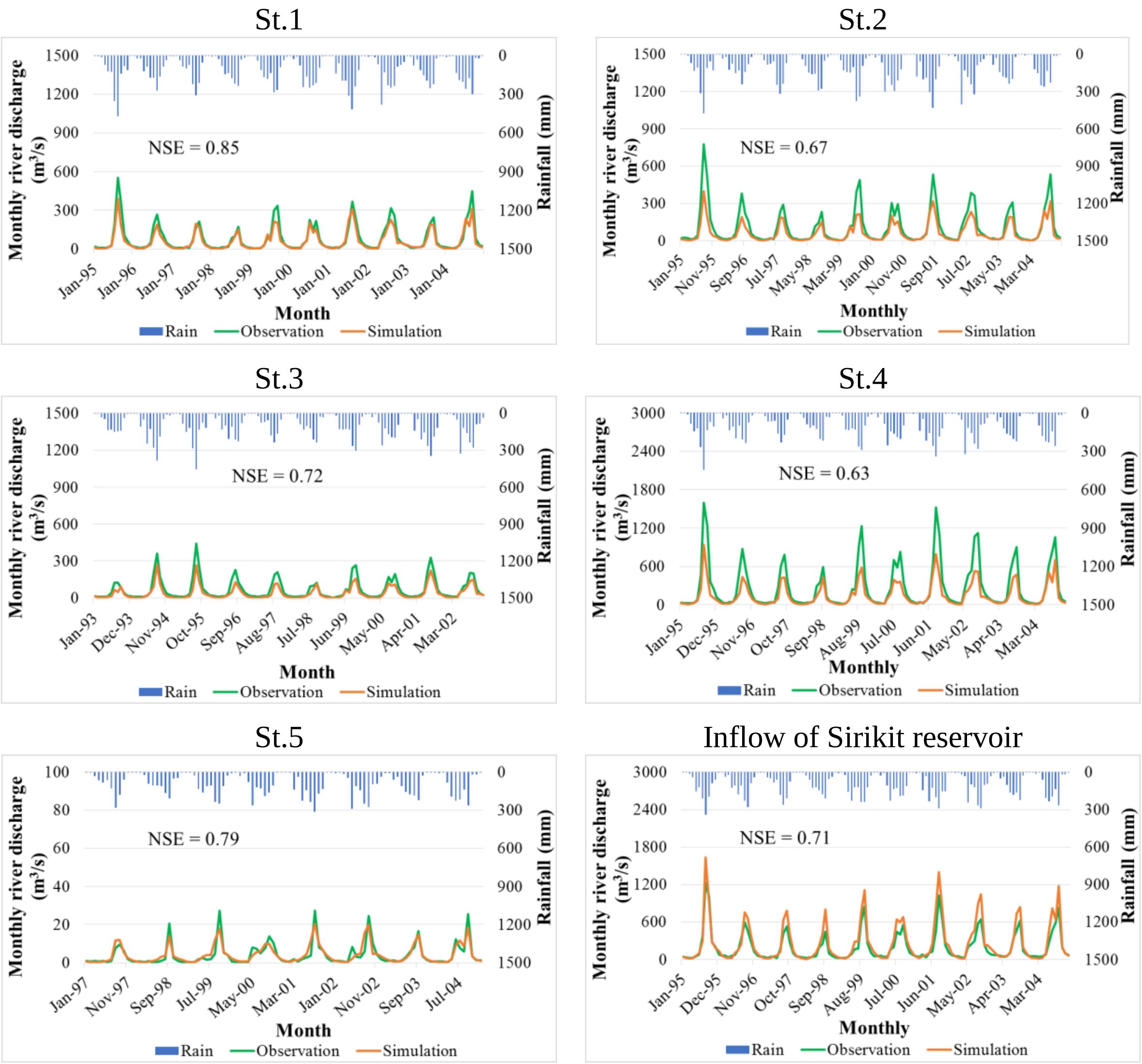


Figure 3.12 The result after validation of H08 model (St.1, St.2, St3, St.4, and St.5 are the name of streamflow station)

The NSE values of these results were close to 1, meaning that the river discharge can be effectively simulated using the H08 model with an optimized set of parameters, and that the H08 model is suitable for estimating the influence of land use change and climate change on river discharge. This is consistent with Mateo's findings regarding the optimization parameters of the H08 Land Surface Model in the Chao Phraya river basin (Mateo *et al*., 2012), i.e., that H08 could be an effective tool in projecting river discharge and could also be used for projections under climate change scenarios.

3.3.4) Soil erosion and sediment models

Soil erosion and sediment models are used to estimate the soil erosion and sediment yield, based on the relationship between soil erosion and sediment yield and their driving factors, including land use, climate, and soil (Morgan and Nearing, 2011, Blaikie, 2016). The potential for soil erosion is determined based on the fundamental factors of surface runoff, infiltration, plant growth, and erosion mechanics (Coit *et al.*, 2014). The sediment model is designed based on an understanding of the process of sedimentation, i.e., the movement of sediment from a source to a sink in a catchment (Bracken *et al.*, 2015). The soil erosion and sediment models may be used to explain the transfer of soil particles from mountainous areas to rivers (Ouyang and Bartholic, 1997, Ganasri and Ramesh, 2016).

Soil erosion and sediment models are useful for estimating future results. Nevertheless, most currently used models focus on soil erosion and there are very few sediment models. Two equations have been widely used worldwide to model sediment. The first combines RUSLE with SDR to calculate monthly sediment yield. The second is a sediment equation based on the precipitation and slope, measured in degrees.

(1) Comparison of the sediment models

Prior to calibration, the results from the two sediment models were compared to determine the optimal model for calculating sediment yield. The sediment yield result from the first equation (RUSLE combined with SDR) was compared with that from the second equation (calculated according to the intensity of precipitation and the slope). The NSE value of the comparison between the simulation data and observational data for the period 1989-2004 indicates that the result yielded by the first model has superior accuracy to that yielded by the second model, due to the number of factors that are consistent with the actual sediment yield scenario. The result is shown in Figure 3.13, NSE value and period of the data shown in Table 3.10.

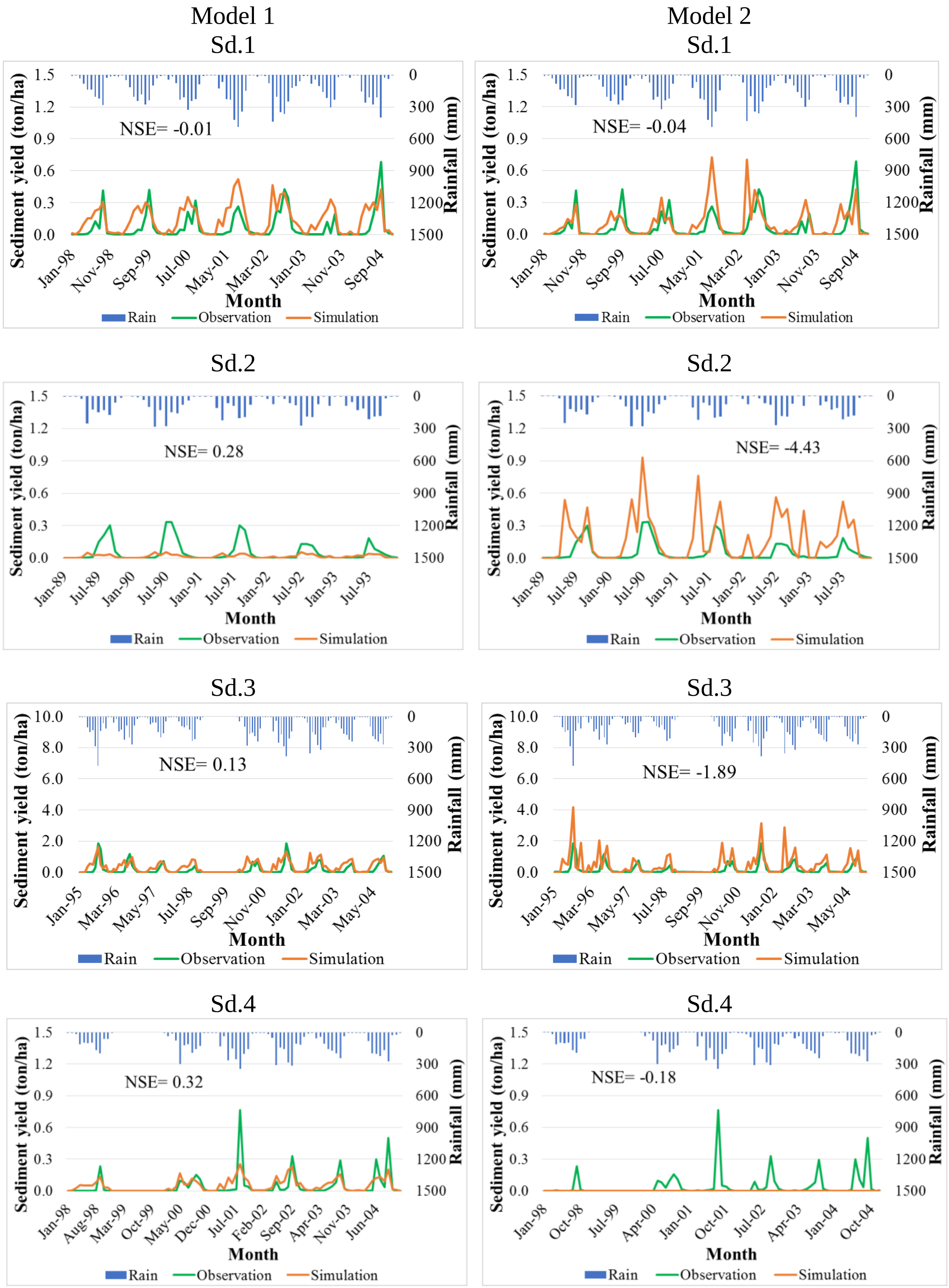


Figure 3.13 The accuracy of the first and second sediment model

Remark: Sd.1, Sd.2, Sd.3, and Sd.4 are the name of sediment station and there are no measurement data on 1999 at sediment station 3 and 4 (sd.3 and sd.4)

Table 3.10 Nash-Sutcliffe efficiency value of first and second sediment model

Station name	**Nash-Sutcliffe efficiency (NSE value)**		**Data periods**
	Model 1 (RUSLE * SDR)	Model 2 (precipitation * slope)	
Sd.1	-0.01	-0.04	1998-2004
Sd.2	0.28	-4.43	1989-1993
Sd.3	0.13	-1.89	1995-1998, 2000-2004
Sd.4	0.32	-0.18	1998, 2000-2004

(2) Calibration and validation of the soil erosion and sediment models

The parameter associated with land use in the soil erosion model is the crop management factor, or C-factor, which measures the combined effects of interrelated cover and management variables and is easily influenced by human activity (Karaburun, 2010). Prior to calibration of the model, the C-factor provided by LDD was used to calculate the soil erosion rate. The C-factor values after calibration are presented in Table 3.11. The soil erosion rate from April to October in 1992 for case C-P was used for calibration with observational data from the Nan watershed research station. The evaluation of the model's accuracy using the NSE demonstrates that the model is well calibrated, with an NSE of 0.61 (Figure 3.14).

Table 3.11 Results of optimum parameter of soil erosion model

Land cover	**C-factor value**	
	Before calibrate	After calibrate
Field crop	0.34	0.42
Evergreen forest	0.001	0.001
Deciduous forest	0.019	0.015
Degraded forest	0.25	0.15
Paddy field	0.28	0.30
Perennial crop	0.15	0.20
Urban	0	0.08

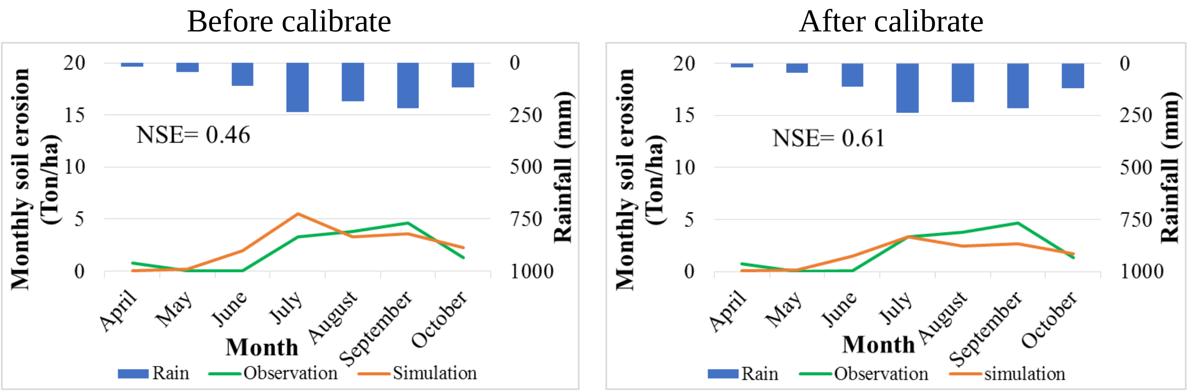


Figure 3.14 The accuracy of soil erosion model before and after calibration

Subsequently, the soil erosion and sediment models were calibrated using the modified C-factor value (Table 3.11), the rain intensity value and peak rainfall in the SDR model, and the setting velocity, depth to bedload, size distribution ratio parameters, and detachment velocity parameter in the sediment transportation model (Table 3.12). The average peak rainfall at the Nan river basin, calculated from 30 years of climate data (1981-2010) and provided by the Thai Meteorological Department (TMD), was initially used as the peak rainfall in the SDR model.

The sediment in the Nan river basin in the simulation case C-P was used to calibrate and validate the storage change from the sediment transportation model. For the calibration, the accuracy and compatibility of the monthly sediment result was evaluated using measurements from the Nan river basin and the results from the model, where the NSE values for case C-P at stations sd.1- sd.3 were 0.72, 0.67, and 0.59, respectively. For the validation, the NSE values for case C-P at stations sd.1, sd.3, and sd.4 were 0.57, 0.75, and 0.44, respectively (Table 3.13). When the NSE value is equal to or higher than 0.5 but lower than 1, both outcomes may be said to be in strong agreement; when the NSE value is equal to or higher than 0 but lower than 0.5, the model's accuracy is moderate; and when the NSE value is lower than 0, the groups are poorly aligned (Kamoshida and Hanasaki, 2016). This calibration demonstrates that the NSE value represented in the sediment model is moderately to highly accurate, and can be used to estimate future sediment storage, with NSE values that are mostly higher than 0.5. The result before and after calibration are shown in Figure 3.15 and the result after validation is shown in Figure 3.16.

Table 3.12 Results of optimum parameter of sediment transportation model

Model	**Parameter**	**Value**	
		Before calibrate	After calibrate
SDR	Rain intensity (mm/hr)	20	11
	Peak rainfall (mm)	1450	1650
Sediment transportation	Parameter of setting velocity	1	0.6
	Depth to bedload	2	5
	Size distribution ratio	1	0.1
	Parameter of detachment velocity	1	0.8

Table 3.13 Nash-Sutcliffe efficiency value from calibration and validation of the sediment model.

Station name	NSE value	Data periods
Calibration		
Station name	NSE value	Data periods
Sd.1	0.72	1998-1999
Sd.2	0.67	1989-1993
Sd.3	0.59	1995-1998
Validation		
Station name	NSE value	Data periods
Sd.1	0.57	2000-2004
Sd.3	0.75	2000-2004
Sd.4	0.44	1998, 2000-2004

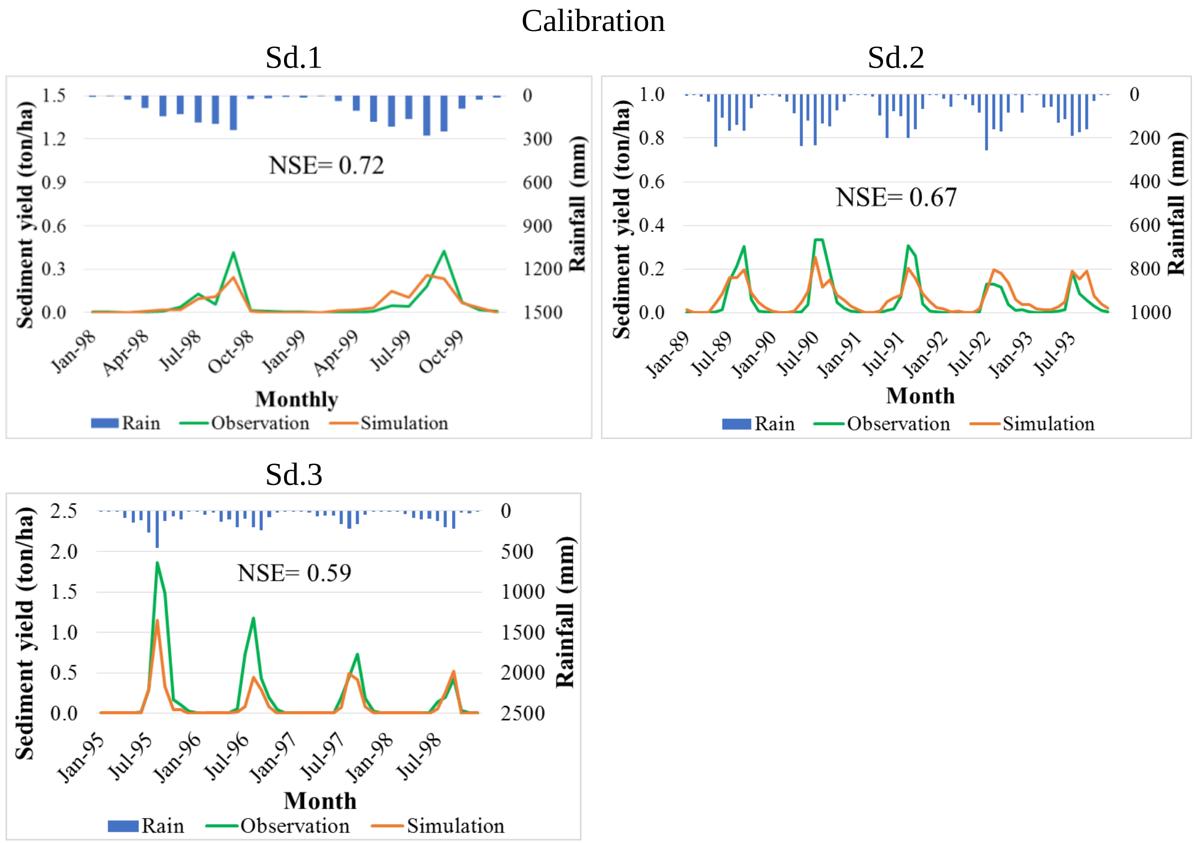
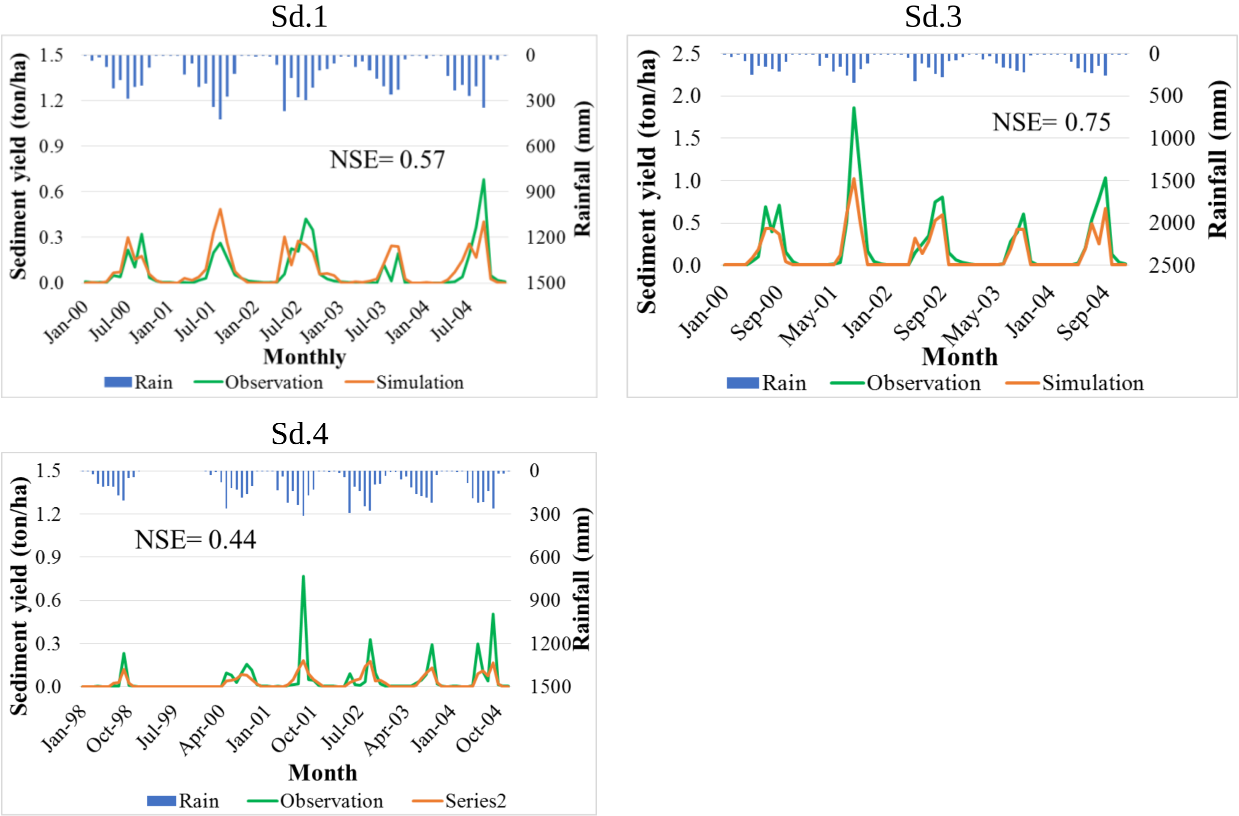


Figure 3.15 The result before and after calibration of sediment model (Sd.1, Sd.2, and Sd.3 are the name of sediment station)

Validation


Sd.1

Sd.3

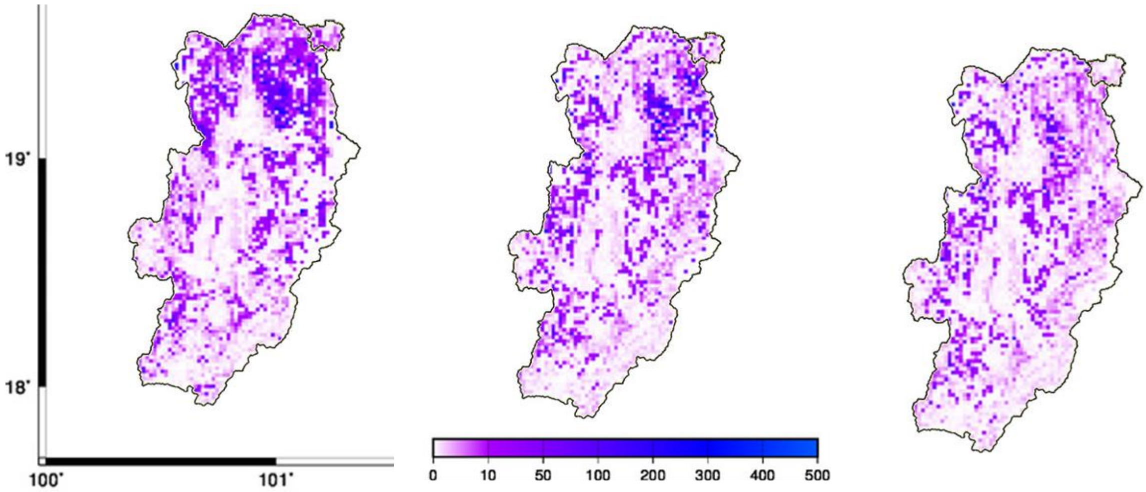
Sd.4

Figure 3.16 The result after validation of sediment model (Sd.1, Sd.2, and Sd.4 are the name of sediment station)

