지리학 석사 학위논문

Estimating Socioeconomic Impact of Building Dams on the Mekong River Using an Integrated System Dynamics

통합 시스템 다이나믹스를 이용한 메콩강 댐 건설의 사회경제적 영향 추정

２０１４년　８월

서울대학교 대학원

지 리 학 과

이 수 연

Estimating Socioeconomic Impact of Building Dams on the Mekong River Using an Integrated System Dynamics

지도교수 박 수 진

이 논문을 지리학 석사 학위논문으로 제출함

2014년 8월

서울대학교 대학원

지리학과

이 수 연

이수연의 석사학위논문을 인준함

2014년 7월

위 원 장 _____ (인)

위 원 _____ (인)

위 원 _____ (인)

Abstract

Estimating Socioeconomic Impact of Building Dams on the Mekong River Using an Integrated System Dynamics

Sooyoun Lee
Geography
Seoul National University

Dam construction is one typical way to utilize river, which retains water resources for drinking and irrigation, mitigates the effects of climate change, and yields electricity. The Mekong, which has been the only river running to the sea without dam through five of six riparian countries, is undergoing hydropower development nowadays amid rapid economic growth of Mekong riparian countries. The purpose of this study is to estimate sediment flux change and corresponding socioeconomic impacts of cascade dam construction on the Mekong River. For this purpose, statistical analysis and integrated system dynamics were employed as methodologies.

In order to understand past effects of dams on the Mekong River and create variable for model validation, t-test, ANOVA test and multiple regression analysis are used. Season, Chinese cascade dam construction, and stations are all significant as to put in the model. By multiple regression analysis, it is shown that Chinese dam construction has a significant effect on suspended sediment concentration in the Lower Mekong Basin with other variables controlled. With the equation from multiple regression, estimated suspended sediment concentration data for each station is produced.

Possible impacts of existing Chinese dams on the Mekong mainstream are modelled using system dynamics approach. The model shows same trend with actual sediment load data. Sediment load shows decreasing trend after Chinese dam construction, but the rate of decrease is 10%, which is smaller than that of previous studies. It can be because this study reflects dynamic feature of trapping capacity of dam reservoirs.

The impacts of future dam constructions are modelled and discussed. Four scenarios with different number of dams in the Lower Mekong Basin are built. According to the results of the model, additional six dams in scenario B trap 140 million tons of sediments more, three more dams in scenario C trap 150 million tons of sediments more, and Sambor dam in scenario D traps 270 million tons of sediments more. The effects of dam constructions in the Upper Mekong Basin seem larger than the effects of dams in the Lower Mekong Basin, but the effects of Chinese dams mitigated by the distance. The net present value of costs of cascade dam construction is estimated from 1.57 to 4.72 billion US dollars.

This study is an attempt to account for not only environmental impact but also agro-economic impact related to dam constructions. Integrated system dynamics can act as an effective tool to integrate various knowledge so that make stakeholders understand and take into account transnational impact of dam construction.

Keyword: The Mekong River, Sediment, Trapping Efficiency, Dam, Integrated System Dynamics

***Student Number*: 2012-20120**

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Backgrounds

A River does not merely supply water resources for drinking, agriculture, and other human needs. River water is considerably different from the same amount of water in a water tank because a river flows through various terrain, forming waterscapes and defining features of riparian life (Molle, Foran, & Kakonen, 2009). The potential energy of river can generate electricity because water flows from high altitude to low altitude. Also, river carries sediments from upstream to downstream, supplying nutrients and sustaining the soil of

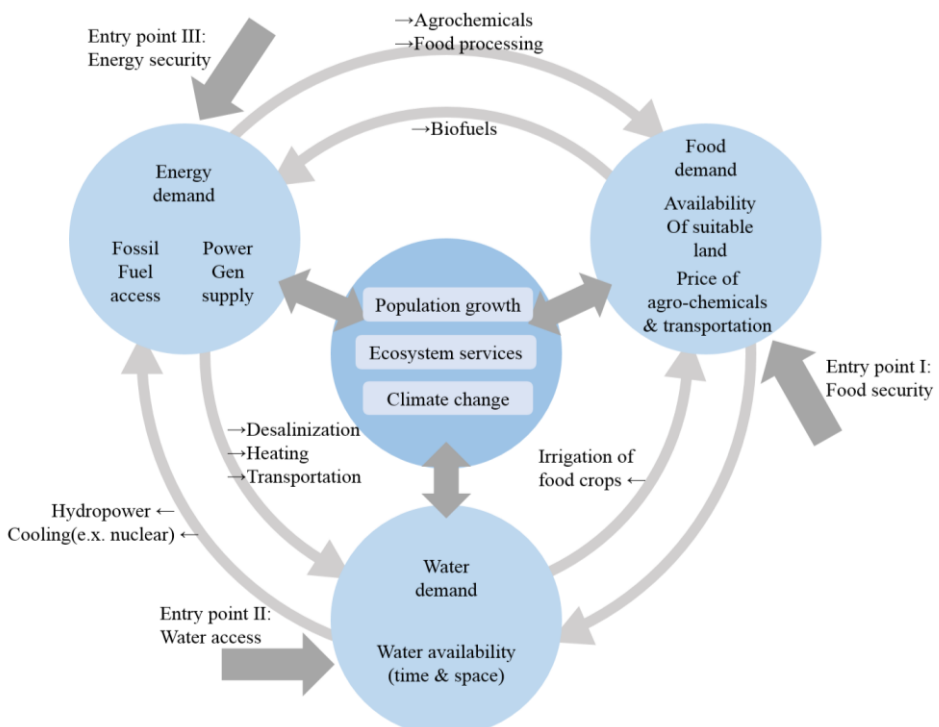

Figure 1 Water-Food-Energy Nexus (revised from Smajgl and Ward (2013))

downstream floodplains. River also serves as a road, especially in developing countries where road transportation is underdeveloped. Moreover, river is a habitat for many animal and plant species, which are deeply related with human life. In this sense, river has high potential to 0be utilized for human life, acting as a mainstay in water-food-energy nexus (Figure 1).

Dam construction is one typical way to utilize river, which retains water resources for drinking and irrigation, mitigates the effects of climate change, and yields electricity. However, dam construction has a trade-off against aforementioned benefits. By blocking the river, dam construction can have an effect on the environmental system. Kummu and Varis (2007) summarized possible positive and negative impacts of dams from related studies (Table 1).

Table 1 Possible Positive and Negative Impacts of the Hydropower Project (Kummu & Varis, 2007)

Action	Positive impacts	Negative impacts
Controlling the flow	Increase capacity for flood control	Changes in the river's natural flow pattern, and possible increase of flow fluctuation
	More assured dry-season flows	Increase average downstream dry-season flows; permanent flooding of important ecosystems
	Increase navigation options	Decrease wet season flows
	Reduce saline intrusion in Delta	Shift of the flood regime, flood arrival delays, shorter flooding period
	Creation of extra irrigation opportunities	

Table 1 Possible Positive and Negative Impacts of the Hydropower Project (Continued) (Kummu & Varis, 2007)

Action	Positive impacts	Negative impacts
Trapping of sediment	Ease navigation in LMB, less problems with sedimentation	Decrease flux of sediment and nutrient
		Increase geomorphological changes, such as bank erosion and bed degradation
Blocking the river		Block migration routes of fishes
		Divide/fragment river ecosystem, disturb local biodiversity

The Mekong, which has been the only river running to the sea without dam through five of six riparian countries, is also undergoing hydropower development nowadays amid rapid economic growth of Mekong riparian countries (Kummu & Varis, 2007). China and Laos have been actively involved in dam development projects, prompted by a huge electricity demand of neighboring countries (Kuenzer et al., 2013). Many dams are either currently located or planned for construction on the Mekong river (Figure 2). Eight dams exist or are planned to be constructed on the Mekong mainstream in the Upper Mekong Basin, and 11 dams are planned on the Mekong mainstream in the Lower Mekong Basin. Xayaburi dam will the first dam to be built among dams under construction in the Lower Mekong River Basin and may serve as a trigger to accelerate construction of other dams (Stone, 2011).

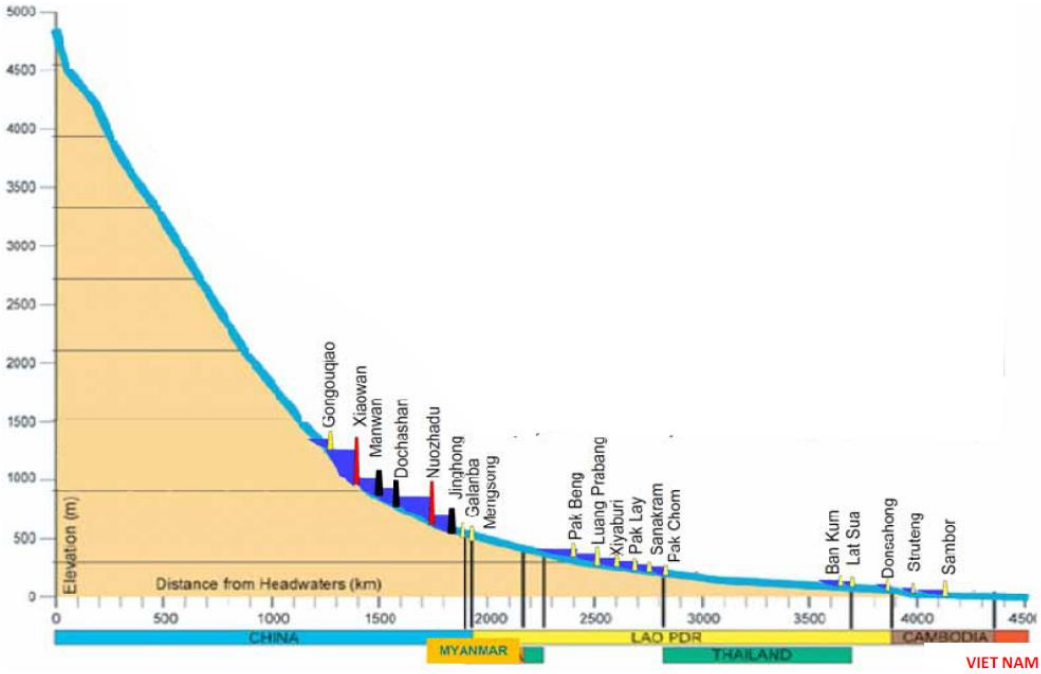

Figure 2 Proposed Mekong Mainstream Hydropower Projects in the Lower Mekong Basin and Yunnan Province, China (ICEM, 2010)

Since the Mekong River is a transnational river, dams built on upstream countries can have significant impacts on downstream countries, resulting in possible conflicts beyond country borders. There are active discussions and vast research related to the effects of dams on the ecosystem of the Mekong river; First, dams can change the sediment system of the river. Second, dams can change the river's flow regime, which can alter the lifestyle of downstream residents. Third, dams can restrict fish migration as a wall, impacting the ecosystem and human livelihoods (Fu & He, 2007; Fu, He, & Lu, 2008; Hirsch, 2010; Kubiszewski, Costanza, Paquet, & Halimi, 2013; Kuenzer et al., 2013; Kummu, Lu, Wang, & Varis, 2010; Matthews, 2012; Stone, 2011; Ziv, Baran, Nam, Rodríguez-Iturbe, & Levin, 2012). These impacts can have ripple impacts across

diverse sectors such as the political relationships among countries, ecological integrity, and energy systems. There are relevant studies on this matter (Hirsch, 2010; Kubiszewski et al., 2013; Matthews, 2012; Ziv et al., 2012).

In particular, hindering sediment transportation of dam construction can have negative impacts on agriculture and fishery, which are major livelihood of downstream population by restraining nutrients and soil from flowing downstream (Kuenzer et al., 2013). The Mekong basin has a system in which soil is eroded, transported, and deposited, and dam construction can have a significant impact on this system. In the case of Vietnam, which is located at the lowest part of the Mekong, agricultural problems can occur if the Vietnam delta is reduced due to the restricted supply of sediment (Biggs, Miller, Hoanh, & Molle, 2009). Moreover, fish production can also be diminished by hydropower dam constructions because part of nutrients attached to the sediment are decreased (Kummu & Varis, 2007).

In order to resolve potential conflicts among upstream and downstream countries, it is crucial to conduct baseline scientific research which can clarify the effects of dams on the river's sediment system. However, only a few studies have been conducted regarding the effects of the Mekong mainstream dams on the sediment system (Fu & He, 2007; Fu, He, & Li, 2006; Fu et al., 2008; Kummu et al., 2010; Kummu & Varis, 2007; Lu & Higgitt, 1999; Lu & Siew, 2006; Lu, Wang, & Carl, 2008; Wang, Lu, & Kummu, 2011). Furthermore, there are limitations of previous studies that data is scarce and the methodology can only static feature of the dam construction.

1.2 Research Purpose and Structure

The purpose of this study is to build a model using integrated system dynamics to assess changes in sediment flux and corresponding downstream agro-economic effects due to the Mekong mainstream cascade dams. The research aims 1) to have a good understanding of the current state of erosion and sediment transportation of the Mekong region; 2) to analyze a sediment trapping amount of the cascade dams in the Upper Mekong Basin, 3) and to model the economic effects of dam construction on agro-economic sectors using integrated system dynamics. The outcome of this study is expected to contribute to a good understanding of dynamic aspects of the dam construction and its related effects on other sectors.

Time scope of this study is 200 years from 1960 to 2160. Sediment trend is understood by analyzing the data from 1960 to the time when dam construction started. From the time of dam construction, change of sediment flux and its corresponding impacts is assessed by analyzing the data until 2007 and modelling sediment trapping capacity of dam reservoir. From 2007 to 2160, the impacts of dam construction is estimated by modelling sediment trapping capacity of dam reservoir.

The study area, previous studies and detailed research methodology for the investigation of dam effects are explained in chapter 2. In chapter 3, variables needed in this study are defined and calculated. After setting variables, past sediment flux is analyzed more elaborately than in previous studies, and the significance of variables related to past sediment flux are examined in chapter 3. In chapter 4, the effect of dam construction on sediment is modelled using

integrated system dynamics and the result of the model is calibrated and validated. By this model, the effects of existing Chinese dams are modelled until 2014. In chapter 5, future agro-economic impacts of the Mekong mainstream dam construction are estimated using integrated system dynamics.

Chapter	Main Questions	Contents
Chapter 1	• Why should study the effect on sediment flux of the dam construction?	• Introduction • Study purpose and structure
Chapter 2	• What is the methodologies to assess the effect of the dam construction?	• Study area • Literature Review • Research Methodology
Chapter 3	• Did dam constructions in the Upper Mekong Basin have impacts on the Mekong mainstream in the Lower Mekong Basin? • What is the historical trend of sediment load of stations located in the Lower Mekong Basin?	• Comparing Means • Multi Regression Analysis • Estimation of the historical sediment load
Chapter 4	• What is the trend of sediment load of stations located in the Lower Mekong Basin considering dynamic features of sediment trapping of dam reservoirs?	• Integrated system dynamics modelling • Calibration and validation with estimation results of the historical sediment load in chapter 3
Chapter 5	• What is the trend of sediment load and related downstream agro-economic impacts of dam constructions?	• Building future scenarios • Assessments of agro-economic impacts of dam constructions
Chapter 6		• Conclusion

Figure 3 Main Questions and Contents of Each Chapter

2. Study Area and Research Methodology

In this chapter, study area, previous studies and research methodology are described. The lifestyle of the Mekong basin is deeply rooted in the river. In chapter 2.1, the waterscape of the Mekong region is illustrated and the current state of the sediment system of the Mekong river is described. In chapter 2.2, previous studies regarding the effects of dam construction on sediment flux are reviewed. Research methodologies of study are explained in chapter 2.3. It is difficult to consider space or topography only using system dynamics. Arc GIS and Excel are utilized to complement this limitation of system dynamics.

2.1 Waterscape of the Mekong Region

The Mekong river is the 12th river in the world with respect to length (4,880km) and 21th river with respect to area of catchment, and flows through China, Myanmar, Laos, Thailand, Cambodia and Vietnam (Suif, Yoshimura, Valeriano, & Seingheng, 2013) (Figure 3). The Mekong River Basin covers an area of approximately 795,000km^2, carrying approximately 475km^3 of water each year. As the Mekong river has a rich ecosystem, it provides a diversity of goods and services for its riparian. The Mekong Basin is home to approximately 60 million people, who highly depend on the river. Agriculture, fishing and forestry are major activities that support the livelihoods of the population.