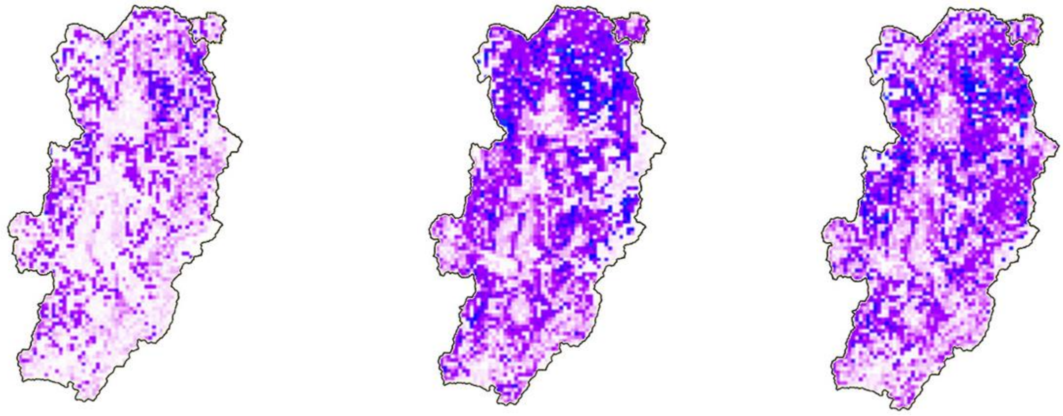
3.4) Impact of climate and land use changes

When the Nan river basin is considered in its entirety, the impact of climate change on soil erosion and sedimentation illustrates that changes in rainfall have a significant effect on the potential for soil erosion, and on the sediment yield. The average annual soil erosion and sediment yield, from the projected climate data for the period 2080-2099 (Case F-P, F-C, F-F1, and F-F2), are demonstrably greater than the average annual soil erosion from current climate data, i.e., for the period 1985-2004 (Case C-P, C-C, C-F1, and C-F2). In addition to climate change, land use change also has a significant effect on soil erosion and sediment yield. The increased total forested area in cases C-F1 and F-F1 helps to protect the surface soil and decrease the impact of rainfall, thus reducing the likelihood of soil erosion, which is the origin of river sediment. Thus, the potential for soil erosion and sediment in cases C-F1 and F-F1 is lower than in other case studies, while the soil erosion and sediment in cases C-P and F-P, with degraded forest accounting for the largest proportion of surface area, and cases C-F2 and F-F2, with significantly decreased forested area, are higher. The average annual soil erosion and sediment yield from current and future scenarios in whole area of Nan river basin are shown in Figure 3.17 and Figure 3.18.

a) Case C-P b) Case C-C c) Case C-F1



d) Case C-F2 e) Case C-P e) Case F-P f) Case F-C



g) Case F-F1 h) Case F-F2

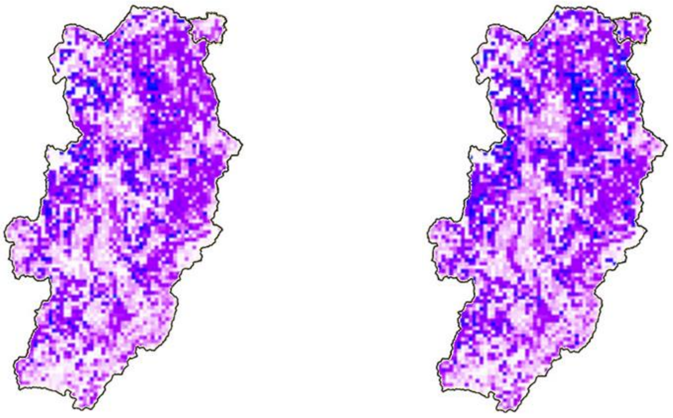


Figure 3.17 The average annual soil erosion of case a) C-P, b) C-C, c) C-F1, d) C-F2, e) F-P, f) F-C, g) F-F1, and h) F-F2

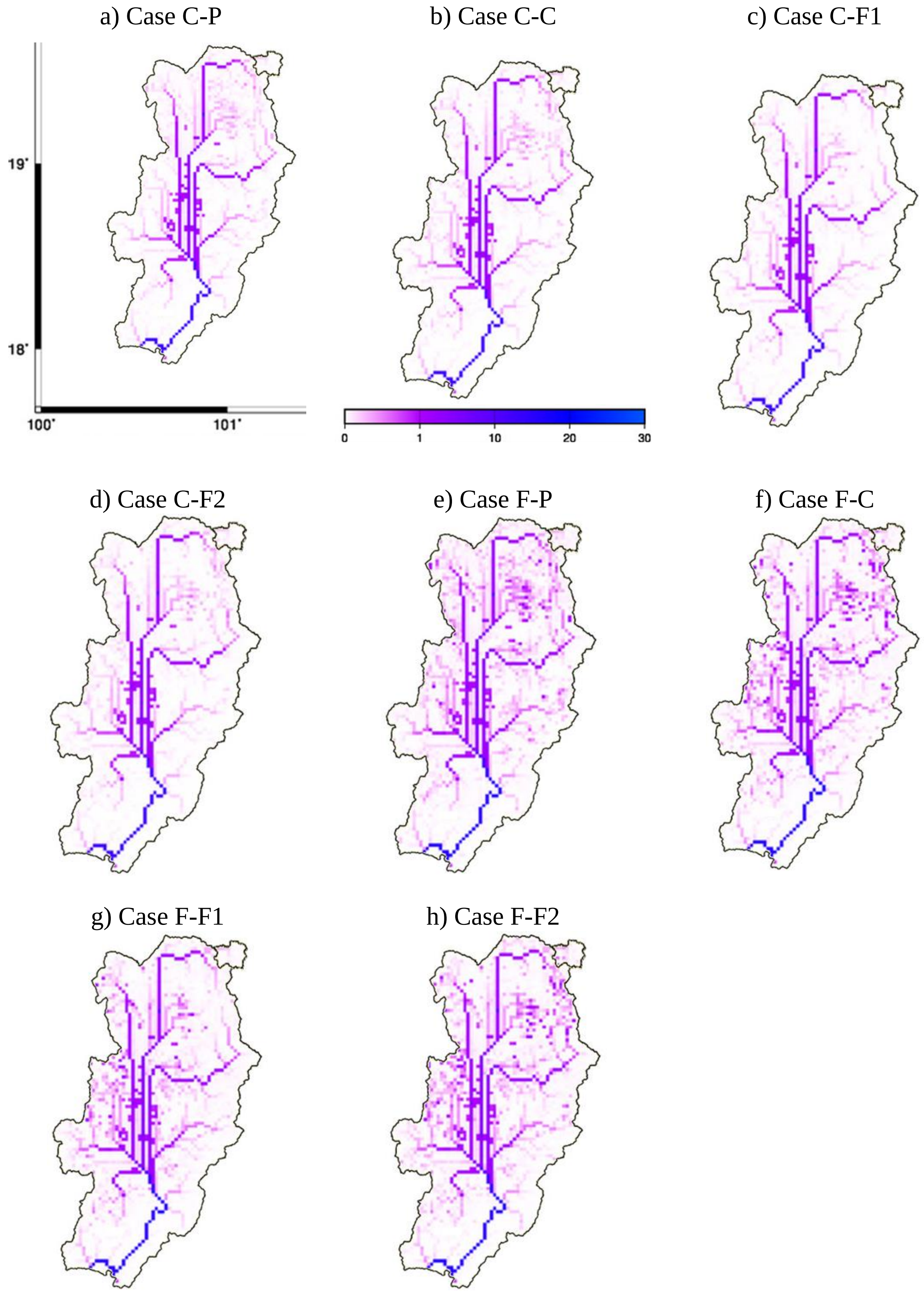

a) Case C-P
b) Case C-C
c) Case C-F1
d) Case C-F2
e) Case F-P
f) Case F-C
g) Case F-F1
h) Case F-F2

Figure 3.18 The average annual sediment yield of case a) C-P, b) C-C, c) C-F1, d) C-F2, e) F-P, f) F-C, g) F-F1, and h) F-F2

To clearly demonstrate the impact of climate change and land use changes on soil erosion and sediment yield, the monthly soil erosion rate in the upstream and downstream areas of the Nan river basin are presented in the next section.

3.4.1) Impacts of climate change

1) Impacts of climate change on soil erosion

1.1) Upstream of the Nan river basin

Regarding the projected impact of climate change, the results indicate that the soil erosion, as attested by the simulation, rainfall, and R-factor value, exhibit similar tendencies. The monthly soil erosion based on climate data for the period 1985–2004, including cases C-P, C-C, C-F (1) and C-F (2), are lower than those from the projected climate data for the period 2080–2099, in cases F-P, F-C, F-F (1) and F-F (2) from June to December, and particularly between May and August, while the results for the period from January to April exhibit the opposite tendency (Figure 3.19). The monthly soil erosion based on current climate data are likely higher than those indicated by future climate data. These results were obtained due to the difference between rainfall (Figure 3.3) and the R-factor value (Figure 3.21). Increasing rainfall can lead to an increased R-factor value, which is the factor that can contribute the soil erosion.

a) Average monthly soil erosion of case C-C, C-F (1), F-C, and F-F (1)

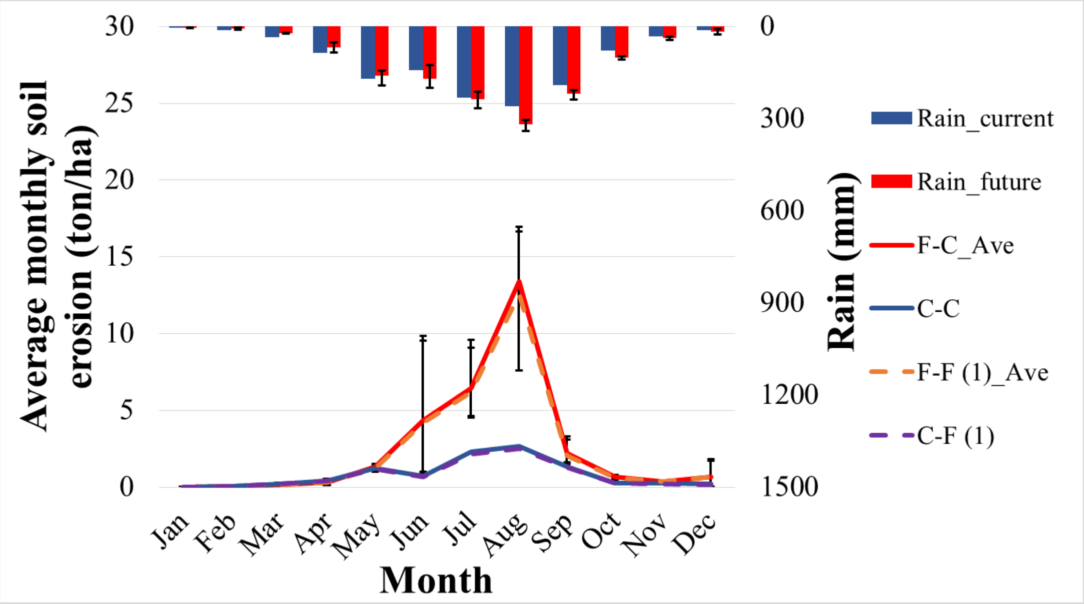


Figure 3.19 Average monthly soil erosion in the case of climate change in upstream area of Nan river basin; a) Average monthly soil erosion case C-C, C-F (1), F-C and F-F (1), and b) Average monthly soil erosion case C-P, C-F (2), F-P and F-F (2)

b) Average monthly soil erosion of case C-P, C-F (2), F-P, and F-F (2)

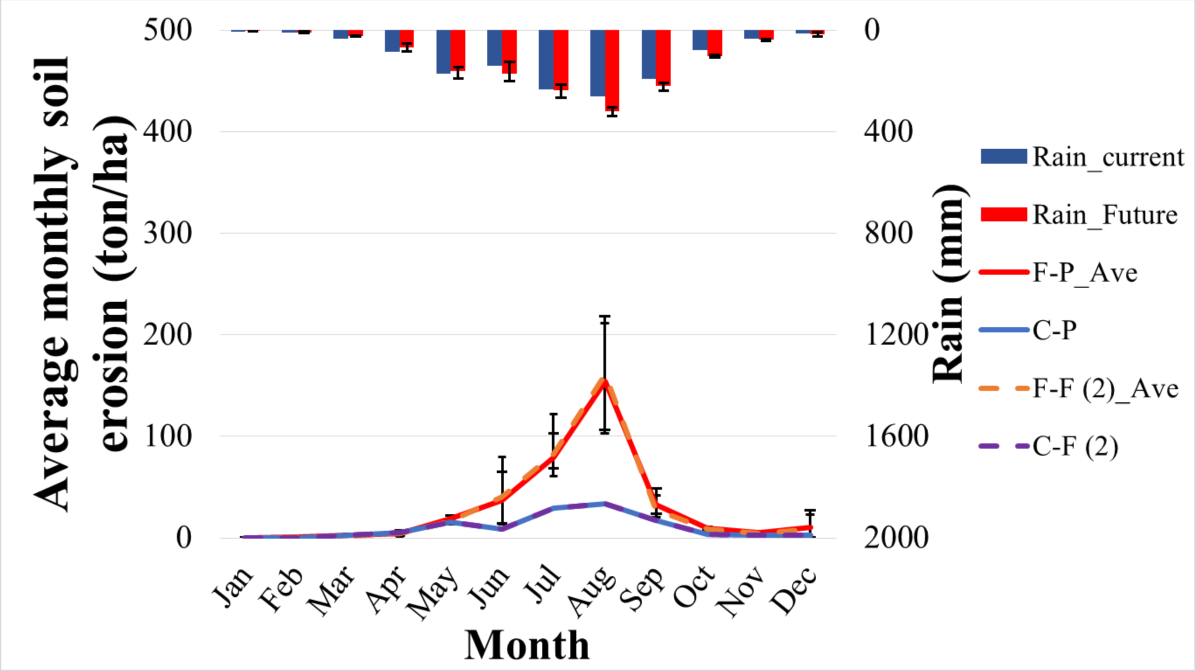
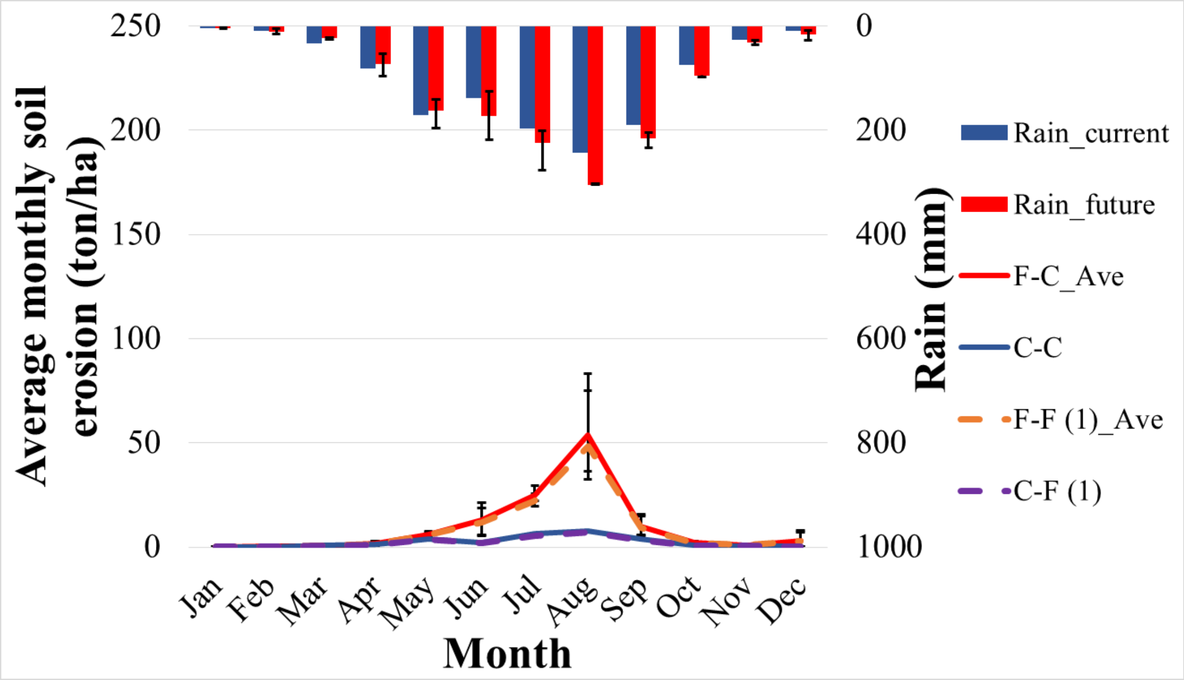


Figure 3.19 Continue

1.2) Downstream of Nan river basin

Considering the future impact of climate change in the downstream area, the results have a similar tendency to those for the upstream area. The monthly soil erosion in April to December according to the future climate data (2080-2099), in cases F-P, F-C, F-F (1) and F-F (2), are higher than those for the current climate (1985-2004), including cases C-P, C-C, C-F (1) and C-F (2) (Figure 3.20). There is little difference in the monthly soil erosion for January to March between current and projected climate data. The results depend on the difference in rainfall between current and future climate data, which is used to calculate the R-factor in RUSLE.

a) Average monthly soil erosion of case C-C, C-F (1), F-C, and F-F (1)



b) Average monthly soil erosion of case C-P, C-F (2), F-P, and F-F (2)

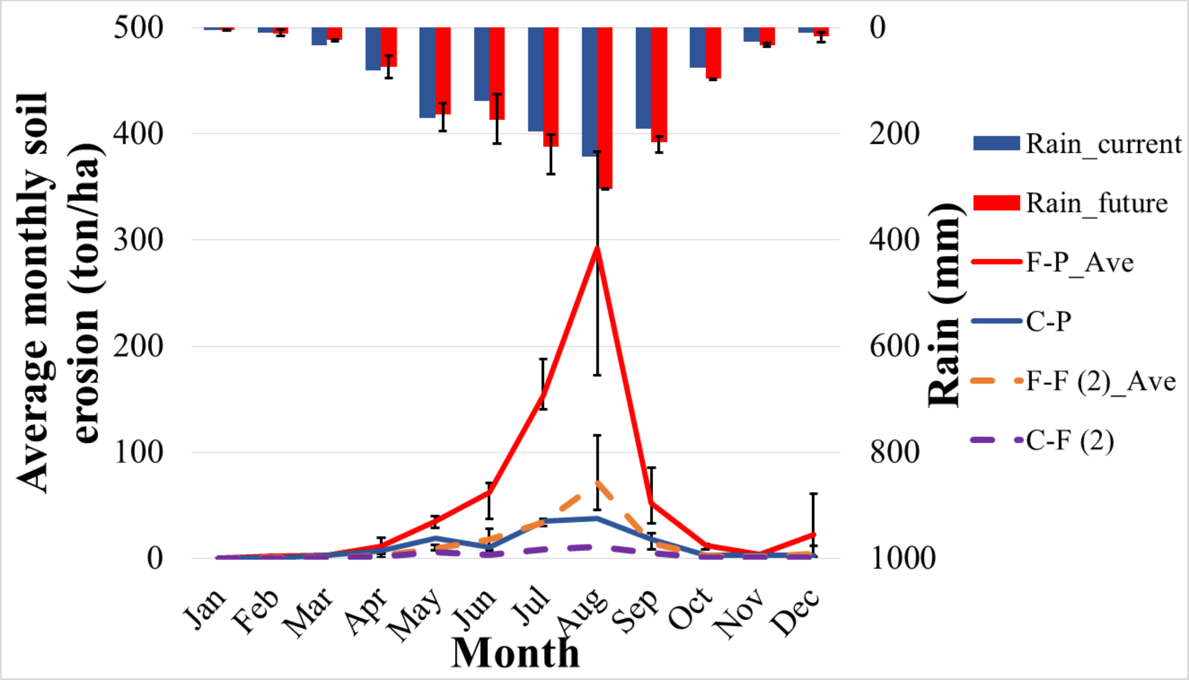
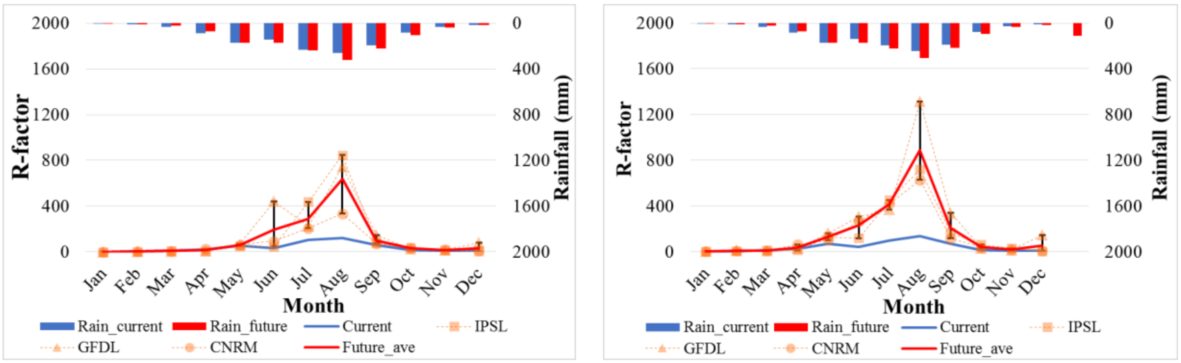


Figure 3.20 Average monthly soil erosion in the case of climate change in downstream area of Nan river basin; a) Average monthly soil erosion case C-C, C-F (1), F-C and F-F (1), and b) Average monthly soil erosion case C-P, C-F (2), F-P and F-F (2)

The rainfall and runoff factor, or R-factor, is the sum of individual storm erosivity. It can be used to explain the influence exerted by raindrops, reflecting the amount and rate of runoff associated with rainfall (Renard *et al*., 1997). The average annual R-factor values in the upstream and downstream areas of the Nan river basin, based on current (1985-2004) rainfall data are 36.2 and 40.5 MJ·mm/ha·day, while based on projected future rainfall data (2080-2099) they are 115.4 and 170 MJ·mm/ha·day, respectively (Figure 3.22 and Table 3.14). The average R-factor value calculated using the daily R-factor equation from projected future daily rainfall is higher than that calculated based on current daily rainfall, particularly from June to August, by approximately 219% and 320% in the upstream and downstream areas of the Nan river basin, respectively (Table 3.15, Figure 3.21 and 3.22). The R-factor value can determine the likelihood of soil erosion, and the increase or decrease in soil erosion rates.

Table 3.14 The average monthly R-factor value from daily rainfall in current and future

Month	**R-factor value**			
	From rainfall data in the current		**From rainfall data in the future**	
	Upstream	Downstream	Upstream	Downstream
Jan	0.6	0.5	0.3	0.7
Feb	1.6	1.9	3.4	7.0
Mar	9.5	12.9	7.6	10.4
Apr	19.2	23.5	13.9	34.2
May	55.5	71.9	59.3	130.9
June	31.8	43.9	194.5	229.5
July	103.3	95.9	289.6	413.3
Aug	119.9	134.0	640.9	886.4
Sep	61.0	69.1	99.0	207.8
Oct	12.8	14.4	29.7	43.6
Nov	10.7	10.6	16.5	21.9
Dec	8.3	7.3	30.3	52.9
Annual	36.2	40.5	115.4	169.9



a) R-factor in upstream

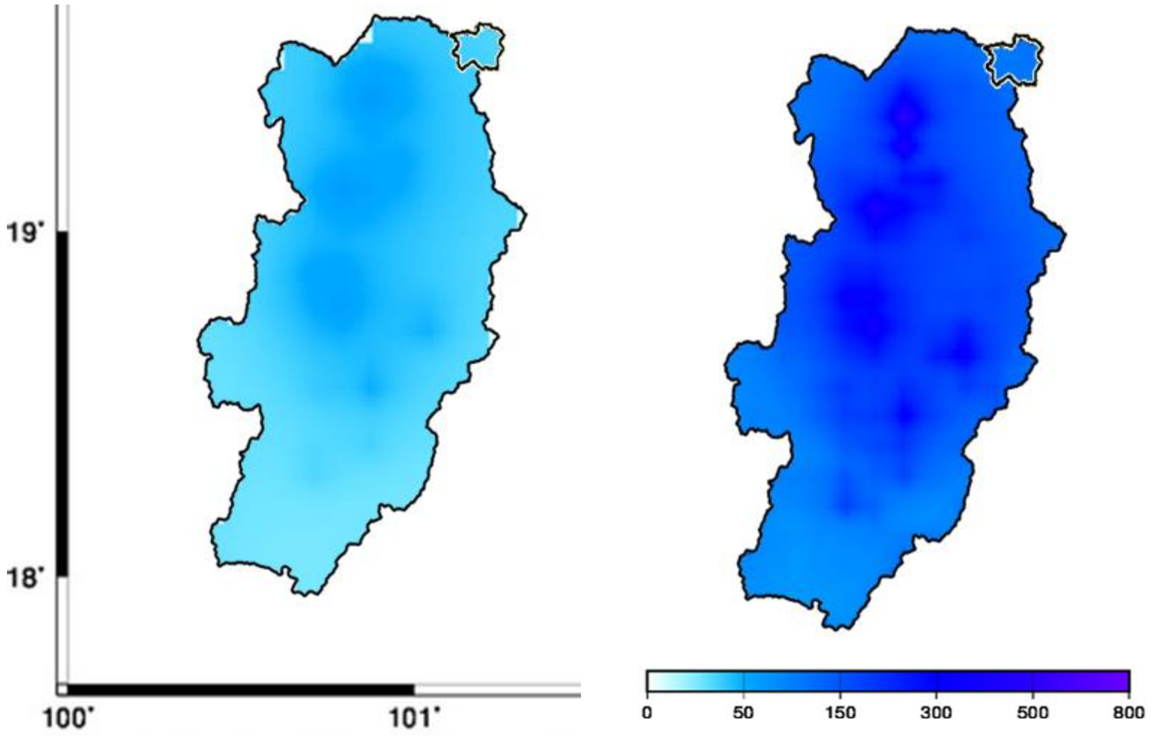
b) R-factor in downstream

Figure 3.21 difference value of rain erosivity (R-factor) in upstream (a) and downstream (b)

Remark: Current is the R-factor from climate dataset in the current (1985-2004). IPSL, GFDL, and CNRM are the R-factor from climate dataset in the future (2080-2099) and Future_ave mean the average R-factor from 3 climate dataset in the future (IPSL, GFDL, and CNRM).

Table 3.15 The difference value and percentage change of R-factor value that calculate from daily rainfall in current and future

Month	**Difference value (MJ·mm/ha·day)**		**% Difference**	
	Upstream	Downstream	Upstream	Downstream
Jan	-0.2	0.3	-43.8	58.1
Feb	1.8	5.1	116.4	262.6
Mar	-1.9	-2.5	-20.4	-19.3
Apr	-5.3	10.7	-27.5	45.6
May	3.8	59.0	6.8	82.1
June	162.7	185.6	512.4	422.7
July	186.3	317.4	180.3	330.9
Aug	521.0	752.4	434.6	561.6
Sep	38.0	138.7	62.3	200.7
Oct	16.9	29.3	132.0	203.9
Nov	5.8	11.4	53.9	107.7
Dec	22.0	45.6	266.3	628.1
Annual	79.2	129.4	219.0	319.7



a) Average R-factor from daily rainfall data in 1985-2004 (current)

b) Average R-factor from daily rainfall data in 2080-2099 (future)

Figure 3.22 Average R-factor from rainfall data in current, 1985-2004 (a) and rainfall data in future, 2080-2099 (b)

Higher rainfall intensity can increase the R-factor, leading to greater detachment of soil in the topsoil surface, resulting in an increased likelihood of soil erosion. However, decreased rainfall may also reduce the occurrence of detachment and lessen the likelihood of erosion. This pattern, whereby soil erosion is observed to increase with increasing rainfall, is consistent with findings from several other studies (Yao *et al.*, 2016). For example, Parson and Stone (2006) studied the effects of intra-storm variations in rainfall intensity on interrill runoff and erosion. Mohamadi and Kavian (2015) studied the effects of rainfall patterns on runoff and soil erosion in field plots. They found that higher erosion rates were associated with storms bringing increased rainfall intensity. Additionally, Vaezi and other (Vaezi *et al.*, 2017) studied of raindrop impact on changes in the physical properties of soil and water erosion under conditions of semi-arid rainfall found that the effect of rainfall on the physical properties of soil increased significantly as rainfall intensity increased, and that higher rainfall intensity contributes to the destruction of soil aggregates and may alter the surface properties of the soil (Vaezi *et al.*, 2017). These results indicated that rainfall impact is a key factor influencing soil erosion and the physical properties of the soil.

2) Impacts of climate change on sediment yield

2.1) Upstream area of the Nan river basin

Similar to the future impact of climate change upstream of the Nan river basin, the simulation results indicate that the sediment yield exhibits the same tendency as do rainfall and soil erosion. The monthly sediment yield from June to December, in cases C-P, C-C, C-F (1) and C-F (2), which used climate data from the period 1985-2004, are lower than those in cases F-P, F-C, F-F (1) and F-F (2), which represent the projected future scenario based on climate data for the period 2080-2099. However, from January to May, monthly sediment yields based on current climate data are likely to be higher than those based on projected future climate data (Figure 3.23). These results are based on the difference in rainfall and the extent of soil erosion.

a) Average monthly sediment yield of case C-C, C-F (1), F-C, and F-F (1)

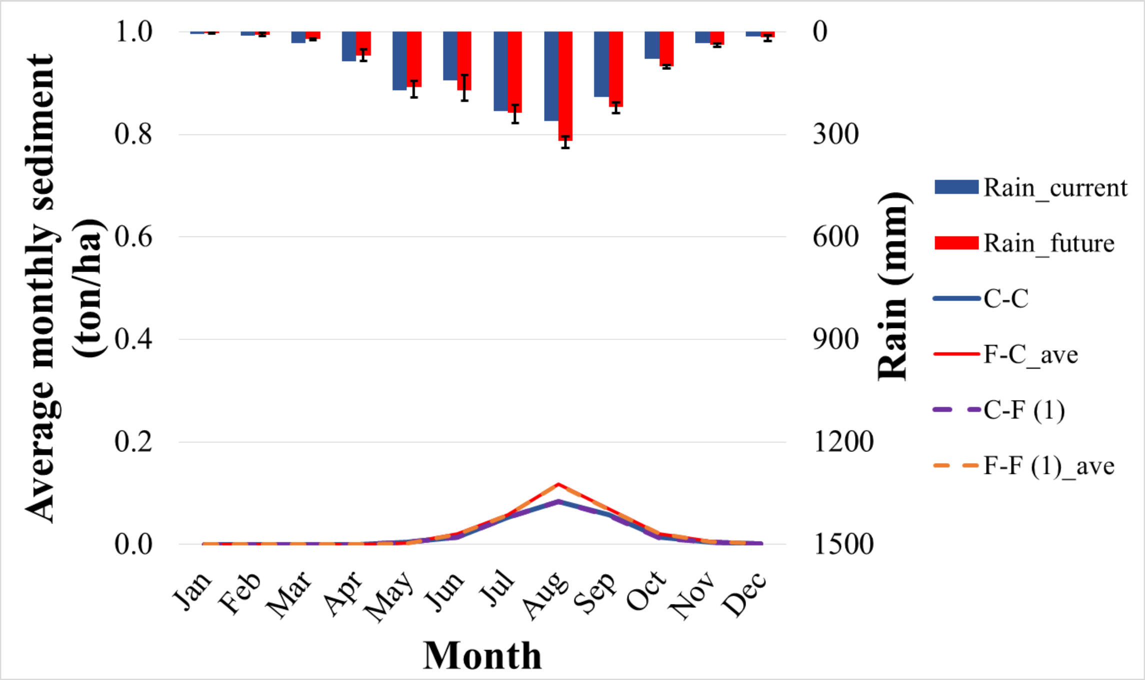


Figure 3.23 Average monthly sediment yield in the case of climate change in upstream area of Nan river basin; a) Average monthly soil erosion case C-C, C-F (1), F-C and F-F (1), and b) Average monthly soil erosion case C-P, C-F (2), F-P and F-F (2)

b) Average monthly sediment yield of case C-P, C-F (2), F-P, and F-F (2)

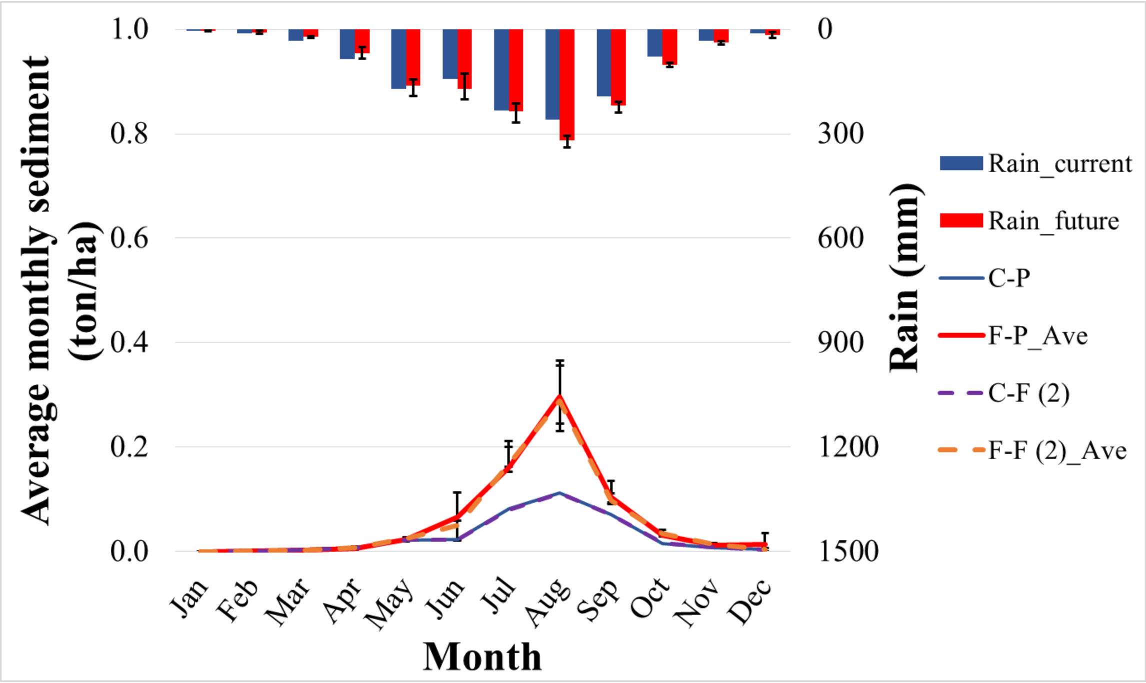
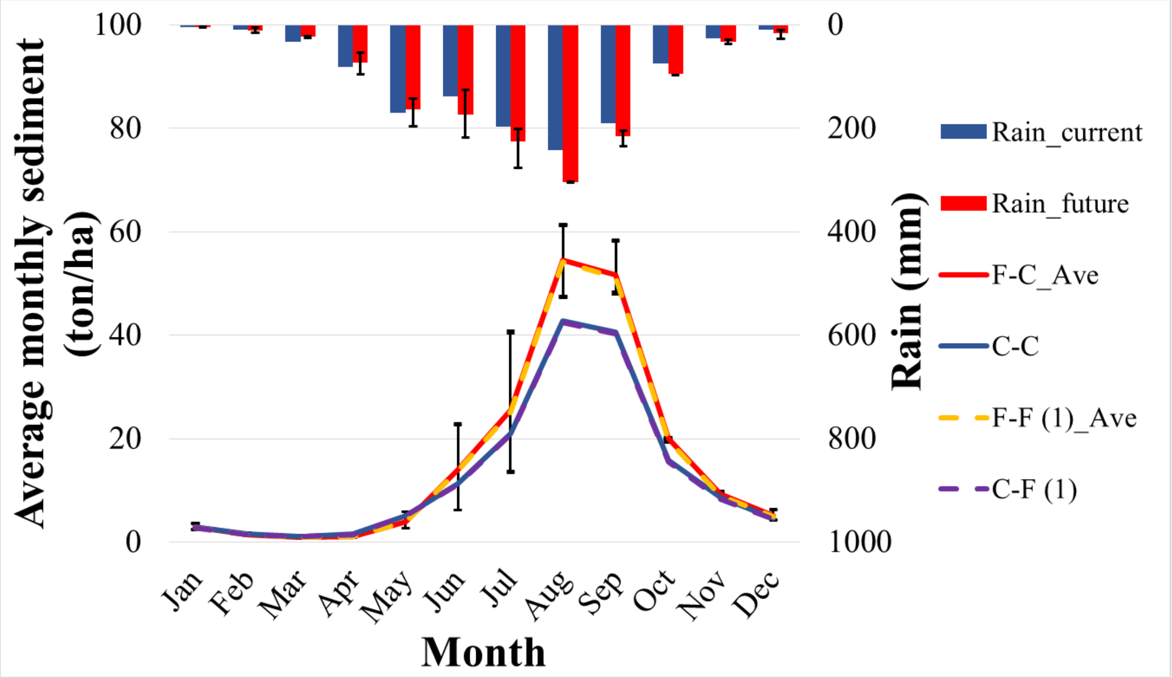


Figure 3.23 Continue

2.2) Downstream area of the Nan river basin

Downstream, with regard to the present and future impact of climate change, the monthly sediment yields from January to May, based on projected future climate data (2080-2099) for cases F-P, F-C, F-F (1) and F-F (2), were lower than those based on climate data for the period 1985-2004, for cases C-P, C-C, C-F (1) and C-F (2) (Figure 3.24); the results for other months stand in contrast to this. These results reflect the rain erosivity associated with rainfall, water flow velocity, and soil erosion, which influences the amount of sediment in the river.

a) Average monthly sediment yield of case C-C, C-F (1), F-C, and F-F (1)



b) Average monthly sediment yield of case C-P, C-F (2), F-P, and F-F (2)

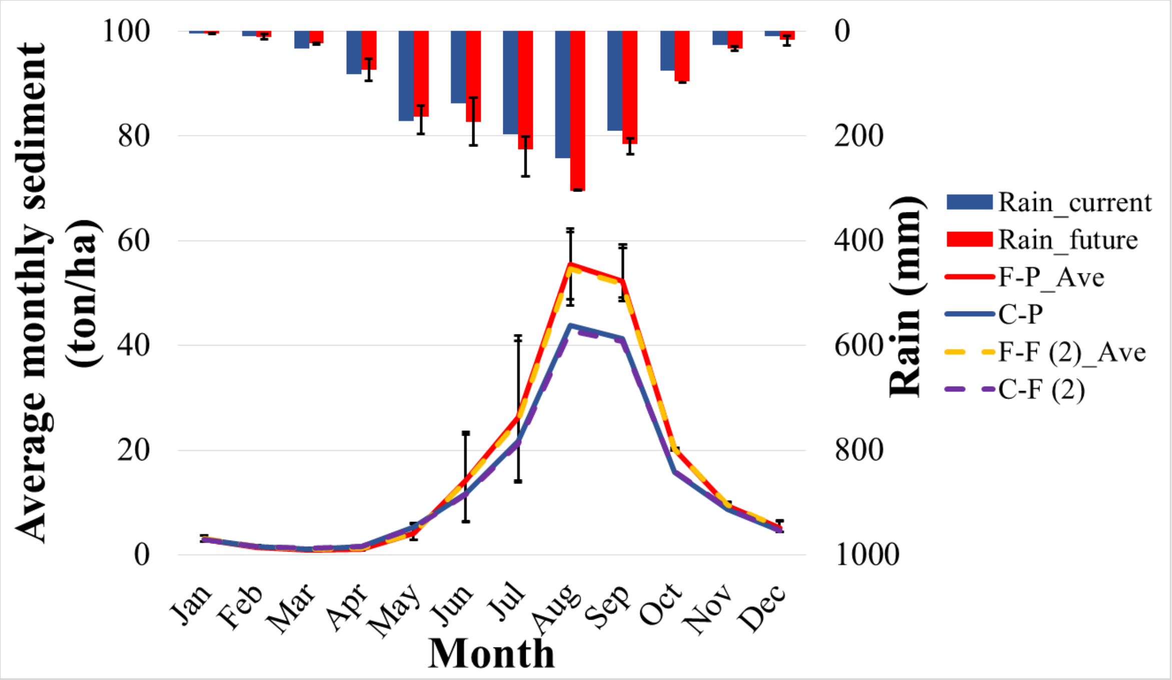
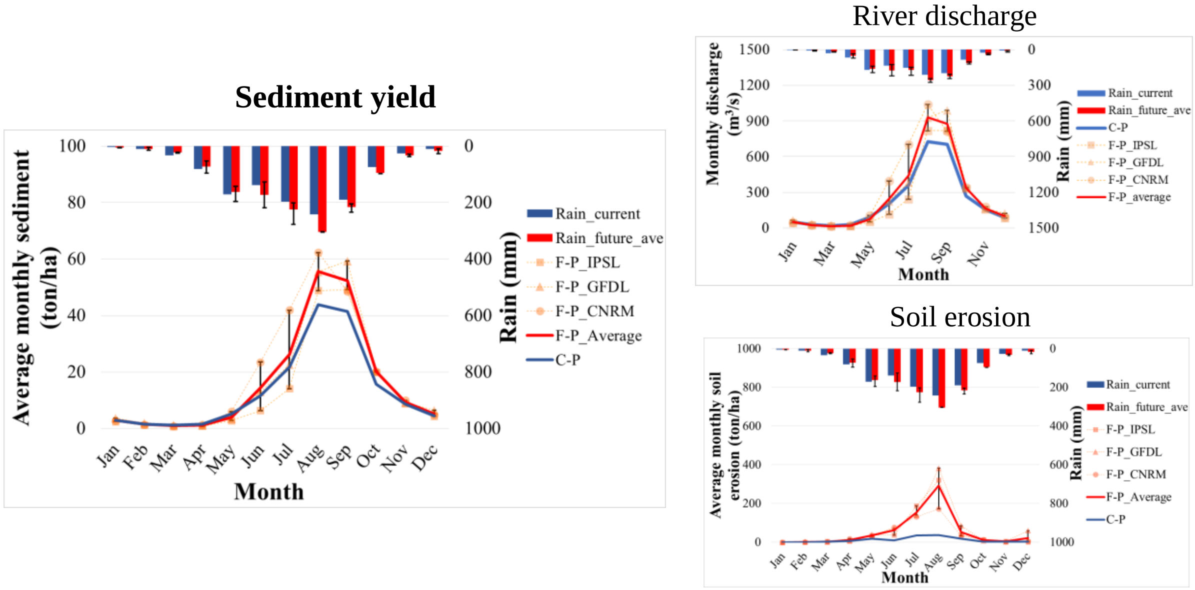


Figure 3.24 Average monthly sediment yield in the case of climate change in downstream area; a) Average monthly soil erosion case C-C, C-F (1), F-C and F-F (1), and b) Average monthly soil erosion case C-P, C-F (2), F-P and F-F (2)

Sediment is the result of erosion and the amount of sediment in a river depends on the amount of eroded soil particles (Morgan, 2005), the sediment delivery ratio by which the soil particles are transported from the site of origin to the river (Coit *et al*., 2014), and the water flow transporting sediment within the river. As the watershed's upstream is the starting point of both the water flow and sediment flow, sedimentation is mainly influenced by soil erosion and runoff, which both increase with intensified rainfall and tend to exhibit similar tendencies to rainfall and soil erosion.

The sedimentation pattern downstream, however, differs from that of soil erosion, due to the slope of the downstream area and river discharge. The variation of river discharge which is related to the change in rainfall, increases the sediment flow when there is severe water flow and cause sedimentation when the flow velocity of the water decreases. Therefore, the accumulation of sediment in the downstream area of Nan river basin is more influenced by the water flow and sediment flow which flows through the river from the upstream area to the downstream than it is by soil erosion around the area. The sample of comparison between sediment yield, average monthly river discharge, and soil erosion in the downstream area (from case C-P and F-P) are shown in Figure 3.25.



Sediment yield

River discharge

Soil erosion

Figure 3.25 The sample of comparison between sediment yield, average monthly river discharge, and soil erosion in the downstream area of Nan river basin (from case C-P and F-P)

3.4.2) Impact of land use change

1) Impact of land use change on soil erosion

1.1) Upstream are of the Nan river basin

After calibration, the new C-factor value was used to estimate soil erosion in a land use change scenario. The impact of land use change upstream on monthly soil erosion, based on current (2016, case C-C and F-C) and future land use, did not differ significantly in future scenario 1 (2036, case C-F (1) and F-F (1)), in which forest area is increased due to the similarity in land cover. However, the results from land use in future scenario 2 (2036, case C-F (2) and F-F (2)), with decreased forest area and changes to the field crop area, were very different compared with those based on land use in 2016 and in the future scenario 1. However, they did not differ from the results based on land use in 2000, although the average C-factor value for past land use (case P) was greater than that of future land use in scenario 2 (case F2) (Figure 3.26). This is due to the fact that, in case F2, most field crop was located in the high slope area, associated with increased soil erosion resulting from land use. The average C-factor which calculate from the ratio of land use area and the C-factor value of each land use type are shown in Table 3.16 and the example method to calculate average C-factor of downstream and upstream area are show in Table 3.17.