The Mekong river originates in Tibet of the Qinghai province in China, at an altitude of 4,970m above mean sea level (Kummu & Varis, 2007; Sahai, 2005). After flowing through the Chinese province of Yunnan to a point south of Yin-

Ching Hung, it forms the border between Myanmar and China. It also becomes a part of the international border between Myanmar and Laos, as well as between Laos and Thailand. Both capitals of Laos and Cambodia are located on the river's bank. The river drains into the South China Sea to the south of Ho Chi Minh City(Sahai, 2005).

About 77 per cent of the drainage area of the river lies within four countries - Laos, Thailand, Cambodia, and Vietnam (Figure 3), called the Lower Mekong Basin (LMB). The Mekong is generally divided into two parts, which are the Upper Mekong including parts of China and Myanmar and the Lower Mekong including Lao PDR, Thailand, Cambodia and Vietnam (Kummu & Varis, 2007). The Mekong basin located in China is called the Upper Mekong Basin (UMB), where the Mekong is called as the Lancang Jiang. The Upper Mekong is a long narrow valley forming roughly 26 per cent of the total area. The Mekong splits into many branches and forms a vast and fertile delta, which is over 40,000㎢ (Sahai, 2005).

The climate of the Indochina peninsula is diverse – ranging from tropical to cool temperate. Climate of the most part of the basin is tropical, but the high peaks on the Tibetan plateau are snow-capped. Climate of the lower part of the basin is seasonal, which is divided into a dry season and a wet season. More than 90% of the available water resources and 95% of the total suspended sediment flux of the Mekong basin runs into the Cambodian floodplains and the Mekong Delta, which are directly dependent on the environmental changes of the Upper Mekong (Kummu & Varis, 2007).

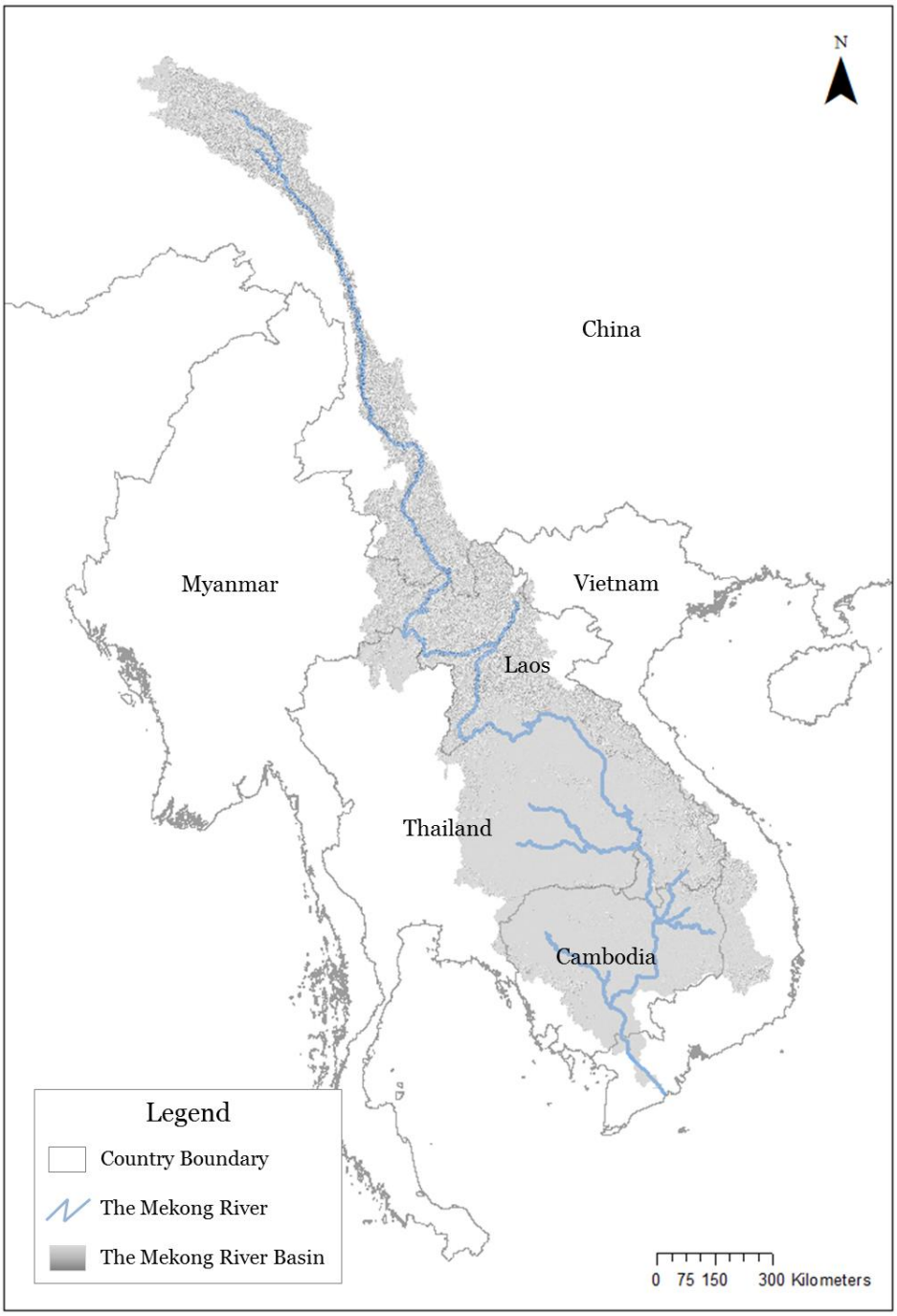

Figure 4 Indochina Peninsula and the Mekong Basin

Annual sediment flux estimation of the Mekong range from 150 million tons to 170 million tons according to a few studies (Kummu & Varis, 2007). According to Gupta and Liew (2007), most of the sediment of upper Cambodia seems to be stored inside the channel and is hardly exchanged between the channel and the floodplain, which is different from other large alluvial rivers. However, sediment exchange between the channel and the floodplain takes place when flooding occurs during the rainy season in the Cambodian floodplains and the Mekong Delta, and the channel is shifted laterally (Gupta, Hock, Xiaojing, & Ping, 2002; Gupta & Liew, 2007).

2.2 Literature Review

Scholars asserted that more scientific research is needed (Kuenzer et al., 2013; Lee, 2013), because the effects of the Mekong mainstream dam construction on sediment transportation have been investigated scientifically only in a few studies (Fu & He, 2007; Fu et al., 2006; Fu et al., 2008; Kummu et al., 2010; Kummu & Varis, 2007; Lu & Higgitt, 1999; Lu & Siew, 2006; Lu et al., 2008; Wang et al., 2011). There are two major methodologies for scientific analysis on sediment flux change due to dam construction in the Mekong River Basin. Some studies analyzed the historical sediment flux data of each station in order to detect whether sediment flux changed before and after dam construction (Fu & He, 2007; Fu et al., 2008; Kummu et al., 2010; Kummu & Varis, 2007; Lu & Siew, 2006; Wang et al., 2011). Other studies assessed the effects of dam construction using the equation regarding reservoir trapping capacity (Fu & He, 2007; Kummu et al., 2010; Kummu & Varis, 2007).

2.2.1 Studies based on historical sediment data

The effects of Chinese mainstream dams have been mainly dealt with because sediment related data is just available from 1960 to 2007 and only Chinese dams exist on the Mekong mainstream as of now. The Manwan dam on the mainstream of the Upper Mekong was completed in 1993, and the Dachaoshan dam was completed in 2003. There is discordance about the extent of effects resulting from dam construction between scholars (Fu et al., 2008; He, Feng, Gan, Magee, & You, 2006; Lu & Siew, 2006), and a few studies conducted by Chinese scholars denied negative impacts of Chinese dams on downstream sediment flux (Lee, 2013).

Lu and Siew (2006) studied water discharge and sediment flux change of the Lower Mekong River in order to detect changes after dam construction. According to this study, mean discharge and seasonal discharge regime has changed little or fluctuated within historical range. However, water level fluctuation has increased after dam construction. Compared to discharge, sediment flux showed considerable difference after dam construction. Sediment flux has diminished, and the sediment loads in immediate downstream decreased by almost half (Lu & Siew, 2006). Lu and Siew (2006) forecast that the completion of the cascade dams on the upper Mekong would lead to decreased frequency, lower magnitude of floods and the reduced amount of sediment based on this analysis. Kummu and Varis (2007) also analyzed suspended sediment fluxes of the Mekong river before and after dam construction. This study concluded that there are significant changes after dam construction. According to this study, suspended sediment flux decreased by 56% following the dam construction at Chiang Saen.

On the contrary, Fu et al. (2006) and Fu et al. (2008) claimed that the effects of Chinese dams have not reached the Lower Mekong Basin. Fu et al. (2006) investigated causal relationships between suspended sediment data between the Yunjinghong station and the Chiang Saen station. Fu et al. (2008) studied sediment flux of the Jizhou, Gaijiu, Yunjinghong stations located in China and compared them to the Chiang Saen station. These studies suggested that the impact of the Manwan reservoir might be smaller compared to the estimation of previous studies (Kummu & Varis, 2007; Lu & Siew, 2006). These studies also suggested that the decrease of sediment flux at Chiang Saen can be the result of other reasons such as intensive land utilization.

However, there are limitations in these studies, which are mostly related to the low quality of data. Lu and Siew (2006) only considered discharge data when estimating missing sediment data, although other factors are relevant to sediment flux as well. Also, since the sampling techniques are different between stations in China and the Lower Mekong Basin, the comparison analyzed between Fu et al. (2006) and Fu et al. (2008) might be insignificant in and of itself. D. E. Walling (2008) underlined that the sporadic nature of data preclude analysis of changes that may occur due to Chinese dam construction. In this sense, using theoretical equation to assess the impact of dams instead of empirical data can be a viable alternative.

2.2.2 Studies based on reservoir trapping capacity equation

There are a limited number of studies using trapping efficiency equation in order to analyze the impact of dam construction (Fu & He, 2007; Kummu et al., 2010; Kummu & Varis, 2007). Because this method is relatively unaffected by

data availability, these studies are able to analyze not only existing dams, but also proposed dams and dams under construction.

Kummu and Varis (2007) studied the impact of the Manwan dam by calculating the trapping efficiency[1] using Brune's method (Brune, 1953). Computed theoretical trapping efficiency is 68% for Manwan, 66% for Dachaoshan, and 92% for Xiaowan and Nuozhadu. The entire cascade of dams has a theoretical trapping efficiency of 94% in total. Fu and He (2007) also calculated the trapping efficiency of the Manwan Reservoir using modified Brune and Siyam models. The result is 60.48% for the Manwan, 30.23% for the Gongguoqiao, 66.05% for the Dachaoshan and 63.5% for the Jinghong dam using modified Brune model. Using modified Siyam model, the figure was 60.03% for the Manwan, 38.81% for the Gongguoqiao, 63.97% for the Dachaoshan, and 62.3%for the Jinghong dam.

Kummu et al. (2010) investigated the potential trapping efficiency of the reservoirs which either exist or are planned for construction in both the Upper Mekong Basin and the Lower Mekong Basin by using Brune's method. According to this study, existing reservoirs especially in the UMB have considerable impacts on sediment fluxes. Also, planned reservoirs will expand these impacts. If all the planned reservoirs are built, the amount of trapped sediment would reach 95-100Mt. Small mainstream reservoirs have greater uncertainty than tributary reservoirs according to sensitivity analysis. This study also emphasized the necessity for further studies about the possible impacts on the Cambodian

[1] Trapping efficiency is the ratio of deposited sediment in the reservoir to sediment input to the reservoir (Kummu et al., 2010).

floodplain and the Mekong Delta.

There are limitations in previous studies that modelled sediment transportation of the Mekong River Basin with theoretical equation. Changes in ecosystem are not made linearly, but have many uncertainties. For instance, the amount of sediments trapped upstream can either increase or decrease the amount of sediments trapped downstream. In this case, trapping efficiency calculated by each reservoir cannot reflect this dynamic feature. Also, changes in sediment flux within the environmental system can have an influence on the human system as well. Since an ecosystem contains complex interactions with the human system, plans and implementation of appropriate environmental policies should be executed based on a holistic understanding of the biophysical, social and economic system processes and their interactions (Jakeman et al., 2013).

2.2.3 Studies Based on System Dynamics

There are modeling methodologies which can integrate different system processes into an unified framework (Jakeman et al., 2013). System dynamics is one of the methodologies which facilitates understanding of the system structure and interactions among systems. System dynamics modelling is a set of methods used to comprehend the structure and behavior of a complex system (Jakeman et al., 2013). System dynamics was first developed by Jay W. Forrester, an electrical engineer and professor of M.I.T., and it was used broadly in order to understand decision-making systems and solve problems in diverse fields (Forrester, 1964, 1968). System dynamics is “the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in

policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" (Forrester, 1958, 1961). System dynamics also can be applied to urban, social, and ecological systems (Borshchev & Filippov, 2004).

System dynamics modelling has been used in investigating the dynamic interactions between the environmental system and the human system in various research. Chang, Hong, and Lee (2008) employed system dynamics modelling for the coastal zone management of Taiwan. Kuper, Mullon, Poncet, and Benga (2003) studied dynamic interactions among human migration, population increase and land degradation of the Niger River delta. Fernández and Selma (2004) dealt with irrigation issue of Spain using system dynamics. Qin, Su, and Khu (2011) explored the interplay between socioeconomic features and water infrastructure in the Shenzhen River Basin.

There are system dynamics studies related to hydropower development and related effects. Saysel, Barlas, and Yenigün (2002) analyzed potential long-term environmental problems related to hydropower production, extension of irrigation, land use, land degradation, agricultural pollution and demography. Ahmad and Simonovic (2004) used spatial system dynamics, which is system dynamics linking with GIS, to model the space-time interaction regarding flood management system in Canada. Hassanzadeh, Zarghami, and Hassanzadeh (2012) modelled water level of the Urmia Lake to determine major factors which affect the level of the late. Saysel et al. (2002) and Hassanzadeh et al. (2012) showed the possibility of system dynamics as a useful laboratory for policy makers.

Regarding soil erosion prediction, system dynamics has not been employed

widely yet. Hanxiong and Mingjan (1999) is the first attempt to simulate land use change and soil erosion using system dynamics. This study modelled soil erosion in the Loess hills of Shaanxi and Shanxi province. Nonlinear dynamic feature of interaction between human and environment system and its impact on erosion are modelled. Yeh, Wang, and Yu (2006) applied system dynamics to simulate soil erosion and nutrient impact on a watershed in Taiwan. Yeh et al. (2006) employed 5 sub-models – soil erosion model, runoff model, transportation model, nutrient model, and economic model – and investigated the interactions among sub-models. System dynamics can be an effective tool in considering various factors such as physical and economic factors and its interactions.

There are advantages of system dynamics modelling proposed by Jakeman et al. (2013) and they are as follows: 1) System dynamics tools are helpful tools that enable modellers and users to enhance understanding and develop system thinking; 2) System dynamics modelling has been accessible to non-modellers with well-developed system dynamics tool such as ithink, Vensim, and Powersim Studio; 3) System dynamics modelling facilitates and encourages stakeholders to participate actively in the modelling process because its system evolves by accumulating knowledge.

It is beneficial to understand and analyze the Mekong with system dynamics modelling because the Mekong is a system where both environmental and social aspects interact with each other. Previous studies have limitations because data were sparse and only phenomena were considered as static, which can be overcome using system dynamics.

2.3 Research Methodology

For the purpose of study, data are examined in several ways. First, commercial GIS software named Arc GIS 10.1 (ESRI) is used to draw a watershed for each station, and calculate the feature of each watershed. Second, Comparing mean and multiple regression analysis are chosen to analyze the significance of the variable statistically. Third, Vensim (Ventana) is employed as a programming tool for system dynamics. Using Vensim, pure dam effects on sediment flux are modelled. In chapter 2.2.1, data for the model is explained. In chapter 2.2.2, statistical analysis used in chapter 3 is described. In chapter 2.2.3, integrated system dynamics is explained.