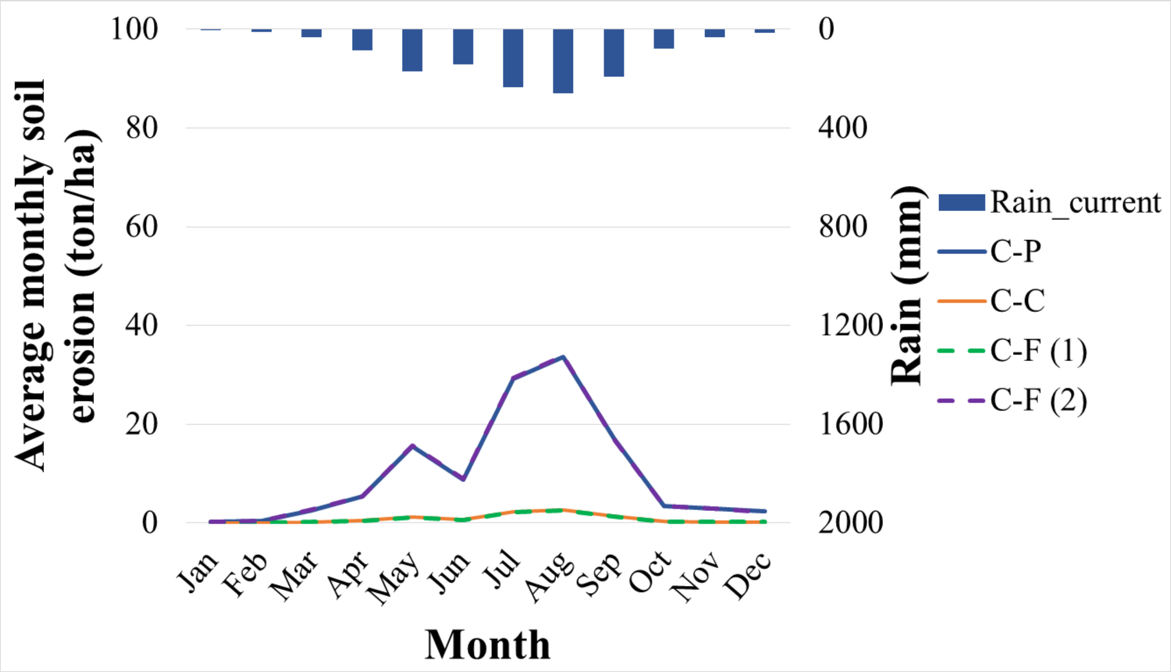
Table 3.16 C-factor of each scenario

Case	Average C-factor value
C-P and F-P	0.18
C-C and F-C	0.11
C-F (1) and F-F (1)	0.03
C-F (2) and F-F (2)	0.14

Table 3.17 The example method to calculate average C-factor

Land use in 2000 (upstream)	Area km^2	Area %	C-factor	C-factor (ratio) = [Σ(Area (%)*C-factor value)]/100
Evergreen forest	0	0	0.001	0.0
Deciduous forest	1	0.6	0.015	0.6*0.015 = 0.01
Degraded forest	149	87.6	0.15	87.6*0.15 = 13.1
Field crop	19	11.2	0.42	11.2*0.42 = 4.7
Paddy field	0	0	0.3	0.0
Perennial crops	0	0	0.2	0.0
Urban	0	0	0.08	0.0
Water	0	0	0	0.0
Total	12000	100		**0.18**

a) Average monthly soil erosion case C-P, C-C, C-F (1) and C-F (2)



b) Average monthly soil erosion case F-P, F-C, F-F (1) and F-F (2)

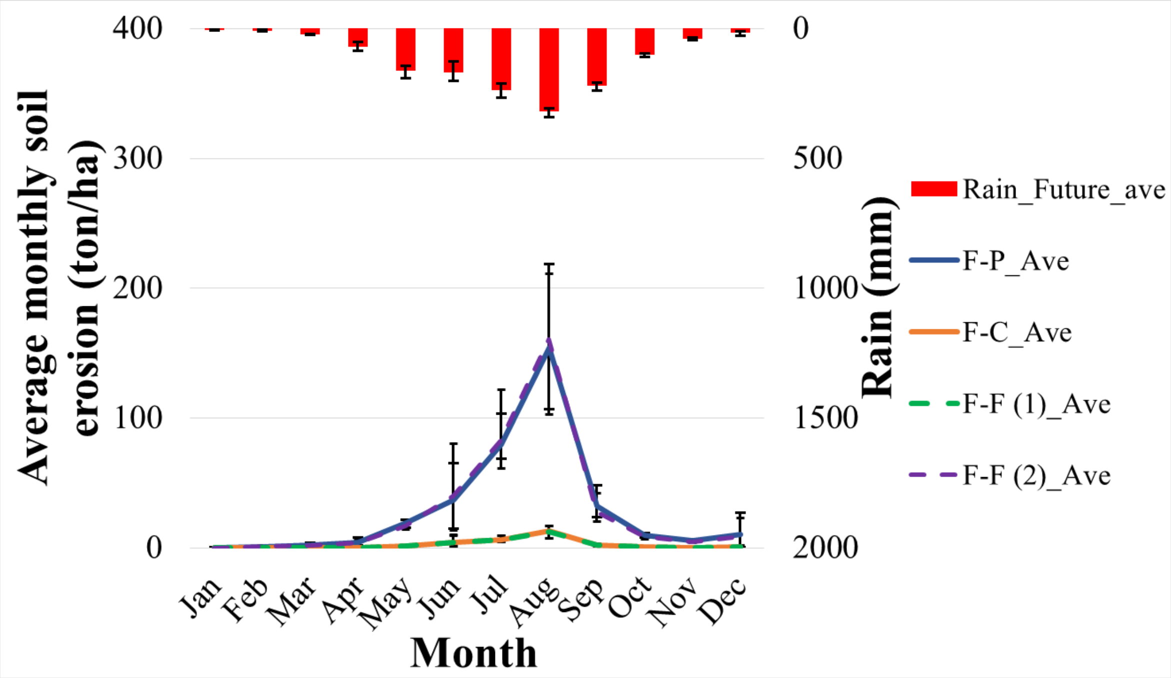
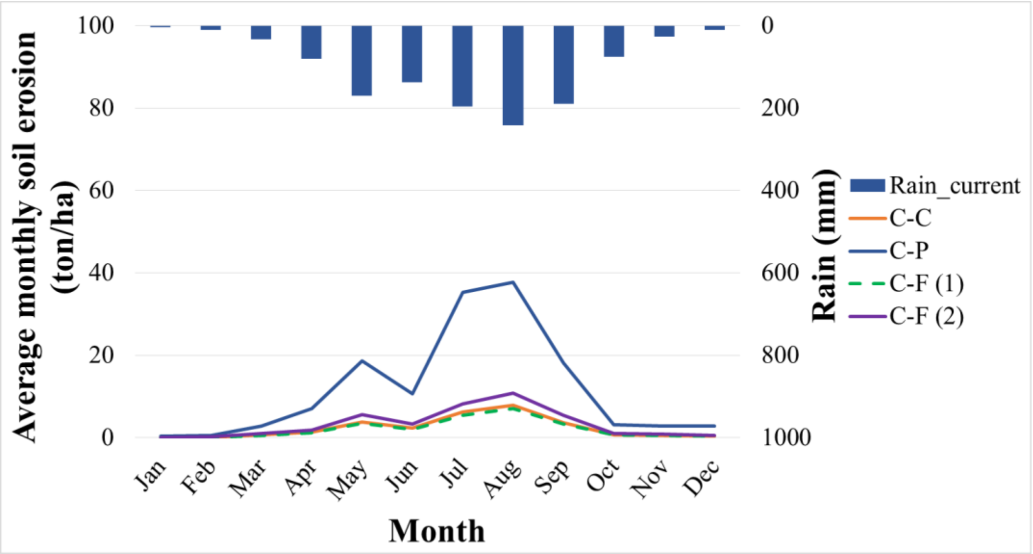


Figure 3.26 Average monthly soil erosion in the case of land use change in upstream area of Nan river basin; a) Average monthly soil erosion from case C-P, C-C, C-F(1) and C-F(2), and b) Average monthly soil erosion from case F-P, F-C, F-F (1) and F-F (2)

1.2) Downstream area of the Nan river basin

The results indicate that the monthly soil erosion resulting from land use in the past (2000, case C-P and F-P) was highest due to the high field crop and degraded forest areas, while monthly soil erosion in the future in scenario 1 (2036, case C-F (1) and F-F (1)) was lowest, owing to increased deciduous forest area (Figure 3.27). These results were obtained using the land cover and C-factor value. The average C-factor value in the downstream area was highest in cases C-P and F-P (Table 3.18 and Figure 3.28).

a) Average monthly soil erosion case C-P, C-C, C-F (1) and C-F (2)



b) Average monthly soil erosion case F-P, F-C, F-F (1) and F-F (2)

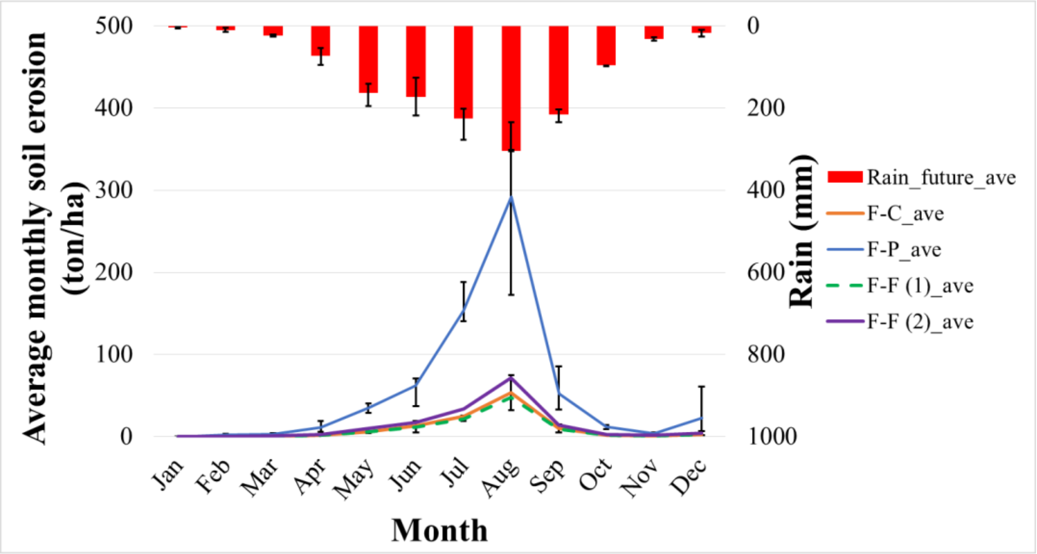
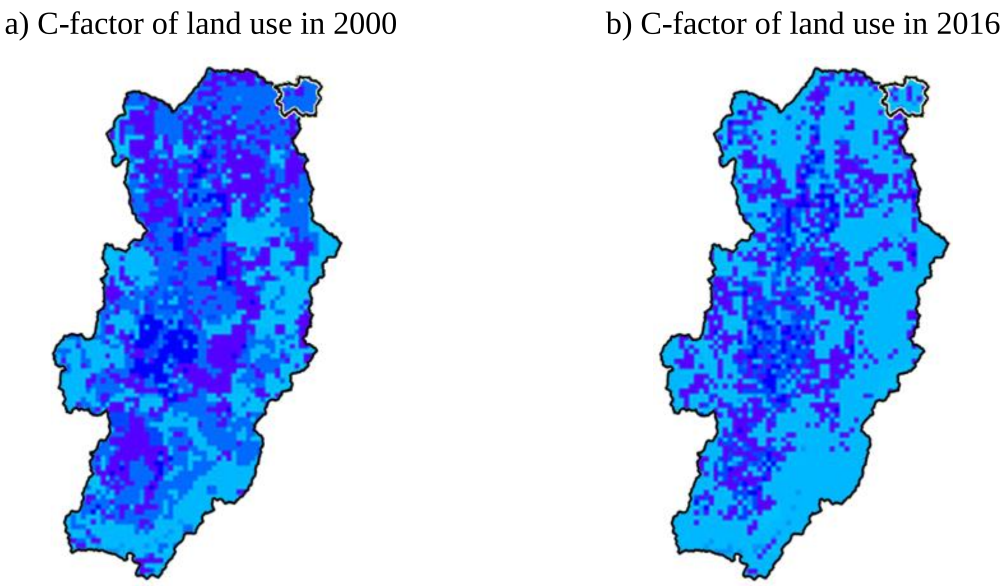


Figure 3.27 Average monthly soil erosion in the case of land use change in downstream area of Nan river basin; a) Average monthly soil erosion from case C-P, C-C, C-F(1) and C-F(2), and b) Average monthly soil erosion from case F-P, F-C, F-F (1) and F-F (2)

Table 3.18 Average C-factor of each scenario in downstream area of Nan river basin

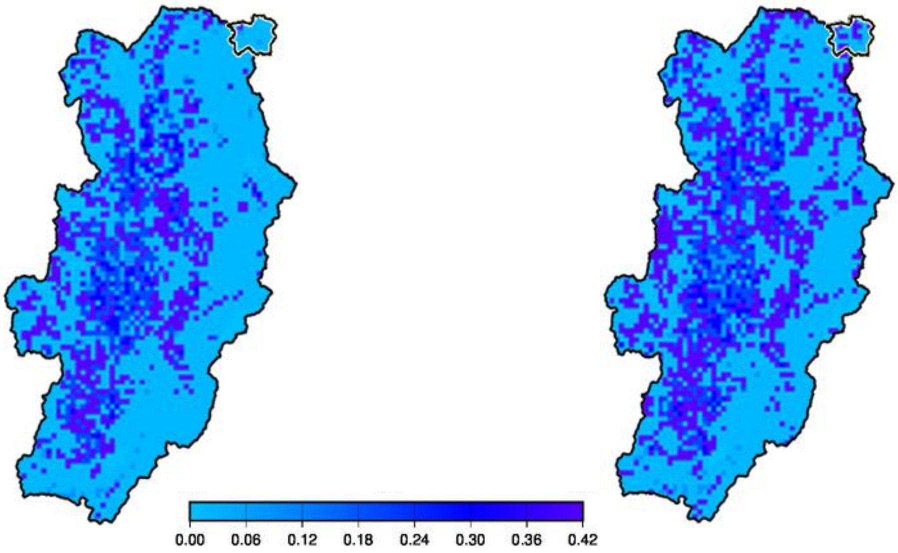
Case	Average C-factor value
C-P and F-P	0.18
C-C and F-C	0.14
C-F (1) and F-F (1)	0.12
C-F (2) and F-F (2)	0.15

The results from this study are consistent with those of previous studies; for example, Elliot W. (1999), Mohammad and Adam (2010), Plangoen *et al.* (2013), and Yao *et al.* (2016) studied the effects of land use management on soil erosion and soil productivity and found that the surface runoff and soil erosion of forested areas were generally low, due to the land cover and soil surface litter (Elliot, 1999, Mohammad and Adam, 2010). Surface litter protects soil from the effects of kinetic energy or rainfall intensity, and results in decreased runoff and soil erosion. These results were obtained due to the differences between land use types with regard to covering and protecting the surface soil from erosion. A key factor related to land use is the C-factor, which can determine the likelihood of soil erosion for each land use type. Agricultural land is at higher risk of soil erosion compared with degraded forest and forested areas. Therefore, the C-factor of agricultural land is higher than that of forested areas and has a significant effect on soil erosion.


a) C-factor of land use in 2000

b) C-factor of land use in 2016

Figure 3.28 The C-factor value of land use in a) 2000, b) 2016, c) future (scenario 1), and d) future (scenario 2)



c) C-factor of land use in future (scenario 1) d) C-factor of land use in future (scenario 2)

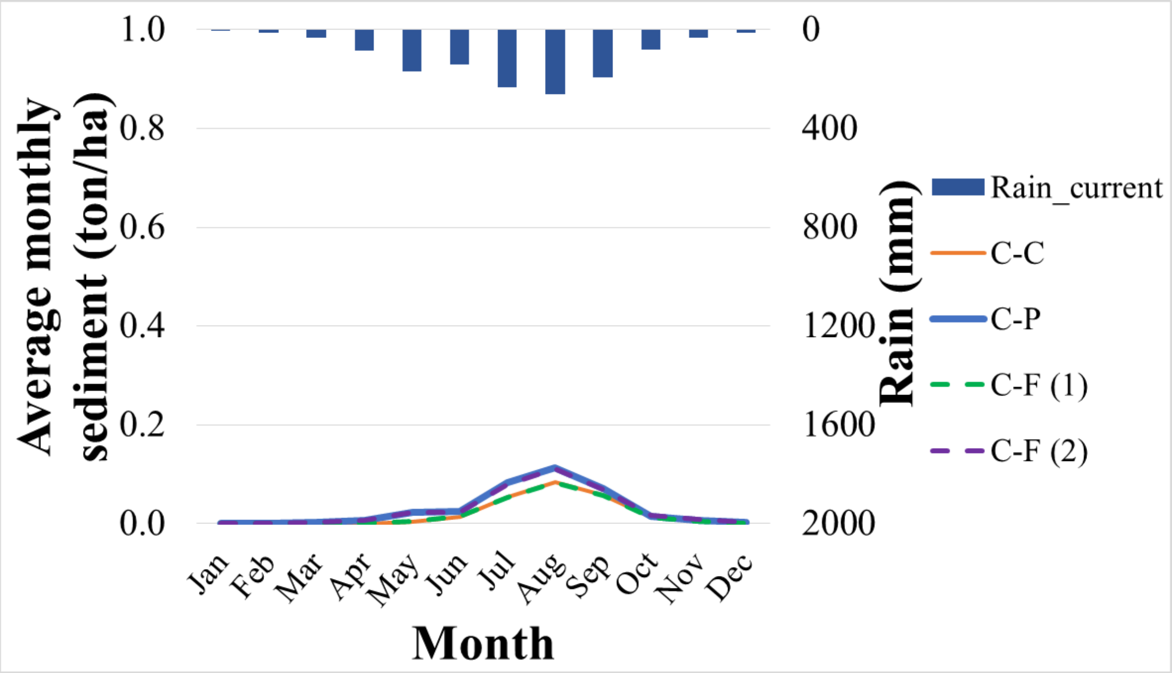
Figure 3.28 Continue

2) Impacts of land use change on the sediment yield

2.1) Upstream area of the Nan river basin

The estimated sediment levels in the upstream area suggest that the sediment yields follow the same trend as soil erosion. Current (2016, case C-C and F-C) and projected future (scenario 1; Case C-F (1) and F-F (1)) land use do not differ, due to the similar land cover. Additionally, the sediment yield calculated from projected land use in 2036 (scenario 2; case C-F (2) and F-F (2)) is similar to the results based on land use in 2000 (case C-P and F-P). However, it is higher than the results from other scenarios (Figure 3.29). These results are attributable to the differences in land use type, which affect soil erosion and, in turn, sediment yield, and to the high slope that influences the sediment delivery ratio, including the river discharge (which affects sediment flow). Thus, sedimentation in the upstream of the Nan river basin is influenced by soil erosion, slope, and water flow.

a) Average monthly sediment yield case C-P, C-C, C-F (1) and C-F (2)



b) Average monthly sediment yield case F-P, F-C, F-F (1) and F-F (2)

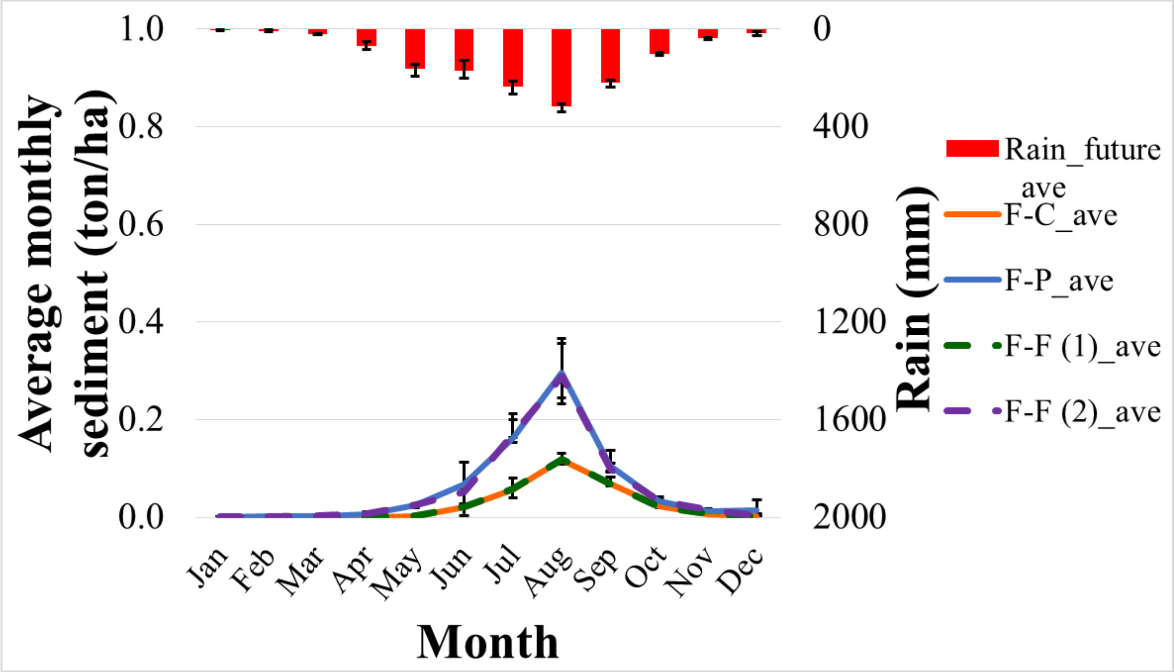
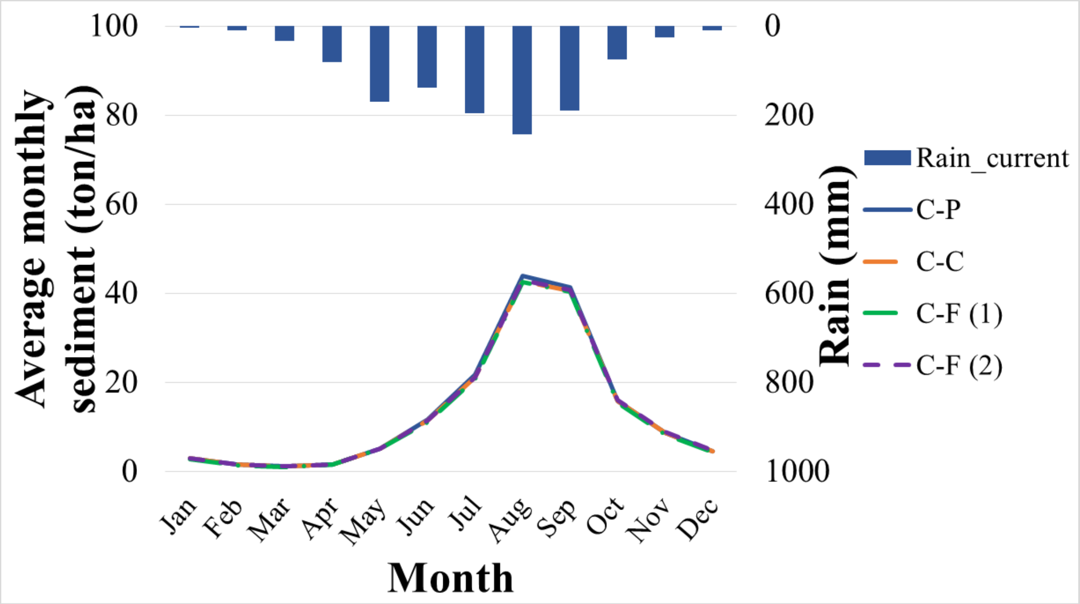


Figure 3.29 Average monthly sediment yield in the case of land use change in upstream area of Nan river basin; a) Average monthly soil erosion from case C-P, C-C, C-F(1) and C-F(2), and b) Average monthly soil erosion from case F-P, F-C, F-F (1) and F-F (2)

2.2) Downstream area of the Nan river basin

The results show that the monthly sediment yield from land use in current (2016) in case C-C and F-C, and the both land use scenario in the future in case C-F (1), C-F (2), F-F (1) and F-F (2), does not vary. The sediment from land use in the past (2000) in case C-P and F-P, are little higher than that from other cases only in August and September. These results obtain due to the land use type of each case study and river discharge. (Figure 3.30).

a) Average monthly sediment yield case C-P, C-C, C-F (1) and C-F (2)



b) Average monthly sediment yield case F-P and F-F (1)

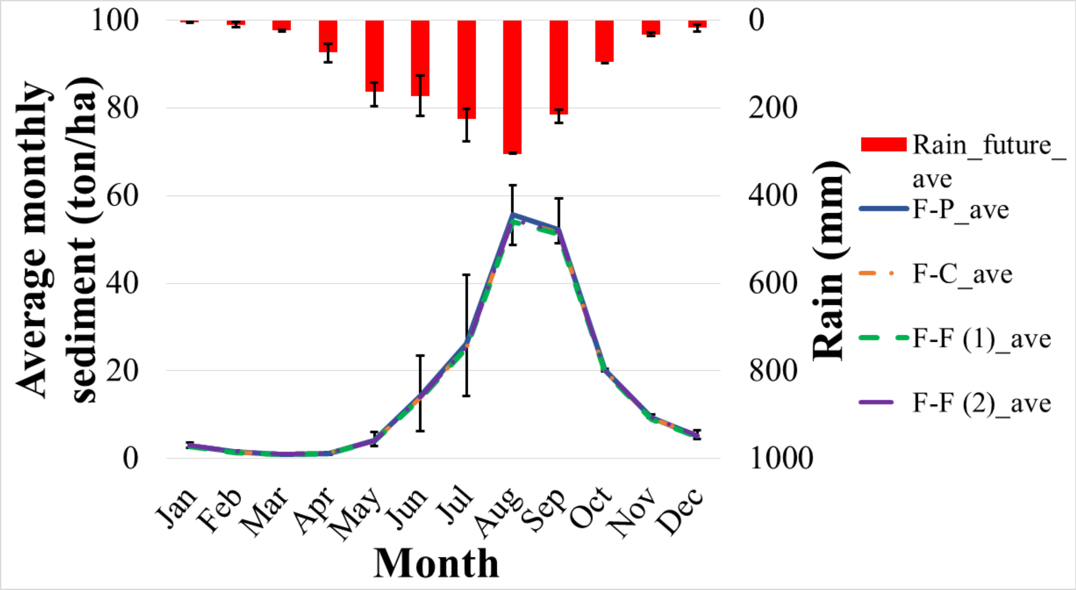


Figure 3.30 Average monthly sediment yield in the case of land use change in downstream area; a) Average monthly soil erosion from case C-P, C-C, C-F(1) and C-F(2), and b) Average monthly soil erosion from case F-P, F-C, F-F (1) and F-F (2)

This study’s findings indicate that the sedimentation process in the upstream area of the Nan river basin is influenced by the extent of soil erosion, which depends on land use type, slope steepness, and river discharge, which can affect sediment delivery ratio and sediment flow in the river. The results suggest that forest cover can help to reduce soil erosion and decrease sediment yield. For example, soil erosion and sediment yield are higher in the scenario that involved a decrease of approximately 5% in forest cover (i.e., land use in 2036 in scenario 2) while the increased forest cover in future land use scenario 1 was observed to help reduce soil erosion and sediment yield.

In the downstream area, the sediment yield levels in all scenarios do not vary, as there is little difference in land use type and river discharge. The results suggest that the majority of sediment that accumulates in the downstream area is more influenced by river discharge (which is the main transport medium for sediment travelling from highlands to lowlands), and the amount of sediment that is being transported, than by soil erosion in the vicinity.

3.5) The extreme climate and land use changes scenarios

The severe effects of climate change and land use changes were demonstrated in this study by examining two scenarios involving land use change and one involving climate change, toward a better appreciation of the impact of extreme climate change and land use change. In reality, however, it would be futile and unfeasible to reduce land use across the entire Nan river basin to a single land use type. The Nam Wa river basin, a branch of the Nan river basin, was therefore selected as a case study for this dissertation. Location of Nam Wa river basin is shown in Figure 3.31.

Both land use change scenarios were designed as follows: 1) the degraded forest and other agricultural terrain, such as paddy fields and perennial crops, in the Nam Wa river basin were converted to field crop, so that field crop accounted for around 50% of the total area, and 2) the entire Nam Wa river basin land cover type was changed to deciduous and evergreen forest based on past land use data (2000). These land use scenarios were calculated using climate data from 2004 from the IMPAC-T project. The climate change scenario was based on land use in 2016 and IMPAC-T project rainfall data from 2011, the year that saw Thailand’s heaviest recorded rainfall, with an average of 2,163.5 mm in the Nam Wa river basin. This rainfall exceeded the average rainfall over a 20-year period (1985-2004), based on the data of the IMPAC-T project and TMD, of approximately 653.7 mm and 903.5 mm, respectively. The results from the severe scenarios were compared with the result in 2004 from case C-C to analyze the impact of climate and land use changes. The detail of each extreme scenarios is shown in Table 3.19 and land use in Nam Wa river basin is shown in Table 3.20 and Figure 3.32.

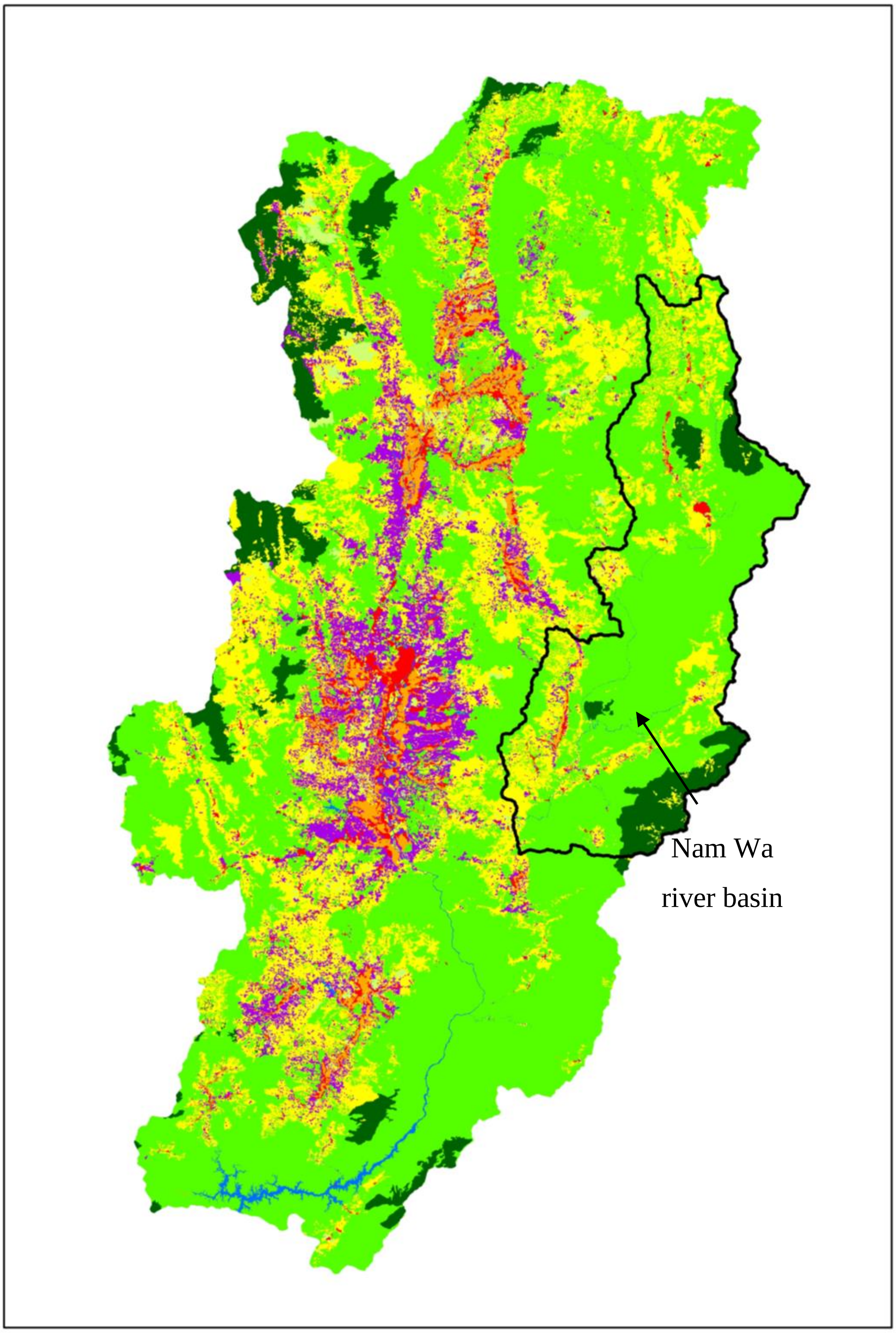


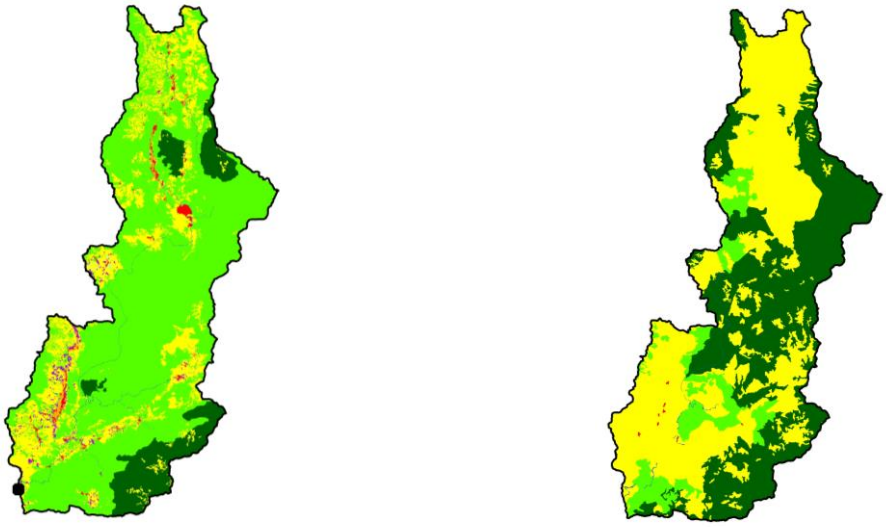
Figure 3.31 Location of Nam Wa river basin

Table 3.19 Detail of each extreme scenarios

Scenario	Land use	Rainfall data
1	Field crop 50%	Rainfall in 2004 from IMPAC-T project
2	Forest area 100%	
3	Land use in 2016	Rainfall in 2011 from IMPAC-T project

a) Land use in 2016

b) Field crop 50%



c) Forest 100%

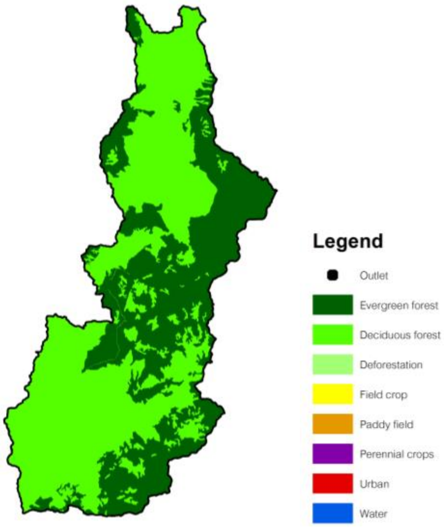
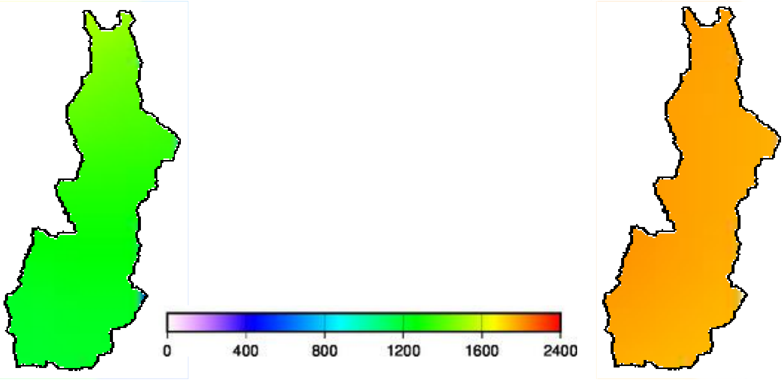


Figure 3.32 Land use in Nan Wa river basin

Table 3.20 Detail of land use in Nam Wa river basin

Scenario Land use type	Area (Km^2)		
	Sc1	Sc2	Sc3 (land use in 2016)
Evergreen forest	836.9	836.9	207.1
Deciduous forest	195.6	1208.1	1367.7
Degraded forest	0	0	3.4
Field crop	1007.6	0	409.7
Paddy field	0	0	13.5
Perennial crops	0	0	19.0
Urban	1.4	0	16.3
Water	3.5	0	8.4
Total	2045.0	2045.0	2045.0



a) Annual rainfall in 2004

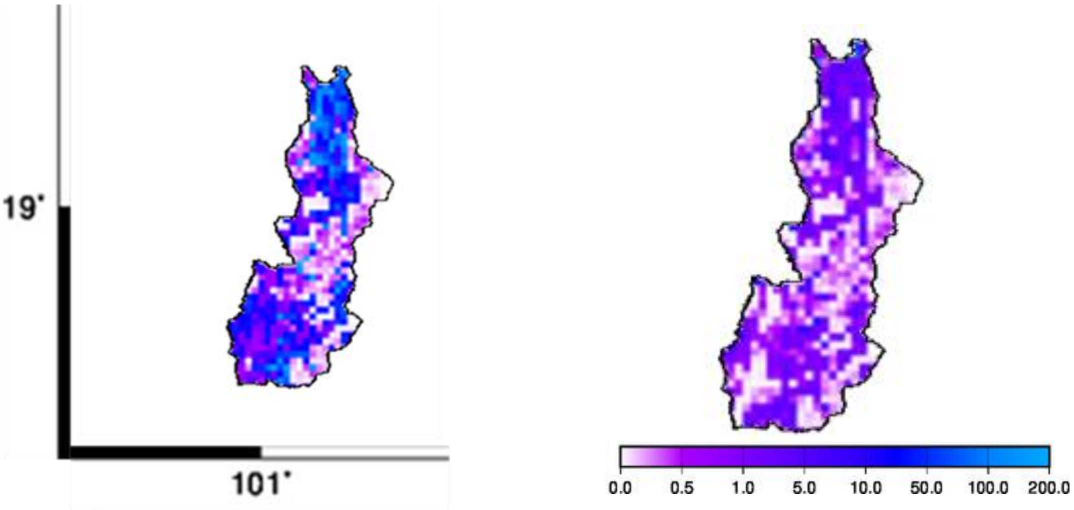
b) Annual rainfall from extreme scenario (2011)

Figure 3.33 Average rainfall from a) 2004 and b) extreme scenario (2011) of Nam Wa river basin

Analysis of the changes in land use illustrates that soil erosion and sediment clearly increased in the area where forest cover was converted to agricultural terrain. However, appropriate land use can help diminish the likelihood of soil erosion and sedimentation. For example, the results from scenario 1 (Sc1), in which field crops accounted for 50% of the total area, were highest in the land use change scenario, and also higher than the results from case C-C. Additionally, the results based on extreme rainfall in scenario 3 (Sc3) are incremental, but in the area covered with evergreen forest, the soil erosion and sedimentation level were lower than those in other areas (Figure 3.34 and 3.36). This is because forest area can protect the surface soil from the severe rainfall and relieve the impact of rainfall. As such, assiduous land use management can reduce the likelihood of soil erosion and sedimentation during extreme rainfall.

The average monthly results show that the soil erosion and sediment yield in Sc1 are higher than those in Sc2, due to the larger area of field crop. Additionally, with regard to climate change, the likelihood of soil erosion and sediment from Sc3 are over three times and twice as high as that in case C-C, respectively. Particularly during the rainy season (mid-April to October), the soil erosion and sediment yield in Sc3 are significantly higher than that in case C-C due to the prolific rainfall. However, during the dry season (November to February), the results vary less than during the rainy season (Figure 3.35 and 3.37).

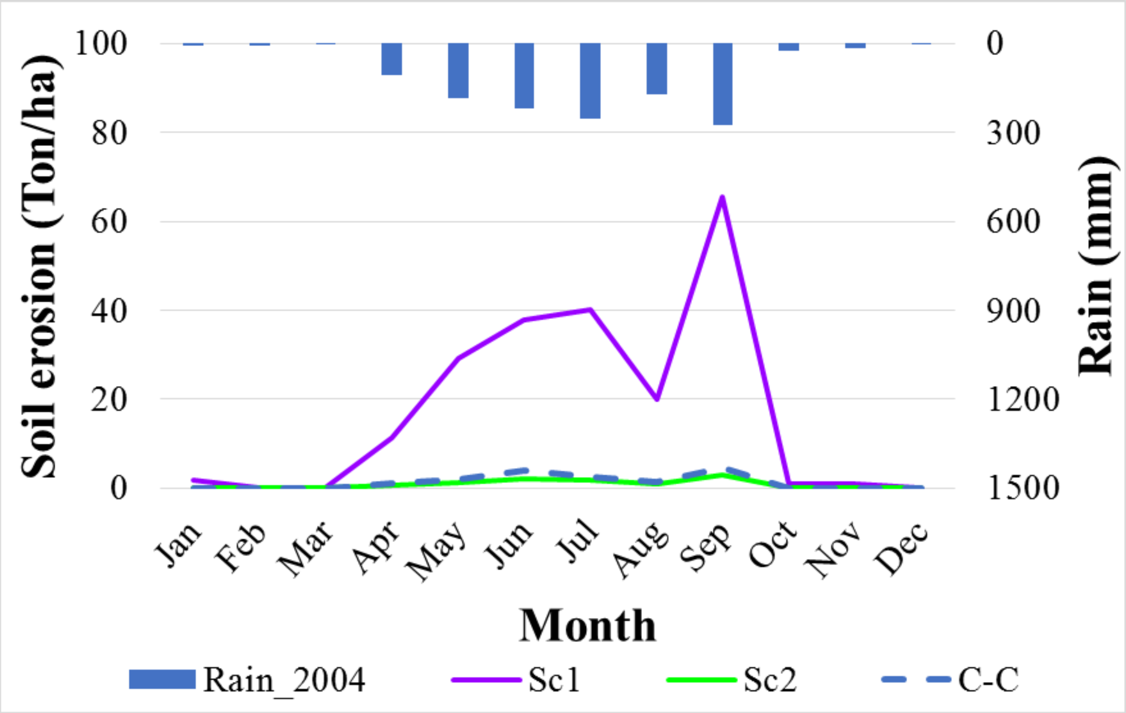
a) Sc1 b) Sc2



c) Sc3 d) case C-C

Figure 3.34 Annual soil erosion in Nam Wa river basin

a) Result from severe land use change scenario



b) Result from severe climate change scenario

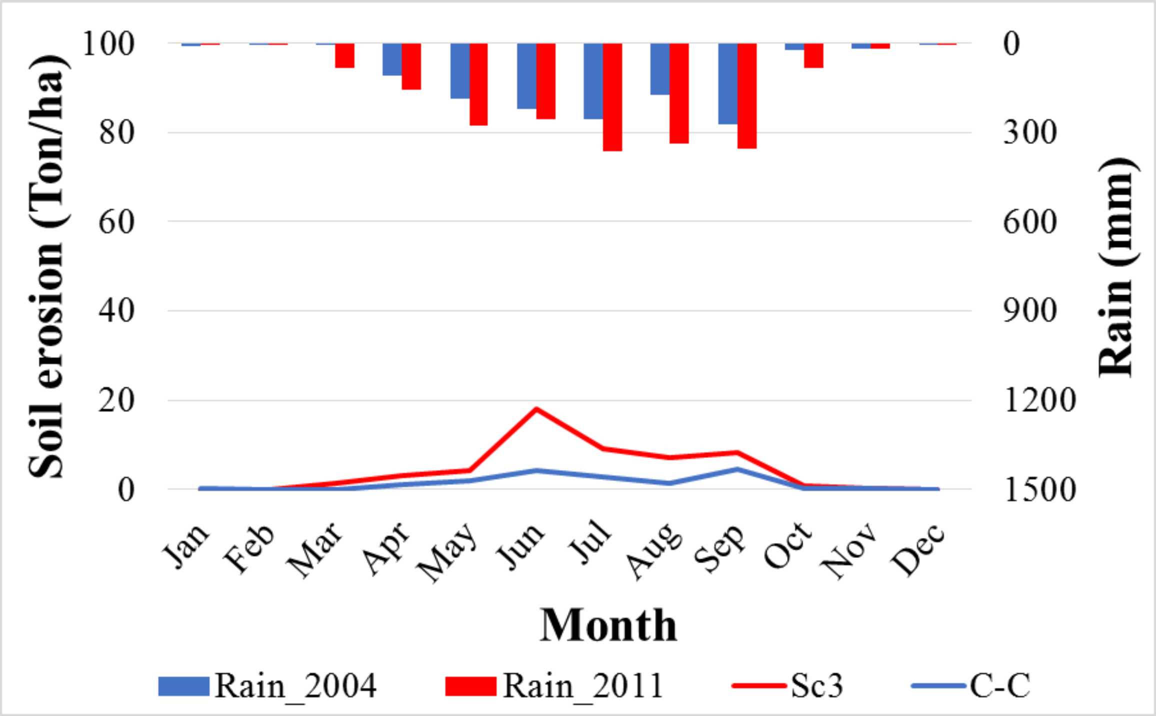
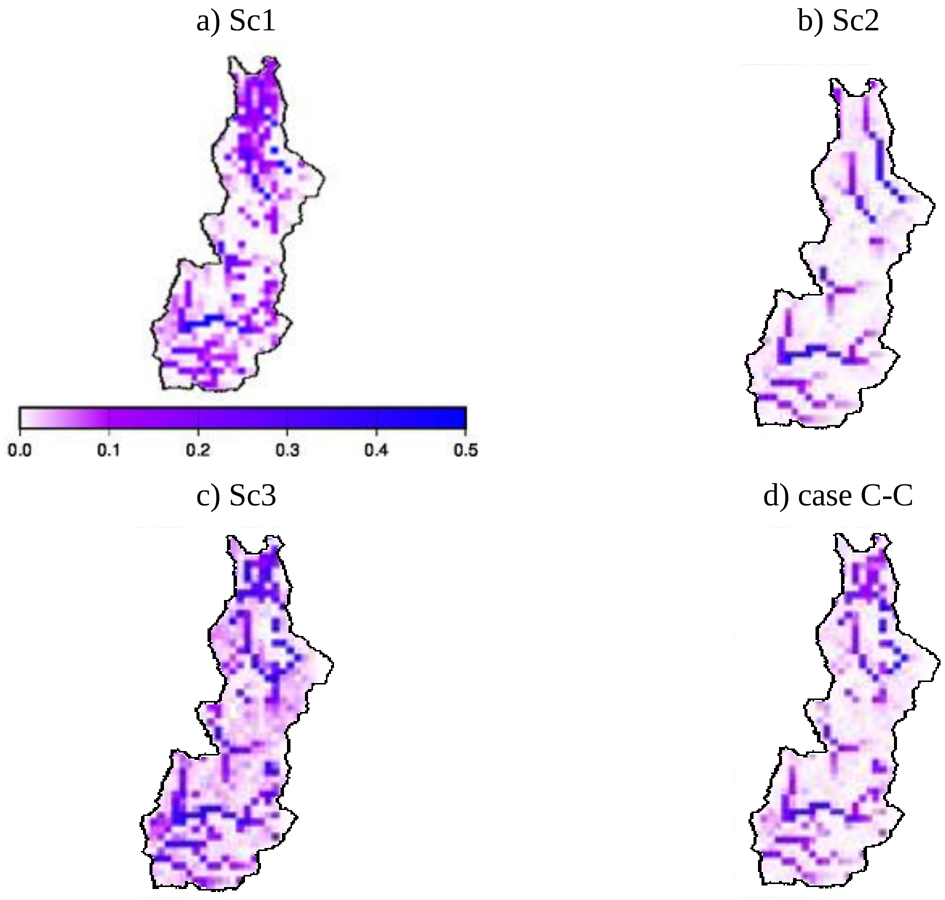