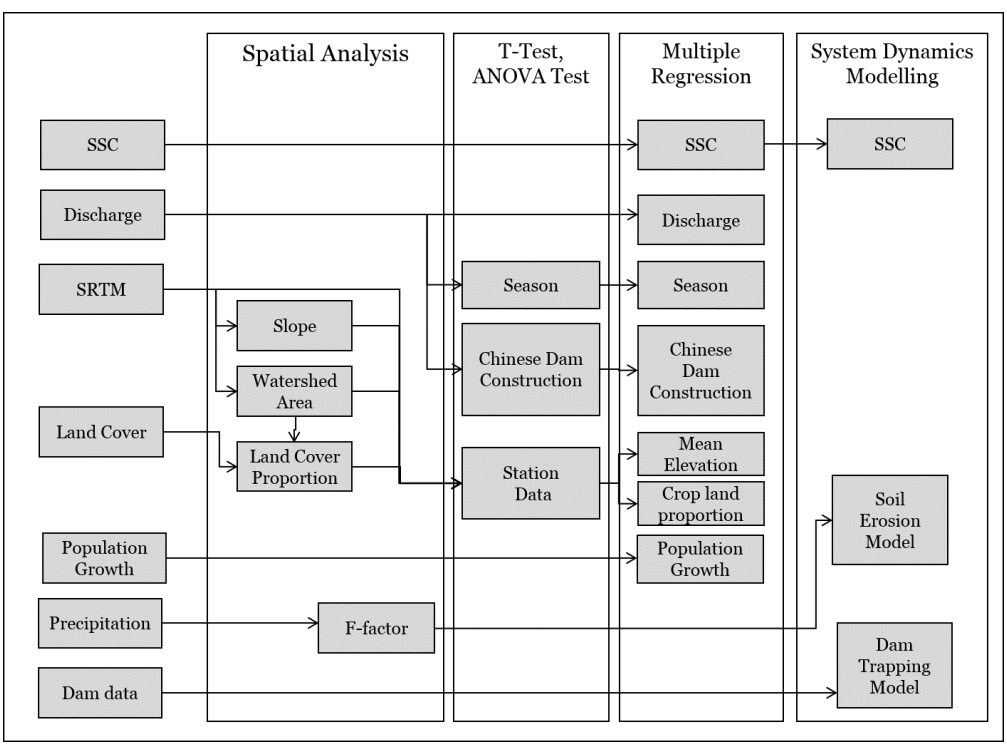

Figure 5 Research Framework for Each Methodology

2.3.1 Data

Data which are known for having a relationship with sediment yield are selected for this study. Suspended sediment concentration, Discharge, digital elevation data from Shuttle Radar Topography Mission (SRTM), land cover, population growth, precipitation, and dam data are needed in order to estimate sediment load and analyze historical dam effects on the Mekong mainstream (table 2). When soil is eroded, topography of the land such as elevation and slope, the amount and the intensity of precipitation, and type of land cover and land use have an impact on the degree of the erosion (Renard, Foster, Weesies, McCool, & Yoder, 1997; Suif et al., 2013; Yeh et al., 2006; Zhou, Yang, Zhao, Cai, & Ya, 2014). After soil is eroded, the sediment is transported by the river. Discharge is known for having relation with sediment concentration in many previous studies (Fu et al., 2008; He et al., 2006; Lu & Siew, 2006). Dams can have an impact on sediment because dams trap sediment in their reservoirs (Kuenzer et al., 2013; Kummu et al., 2010; Kummu & Varis, 2007).

Discharge and suspended sediment concentration data of this study is published by the Secretariat of the Mekong River Commission (MRC). MRC was established in April 1995 to lead and promote co-operation among member countries. The Secretariat of MRC is a technical arm for the MRC, providing scientific knowledge to help decision-making of member countries. Historical records of discharge, suspended sediment concentration (SSC), precipitation, and evaporation are extracted from a series of historical records published by MRC from 1910 to 2008. Since there is no reliable data on bedload sediment, one aspect of the dam effect cannot be investigated (Kummu & Varis, 2007).

Table 2 Source and Description of Data in this Study

Data	Source	Description
Discharge	Mekong River Comission data portal[a]	Daily data from 1960 to 2007
Suspended Sediment Concentration	Mekong River Comission data portal[a]	Daily but sporadic data from 1960 to 2007
SRTM	U.S.Geological Survey[b]	50m x 50m resolution
Landcover	European Space Agency[c]	Globcover 2009, which is an ESA initiative which began in 2005 in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP
Precipitation	Worldclim[d]	Long term average monthly precipitation
Population growth	Worldbank[e]	Yearly population growth data from 1960 to 2012
Dam related data	(Kuenzer et al., 2013; Kummu et al., 2010)	Expected installed capacity, project status, commission year, drainage area of reservoirs, discharge of each reservoir, and active storage volume

Sources:

a. http://portal.mrcmekong.org/

b. http://www.usgs.org/

c. http://due.esrin.esa.int/globcover/

d. http://worldclim.org/

e. http://www.worldbank.org/

SRTM is used for statistical analysis to calculate mean elevation for watershed of each station and for USLE calculation. SRTM data is from U.S. Geological Survey, and the resolution of SRTM is 50m × 50m. Landcover data is used for calculating proportions of land cover of each station and for USLE calculation. Landcover data is referred from Globcover 2009, provided by the European Space Agency. Precipitation data is used for USLE calculation to calculate R factor. Precipitation data is long term average monthly data from Worldclim. Population growth rate is used for statistical analysis. Population growth rate data is referred from Worldbank. Dam related data is used for integrated system dynamics. Dam related data is from Kuenzer et al. (2013) and Kummu et al. (2010).

There are 154 stations for measuring discharge and 69 stations for measuring suspended sediment concentration. Measurements of discharge take place daily, but measurements of suspended sediment concentration are relatively sporadic, ranging from one to six times per month. Sampling frequency is also varied between different time periods because of the political instability in some of the regions (Lu & Siew, 2006). Sporadic data due to irregular sampling interval and the exclusion of the bedload component may result in an underestimation of the amount of sediments during peak flows (Ibàñez, Prat, & Canicio, 1996; Lu & Higgitt, 1999; Lu & Siew, 2006; Phillips, Slattery, & Musselman, 2004). Missing suspended sediment concentration data needs to be estimated in order to calculate historical sediment loads of the region, which becomes a baseline for future estimation.

Among stations located on the Mekong mainstream, 10 Stations which have both discharge and suspended sediment concentration data are selected for

analysis to investigate mainstream dam effect (Figure 6). Outliers which are more than two standard deviations from the mean are excluded in order to clearly understand the tendency of sediment data. The largest number of data is 1,481 of Mukdahan, Thailand, and the smallest number of data is 124 of Pakse, Laos. The difference between these two station is 1,357. Total number of suspended sediment concentration data is 5,240 (Table 3).

Table 3 Locations of Hydrological Stations and the Number of Data of Each Station

Station Number	Location	Country	The number of data
010501	Chiang Saen	Thailand	872
010601	Sop Kok	Thailand	135
011201	Luang Prabang	Laos	316
011903	Chiang Kaen	Thailand	516
011904	Pa Mong Dam Site	Thailand	218
012001	Nong Khai	Thailand	1,015
013101	Nakhon Phanom	Thailand	141
013402	Mukdahan	Thailand	1,481
013801	Khong Chiam	Thailand	422
013901	Pakse	Laos	124
		Total	5,240

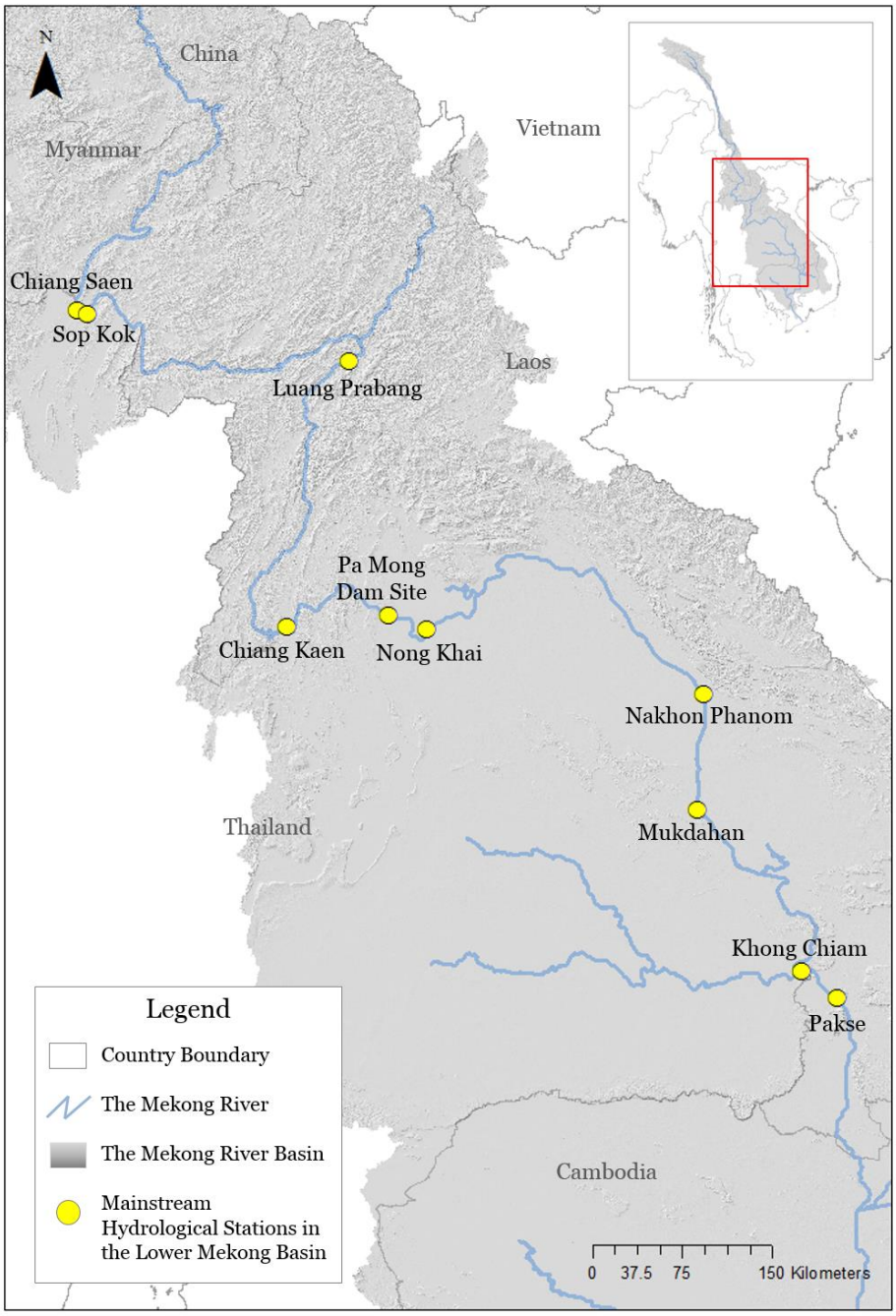

Figure 6 Locations of Mainstream Hydrological Station in the Lower Mekong Basin

2.3.2 Statistical Analysis

In this study, the variables related to suspended sediment concentration data are established. The significance of these variables needs to be tested in order to testify the hypothesis that other variables also have effects on sediment flux. The significance of season and Chinese cascade dam construction variables are tested using a T-test. The t-test is used to determine whether two sets of data are significantly different from each other. Analysis of variance is to determine whether more than two groups are significantly different from each other. This analysis is used to test significance of variables such as elevation, slope, and land cover.

After testing significance of each variable, multiple regression analysis is used to estimate suspended sediment concentration data. Moreover, whether Chinese dam construction has had a significant impact on suspended sediment concentration is examined with other variables controlled. Variables incorporated in multiple regression analysis are discharge, season, mean elevation of each watershed, proportion of land cover of each watershed, population growth of each year of each country, and Chinese dam construction. Purpose and Variables of each statistical analysis are described briefly in table 4. More detailed analysis process and results are explained in chapter 3.

Table 4 Purpose and Variables of Statistical Analysis in this study

Purpose	Method	Dependent Variable	Independent Variables
- Testing Significance of Variables	- T-Test	Suspended Sediment Concentration	Season Chinese dam construction
- Testing Significance of the effects of dam construction with other variables constrained - Estimating Sediment Yield	-One-way ANOVA Test -Multi Regression Analysis		Station Discharge, Season, Elevation of the watershed, Chinese dam construction

2.3.3 Integrated System Dynamics

System dynamics tools are useful in scenario building and simulations (Yeh et al., 2006), but it lacks the ability of spatial modelling due to its nature of aggregating system behavior (Jakeman et al., 2013). In this study, Vensim professional 6.2 is employed as a core programming tool to integrate data produced by ArcGIS and EXCEL, to compensate for the aforementioned weakness. Using GIS Software ArcGIS10.1, spatial data including watershed areas, precipitation, elevation, slope and landcover for each basin is analyzed and calculated. EXCEL works as a linking tool between ArcGIS10.1 and Vensim. Vensim is a useful tool to model interactive and interdependent links among input parameters (Yeh et al., 2006). One of the strength of Vensim is that the operation of scenario analysis is easy. It can trace interactive relationship among

input, intermediate result, and output (Yeh et al., 2006).

The overall goal of this system dynamics model is to assess agro-economic impacts of dam constructions on the Mekong River. Soil erosion and sediment yield model is employed in order to investigate possible soil erosion amount of the Mekong River Basin. Trapping sediment of dam reservoir is modelled by Brune's equation to scrutinize downstream impacts of dams on sediment flux of the Mekong river.

In particular, agro-economic impacts of dam constructions are analyzed in this study. Decrease of sediment flux due to dam construction can reduce area of the Mekong Delta, affecting the land use of the Mekong Delta. Potential change of Delta area and corresponding agro-economic impacts are modelled and analyzed in this study. Agro-economic impacts are examined by the change of income from rice production which is the most important sector in the Mekong Delta. Detailed modelling process and results of the model are described in chapter 4, and possible future impacts are discussed in chapter 5.

3. Past Sediment Flux in the Mekong River Basin

In this chapter, the past sediment flux of the Mekong mainstream is analyzed and estimated. Factors related to sediment erosion should be considered and controlled to clarify the effect of dam construction on the Mekong mainstream. First, relevant variables to sediment erosion are defined in Chapter 3.1. Second, suspended sediment concentration is statistically analyzed and estimated in Chapter 3.2. Third, past sediment flux is estimated by the result of Chapter 3.2 in Chapter 3.3.

3.1 Defining Variables

In Chapter 3.2 and 3.3, suspended sediment concentration data is statistically examined and estimated with other relevant factors. In order to estimate past suspended sediment concentration more accurately, other factors as well as discharge which may affect suspended sediment concentration should be defined and included in the analysis. Since suspended sediment concentration data exists by stations, other data needs to be converted by each station in order to be analyzed. Factors known for having an impact on sediment yield which are explained in 2.3.1 are considered in this study, and factors which have high m ulticollinearity are excluded. Therefore, relevant variables used in this study are discharge, season, elevation, landcover proportion, population growth rate of each year, which are described briefly in Table 4. The effect of Chinese cascade dam construction is also considered in this study reflecting on previous studies (Fu & He, 2007; Fu et al., 2008; Kummu et al., 2010; Kummu & Varis, 2007; Lu & Siew, 2006).

Table 5 Environmental Variables to Estimate Suspended Sediment Concentration in the Study Area

Variable Name	Description
Discharge	Daily discharge amount of each station
Season	0 = dry season, 1 = wet season
Elevation	Average of elevation of each watershed
Landcover proportion	Proportion of agriculture land of each watershed
Population growth rate of each year by each country	Population Growth Rate variable is included as a pressure on landcover change
Chinese cascade dam construction	The effects of Chinese cascade dam construction 0= before dam construction, 1= after dam construction

3.1.1 Suspended Sediment Concentration variable and Discharge variable

Distributions of suspended sediment concentration and discharge are both right-skewed (Figure 6, a, b). For regression, both data needed to be converted to log scale. After converting to log scale, distributions of suspended sediment concentration and discharge data are illustrated in c and d in figure 6. Suspended sediment data in log scale and discharge in log scale form nearly normal distributions.