Figure 3.35 The soil erosion from a) severe land use change scenarios, and b) severe climate change scenario at the Nam Wa river basin


a) Sc1

b) Sc2

c) Sc3

d) case C-C

Figure 3.36 Annual sediment yield in Nam Wa river basin

a) Result from severe land use change scenario

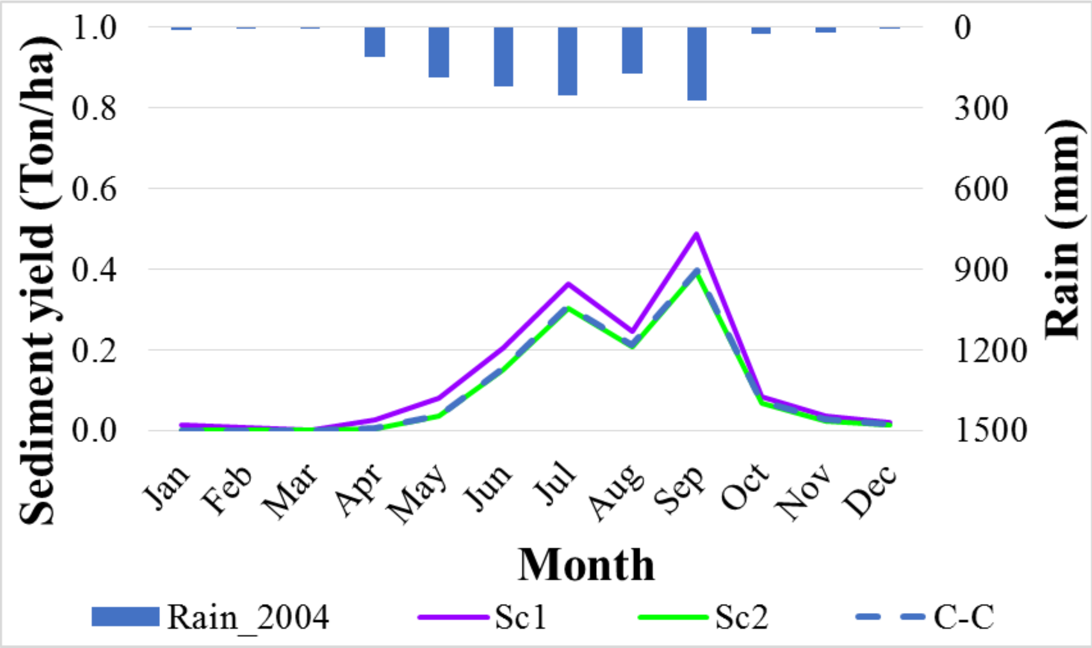


Figure 3.37 The sediment yield from a) severe land use change scenarios, and b) severe climate change scenario at the Nam Wa river basin

b) Result from severe climate change scenario

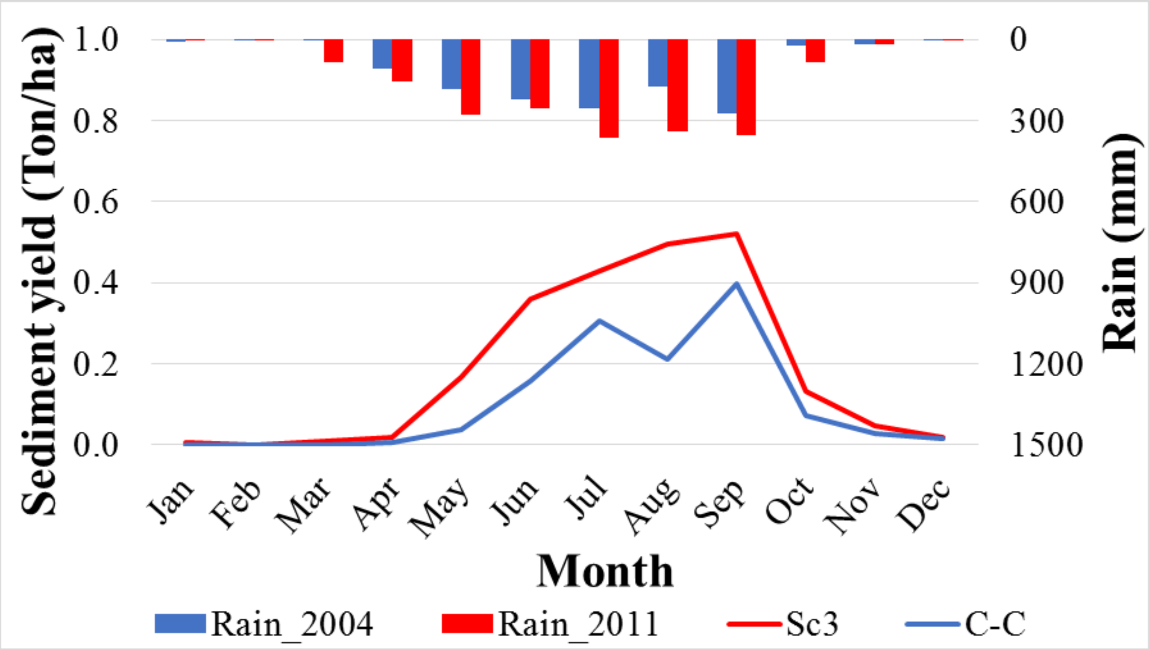


Figure 3.37 Continue

Remark: Sc stands for scenario

3.6) Difference value and percentage change data

Difference value and percentage change data with regard to climate change and land-use change were used to identify the factor having the largest impact on soil erosion and sediment, i.e., climate change or land use change. Future percentage changes and difference values are determined by increasing or decreasing the percentages and values of soil erosion and sediment, calculated from the monthly averages.

The results suggest that changes in both climate and land use significantly affect soil erosion and sedimentation. The differences in each scenario indicate that, when forest cover is decreased or converted to agricultural terrain, land use change is likely to have a greater impact than climate change. However, climate change tends to have a greater effect on soil erosion and sediment yield than land use change in areas that have undergone only slight changes in land use. Additionally, the results for the upstream area of Nan river basin indicate that differences in land use type are associated with greater change than are climate differences. By contrast, in the downstream area, climate change is likely to have a greater impact than land use change on both soil erosion and sediment.

These results obtained due to the projected future changes in climate and land use. This study envisaged future land use by increasing and decreasing forest cover across the entire Nan river basin based on current land use data, wherein forest cover accounts for 5% of the total area. Thus, land use change in the downstream area of Nan river basin underwent an average change of at least 5% of the total area, while the upstream area underwent an average change of up to 20% of the total area. Climate change in the upstream and downstream areas underwent average changes of 9% and 14%, or approximately 10 and 14 mm, respectively. As such, the percentage change of land use in the upstream area is greater than it is downstream, while the percentage change of climate change is greater downstream. Therefore, this study’s findings suggest that land use change is more likely than climate change to influence soil erosion and sediment in the upstream area, while in the downstream area, climate change is more likely than land use change to have an effect. The percentage change and difference value of each scenario in upstream and downstream are shown in Figure 3.38-3.41.

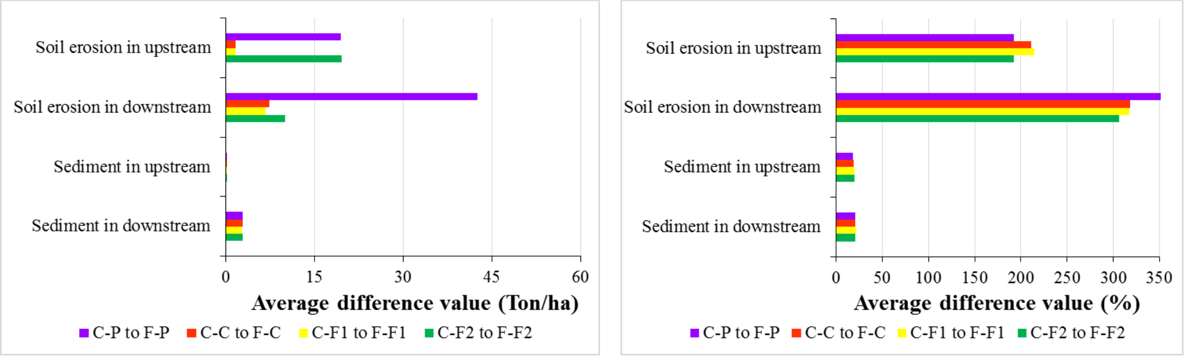
Table 3.21 The average difference value from the result in case of climate change

Case study		Average difference value							
		Ton/ha				%			
		C-P to F-P	C-C to F-C	C-F1 to F-F1	C-F2 to F-F2	C-P to F-P	C-C to F-C	C-F1 to F-F1	C-F2 to F-F2
Soil erosion	Upstream	19.5	1.7	1.6	19.6	192.6	211.4	214.0	192.4
	Downstream	42.5	7.4	6.6	10.0	363.7	318.5	317.2	306.3
Sediment	Upstream	0.0	0.0	0.0	0.0	18.0	18.9	19.6	19.7
	Downstream	2.8	2.8	2.8	2.8	20.9	21.1	21.4	21.0

Table 3.22 The average difference value from the result in case of land change

Case study		Average difference value																					
		Ton/ha											%										
		C-P to C-C	C-P to C-F1	C-P to C-F2	C-C to C-F1	C-C to C-F2	F-P to F-C	F-P to F-F1	F-P to F-F2	F-C to F-F1	F-C to F-F2	F-F1 to F-F2	C-P to C-C	C-P to C-F1	C-P to C-F2	C-C to C-F1	C-C to C-F2	F-P to F-C	F-P to F-F1	F-P to F-F2	F-C to F-F1	F-C to F-F2	F-F1 to F-F2
Soil erosion	Upstream	-9.3	-9.4	0.1	0.0	9.4	-27.1	-27.3	0.2	-0.1	27.3	27.4	-92.1	-92.6	0.7	-6.0	1171.9	-91.6	-92.0	0.6	-5.2	1094.6	1159.7
	Downstream	-9.4	-9.6	-8.4	-0.2	0.9	-44.5	-45.5	-40.9	-1.0	3.6	4.6	-80.1	-82.1	-72.0	-9.8	40.8	-82.1	-83.9	-75.5	-10.1	36.7	52.0
Sediment	Upstream	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-33.7	-35.1	-3.8	-2.0	45.2	-33.2	-34.1	-2.4	-1.4	46.1	48.2
	Downstream	-0.2	-0.4	-0.1	-0.2	0.1	-0.3	-0.5	-0.1	-0.2	0.1	0.3	-1.7	-3.3	-1.0	-1.6	0.7	-1.6	-2.9	-0.9	-1.3	0.6	2.0

Climate change



Land use change

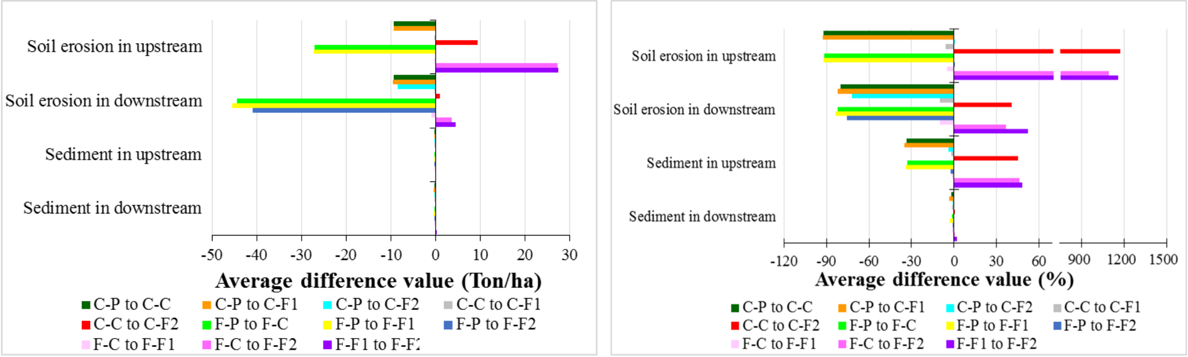
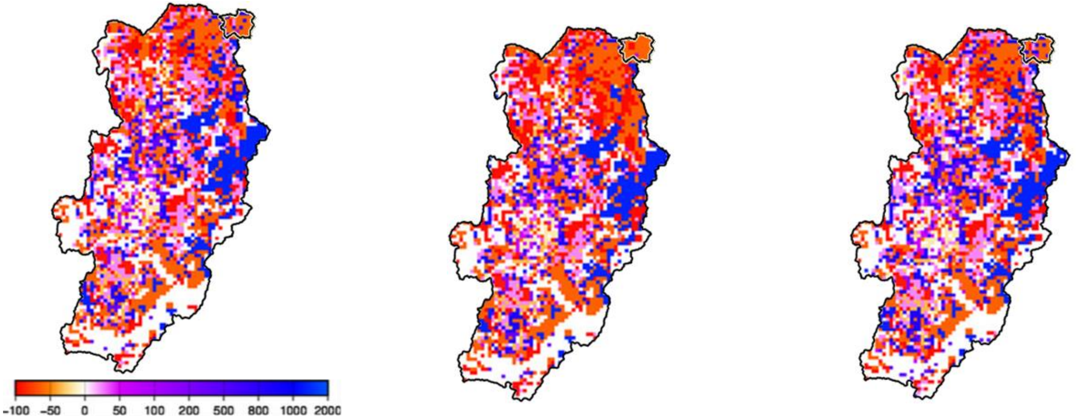
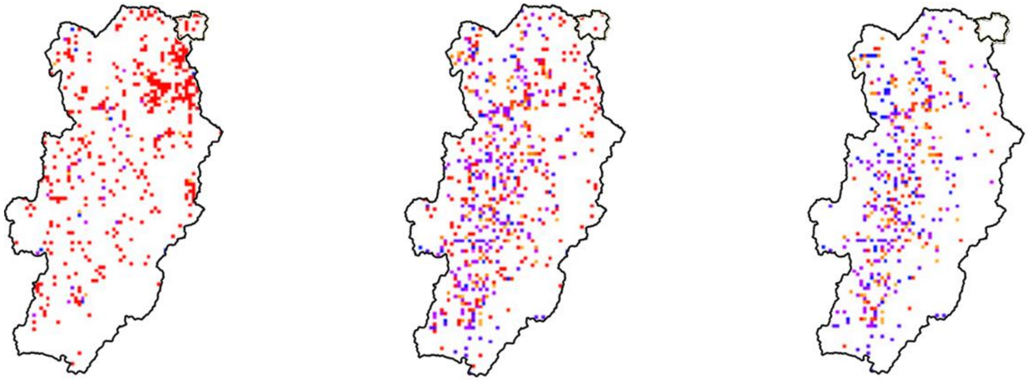


Figure 3.38 The average difference value of climate and land use change scenario


a) case F-P to F-C

b) case F-P to F-F1

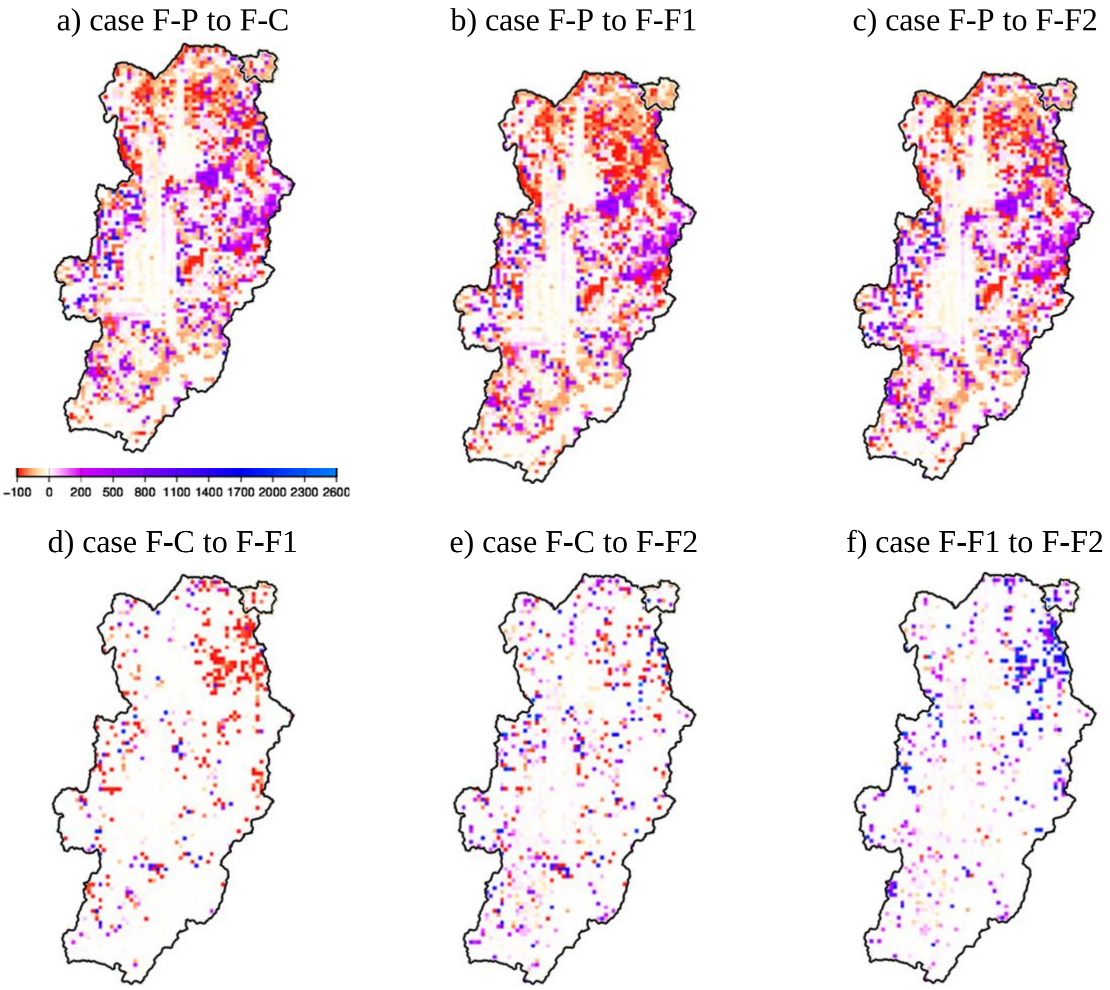
c) case F-P to F-F2


d) case F-C to F-F1

e) case F-C to F-F2

f) case F-F1 to F-F2

Figure 3.39 The example percentage change of soil erosion in case of land use change


a) case F-P to F-C

b) case F-P to F-F1

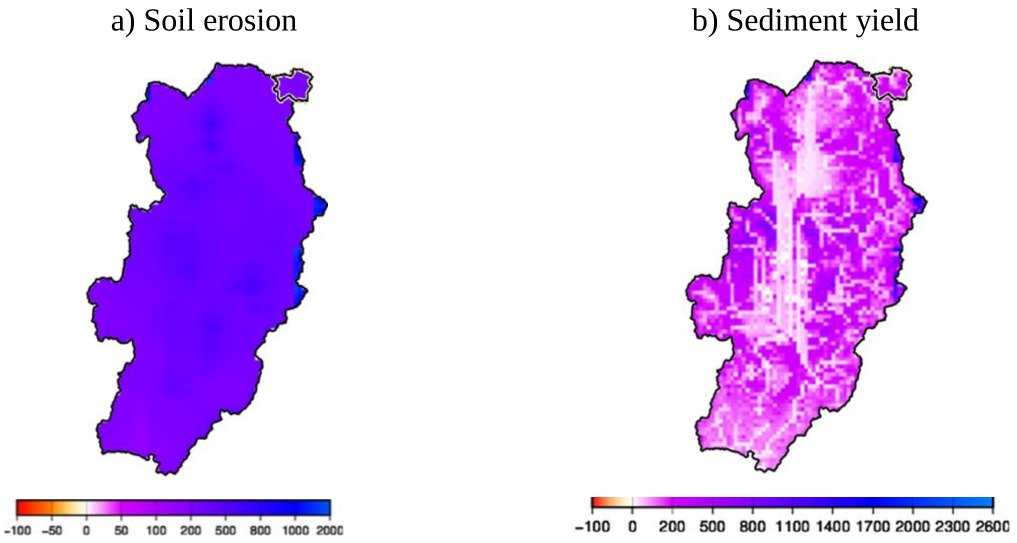
c) case F-P to F-F2

d) case F-C to F-F1

e) case F-C to F-F2

f) case F-F1 to F-F2

Figure 3.40 The example percentage change of sediment yield in case of land use change


a) Soil erosion

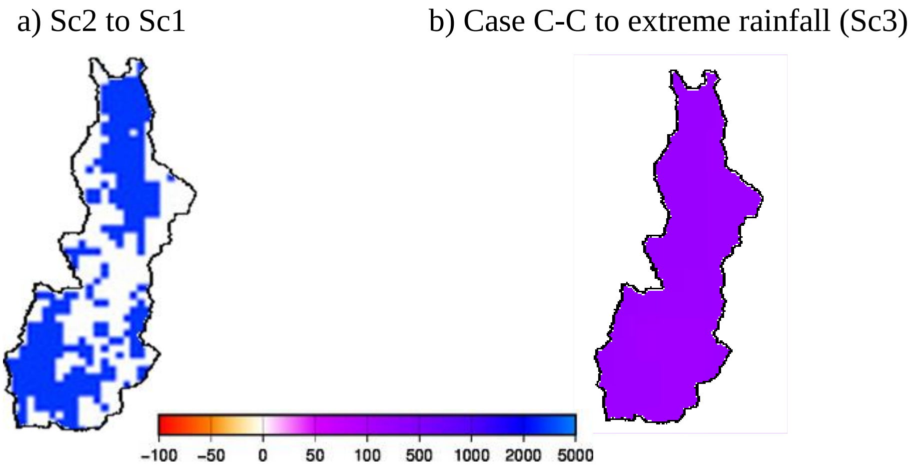
b) Sediment yield

Figure 3.41 The example percentage change of climate change scenario between the result from case C-P and F-P

Regarding the extreme scenario, in the entire Nam Wa river basin, the results suggest that climate change is more likely than land use change to have a significant impact on sediment yield, but the opposite is the case with regard to soil erosion (Figure 3.42 and 3.43). Soil erosion can increase by up to more than 2,000% in response to changes in land use, whereby forest is replaced by field crop, while soil erosion will increase by approximately 235% under severe rainfall. Furthermore, the difference values and percentage changes indicate that the sediment yield varies more due to severe climate than to land use change, whereby forest is replaced by field crop or vice versa. The sediment yield increase exceeds 79% in the extreme rainfall scenario, while it is increased by approximately 31% in response to land use change, whereby forest is replaced by field crop (Table 3.23).

Table 3.23 The average percentage change and difference value from the results in case of extreme scenario at the Nam Wa river basin

	Average percentage change (%)		Average difference value (Ton/ha)	
	Extreme rainfall (case C-C to Sc4)	Land use change (Sc2 to Sc1)	Extreme rainfall (case C-C to Sc4)	Land use change (Sc2 to Sc1)
Soil erosion	235.3	2002.9	3.1	16.5
Sediment	78.6	31.2	0.08	0.03



a) Sc2 to Sc1

b) Case C-C to extreme rainfall (Sc3)

Figure 3.42 The percentage change of soil erosion in Nam Wa river basin

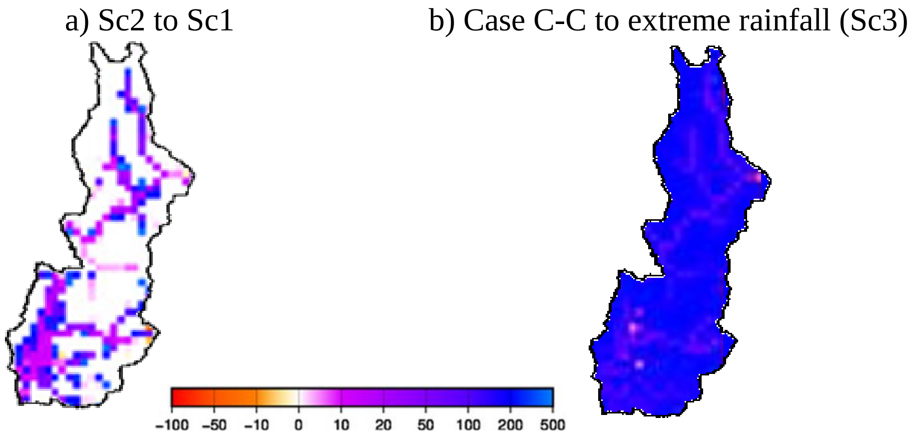


Figure 3.43 The percentage change of sediment yield in Nam Wa river basin

This study generates the following conclusions:

1) The soil erosion and sediment models are well calibrated and can be used to simulate future scenarios, since the NSE calibration and validation values exceed 0.5.

2) The impact of climate change demonstrates that soil erosion is influenced by the variations in the R-factor associated with rainfall. The amount of sediment in the river depends on the amount of eroded soil particles, the sediment delivery ratio, and river discharge. However, the sediment yield in the downstream area is primarily influenced by river discharge, which is the main factor that impacts sediment transportation. Additionally, the factor most associated with land use is the C-factor, or crop management factor, which influences the likelihood of soil erosion associated with each land use type. Land use change whereby forest is converted to agricultural land has a greater effect on soil erosion and sediment than does a change from one type of agriculture to another, due to the difference in the C-factor value.