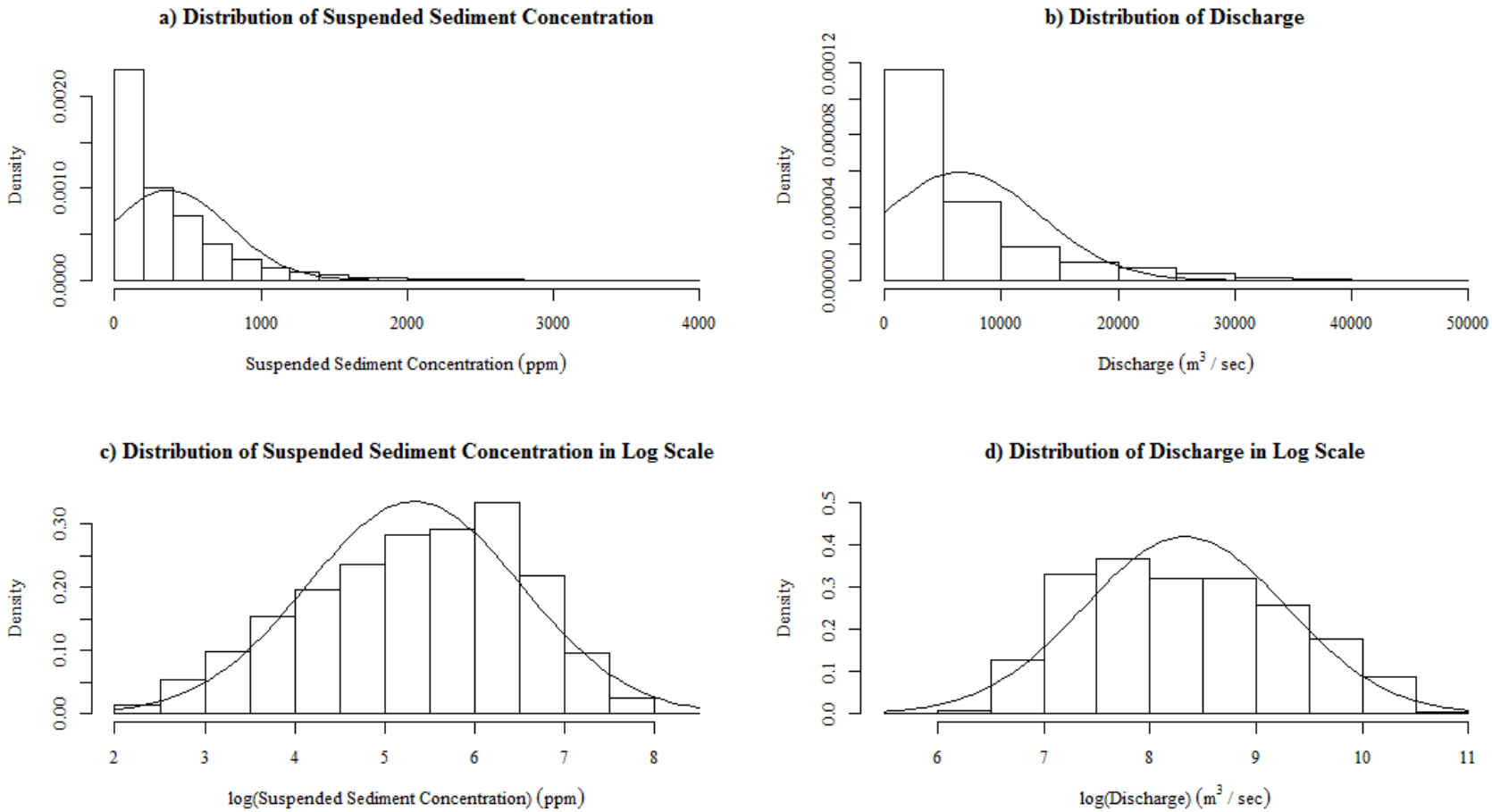

Figure 7 Distribution of Suspended Sediment Concentration and Discharge Data

Discharge is known for having a close relation with suspended sediment concentration and used to estimate sediment load in previous studies (Fu & He, 2007; Kummu et al., 2010; Kummu & Varis, 2007; D. E. Walling, 2008). It is known that empirical relation between discharge and suspended sediment concentration can be expressed as follows (D. Walling, 1977; D. E. Walling, 2008):

$$C_s = aQ^b$$

Where C_s is Suspended sediment concentration and Q is discharge.

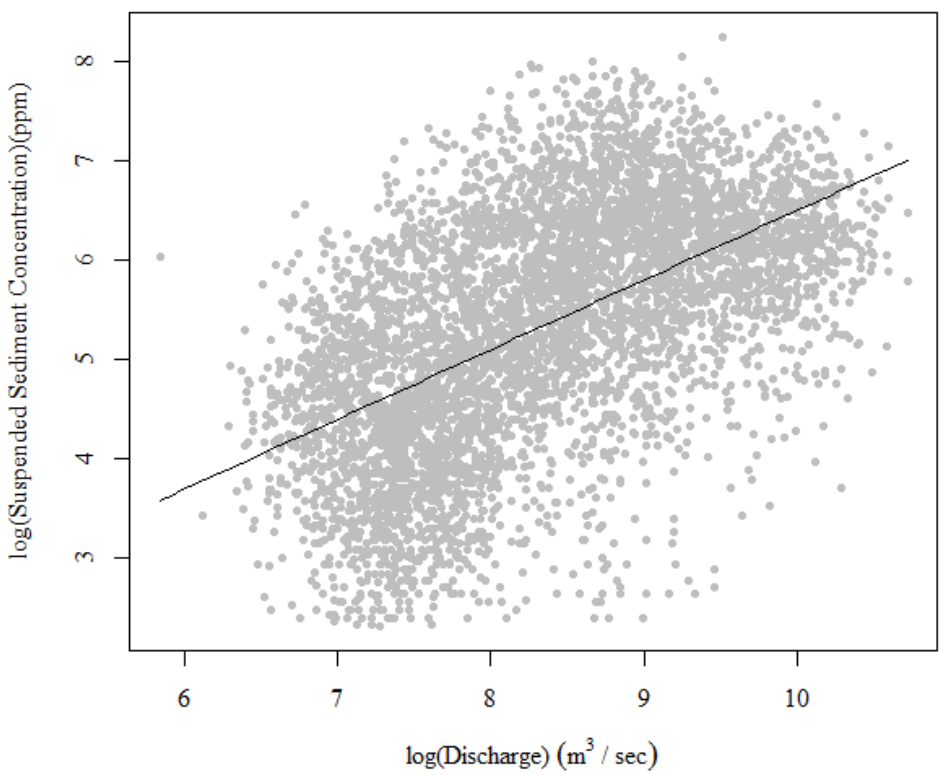

Figure 8 Relations between Sediment and Discharge of the Mekong River

However, the actual relation between discharge and suspended sediment concentration does not clearly appear what the equation suggests in the Mekong River Basin. The actual relation between discharge and suspended sediment concentration in the Mekong River Basin is illustrated in figure 8. Pearson correlation coefficient (r) is 0.56, and coefficient of determination (R^2) is 0.31. It means that there are other possible factors affecting suspended sediment concentration. Therefore, multiple regression analysis with additional variables is needed to explain the suspended sediment concentration in the Mekong River Basin.

3.1.2 Season variable

Season variable represents seasonal characteristics of Southeast Asia. In the Mekong Basin, the climate is seasonal, especially in the lower parts of the basin. The Northeast Monsoon causes dryness and cooler temperatures from November to February, while the Southwest Monsoon brings wetness and hotter temperature between June and September (Kummu & Varis, 2007). Therefore, suspended sediment concentration is expected to increase in wet season, and to decrease in dry season. Based on this seasonal difference, the season variable is defined as follows:

$$\begin{cases} 0 = Dry\ Season(From\ November\ to\ April) \\ 1 = Wet\ Season(From\ May\ to\ October) \end{cases}$$

3.1.3 Variables related to station watershed

Suspended sediment concentration can also be affected by landscape and landcover features of the watersheds. In order to reflect the fact that geomorphologic characteristics can have an effect on sediment erosion, watershed boundary for each station need to be defined in order to calculate mean elevation and landcover proportion for each watershed of hydrological station. The higher are the elevation of the watershed and proportion of agricultural land, the more erosion can occur.

To define watershed for each station, ArcGIS 10.1 is used. Using ArcGIS, areas which can affect the suspended sediment concentration level of each station can be defined, which is watershed for each station. In order to define watershed correctly, locations and relationship of stations are used. First, in order to obtain reasonable results, station locations are corrected by pour point tool. The pour point tool can find the deepest point in certain radius, making it clearer to draw watershed boundary of each station. Using the corrected station location and elevation data, watershed for each station is defined (Figure 8). Based on watershed for each station, average elevation and proportion of agricultural land for each watershed are calculated. The calculation is conducted using zonal statistics tool in ArcGIS 10.1.

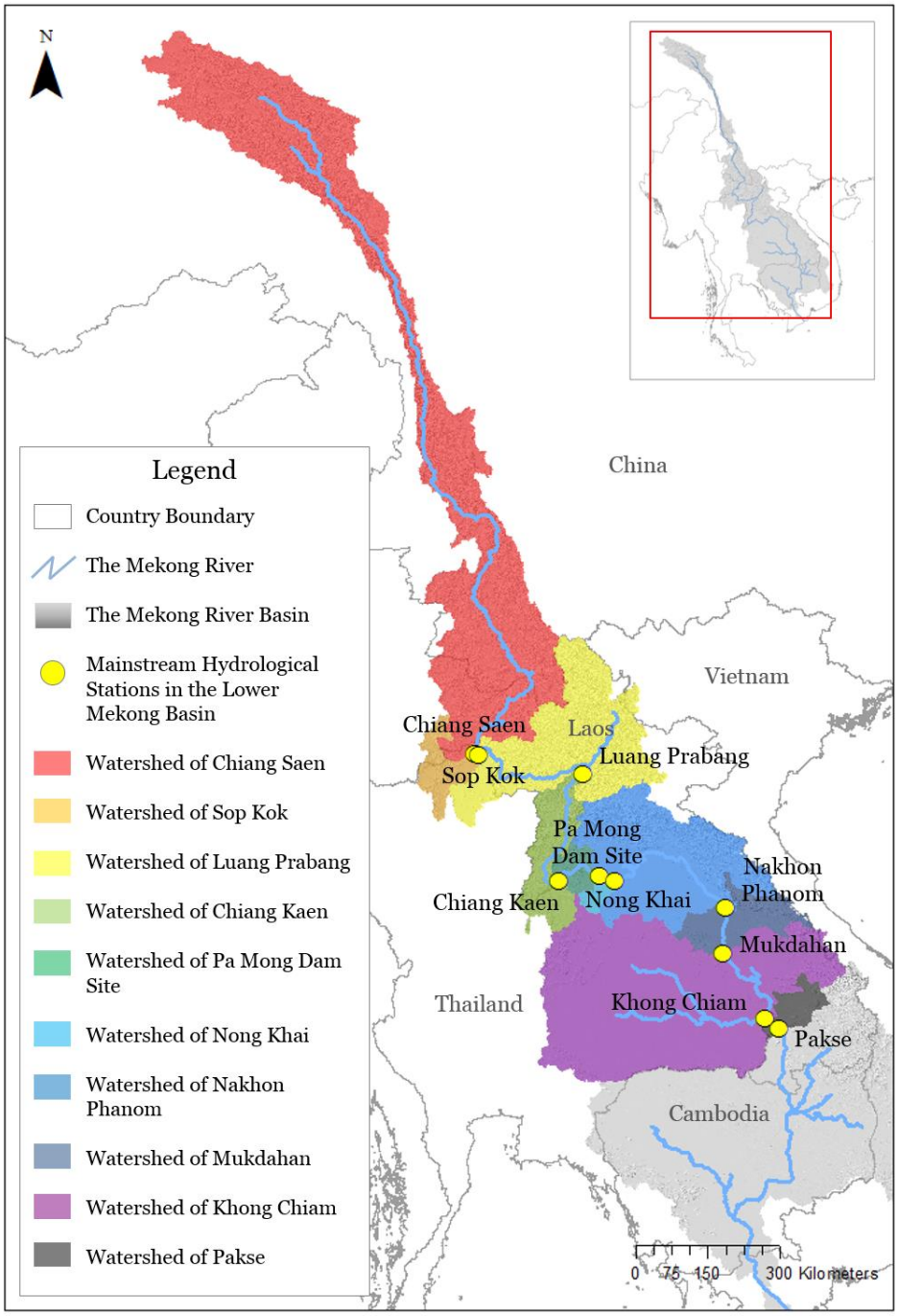

Figure 9 Delineation of Watershed for Each Hydrological Station

3.1.4 Population growth rate variable

Sediment yields can be affected by land use. For example, if a forest is converted into an agricultural land, the level of erosion will increase. Therefore, land cover change should be considered. Population growth is main cause of land cover change. When population increases, there are pressures on forest or pasture land to be converted into urban or agricultural land, and this may increase the amount of sediment erosion. Population growth rate of Thailand and Lao PDR of each year is used as a variable. Annual population growth rate is referred from the Worldbank database.

3.1.5 Chinese cascade dam construction variable

As reviewed in the previous chapter, studies on dam effects on the Mekong show that there are conflicts between scholars about the impact of Chinese cascade dams on sediment flux on the Mekong river (Fu & He, 2007; Fu et al., 2008; Kummu et al., 2010; Kummu & Varis, 2007; Lu & Siew, 2006). In order to investigate this issue and clarify the impact of the dam, variable regarding Chinese cascade dam construction is built as follows.

$$\begin{cases} 0 = Before\ dam\ construction(before\ 1993) \\ 1 = \ After\ dam\ construction(after\ 1993) \end{cases}$$

3.2 Statistical Results

In this chapter, suspended sediment concentration data is statistically examined. First, the significance of variables which may have an effect on suspended sediment concentration is tested using comparing means method in Chapter 3.2.1. Second, suspended sediment concentration data is estimated with relevant variables using multiple regression analysis. In particular, the significance of the effect corresponding to Chinese dam construction is tested with other variables controlled.

3.2.1 Compare Means to Clarify Significance of Variables

Comparing means is used such as T-test and ANOVA test in order to clarify significance of season variable, Chinese cascade dam variable, and variables related to station watershed.

Table 6 Results of t-test of Season Variable

Levene's Test for Equality of Variances		t-test for Equality of Means (Variances are assumed to be equal)		
F value	Significance probability(p-value)	t-value	Degree of freedom	Significance probability (p-value)
0.005	0.944	-48.455	5,238	0.000

For the season variable, the t-test is used. In case of the season variable, Levene's Test for equality of variances is conducted to check the equality of

variances between two groups. The F value is 0.005 and significance probability (*p*-value) is 0.944, which cannot reject null hypothesis that the variances between the two groups are equal. Therefore, variances between two groups are assumed to be equal. The t value is -48.455, degree of freedom is 5,238, and significance probability (p-value) is 0.000, which shows that there is a significant difference between means of dry season and wet season in significance level(α) 0.01.

Table 7 Results of t-test of Chinese Dam Construction Variable

Levene's Test for Equality of Variances		t-test for Equality of Means (variances are assumed not to be equal)		
F value	Significance probability(p-value)	t-value	Degree of freedom	Significance probability (p-value)
26.648	0.000	2.681	2994.346	0.007

For the Chinese cascade dam variable, the t-test is also used (table 6). First, Levene's Test for equality of variances is conducted to check the equality of variances between two groups. The F value is 26.648 and significance probability(p-value) is 0.000, which means the variance between the two groups can be different. In the case when equal variance is not assumed, the t value is 2.681, degree of freedom is 2994.346 and significance probability(p-value) is 0.007, which shows that means of suspended sediment concentration before Chinese cascade dam construction and after construction are significantly different in significance level(α) 0.01.

The one-way ANOVA test is used in order to test significance of variables related to station watershed such as elevation, slope and landcover. The explained variable is suspended sediment concentration, and explaining variable is 10 stations. The F value is 55.759 and significance probability is 0.000, which means there are considerable differences among stations in significance level(α) 0.01. Difference of means of suspended sediment concentration data among stations is shown in figure 10.

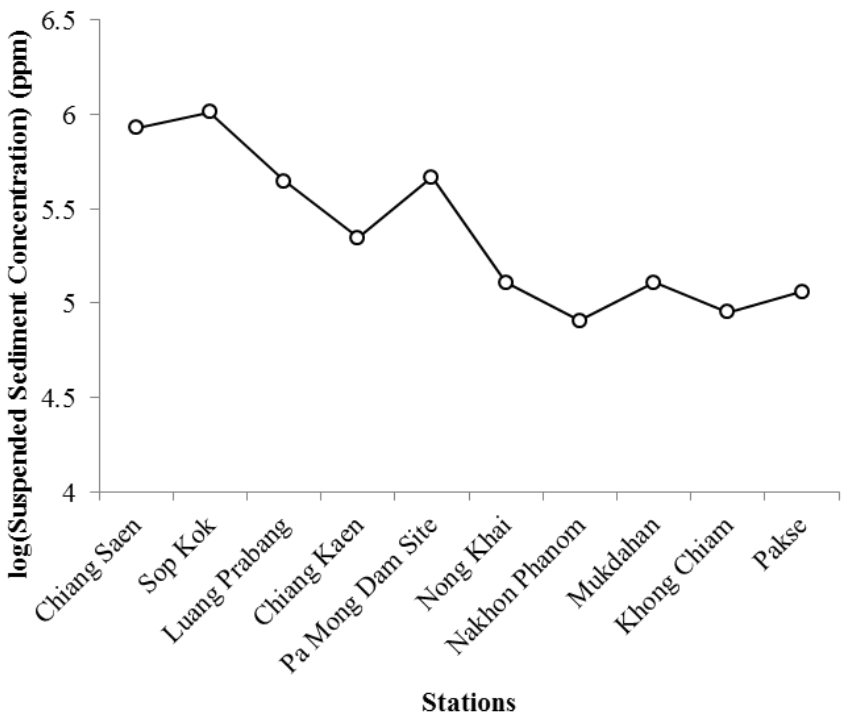

Figure 10 Difference of Means of suspended sediment concentration among stations

According to comparison of means, the significance of the season variable, the Chinese cascade dam variable, and variables related to station watershed are identified. Therefore, all of those variables can be used as effective variables in multiple regression of chapter 3.2.2.