3) The monthly percentage change data reveal that changes in both climate and land use significantly affect soil erosion and sediment in the river. However, in the upstream area, the impact of land use change tends to be greater than the impact of climate change on soil erosion and sediment yield. By contrast, in the downstream area, climate change is likely to have a greater impact than land use change on both soil erosion and sedimentation. These results are based on projected future changes in climate and land use. Furthermore, the extreme scenarios suggest that land use change has a greater impact on soil erosion than climate change, while climate change has a greater impact than land use change on sedimentation.

The conclusion of this chapter are also mention in chapter 5.

Chapter 4

The extent of sediment inflow to the reservoir

Sediment flow to the reservoir causes loss of storage and reduces the reservoir's lifespan. Climate change and land use change have a definite impact on fluctuations in the amount of sediment inflow to the reservoir. However, studies concerning sediment inflow to reservoirs are scarce, as are those concerning sediment yield, due to the limited availability of measurement data and its having received little scholarly attention. It is likely that it has been overlooked by researcher due to the gradual nature of the process by which sediment fills up a reservoir (Palmieri *et al.*, 2001 Tigrek and Aras, 2011). However, sedimentation remains a significant problem for older or smaller reservoirs that lack the requisite resources to prevent or clear accumulated sediment in the reservoir. Therefore, this dissertation aims to estimate sediment inflow to reservoirs under both normal and extreme climate change and land use change scenarios.

Therefore, this study estimates the most likely sediment amounts in three reservoirs in the Nan river basin, including Sirikit reservoir, which is the largest, and Nam Wa and Nam Hi reservoirs, which are more moderate in size. The location and land use area of the reservoirs in Nan river basin is shown in Figure 4.1, Tables 4.1 and 4.2, respectively. For the purpose of the study, it is assumed that reservoir sediment levels will increase at the same rate as sediment flow in the vicinity of the reservoir's floodgate. The sediment levels were estimated for all reservoirs based on the annual average sediment in current and future scenarios, beginning from 0 million tons in the year of the reservoir's construction, with the maximum storage capacity used as the end value. This study analyzes the impact of climate and land use changes on sediment inflow to the reservoirs in two case studies. In the first case study, the results from cases C-C, C-F1, C-F2, and F-C are used as the values of sediment inflow to the reservoir. The second case study constitutes an analysis of the impact of climate and land use changes using the results from extreme climate and land use change scenarios. Both simulate the extent of sediment inflow to the reservoir on the assumption that the sediment flows at a constant rate, and that the reservoirs lack the resources necessary to prevent or clear up the accumulated sediment.

Table 4.1 Land use in the catchment area of Nam Wa reservoir

Year / Land use type	Area (Km^2)			
	2000	2016	2036 (1)	2036 (2)
Evergreen forest	836.9	207.1	208.1	197.8
Deciduous forest	195.6	1367.7	1573.3	1342.5
Degraded forest	482.1	3.4	0.0	1.4
Field crop	507.7	409.7	203.0	449.6
Paddy field	14.1	13.5	16.9	12.2
Perennial crops	3.8	19.0	19.0	15.0
Urban	1.4	16.3	16.1	20.2
Water	3.5	8.4	8.6	6.2
Total	2045.0	2045.0	2045.0	2045.0

Table 4.2 Land use in the catchment area of Nam Hi reservoir

Year / Land use type	Area (Km^2)			
	2000	2016	2036 (1)	2036 (2)
Evergreen forest	0.0	0.0	0.0	0.0
Deciduous forest	1.8	28.2	22.8	16.7
Degraded forest	17.5	0.1	0.0	0.0
Field crop	10.3	10.1	10.3	15.9
Paddy field	10.5	0.6	0.1	0.8
Perennial crops	0.4	6.1	6.1	5.1
Urban	0.0	0.0	0.0	0.9
Water	0.0	1.1	1.1	1.0
Total	40.1	40.1	40.1	40.1

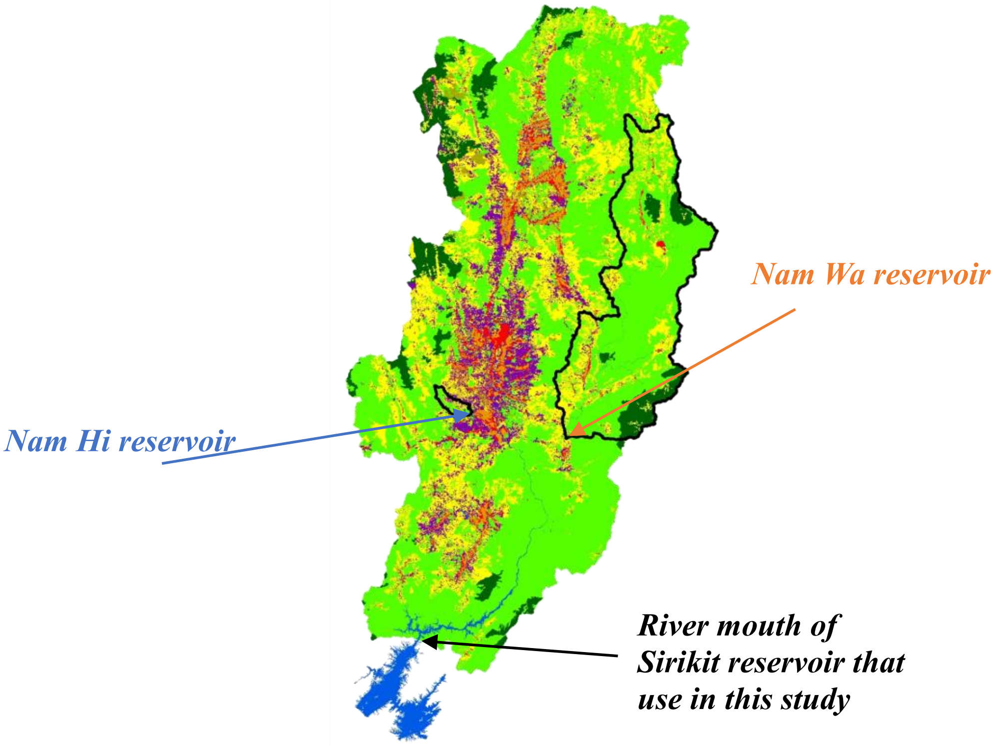


Figure 4.1 Location of Sirikit reservoir, Nam Wa, and Nam Hi reservoir

4.1) Sediment inflow to the reservoirs based on the results of cases C-C, C-F1, C-F2, and F-C

In the future scenario, the annual average sediment flow in the vicinity of the reservoir’s floodgate, calculated from climate data for the period 1985-2004 and land use in 2016 (case C-C), was used as the incremental increase in sediment yield from the second year after construction of the reservoir to the years 2035 and 2079, with respect to land use change and climate change, respectively. Subsequently, regarding climate change, the annual average sediment flow in the case using projected climate data for 2080-2099 and land use data for 2016 (case F-C) was used as the incremental increase in sediment yield from 2080 to the final year that the reservoir was filled with sediment, or the final year that the total sediment in the reservoir was equivalent to the reservoir’s maximum storage capacity. Additionally, regarding land use change, the results from cases C-F1 and C-F2 (projected land use for 2036) were used as the incremental increase in sediment yield from 2036 to the final year (Table 4.3).

For the current scenario, with regard to both climate change and land use changes, the annual average sediment flow in the vicinity of the reservoir’s floodgate water gate, as recorded in climate data for the period 1985-2004 in case C-C, were used as the incremental increase in the sediment yield from the second year after the reservoir’s construction to the final year that the reservoir was filled with sediment (Table 4.3).

Table 4.3 Detail of the data that use to study the incremental of sediment in the reservoir

Current scenario		**Future scenario**			
		Climate change		**Land use change**	
Case study	Year that used the result as an incremental value	Case study	Year that used the result as an incremental value	Case study	Year that used the result as an incremental value
C-C	the second year after created the reservoir to the final year	C-C	the second year after created the reservoir to the year 2079	C-C	the second year after created the reservoir to the year 2035
		F-C	2080 to the final year	C-F1 and C-F2	2036 to the final year

Remark: Every scenario start from 0 Million ton

Regarding climate change, the results indicated that the sediment inflow to the reservoir in the future scenario increased due to increased rainfall and a higher risk of swifter sediment flow versus the current average. This indicates that the reservoir may become full of sediment within 300 years.

Regarding land use change, the results suggest that the expansion of forest cover can help to regulate soil erosion and slow down the increase in sediment in reservoirs. Land use in future scenario 1, involved increased forest cover and, in 2016, had more deciduous forest cover than was factored into the land use data for future scenario 2, the rate of sediment inflow to the reservoirs was less than that in the case that depended on land use changes in future scenario 2. Under these conditions, the reservoir was likely to be functional for longer, due to the more gradual sedimentary increment. However, decreased forest cover causes higher soil erosion and leads to faster accumulation of sediment in reservoirs.

The potential of increased sediment in 3 reservoirs including Sirikit reservoir, Nam Wa and Nam Hi reservoir in Nan river basin shown in Figure 4.2, the annual average sediment flow near the water gate of the reservoir are shown in Table 4.4 and the maximum of storage capacity of each reservoir and the final year that sediment will full in the reservoir from prediction are shown in Table 4.5.

Table 4.4 Average sediment flows near the water gate of the reservoir in Nan river basin

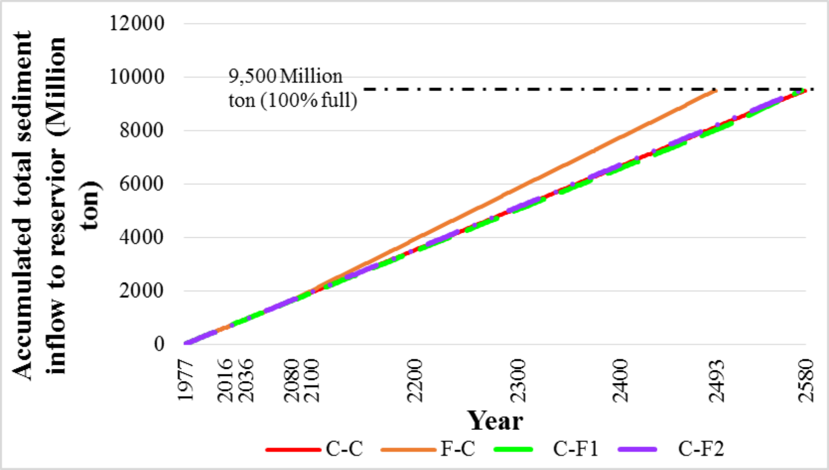
Name of reservoir	**Average sediment yield of each case study (Ton)**						
	C-C	C-F1	C-F2	F-C_ip	F-C_ge	F-C_cn	F-C_average
Sirikit	15.8	15.5	15.9	15.7	19.5	22.0	19.1
Nam Wa	0.020	0.020	0.020	0.021	0.028	0.035	0.028
Nam Hi	0.008	0.007	0.008	0.008	0.010	0.011	0.009

Remark: ip, ge and cn mean climate data from IPSL-CM5A-LR, GFDL-ESM2M and CNRM-CM5 datasets, respectively.

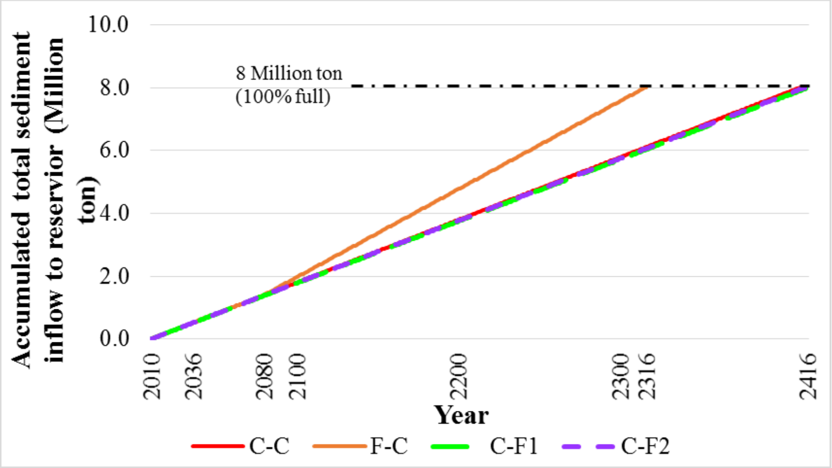
Table 4.5 The maximum water storage of each reservoir and the final year that sediment will be full in the reservoir

Name of reservoir	The maximum of storage capacity (MCM)	Beginning year	Catchment area (km^2)	Final year		Number of years (from beginning to end) (years)		Number of years (from current (2018) to end) (years)	
				Climate change	Land use change	Climate change	Land use change	Climate change	Land use change
Sirikit	9500	1977	12,000	2493	2576-2580	516	599-603	475	558-562
Nam Wa	8	2010	2,050	2316	2411-2416	306	401-406	298	393-398
Nam Hi	6	2003	41	2667	2758-2815	664	755-812	649	740-797

a) Accumulated total sediment inflow to the Sirikit reservoir



b) Accumulated total sediment inflow to the Nam Wa reservoir



c) Accumulated total sediment inflow to the Nam Hi reservoir

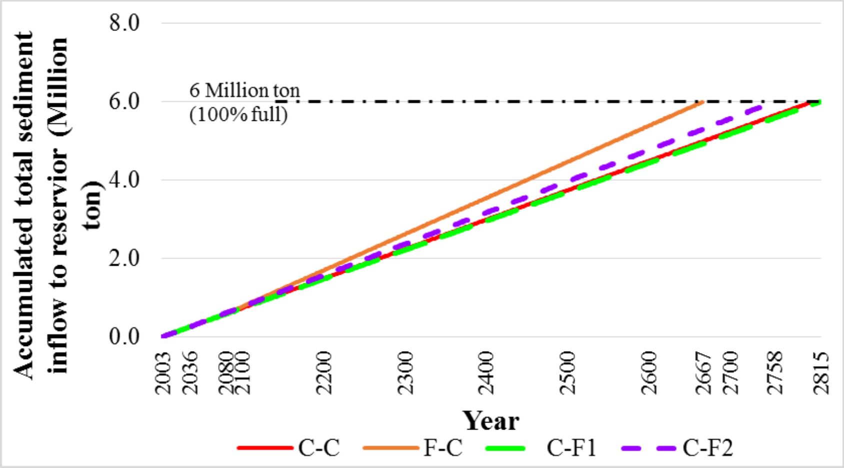


Figure 4.2 Accumulated total sediment inflow to the reservoir; a) Accumulated total sediment inflow to the Sirikit reservoir, b) Accumulated total sediment inflow to the Nam Wa reservoir, and c) Accumulated total sediment inflow to the Nam Hi reservoir

The results from Sirikit, Nam Wa and Nam Hi reservoirs verify that increased rainfall can lead to rapid accumulation of sediment in reservoirs, even when there are no changes in land use. Additionally, the results from Nam Hi reservoir illustrate that an expansion of forest cover can reduce the likelihood of sediment flow into the reservoir, although inappropriate land use may increase the likelihood that sedimentary flow will occur, reducing the reservoir's storage capacity. However, the results from this particular case study are inconclusive, due to the very slight changes in climate and land use. Thus, the results from the severe climate and land use changes scenario are presented below.

4.2) Sediment inflow to reservoirs based on the results from the extreme climate change and land use change scenarios

This section presents the results regarding the likely extent of sediment inflow to the reservoirs based on the extreme scenarios of land use change and climate change, which followed the extreme climate and land use change scenarios outlined in the previous chapter with regard to the catchment area of the Nam Wa reservoir.

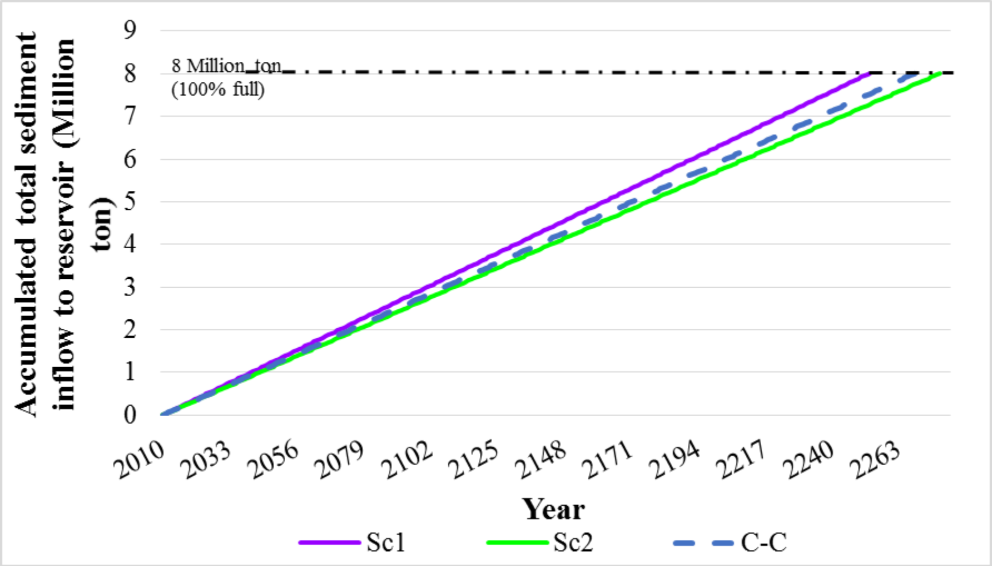
The extreme land use change scenarios illustrate that increased field crop area can increase the likelihood of soil erosion and sedimentation. For example, if approximately 50% of the total catchment area of the Nam Wa reservoir is covered with field crop (Sc1), the reservoir may become filled with sediment within 235 years from now. However, if the same area is covered with forest, as in scenario 3 (Sc3) the reservoir's lifetime may be extended by a further 260 years prior to filling up with sediment (Figure 4.3 and Table 4.6).

In the case of climate change, the amount of sediment inflow to the reservoir in Sc3 is twice as high in case C-C, at an average of 0.068 million tons. The Sc3 results, which use the climate data from 2011 to produce estimates, suggest that the reservoir may become full of sediment within 110 years if rainfall in Nan river basin continues at the same levels, or at similar levels to those recorded in 2011. The accumulated total sediment inflow to the Nam Wa reservoir is shown in Figure 4.3 the annual average sediment flow near the water gate of the reservoir and the final year that sediment will full in the reservoir from prediction are shown in Table 4.6.

Table 4.6 Average sediment flows near the water gate of the Nam Wa reservoir and the final year that sediment will be full in the Nam Wa reservoir

Final year		Number of years (from beginning to end) (years)		Number of years (from current (2018) to end) (years)		Average sediment yield of each scenario (Ton)			
Climate change	Land use change	Climate change	Land use change	Climate change	Land use change	Sc1	Sc2	Sc3	C-C
2128	2253-2277	118	243-267	110	235-259	0.033	0.03	0.068	0.031

a) Result from severe land use change scenario



b) Result from severe climate change scenario

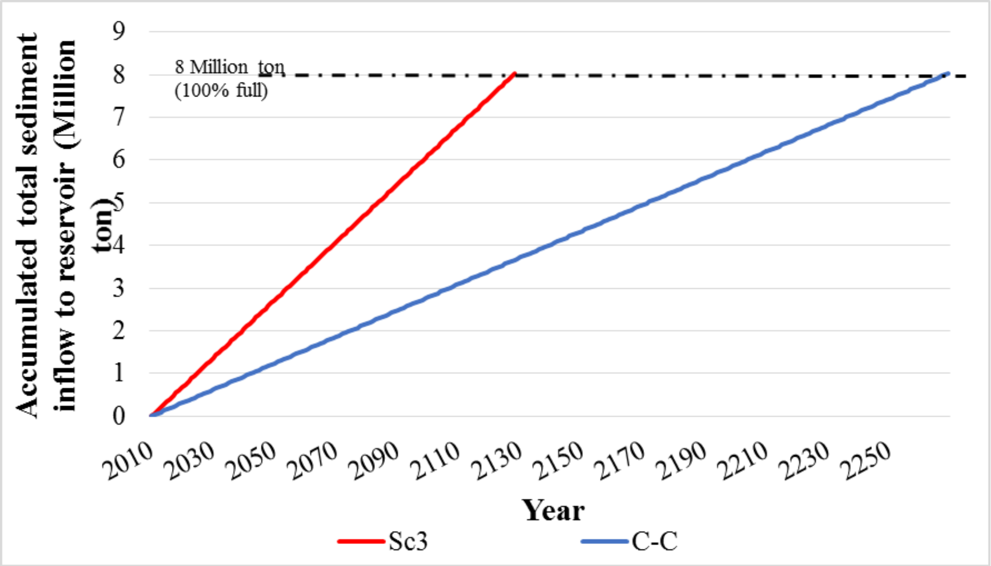


Figure 4.3 Accumulated total sediment inflow to the Nam Wa reservoir from a) severe land use change scenarios, and b) severe climate change scenario

The results from both case studies strongly suggest that increased forest cover will protect the soil surface from rainfall, decreasing surface runoff and the extent of soil erosion, from which sediment yield originates (Nunes *et al.*, 2011, Paiboonvorachat and Oyana, 2011, Ochoa *et al.*, 2016 Vanwalleghem *et al*., 2017). Moreover, appropriate land management, including refraining from farming in steep areas (i.e., where the slope is steeper than 35%), and suitable conservation practices can reduce the extent of soil erosion and decelerate the accumulation of sediment in rivers during extreme precipitation events (Lertwattanaruk, 2014, Gomez-Macpherson *et al*., 2016, Srathongtien, 2016, Gomez *et al.*, 2018). Furthermore, intensified precipitation can lead to increased runoff and river discharge (Champathong *et al*., 2013, Watanabe *et al*., 2014, Chacuttrikul *et al*., 2018), which has led to recommendations that check dams be constructed to reduce peak discharge and trap the sediment before it can flow into the reservoir (Polyakov *et al.*,2014, Wang *et al*., (2014), Guyassa *et al.*, 2015). Guyassa *et al.* (2015) observed that the implementation of check dams combined with vegetation considerably reduced peak discharge, which is the primary factor controlling the sedimentary flow rate, while Wang *et al*. (2014) observed that check dams can trap sediment and that these trapped sedimentary particles can also yield useful information about local erosion processes. Consequently, the check dams are a practical means of decelerating sediment flow and supporting watershed restoration (Polyakov *et al*., 2014).

These measures can help to protect surface soil, decrease surface runoff, and reduce the extent of soil erosion and sediment flow into the reservoir caused by changes in climate and land use, as well as help to extend reservoirs' lifespans. However, to maximize benefit, the area's condition must be considered prior to deciding on the appropriate conservation measures.

It may thus be concluded that expansion of forest cover can help to reduce the extent of sediment flow to the reservoir, while inappropriate land use can increase sediment flow, thereby decreasing the reservoir's storage capacity. Therefore, to reduce soil erosion and slow down sediment flow, suitable land use planning tailored to the catchment area should be implemented.

Chapter 5

Conclusion

This study estimated future soil erosion and sediment yields in cases using data from different years with boundary conditions, and sought to determine whether climate change or land use change has a greater impact on soil erosion and sediment yield, by applying a model developed from RUSLE, SDR and a sediment transport equation. Based on the results, the following conclusions may be drawn:

1) Based on the results in chapter 2 that show the R-factor equation, the sediment yield calculated from the daily R-factor equation approaches that reported in the observational data from RID, taking into consideration some mistakes associated with the SEE value.

2) The sediment yields simulated by the model using climate data from the period 1985-2004 and land use data from 2000 (case C-P) were used to calibrate the model with observational data from Royal Irrigation Department (RID), and Nash-Sutcliffe Efficiency Coefficient (NSE) was used to verify the accuracy of the model simulation. The results indicated that the model is well calibrated and can be used to simulate future scenarios, since the NSE values from calibration and validation are higher than 0.5.