3.2.2 Multiple Regression

In order to clarify the relationship between suspended sediment and other variables, a multiple regression analysis is conducted. A dependent variable is suspended sediment concentration. Independent variables are the season variable, the discharge variable, crop area percentage of each station watershed, mean elevation of each station watershed and construction of Chinese cascade dam variable. Watershed area of each station and proportion of other land cover type are not included in the regression because of collinearity with other variables. Expected relation equation, which is developed from simple sediment-discharge relation equation, is as follows:

$$\begin{aligned}\log(\text{Suspended Sediment Concentration}) \\ &= a + b \times \log(Discharge) + c \times (Season) \\ &+ \mathrm{d} \times (\text{Crop area percentage of each station watershed}) \\ &+ \mathrm{e} \times (\text{Population Growth of Each Year}) \\ &+ f \times (Mean\ elevation\ of\ each\ watershed) \\ &+ g \times (Construction\ of\ Chinese\ Cascade\ dams) + e\end{aligned}$$

Suspended sediment concentration would have positive relation with discharge because more water can induce more erosion, as showed in figure 7. For the same reason, suspended sediment concentration would have positive

relation with the season variable, which is 0 for dry season and 1 for wet season. Suspended sediment concentration would also have positive relation with crop area percentage of each watershed because agriculture is one of the significant reasons of soil erosion. Suspended sediment concentration would have positive relation with population growth, because population growth precipitates more intensive land use, such as agriculture and development, which in turn leads to more erosion. Higher elevation would cause more erosion, so the relation between mean elevation of watershed and suspended sediment concentration would be positive. Construction of the Chinese cascade dams variable would have negative relation with SSC, because dams block the river and trap sediments within the reservoir. The expected signs are summarized in table 7.

Table 8 Expected Signs of Parameters for Each Variable Representing Relations between Each Variable and Suspended Sediment Concentration in Multiple Regression Analysis

Variables	Parameters	Expected Sign of parameter
Discharge	b	+
Season	c	+
Crop area percentage of each watershed	d	+
Population growth of each year	e	+
Elevation mean of each watershed	f	+
Chinese Cascade Dams	g	-

Multiple regression analysis is conducted. R^2 and Adjusted R^2, which represent explanation power of model, are both 0.62. This model can explain the variance of suspended sediment concentration better than regression model which only has discharge variable of R^2 which is 0.31.

Coefficients of the model are shown in table 8. Signs of variables are shown as expected in table 7. Season variable, discharge variable, average elevation variable, population growth rate variable and proportion of crop land variable have positive relationship with suspended sediment concentration. Also, the Chinese cascade dam construction variable has negative relationship with suspended sediment concentration. Every significance probability except population growth is 0.00, which means those variables have significant relationships with suspended sediment concentration. Significance probability of population growth rate variable is 0.94, which means significance of the variable cannot be ensured, but the sign of the variable is in concordance with expectation. In particular, the effect of the Chinese cascade dam construction is shown as significant with other variables controlled.

Table 9 Coefficients of multiple regression analysis of suspended sediment concentration

	Unstandardized Coefficients (B)	Standardized Coefficients (β)	Significance
(Constant)	-7.360		.000
Season (discrete)	.270	.111	.000
Discharge ($logm^2$)	.906	.723	.000

Mean elevation of each watershed	.002	.727	.000
Chinese dam construction(discrete)	-.273	-.107	.000
Population growth rate of each year by each country	.002	.001	.938
Proportion of cropland of each watershed	1.817	.161	.000

Among variables, average elevation of watershed in log scale has the most significant relationship with suspended sediment concentration, whose standardized coefficient is the biggest. It means watersheds located upstream are more prone to erosion. On the contrary, population growth rate variable has the least significant relationship. This may be because population growth rate variable can be just one of the reasons which make the changes in land cover, and cannot fully represent the effects of land cover change on sediment flux.

Based on this multiple regression analysis, relation function between SSC and other variables is as follows:

$$\begin{aligned}
&\log(\text{Suspended Sediment Concentration}) \\
&\quad = -7.360 + 0.906 \times \log(Discharge) + 0.270 \times (Season) \\
&\quad + 1.817 \times (\text{Crop area percentage of each station watershed}) \\
&\quad + 0.002 \times (\text{Population growth of each year}) \\
&\quad + 0.002 \times (Elevation\ mean\ of\ each\ watershed) \\
&\quad - 0.273 \times (Construction\ of\ Chinese\ Cascade\ dams)
\end{aligned}$$

3.3 Mainstream Sediment Flux in the Mekong River Basin

According to the equation derived from Chapter 3.2, suspended sediment concentration flux of mainstream stations is estimated using daily discharge data and other data related to aforementioned variables. With 1000 times of the Montecarlo simulation, suspended sediment concentration is calculated and averaged.

In order to understand the actual sediment yield of the region, sediment load should be calculated. The relation expression of sediment load and discharge, and suspended sediment concentration is as follows (Gray & Simões, 2008):

$$\mathrm{SL} = \mathrm{Q}C_s$$

SL refers to sediment load, while Q is discharge and C_S is sediment concentration. Following this equation, sediment load is calculated for each station. Figure 10 and Figure 11 are the examples of the Chiang Saen station which is the closest station to the Upper Mekong Basin. Figure 10 shows seasonal trend clearly which sediment load increases in wet season and decreases in dry season. Figure 11 shows downward trend of yearly sediment load at the Chiang Saen Station.

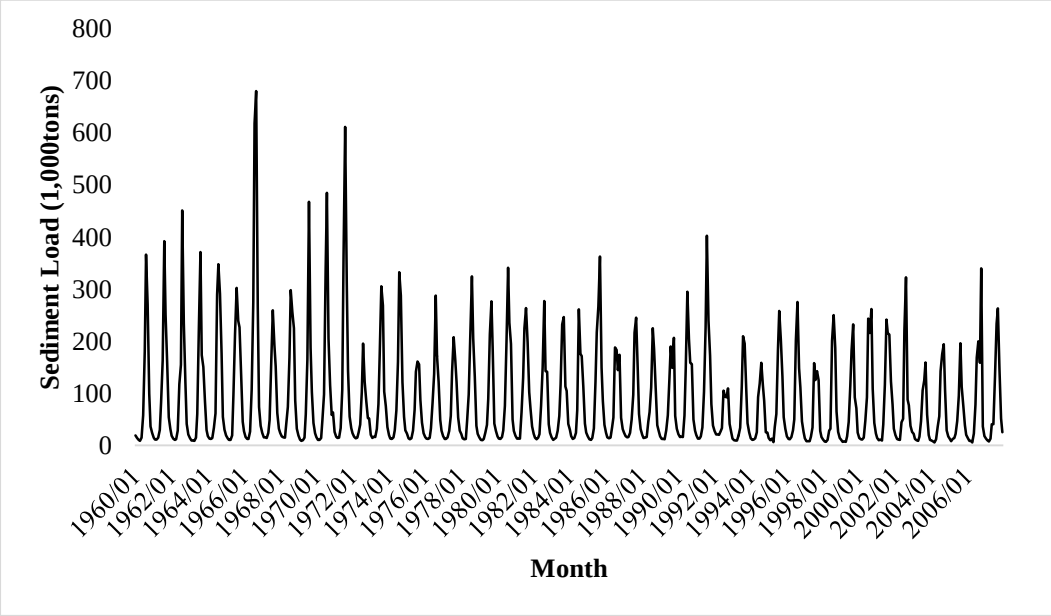

Figure 11 Monthly Sediment Load of the Chiang Saen Station

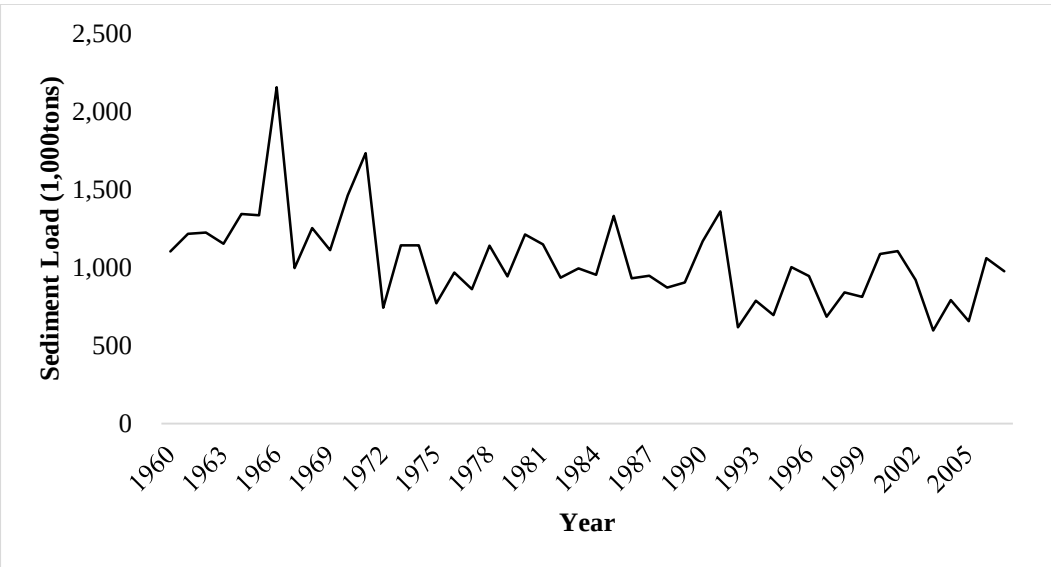

Figure 12 Yearly Sediment Load of the Chiang Saen Station

In this chapter, Chinese cascade dam construction started from 1993 has significantly changed suspended sediment concentration by comparing means before and after construction of Chinese dams and multi regression analysis. In the previous studies, comparison of temporal differences between the times before and after construction of Chinese dams has also been adopted to examine the effects of dam construction.

Lu and Siew (2006) estimated sediment flux by using the relation equation between suspended sediment concentration and discharge. Lu and Siew (2006) interpreted peak of the sediment load of 1991 due to the surge of water discharge in that year, and this study does show the same trend. Also, Lu and Siew (2006) analyzed the mean annual sediment load change before and after dam construction with existing suspended sediment data. It shows that sediment load decreased from 74.1 x 10^6 t/a(1962-1992) to 34.5 x 10^6 t/a(1993-2000). Kummu and Varis (2007) also compared sediment data before and after the Manwan Dam closure in 1993. Sediment data in this study is from two different sources, which are Mekong River Commission hydrological database (HYMOS) and Mekong River Commission Water Quality Monitoring Network (WQMN). According to this study, the mean annual suspended sediment flux decreased from 71 x 10^6 t/a(1962-1992) to 31 x 10^6 t/a(1993-2000) at Chiang Saen station. These two studies concluded that Chinese dam construction has significant impacts on sediment flux of the Lower Mekong Basin, which decreased almost 50% after dam construction. This study also concluded that the change of sediment flux is significant by mean comparison and multi regression analysis. However, the decrease rate of sediment flux is different from previous studies, which is 23% after dam construction. This result is possibly because this study considered other factors such as elevation and cropland proposition which are assumed as

static feature of each watershed in this study.

In contrast, Fu et al. (2006) analyzed Chinese sediment data and data of Chiang Saen station in the Lower Mekong Basin by using Granger causality test. By this analysis, this study concluded that the sediment flux change of Chiang Saen station is not because of dam construction, but because of other possible reasons such as intensive land use. However, this study used monthly data for the comparison, while sediment transportation between two stations possibly takes less than a month. Fu et al. (2008) also compared data of Jiuzhou, Gajiu and Yunjinghong station located in the Upper Mekong Basin, with data of Chiang Saen station located in the Lower Mekong Basin.

This study suggested that while the Manwan dam might have caused downstream effects, the effect has not reached outside the boundary of China to the Lower Mekong Basin. In this sense, Fu et al. (2008) also suggested that change of suspended sediment concentration at Chiang Saen station might be caused by other reasons. In this chapter, factors that have the potential to affect suspended sediment concentration are selected and controlled to investigate pure effects of dam construction. As a result, dam construction is still significant with other factors controlled. Therefore, it is possible that the Manwan dam and successive dam constructions have affected sediment flux of the Lower Mekong Basin which is contrast to the result of Fu et al. (2006) and Fu et al. (2008).

However, these empirical research has a critical weakness that the results heavily depend on the quality of data. Because of limited accessibility of Chinese data, research on the change of sediment inputs from the Upper Mekong Basin is only conducted by Chinese scholars and most of the studies are concentrated on

stations in the Lower Mekong Basin. Moreover, suspended sediment concentration data in Lower Mekong Basin are dispersed and limited, which may increase the possible error in determining the change in suspended sediment fluxes. D. E. Walling (2008) suggested that it is tempting to conclude that the lower annual sediment load of Chiang Saen station is because of Chinese dam construction, but it can be hasty conclusion because of the sediment data of this area has a limitation to represent the true suspended sediment concentration. Further, the sampling techniques of the Upper Mekong Basin and the Lower Mekong Basin are possibly different from each other. Theoretical approach can be an alternative to overcome these limitations. In chapter 4, theoretical trapping amount of reservoir is modelled by Brune (1953)'s trapping efficiency equation based on system dynamics approach. The estimated sediment load of chapter 3 is used in chapter 4 for calibration baseline.

4. Assessment of Possible Impacts of Dams on the Sediment Flux of the Mekong River

In this chapter, potential effects of existing dams on the Mekong River are modelled using the integrated system dynamics. First, the integrated system dynamics model which consists of three sub-models is built in chapter 4.1. Sediments are eroded, transported, and deposited, and trapped in the reservoir if dams are constructed. Therefore, three sub-models are built as follows: potential erosion model to model erosion and transportation of sediments, dam trapping model to model trapping amount of sediment by reservoir, and agro-economic model to model its agro-economic impact.

In chapter 4.2, the model is calibrated and validated with the data produced in chapter 3.3. Because historical data is available from 1960 to 2007 and only two Chinese dams were built during that period, the results of system dynamics model with two Chinese dams are compared with the historical data and calibrated. In order to show the validity of the model, actual data and the simulation result of the Chiang Saen station are compared.

In chapter 4.3, results of the model is shown and compared with other studies. The result of the model reflects dynamic feature of trapping sediments by dam reservoir. Also, applicability and limitation of the model are discussed.

4.1 Integrated System Dynamics Model

In this chapter, three sub-models are built. The first sub-model is potential erosion model using the Universal Soil Loss Equation(USLE) in Chapter 4.1.1 (Csiki & Rhoads, 2014). The second sub-model is dam trapping model using the Trapping Efficiency(TE) in Chapter 4.1.2 (Brune, 1953), and the last sub-model is agro-economic model in Chapter 4.1.3, which calculates economic profit from rice cultivation to identify economic costs incurred by sediment flux changes.

4.1.1 Potential Erosion Model

The Universal Soil Loss Equation (USLE) (Csiki & Rhoads, 2014) and The Revised Universal Soil Loss Equation (RUSLE) (Li et al., 2013) were developed in order to calculate potential annual erosion. Although there are lots of models developed after USLE to predict soil erosion such as the Water Erosion Prediction Project (Kuenzer et al., 2013), the Soil and Water Assessment Tool (Li et al., 2012), and the European Soil Erosion Model (Syvitski & Saito, 2007), USLE is still a popular model to use. This is because 1) between empirical and physical models, empirical model is more popular due to low data requirement and relatively well verified estimates; and 2) USLE and its revised version, RUSLE, are versatile and easily integrated with other spatial analysis methods (Chen, Son, Chang, & Chen, 2011; Lu et al., 2008; Vaidyanathan, 2012; Zhou et al., 2014).

Considering data feasibility, USLE is a more appropriate method than RUSLE. For the Mekong region, data related to calculated potential erosion amount is very scarce. Moreover, the research area is extensive, which makes it

impractical to conduct a large number of field research. Therefore, USLE model is used in this study to compute potential erosion amount and predict future potential erosion amount using precipitation data. Casual map of sediment yield for each basin using USLE and delivery ratio is illustrated in figure 12.

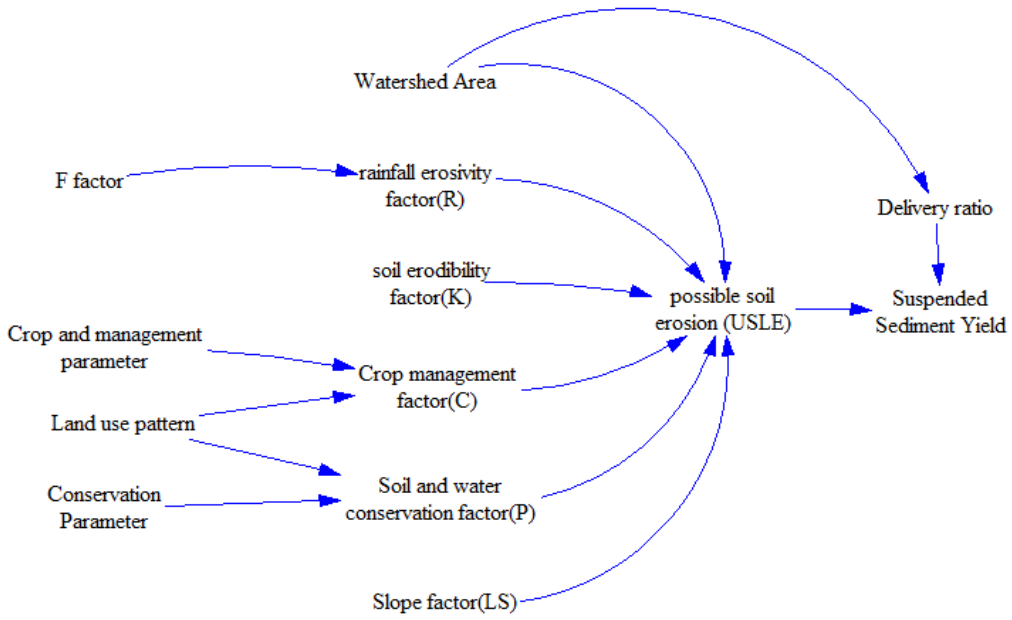

Figure 13 Casual Map of Sediment Yield for Each Basin Using USLE

In the USLE model, average annual soil loss is expressed as follows:

$$A = R \times K \times LS \times C \times P$$

A is the amount of average annual soil loss (t/ha/y). In order to compute A, R, K, L, S, C, P factors need to be calculated. R is the rainfall erosivity factor (MJ mm/ [ha h y]), K is the soil erodibility factor (t h/MJ/mm), L is the slope length factor, S is the slope steepness factor, C is the cover and management practices

factor, and P is the soil erosion control practices factor.

The R factor is derived by using the modified Fournier index. The modified Fournier index is a suitable method for the region concerned for this study, because only long term average monthly data was acquired as precipitation data. Arnoldus (1977)'s modified Fournier's index is as follows:

$$F = \frac{\sum_{i=1}^{12} p_i^2}{P}$$

Where F is the modified Fournier's index, p_i is average monthly precipitation, and P is average annual precipitation. Precipitation data is derived from WorldClim, which is a set of global climate data in layers or grids with a spatial resolution of about $1km^2$.

The K factor is calculated using J. Williams, Renard, and Dyke (1983)'s method, which is appropriate for a region with low data availability. Soil parameters used in this study were derived from the Harmonized World Soil Database.

Digital elevation model(DEM) data is used to calculate the LS factor. The unit stream power algorithm is easily computed by multiplying a flow accumulation grid with its cell slope (Molle et al., 2009). The DEM data is derived from USGS SRTM. The cell size of SRTM is 50m in the Mekong region.

The C factor and the P factor, which are factors related to land use and conservation practice, are calculated using the land use type identified by land cover type (Yang, Kanae, Oki, Koike, & Musiake, 2003). An average value of C

factor which corresponds to mean annual canopy coverage is used to calculate C factor according to the USDA handbook. The P factor in this study is introduced to the agricultural practice only (Yang et al., 2003).

Sediment delivery ratio represents the sediment lag between the actual sediment yield and potential erosion (Ferro & Minacapilli, 1995). In this study, delivery ratio is calculated as the fraction of gross erosion which is expected to be delivered to the outlet of the watershed. Sediment delivery ratio is calculated by comparing possible soil erosion using the USLE and actual suspended sediment load data which is calculated in chapter 3.3. Data before 1992 is used in order to avoid disturbances accompanying dam construction.

Not only the delivery ratio in the basin, but also the delivery ratio in the channel, is important to sediment yield and transportation. In this study, a channel is assumed as a pipe, of which the delivery ratio is 1. It means that sediments can go down straight to the mouth of the Mekong basin if sediment enters the mainstream channel. As delivery ratio in the channel can be controlled, the output based on controlling channel delivery ratio can be monitored.

4.1.2 Dam Trapping Model

Dam construction has a significant impact on sediment system because dam blocks the river and hinders sediment transportation. Many studies dealt with trapping efficiency of the dam, which is related to the storage capacity of reservoirs and the discharge of the basin (Brune, 1953; Kummu et al., 2010; Kummu & Varis, 2007; Vörösmarty et al., 2003). Vörösmarty et al. (2003) investigated the effects of reservoirs on sediment retention on a global scale.

According to this study, more than 50% of sediment flux in the basin scale is possibly captured by artificial reservoirs. Large dams can alter natural river systems and about 472 million people across the world are living near downstream rivers of dam and affected by dam construction (Richter et al., 2010).

The trapping efficiency of large reservoirs(Volume > $10^7 m^3$), which is a fraction of the total sediment load kept by a reservoir, is generally over 99% (Graf, 1999; G. P. Williams & Wolman, 1984), and the trapping efficiency is between 10 and 90% in case of smaller dams (Brune, 1953). The Brune (1953)'s equation is widely used to calculate the trapping efficiency because it is simple and does not require any detailed data of the reservoir or sediment. Thus, this technique can be applied for the region where available data are extremely scarce. Brune's equation is as follows:

$$\mathrm{TE} = 1 - \frac{0.5}{\sqrt{\Delta\tau_R}}$$

$\Delta\tau_R$ refers to the local residence time change. It is calculated with the following equation:

$$\Delta\tau_R = \frac{\sum_1^{n_j} V_i}{Q}$$

Where V_i is the storage capacity of the *i*th reservoir in the *j*th regulated sub-basin (km^3), Q is the discharge at the mouth of the *j*th sub-basin (km^3a^{-1}).

In addition to Brune's method, dynamic feature of sediment trapping is incorporated in this study. When sediments are trapped over time, the storage

capacity(V_i) becomes reduced because of deposited sediments. Previous studies using this equation could not capture this dynamic feature. However, this dynamic characteristic has an impact not only on trapping efficiency of the reservoir of the dam, but also on trapping efficiency of the reservoir of other dams located downstream. Reflecting this to the model, reservoir capacity is decreased by the increasing trapped sediments, and it influences the trapping efficiency(TE). Therefore, dam trapping process forms a feedback loop. Causal map of dam trapping process is shown in figure 13.

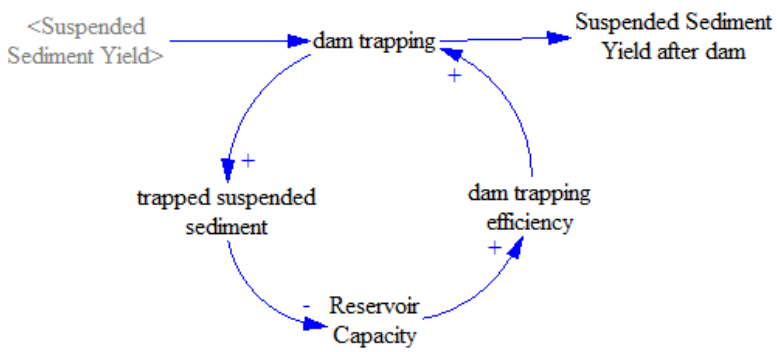

Figure 14 Causal Map of Trapping Efficiency of Dam Model Using Brune's Equation

4.1.3 Agro-economic Model

After all dams are modelled according to the selected scenario, the effect of sediment flux change is measured by the change of delta area. In this study, the equation which represents delta area is related with average discharge, sediment load and the shelf depth (Syvitski & Saito, 2007). The equation is as follows:

$$A_D = 1.07 Q_{av}^{1.1} Q_{s+b}^{0.45} / D_{Sh}$$

Where, A_D is the area of a delta(km²), Q_{av} is average discharge(m³/s), Q_{s+b} is the total sediment load, and D_{sh} is the shelf depth. From the change of delta size, the change of agricultural land is estimated and calculated as a monetary value to identify its benefit and cost. Because more than 53% of Vietnamese rice fields are located in the Mekong Delta and produce 80-85% of the country's annual rice export (Chen et al., 2011; T. M. H. Nguyen, Kawaguchi, & 川口雅正, 2002), effects on the rice production of the Vietnam delta can have ripple effects across related sectors. According to T. T. H. Nguyen, De Bie, Ali, Smaling, and Chu (2012), area of rice based agriculture system in the Mekong Delta is 15,760km², takes up 40% of the Mekong Delta. Rice yield of the Mekong Delta is 575 ton/km² in 2012 according to Ministry of Agriculture and Rural Development (MARD) of Vietnam. Vietnamese rice price per ton in 2013 was USD 434.44 (Wordbank commodity price data). With this information, Agro-economic impact of sediment flux change is measured as following equation:

$$\begin{aligned}&(\text{Income from Rice Production})\\&\qquad = (Delta\ Area)\\&\qquad \times (Proportion\ of\ Agricultural\ land\ of\ Delta\ Area)\\&\qquad \times (Rice\ Production\ Efficiency) \times (Vietnamese\ Rice\ Price)\end{aligned}$$

Causal map of agro-economic impact is shown in figure 14.

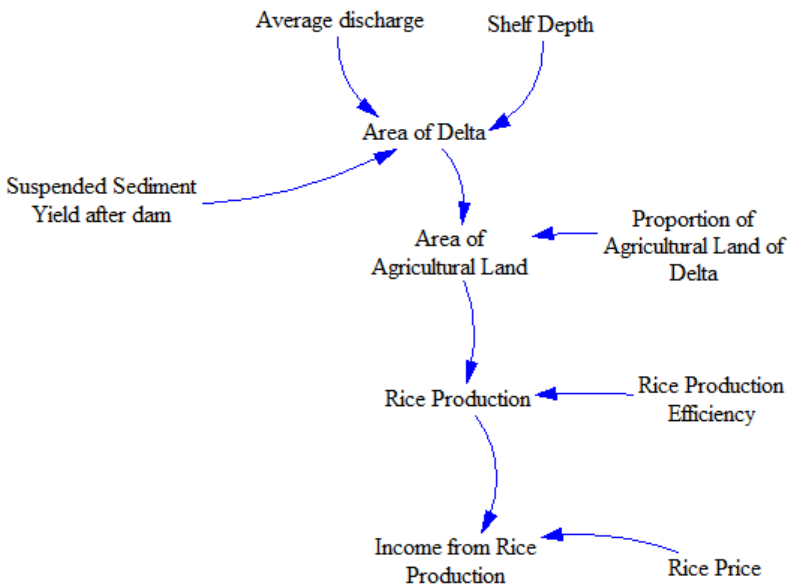

Figure 15 Casual Map of Agro-economic Model

4.2 Model Calibration and Validation

In order to validate the model, the historical data of the Chiang Saen station (010501) is used because the Chiang Saen station is the nearest station to the Upper Mekong Basin among selected stations. Flow diagram of the Chiang Saen station is demonstrated in figure 15. In the data period of 1960-2007, two dams were built in the Upper Mekong Basin. Therefore, sediment yield model with two dams is created and validated with the data. The structure of model with two dams is shown in figure 16. Each dam has its own basin and potential soil erosion is calculated by each basin.

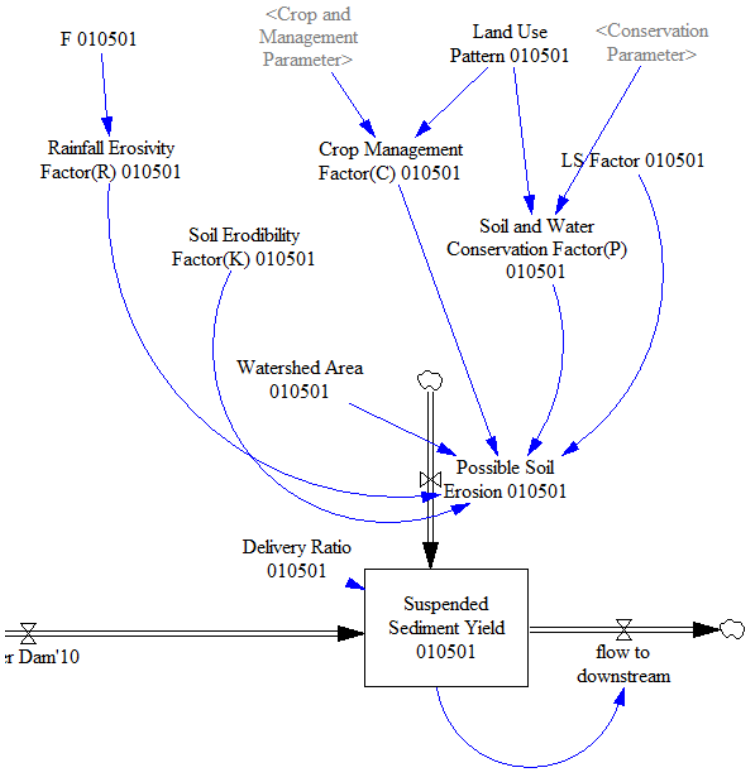

Figure 16 Flow diagram of Chiang Saen Station (010501)

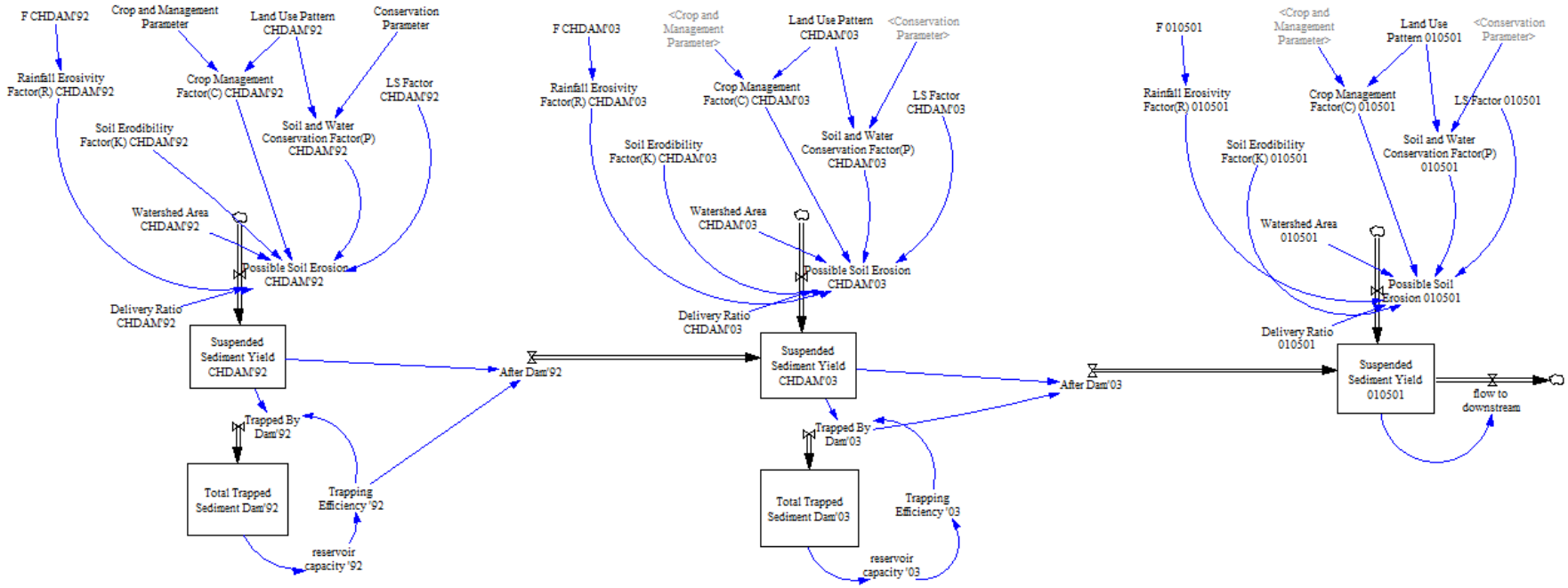

Figure 17 Model Structure with Manwan Dam and Dachaoshan Dam

The model is validated and calibrated with the data from Chapter 3.3. The estimated amount of sediment load before 1992 is calibrated with the average of actual sediment load data before 1992 by adjusting delivery ratio of the watershed. The result of USLE model is the potential erosion amount of the watershed, and estimation amount of sediment load computed in Chapter 3.3 is the actual sediment load. The delivery ratio is the ratio between these two figures.