Furthermore, the results detailed in chapter 3 demonstrate the impact of climate change and land use changes on soil erosion and sediment in the Nan river basin, including the effects of extreme scenarios in the Nam Wa river basin. The data pertaining to the consequences of climate change indicate that monthly soil erosion are influenced by variations in the R-factor, which is associated with the rainfall. Increased or intensified rainfall can increase the R-factor, leading to the detachment of greater amounts of soil from the topsoil surface, in turn leading to increased soil erosion. Moreover, the level of sediment in the river depends on the eroded soil particles, the sediment delivery ratio by which sediment is transported from its site of origin to the river, and river discharge. However, the sediment yield downstream is primarily influenced by river discharge, which is the factor that has the greatest impact on sediment transportation, and is in turn influenced by rainfall.

Regarding land use change, the C-factor, or crop management factor, accounts for the extent of soil erosion associated with each land use type. The results suggest that the amount of soil erosion and sediment yield from forested areas is lower than that from agricultural areas. The soil erosion and sediment yield from field crops is highest, while those from forested areas are lowest. Land use change whereby forest cover is replaced with agricultural land has a greater effect on soil erosion and sediment than does a change from one type of agriculture to another due to the difference of C-factor value. Additionally, the results from the extreme scenario suggest that suitable land use management can reduce the extent of soil erosion and sediment yield during extreme rainfall events.

The monthly percentage change data demonstrate that changes in both climate and land use have a significant impact on soil erosion and sediment yield. However, in the upstream area, the land use change exerts a greater influence on soil erosion and sediment yield than does climate change. By contrast, in the downstream area, climate change is more likely to have a greater impact than land use change on both soil erosion and sediment, based on projected future changes in climate and land use. Furthermore, the extreme scenarios suggest that land use change tends to be have a greater impact than climate change on soil erosion, while climate change has a greater impact than land use change on sediment yield.

3) The data on annual average sediment inflow to the reservoirs, detailed in chapter 4, indicate that the expansion of forest cover can help to reduce the extent of sediment flow to reservoirs, while inappropriate land use can exacerbate sediment flow, thus diminishing the reservoir’s storage capacity. Suitable land use planning, tailored to the catchment area, should be implemented to reduce the extent of soil erosion and decelerate sediment flow.

This study examined how a keen and sensitive appreciation of the effects of land use change and climate change, under simulated sedimentation scenarios, can be beneficial in designing optimal land use strategies that are effective in reducing soil erosion damage and decreasing sediment accumulation in rivers, including planning to mitigate the future impact of climate change.

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Appendix A

Model description

1) Hydrological model: H08 model

This study used the H08 model, which is an open-source global hydrological model, to estimate surface runoff and river discharge. It can be easily and effectively applied to computer systems. The H08 model can consider the interactions between natural hydrological processes and human activities by integrating several factors related to water management (Mateo *et al*., 2014, Hanasaki *et al*., 2018). The H08 model comprises six modules, including a (1) land surface process module, (2) river module, (3) crop growth module, (4) reservoir operation module, (5) environmental water module, and (6) anthropogenic water withdrawal module (Hanasaki and Yamamoto, 2010). The H08 model can simulate both natural water flow and water flow that is influenced or directed by human activity (Hanasaki *et al*., 2008). This study used only the land surface process and river modules to estimate runoff and river discharge, respectively.

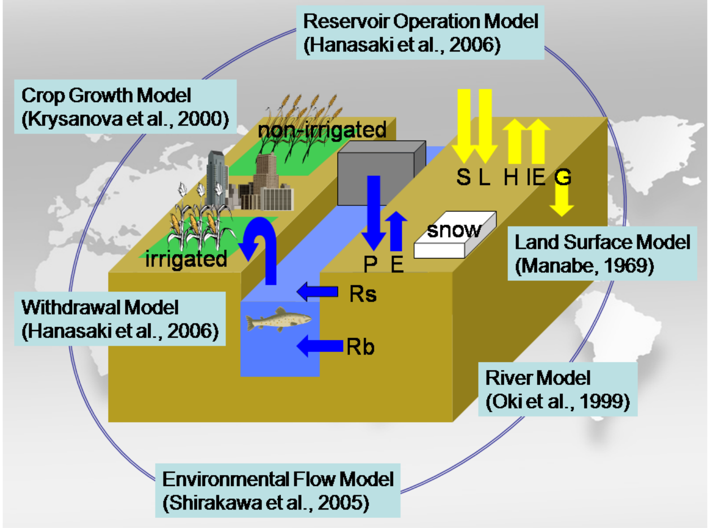

Figure S1 H08 model (Hanasaki *et al*., 2008)

1.1) Land surface process module

The land surface process module is based on a standard bucket model, in which sub-surface runoff occurs continuously, and there is a single soil moisture layer for all soil and vegetation types to model soil moisture. The land surface process module can calculate both hydrological balance and energy balance (Hanasaki *et al*., 2008). Process and equation in Land surface process module are shown in Figure S2.

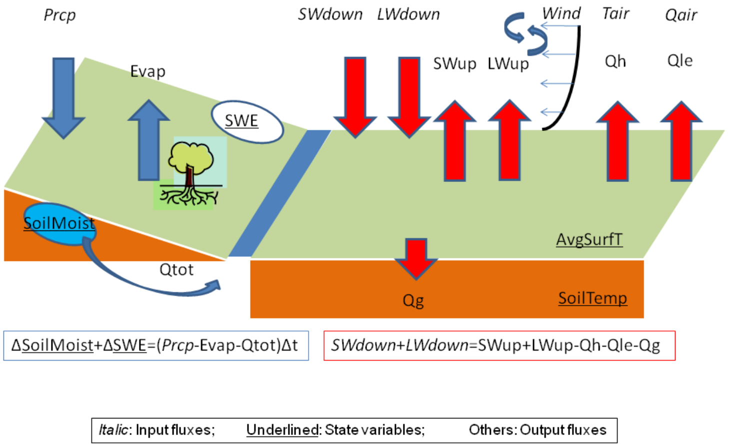

Figure S2 Process and equations in Land surface process module (Hanasaki and Yamamoto, 2010)

1.2) River module

The river module is based on the Total Runoff Integrated Pathways (TRIP) model. This model uses runoff data from the land surface process module to calculate river flow. The river module assumes that the river flows in straight channels at a constant velocity from upstream to downstream (Hanasaki and Yamamoto, 2010), based on flow direction data obtained from a Digital Elevation Model (DEM). Process and equation in river module is shown in Figure S3.

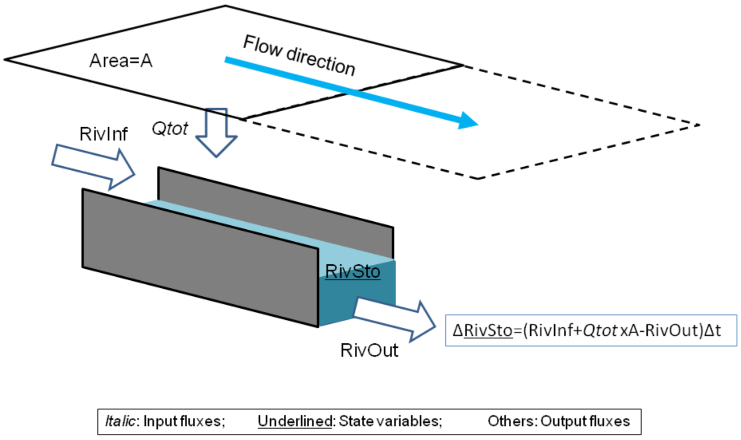

Figure S3 Process and equations of the H08 river module (Hanasaki and Yamamoto, 2010)

2) Soil erosion and sediment models

Soil erosion and sediment models are used to estimate soil erosion and sediment yield according to their relationships with their driving factors, such as land use, climate, and soil (Morgan and Nearing, 2011, Blaikie, 2016). The soil erosion model is aimed at determining the extent to which soil erosion occurs based on the fundamental factors of surface runoff, infiltration, plant growth and erosion mechanics (Coit *et al*., 2014). The sediment model is aimed at understanding the process of sedimentation, that is, the movement of sediment from a source to a sink in a catchment (Bracken *et al.*, 2015). The soil erosion and sediment models may be used to examine the transfer of soil particles from mountainous areas to river, and are useful for estimating future conditions (Ouyang and Bartholic, 1997, Ganasri and Ramesh, 2016). However, the majority of models currently focus on soil erosion, with little attention paid to sedimentation processes.

2.1) Soil erosion model

Soil erosion is one of the most challenging problems worldwide: it degrades water quality and limits the soil's ability to support plant life due to the removal of topsoil, which impedes the development of plant roots (Prasannakumar *et al*., 2011, Tucker, 2018).

To calculate soil erosion, this study uses the RUSLE, which is the optimal equation for estimating the relationship between soil erosion and land use, due to its incorporation of the land cover management factor (C-factor) (Leh *et al.*, 2013). RUSLE is best known for its applicability in modelling erosion potential for soil conservation planning worldwide (Zhang *et al*., 2013). It is the most reliable model and yields results that align with measurement data (Tiwari *et al*., 2000, Cecilio *et al*., 2004, Stolpe, 2005, Wade *et al*., 2012, Mondal *et al*., 2018). Moreover, RUSLE can be used in conjunction with the SDR model to effectively evaluate the sediment levels in a river. RUSLE is the updated version of USLE, which was developed by Renard and others in conjunction with the USDA (Merritt *et al*., 2003). RUSLE's formula is identical to that of USLE, but with enhancements of each factor. For example, the developers improved the rainfall factor by adding a factor related to runoff, a new equation to reflect slope length and steepness, and a new conservation practice value (Renard *et al*., 1997).

The formula of RUSLE is:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (1)$$

Where *A* is the computed soil loss per unit of area, expressed in the units selected of *K-factor* and period selected of *R-factor*. In this study, the unit of *A* is ton/ha/month, *R-factor* is rainfall-runoff erosivity factor, *K-factor* is soil erodibility factor, *L-factor* is slope length factor, *S-factor* is slope steepness factor, *C-factor* is land cover management factor, and *P-factor* is conservation practice factor.

1) Rainfall-runoff erosivity factor (R-factor)

R-factor is related to rainfall, which is the primary factor that affects soil erosion (National Geographic, 2018). It can break down soil aggregates and disperse the aggregate material. Very fine sand, silt, and clay are easily displaced by raindrop splash and runoff water (Ritter, 2012). R-factor can be determined from 15-minute rainfall data using the equation developed by Renard *et al.* (1997):

$$\textit{R-factor} = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m} E_k (I_{30})_k\right] \qquad (2)$$

Where E is the total storm kinetic energy (MJ/ha),

I_{30} is the maximum 30-minute rainfall intensity (mm/hr),

j is an index of the number of years used to produce the average,

k is an index of the number of storms in each year,

n is the number of years used to obtain the average *R-factor*, and

m is the number of storms in each year.

2) Soil erodibility factor (K-factor)

Soil erodibility is a dynamic property influenced by land management. Inherent soil texture, soil structure, soil organic matter content, and water retention can determine soil erodibility. Higher organic matter content and improved soil structure result in faster infiltration rates and greater resistance to erosion. Larger soil particles, such as sand, sandy loam, and loam tend to be less erodible than silt, very fine sand, and clay, which have smaller particle sizes (Ritter, 2012).

The K-factor value can be determined by particle size using the equation developed by Renard *et al.* (1997), or by following the K-factor values determined by the LDD of Thailand (LDD, 2000). LDD divided Thailand's soil into 62 groups, based on the soils' characteristics, and used the results from laboratory analyses concerning soil texture, soil structure, and organic matter content to determine the K-factor value for each soil group. The values are shown in Table S1. The equation from Renard *et al*. (1997) is:

$$K\text{-}factor = 7.594 \cdot \left\{0.0034 + 0.0405\, exp\left[-\frac{1}{2}\left(\frac{log(Dg) + 1.659}{0.7101}\right)^2\right]\right\} \qquad (15)$$

$$Dg\ (mm) = exp(0.01 \sum f_i\ ln\ m_i) \qquad (16)$$

Where f_i is the primary particle size in percent of each grid cell and m_i is the mean of particle size.

Table S1 K-factor value from Land Development Department of Thailand

Soil group	K-factor value
1-5, 8, 10-14, 27-28, 51	0.02
6-7, 9, 15-20, 25-26, 32, 35-40, 45, 47-49, 53, 56, 60-61	0.04
21, 57-59	0.05
22-24, 41-44	0.01
29-31, 34, 46, 50, 52, 54-55	0.03
33	0.06
62	Calculate from equation (0.047)

3) Slope length factor and slope steepness factor (L-factor and S-factor)

The L-factor and S-factor are related to the topography of the area. Slope length is the horizontal distance of the grid cell, or the horizontal distance from the starting point of overland flow to the deposition area of the sediment (USDA, 1997). The L-factor and S-factor are the ratio of soil loss from field slope length and field slope gradient, respectively. Long and steep slopes are associated with increased runoff flow velocity, which has a significant influence on erosion (Assouline and Ben-Hur, 2006, Shen *et al.*, 2016). L-factor and S-factor can be calculated as follows (Wischmeier and Smith, 1978):

$$L\text{-}factor = \left(\frac{l}{22.13}\right)^m \qquad (17)$$

$$S\text{-}factor = (0.43 + 0.30s + 0.043s^2)/6.574 \qquad (18)$$

Where l is slope length (meter), s is the slope in percent and m is dimensionless exponential. Value of m is dependent on s parameter; if $s < 1\%$ then $m = 0.2$, if $1 < s < 3$ then $m = 0.3$, if $3 < s < 5$ then $m = 0.4$ and if $s > 5$ then $m = 0.5$.

4) Land cover factor (C-factor)

The C-factor is related to land cover and crop management, which are the primary factors that protect the soil surface from rainfall, decelerate the overland flow and reduce the extent of soil erosion (Santos *et al*., 2017, Feng *et al*., 2018). Land cover can help to reduce the impact of rainfall's kinetic energy, while poor agricultural practices or reduction of land cover can lead to the breakdown of soil aggregate and loss of organic matter (Jomaa *et al*., 2010, Santosa *et al*., 2010). Furthermore, the C-factor measures the combined effects of interrelated cover and management variables, and factors that are easily altered by human activities (Karaburun, 2010). LDD determined the C-factor from the main land use of Thailand and the values are shown in Table S2.

Table S2 C-factor value from Land Development Department of Thailand

Land cover	C-factor value
Paddy field	0.28
Mixed field crops	0.34
Evergreen forest	0.001
Degraded evergreen forest	0.04
Deciduous forest	0.019
Degraded deciduous forest	0.25
Forest plantation	0.088
Perennial crop	0.15
Urban	0
Water body	0

5) Conservation factor (P-factor)

Soil conservation measures are implemented to protect the surface soil from rainfall impact. The main purpose of such measures is to increase infiltration and reduce surface runoff. Soil conservation measures, such as terracing and contouring, can help to reduce soil erosion by reducing the concentration of surface water and limiting the water's motion (Ritter, 2012). There are many methods of soil conservation: for example, terracing is a means of adjusting the surface level and reducing the slope to control erosion in the sloped area (Zhao *et al*., 2013).

P-factor is related to conservation and measures that protect against soil erosion. It may be considered as a ratio of soil loss rate to the activity or behavior that has caused the soil loss. Wischmeier and Smith (1978) determined the P-factor based on the conservation measures and slope class in an experimental plot and values are shown in Table S3.

Table S3 P-factor value of each conservation measure

Slope (%)	**Contouring**		**Contour Strip-cropping**		**Terracing**		
	Maximum length (m)	P-factor value	Width of cropping (m)	P-factor value	P-factor value (when contouring in terrace)	P-factor value (when strip-cropping in terrace)	P-factor value (when has water way in terrace system)
1-2	120	0.6	40	0.30	0.6	0.30	0.12
3-5	90	0.5	30	0.25	0.5	0.25	0.10
6-8	60	0.5	30	0.25	0.5	0.25	0.10
9-12	40	0.6	24	0.30	0.6	0.30	0.12
13-16	25	0.7	24	0.35	0.7	0.35	0.14
17-20	18	0.8	18	0.40	0.8	0.40	0.16
21-25	15	0.9	15	0.45	0.9	0.45	0.18

2.2) Sediment model

Two equations are used worldwide to model sedimentation. The first is Revised Universal Soil Loss Equation (RUSLE) combined with the sediment delivery ratio (SDR) to calculate monthly sediment yield. The second is the sediment equation, which calculates sediment yield based on precipitation and slope measured in degrees.

1) RUSLE combines with SDR

SDR represents the efficiency of the watershed in moving soil particles from the eroded area to the point where the sediment is measured (USDA, 1998). SDR can be calculating by the following equation (Arnold *et al*., 1996):

$$SDR = \left(\frac{q_p}{r_{ep}}\right)^{0.56} \tag{19}$$

Where q_p is a peak runoff rate in mm/hr and r_{ep} is a peak rainfall excess rate in mm/hr, that can be calculating by the following equation:

$$q_p = C \cdot I \cdot A \tag{20}$$

$$r_{ep} = r_p - f \tag{21}$$

Where C is runoff coefficient,

I is rainfall intensity (mm/hr),

A is Drainage area (m^2),

r_p is peak rainfall rate, and

f is the average infiltration rate.

$$f = (R - Q)/DUR \tag{22}$$

Where R is rainfall, and Q is runoff

DUR is duration of rainfall event in hour = $4.605(R/r_p)$ (23)

Sediment yield in a river may be calculated by multiplying the soil erosion results from RUSLE by SDR. In this study, the result is shown on a monthly time scale.

2) Sediment equation calculated from precipitation and slope

This step used the equation from Hatono (2018), who modified the sediment equation from Sunada and Hasegawa (1994) to calculate sediment yield.

$$Sediment\ yield = \frac{\beta \theta^2 r^2}{100} \tag{24}$$

Where β is constant value = 0.01, θ is slope (degree) and r is rainfall (mm/hr)

2.3) Sediment transportation model

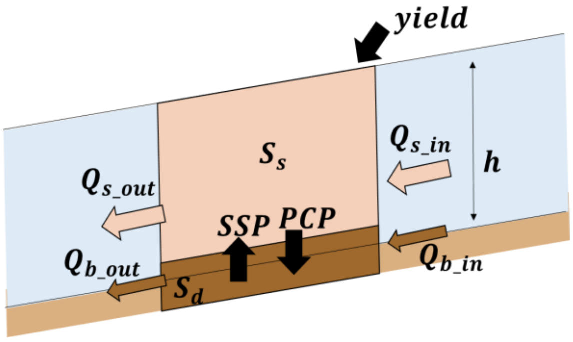

Figure S4 Schematic diagram of sediment transportation model. (Hatono, 2018)

The sediment transportation model was used to calculate the storage changes associated with the deposition and suspension of sediment. Storage change of sediment can be calculated by the following equation:

$$S_s = S_s^t + \sum_{k}^{upstream} Q_{s\_in}^t - Q_{s\_out}^t + SSP^t - PCP^t + Yield^t \tag{25}$$

$$S_d = S_d^t + \sum_{k}^{upstream} Q_{b\_in}^t - Q_{b\_out}^t + PCP^t - SSP^t \tag{26}$$

Where S_s is storage change of suspended sediment (m^3),

S_d is storage change of bedload sediment (m^3),

$Q_{s\_in}^t$ and $Q_{s\_out}^t$ are suspended sediment inflow and outflow,

$Q_{b\_in}^t$ and $Q_{b\_out}^t$ are bedload sediment inflow and outflow,

SSP is suspended sediment from bedload,

PCP is deposition of sediment, and

$Yield$ is sediment yield (m^3), respectively.

$$Q_{s\_out}^t = C \cdot Q_w \tag{27}$$

$$PCP = W_f CA \tag{28}$$

$$SSP = q_{su} A \tag{29}$$

Where C is suspended sediment concentration,

Q_w is river discharge (m^3/s),

W_f is setting velocity (m/s),

q_{su} is suspension velocity (m/s), and

A is area (m^2), respectively.

3) Land use model: CLUE model

The Conversion of Land Use and its Effects modelling framework (CLUE) framework is an integrated land use change model (Verburg *et al*., 1999). It uses the relationship between historical land use and its driving factors in combination with dynamic modelling to simulate future land use change scenarios (Zhou *et al*., 2013).

3.1) Model component

The CLUE model is sub-divided into two distinct components. The first comprises the non-spatial demand modules used to calculate the change in area for all land use categories at the aggregate level. The second is the spatially explicit allocation module, which simulates changes in land use at different locations using a raster-based system (Verburg, 2015).

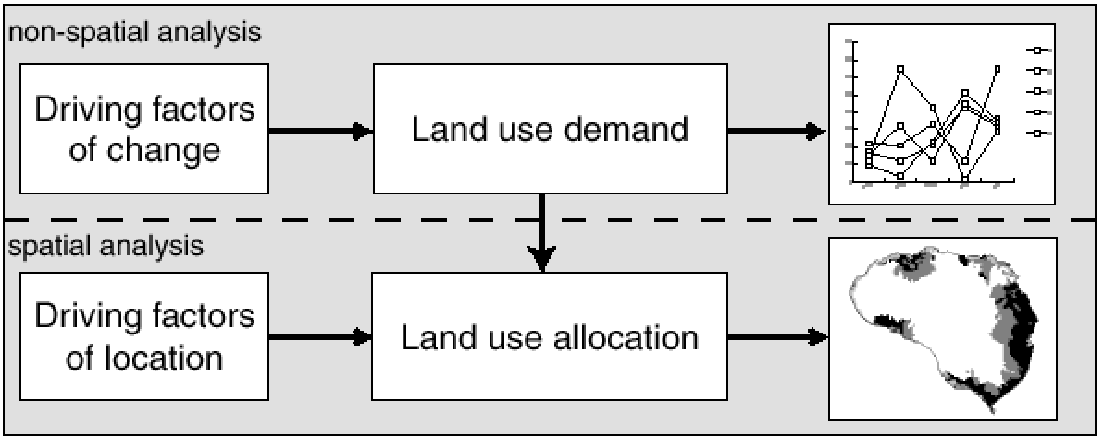

Figure S5 CLUE model component (Verburg, 2010)

2.2.2) Factors that related to the allocation of land use requirements.

(1) Spatial policies and restrictions are defined as restricted areas, such as forest reserves that are designated no-logging zones, etc. Additionally, certain types of condition may be implemented in the conversion matrix (Verburg, 2007).

(2) Land use requirements (demand) are calculated as part of a specific scenario within the entire area. Land use requirements are simulated by setting all required changes in land use, depending on the case study or situation. Prediction trends regarding past-to-future land use change are also common techniques for calculating land use requirements (Verburg and Overmars, 2009).

(3) The land use type-specific conversion setting determines the temporal dynamics of the simulation. It is based on two factors: 1) conversion elasticities, which involve the difficulty of changing land use for each type and 2) land use transition sequences. The difficulty level of the change is between 0, denoting easy to change, and 1, denoting that the land use cannot be changed (Verburg, 2007).

0 indicates that this land use type can be changed freely from the current land use, or that some land uses may be transferred from one area and distributed to other areas simultaneously.

> 0 and < 1 means that permission to change has been granted. The land use types that have higher values may be less conducive to change than other types.

1 indicates that the addition, removal or change of this type of land use is not permitted or feasible.

(4) Location characteristics

Land use change will occur in the most appropriate areas for each land use type, which may be ascertained from contributing factors (Verburg, 2010) using the equation as followed:

$$R_{ki} = C + a_k X_{1i} + b_k X_{2i} + \ldots.. \qquad (30)$$

When R_{ki} is the preference to devote location i to land use type k

C is constant value

$X_{1,\,2,\ldots}$ are biophysical or socio-economical characteristics of location i

a_k and b_k are the relative impact of these characteristics on the preference for land use type k