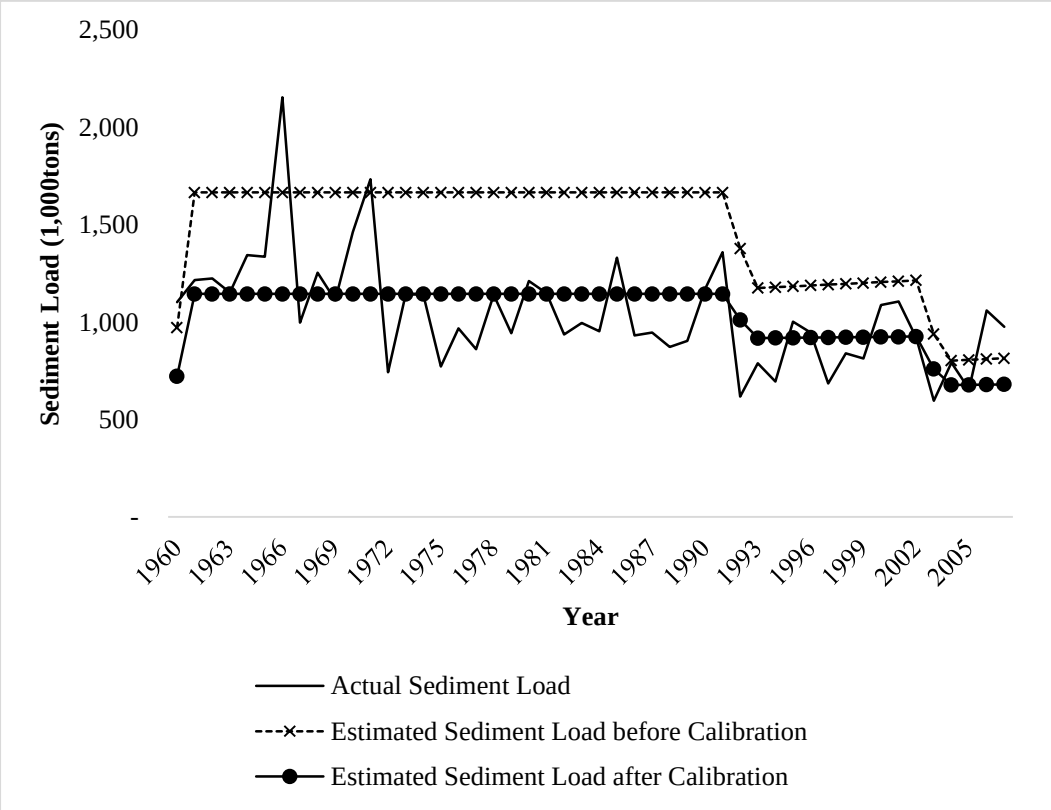

Figure 18 Estimated Sediment Load and Actual Sediment Load

This is intended to match the model with the data before having been disturbed by dam construction. The result of the model with two dams is illustrated in figure 17. The result of simulation seems static related to actual data.

This is because the purpose of this model is to detect pure dam effect with other factors controlled. Long term monthly average precipitation data is used for the purpose of the model, so the effect of the rainfall on sediment erosion is assumed same every year. It seems that the model represents the trend of actual data, but a more detailed comparison with the actual sediment data is needed because the variation of the model output is relatively static.

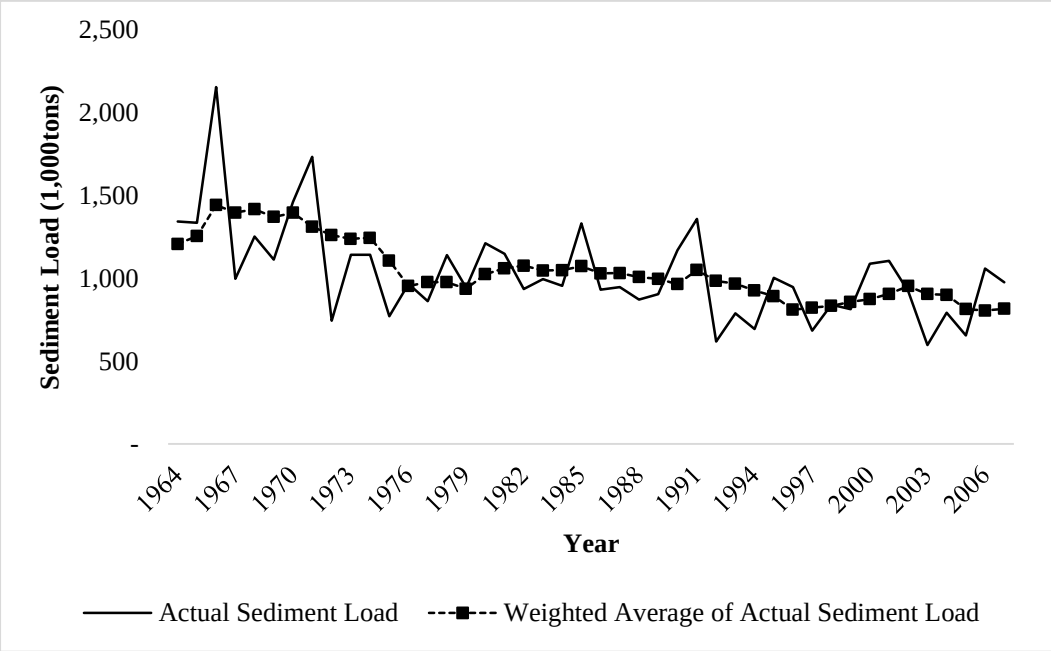

Figure 19 Weighted Averaged Annual Sediment Load of Chiang Saen station

The erosion amount from 1970 to 1992 does not change until the Manwan dam is constructed. To compare the output with real sediment load data, a more sophisticated weighted-average method is used for every 5 years. Weighted-average data of the Chiang Saen station is shown in figure 18 in a dotted line. It shows a decreasing trend from 1960 to 2007.

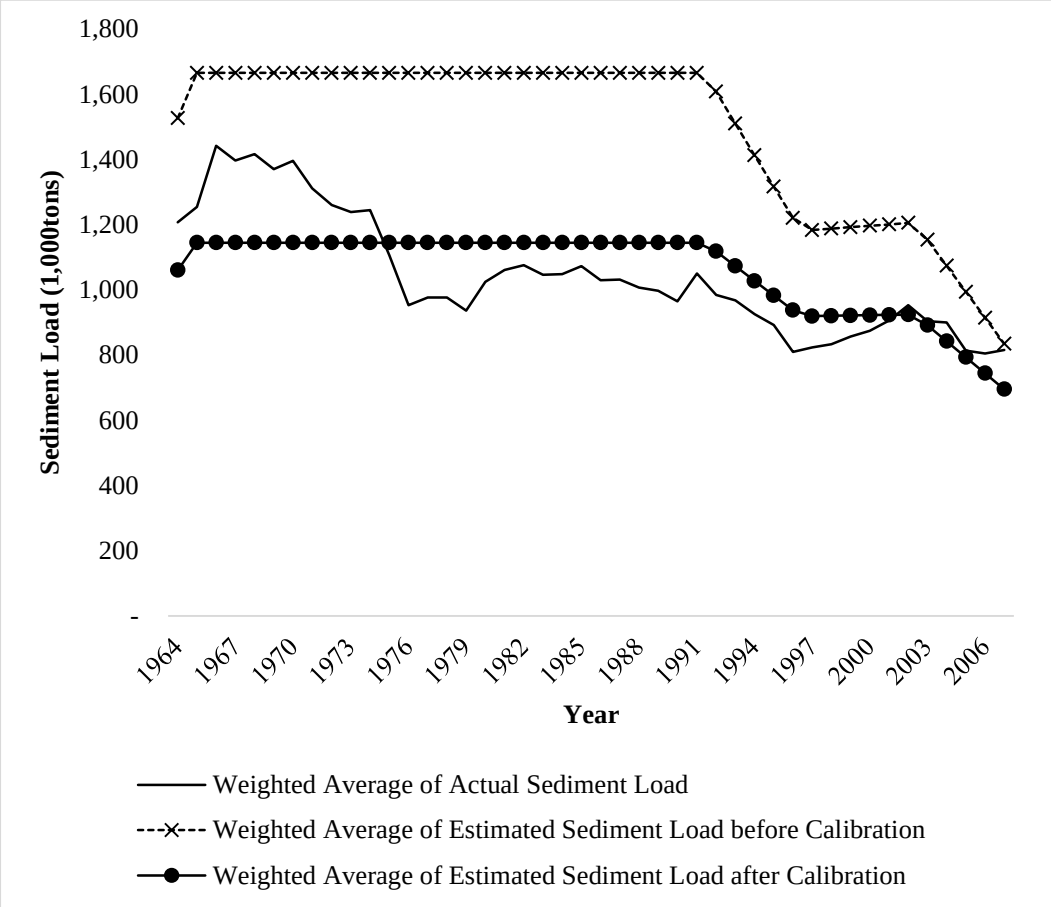

Figure 20 Actual and Estimated Weighted Average Sediment Load

Figure 19 demonstrates the comparison between actual and estimated weighted average sediment load before and after calibration. After the first dam construction, it shows a downward trend, which is in line with the actual weighted average data. After the second dam construction, the model output shows a decreasing trend once again. Actual data shows a slightly upward trend just before the dam construction in 1992 and in 2003, but it shows a downward trend following the dam construction as the model shows.

Table 10 RMSE of the Model before and after Calibration (ton)

Original Data			Weighted Averaged Data		
Standard Deviation of Actual Sediment Data	RMSE before calibration	RMSE after calibration	Standard Deviation of Actual Sediment Data	RMSE before calibration	RMSE after calibration
284,459	517,509	259,366	183,823	486,302	138,266

RMSE of the model to actual sediment load data is calculated (table 9). In comparison of original data, RMSE before calibration is 517,509 ton and RMSE after calibration is 259,366 ton. In comparison of weighted averaged data, RMSE before calibration is 486,302 ton and RMSE after calibration is 138,266 ton. RMSE is reduced more than 50% after calibration both in comparison of original data and weighted averaged data. Moreover, RMSE after calibration is lower than standard deviation of actual sediment load data in both comparison.

Estimated sediment load of the model from 1988 to 2007 is as figure 20. Sediment load decreases in 1992 and in 2003 when Manwan dam and Dachaoshan dam were built. After the Manwan dam was built, a sediment load decreased from 1,012,000 ton/year to 917,916 ton/year, which is 10% decrease after dam construction. After Dachaoshan dam was built, sediment load decreased from 925,876 ton/year to 677,172 ton/year, which is 27% after dam construction.

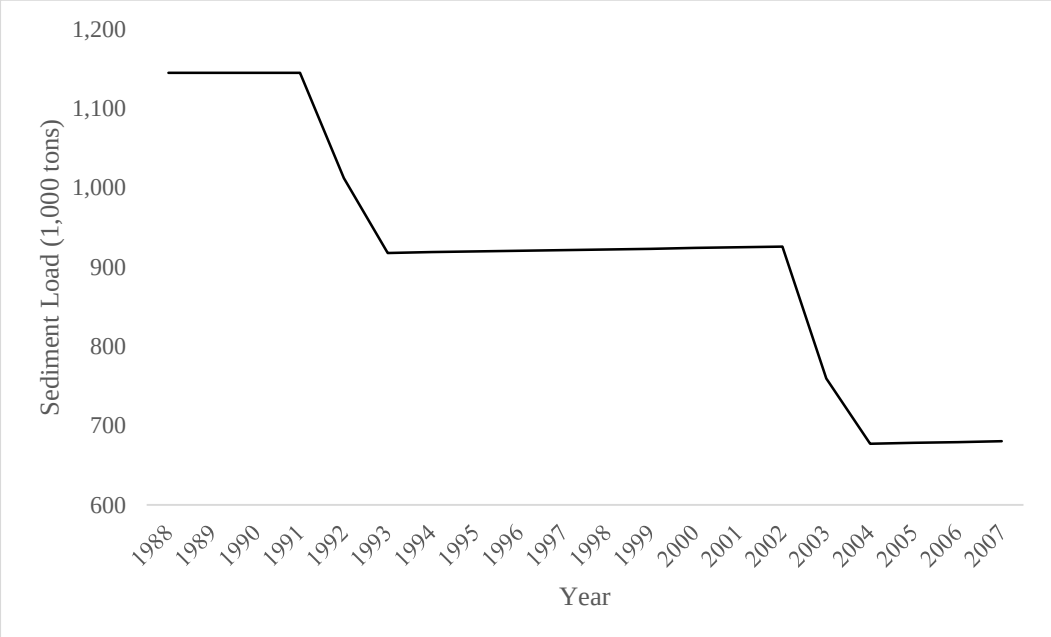

Figure 21 Estimated Sediment Load by Integrated System Dynamics Model from 1988 to 2007 with Two Dams at Chiang Saen Station

4.3 The effects of existing dams and Discussions

In this chapter, the effects of existing dams are modelled by integrated system dynamics model. Among eight dams planned on the Mekong mainstream in the Upper Mekong Basin, six dams have already been constructed. Information of the Mekong mainstream dams including expected installed capacity, project status, commission year, drainage area of reservoirs, discharge of each reservoir, and active storage volume of reservoirs are shown in Table 11. The information of drainage area, and discharge and active storage volumes are used to calculate and calibrate trapping efficiency in this study.

Table 11 Information of Mekong mainstream dams in the Upper Mekong Basin (Kuenzer et al., 2013; Kummu et al., 2010 and wikipedia)

		General Information					
		Expected installed capacity (MW)	Project Status	Commission year	$A_k(km^2)$	$Q_k(km^3yr^{-1})$	$V_k(km^3)$
Upper Mekong Basin (UMB) Reservoirs							
A	Gonguoqiao	750	C	2008	97,200	31.1	0.120
B	Xiaowan	4,200	C	2009	113,300	38.5	9.900
C	Manwan	1,500	C	1992	114,500	38.8	0.344
D	Dachaoshan	1,350	C	2003	121,000	42.3	0.467
E	Nuozhadu	5,500	C	2012	144,700	55.2	12.300
F	Jinghong	1,750	C	2010	149,100	58.0	0.577
G	Ganlanba	150	P/O	-	151,800	59.3	0.120
H	Mengsong	-	P/O	-	160,000	63.7	0.120

C: Complete, O: Ongoing, P: Planned

Six dams are modelled by integrated system dynamics approach. Model flowchart with eight dams of the Upper Mekong Basin is shown in figure 22. Gongguoqiao, Xiaowan, Manwan, Dachoshan, Nuozhadu and Jinghong dam, which have already been built, are modelled, and Galanba and Mengsong are excluded because the plans to build those dams have not been settled yet. Galanba and Mengsong are shown in figure 22 as blue color.

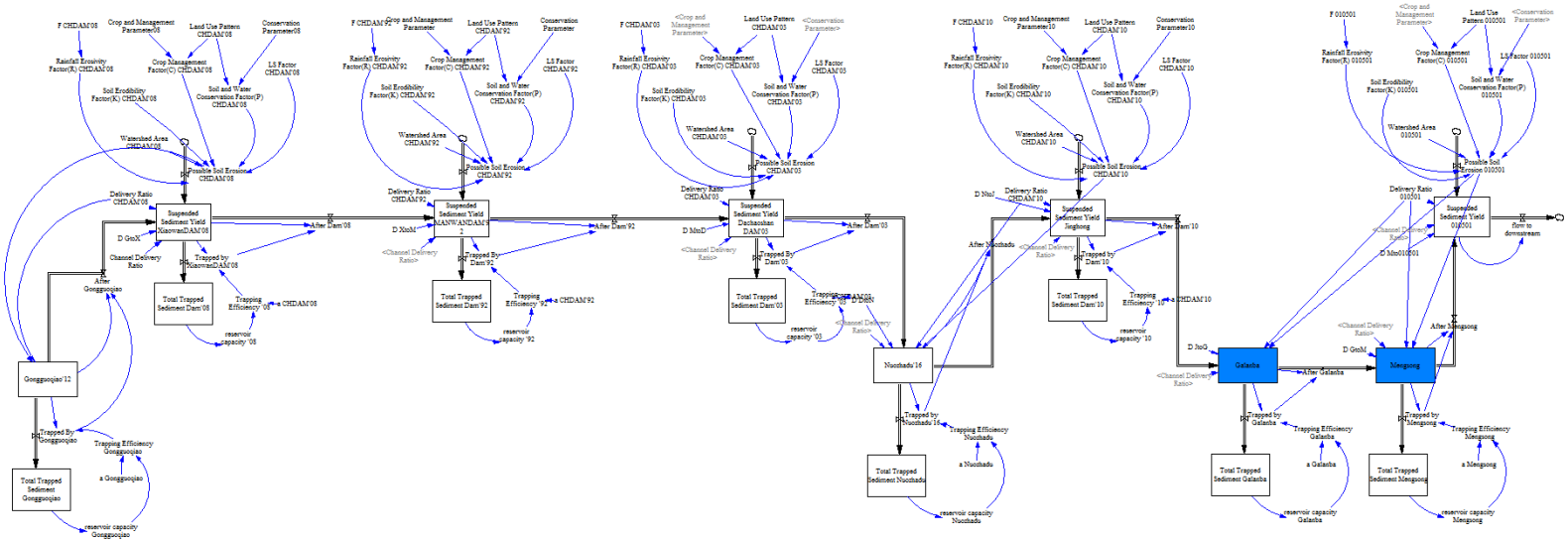

Figure 22 System Dynamics Model Flowchart with six dams of the Upper Mekong Basin

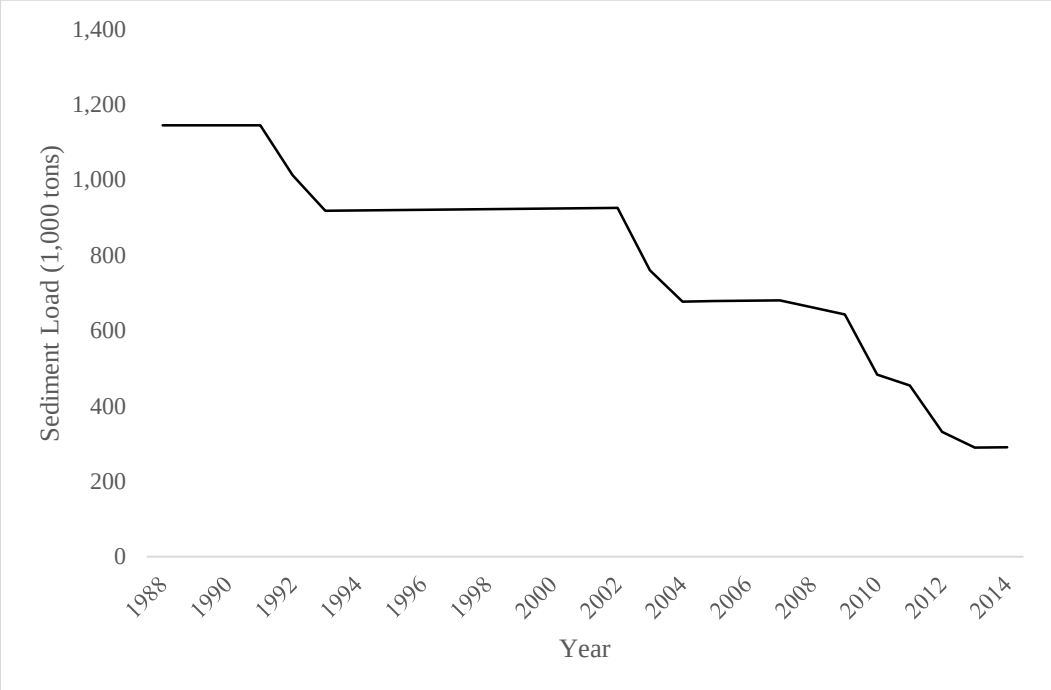

Figure 23 Estimated Sediment Load by Integrated System Dynamics Model from 1988 to 2014 with Six Dams at Chiang Saen station

Estimated sediment load by integrated system dynamics model from 1988 to 2014 with six mainstream dams in the Upper Mekong Basin is shown as figure 23. Six dams are assumed to be constructed in commission years, which are 1992, 2003, 2008, 2009, 2010, and 2012. After Nuozhadu dam was constructed, sediment load decreased 75% compared to 1998. Decrease trend of sediment load of Chiang Saen station doesn't shows linear pattern, because dynamic feature of trapping of dam reservoir is reflected in the model. Therefore, trend of sediment load shows slightly increasing pattern after each dam construction. For example, between Manwan dam construction and Dachaoshan dam construction, sediment load show slight increasing pattern because trapping efficiency of Manwan dam decrease as time goes from 917,916 ton/year to 925,876 ton/year.

This reflects dynamic feature of trapping sediments by dam reservoir, which was not underlined in previous studies.

Lu and Siew (2006) and Kummu and Varis (2007) concluded that sediment load after dam construction decreased about 50%. These studies compared mean between the times before and after dam construction using empirical data. Kummu and Varis (2007) also calculated theoretical trapping efficiency in the Upper Mekong Basin. This study asserted that if all cascade dams in the Upper Mekong Basin are built, 94% of the suspended sediment load coming from China will be trapped by the reservoirs. Kummu et al. (2010) also computed theoretical trapping efficiency of dams of the Upper Mekong Basin same as Kummu and Varis (2007).

In this study, decrease rate of Manwan dam and Dachaosan dam construction is 10% of sediment load before dam construction which is lesser than Lu and Siew (2006) and Kummu and Varis (2007), and that of six dam is 75% of sediment load before dam construction which is lesser than (Kummu & Varis, 2007). The difference of the results between this study and previous studies can be because this study considered the dynamic feature of trapping process of reservoir and the influences of upper reservoirs on lower reservoirs. Kummu and Varis (2007) also mentioned that it should be noted that trapping of downstream reservoirs is affected by trapping of upstream reservoirs.

In contrast, Fu et al. (2006) and Fu et al. (2008) claimed that Chinese cascade dam construction has minor impacts on the sediment load change at Chiang Saen station. However, sediment load at Chiang Saen station diminished after dam constructions from this study, which is contrary to the result of Fu et al.

(2006) and Fu et al. (2008). This results suggest that dam construction in the Upper Mekong Basin can reduce sediment load of the Lower Mekong Basin. In this sense, the sampling methods of suspended sediment concentration between China and the Mekong River Commission can be different, or the reliability of the data of either China or the Mekong River Commission might be low.

This model can show the trend of the sediment load change due to dam constructions. Also, it can reflect dynamic feature of trapping sediments due to dam reservoirs, and the influence of upstream reservoirs on downstream reservoirs. However, this model should be applied carefully because it intentionally neglected the effect of precipitation on sediment erosion in order to understand the effects of dam constructions solely. Therefore, this model can only be utilized for the purpose of understanding pure dam effects on the Mekong Basin with other factors controlled. In the next chapter, future effects of dams are estimated with four scenarios using the model built in this chapter.

5. Model Application to Assessment of the Socioeconomic Impacts of Dams in the Mekong River Basin

In this chapter, the model built in chapter 4 is applied to estimate future impacts of cascade dams on the Mekong River mainstream. In 5.1, the model is built for the whole Mekong Basin, and effects of dam construction on agro-economic sector are analyzed with four future scenarios. In 5.2, total trapping sediment amount, changes in the Chiang Saen station which is the nearest station to the Upper Mekong Basin and the Pakse station which is the nearest station to the Mekong Delta, changes of delta area and corresponding agro-economic changes are investigated as a result. In 5.3, the socioeconomic impacts and the applicability of the model are discussed.

5.1 Integrated System Dynamics Model for Future Estimation

19 dams already either exist or are planned for construction on the Mekong River mainstream. There are also many tributary dams on the Upper Mekong Basin and the Lower Mekong Basin, but these tributary dams are excluded in this study in order to investigate the effects of mainstream dams primarily. In the Lower Mekong Basin, 11 dams are planned or already under construction. Information of the Mekong mainstream dams including expected installed capacity, project status, commission year, drainage area of reservoirs, discharge of each reservoir, and active storage volume of reservoirs are shown in Table 12. The information of drainage area, and discharge and active storage volumes are used to calculate and calibrate trapping efficiency in this study.

Table 12 Information of Mekong mainstream dams in the Lower Mekong Basin (Kuenzer et al., 2013; Kummu et al., 2010)

		General Information					
		Expected installed capacity (MW)	Project Status	Commission year	$A_k(km^2)$	$Q_k(km^3yr^{-1})$	$V_k(km^3)$
Lower Mekong Basin (LMB) Reservoirs							
A	Pakbeng	1,230	P	2016	218,000	100	0.442
B	Luang Prabang	1,410	P	2016	230,000	120.2	0.734
C	Xayabuly	1,285	O	2019	272,000	125.8	0.225
D	Paklay	1,320	P	2016	283,000	127.1	0.384
E	Sanakham	1,200	P	2018	292,000	131.2	0.106
F	Sangthong-Pakchom	1,079	P	2017	295,500	138.3	0.012
G	Ban Kum	1,872	P	2017	418,400	288.5	0.000
H	Latsua	686	P	2018	550,000	302.7	0.000
I	Don Sahong	360	P	2013	553,000	325.1	0.115
J	Stung Treng	980	P	-	635,000	432.5	0.070
K	Sambor	3,300	P	2020	646,000	439.9	2.000
	Basin Mouth				815,000	505	

C: Complete, O: Ongoing, P: Planned

The integrated system dynamics model is built for modelling future dam effect based on the calibration of chapter 4. Actual sediment load data is only available for the Lower Mekong Basin, and the model is divided for convenience of the modelling to set the scenario and run the model. The flowcharts of the model are illustrated in figure 22 and figure 24. The model flowchart of the Upper Mekong Basin is shown in figure 22, and the flowchart of the Lower Mekong Basin is shown in figure 22. Two models are linked by a variable named “flow to downstream”.

In 5.1.1, scenarios for analysis are built by different plans for dam constructions. Four scenarios were built in total, and detailed information is explained in the chapter. In 5.1.2, method to calculate and compare costs of dam constructions of each scenario is introduced.

5.1.1 Building Scenarios

Among 19 dams which already exist or are planned on the Mekong mainstream, three dams are excluded in this analysis because the commission dates of the three dams are not publicized yet. Therefore, except Galanba, Mengsong and Stung Treng, 16 dams are included in the following scenarios, consisting of six dams of the Upper Mekong Basin and 10 dams of the Lower Mekong Basin.

Table 13 Four Scenarios for System Dynamics Model

	Existing 4 Chinese Dam
No mainstream dams in LMB	A (Baseline)
6 mainstream dams on upper LMB	B
No Cambodian mainstream dams in LMB	C
All Mainstream dams in LMB	D

Scenarios are set up based on Basin Development Scenarios of MRC (MRC, 2011) (Table 13). Basin Development Scenario is about dam construction on the Mekong River, and impacts on environmental system are analyzed by future scenarios which are set up by MRC.

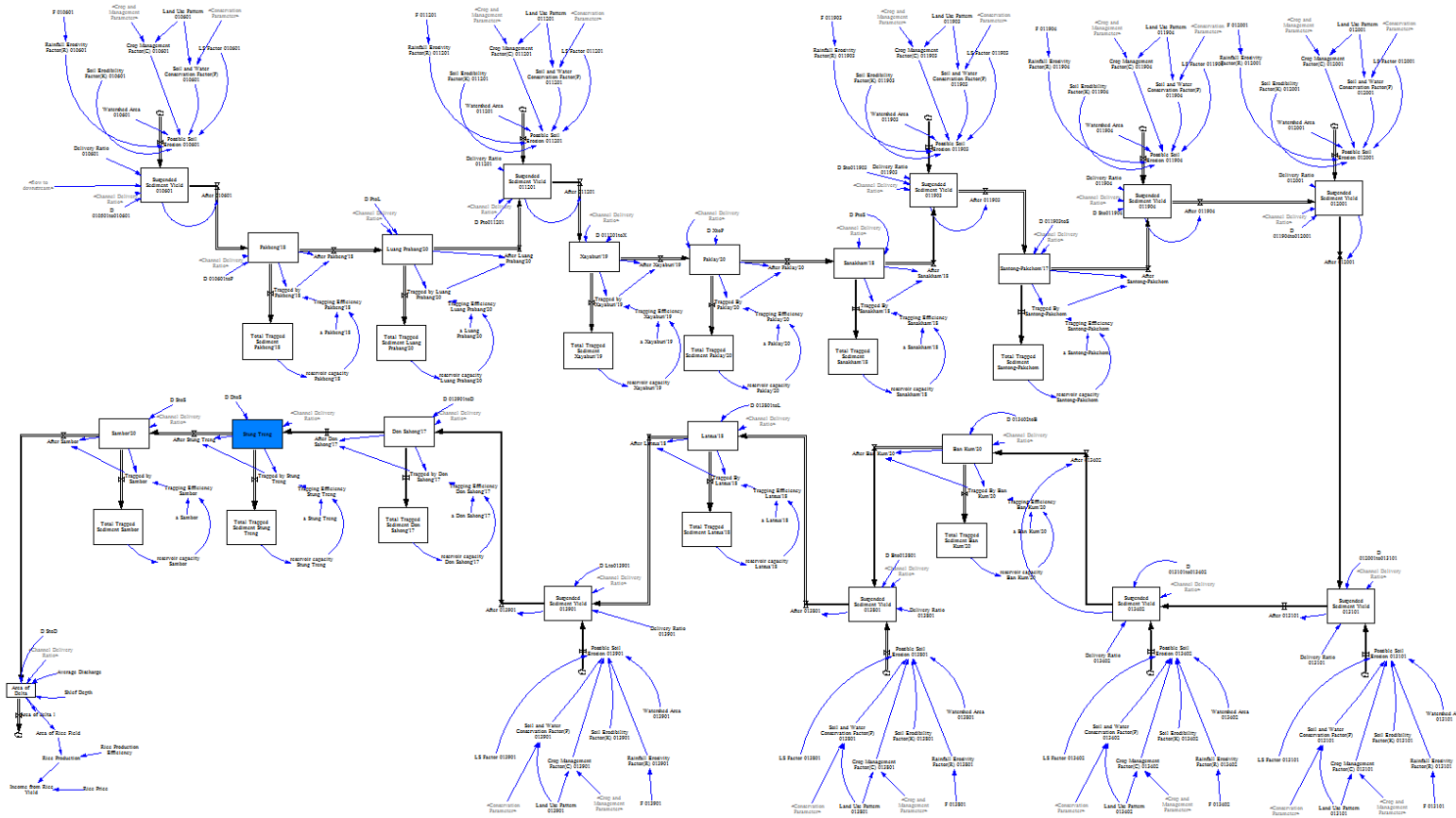

Figure 24 System Dynamics Model Flowchart with 11 dams of the Lower Mekong Basin

Table 14 The Number of Dams according to Scenarios

Scenarios	The Number of Dams	Dams in UMB	Dams in LMB
A (Baseline)	6	Xiaowan, Manwan, Dachaoshan, Jinghong, Gongguoqiao,Nuozhadu	-
B	12	Xiaowan, Manwan, Dachaoshan, Jinghong, Gongguoqiao,Nuozhadu	Pakbeng, Luang Prabang, Xayabuly, Paklay, Sanakham, Sangthong-Pakchom
C	15	Xiaowan, Manwan, Dachaoshan, Jinghong, Gongguoqiao,Nuozhadu	Pakbeng, Luang Prabang, Xayabuly, Paklay, Sanakham, Sangthong-Pakchom, Ban Kum, Latsua, Don sahong
D	16	Xiaowan, Manwan, Dachaoshan, Jinghong, Gongguoqiao,Nuozhadu	Pakbeng, Luang Prabang, Xayabuly, Paklay, Sanakham, Sangthong-Pakchom, Ban Kum, Latsua, Don Sahong, Sambor

Base line scenario A (status quo) is on existing six dams in the Upper Mekong Basin (Xiaowan, Manwan, Dachaoshan, Jinghong, Gongguoqiao, and Nuozhadu) and no other additional dam. Scenario B is six Chinese dams and six additional mainstream dams on upper Lower Mekong Basin added to scenario A. Scenario C is nine mainstream dams in the Lower Mekong Basin added to scenario A. Scenario D is 11 mainstream dams in the Lower Mekong Basin added to scenario A. Detailed information of scenarios is shown in table 14.

5.1.2 Scenario-based Cost Estimation of Dam Constructions

Costs of dam constructions can expressed as an opportunity cost, which is potential income if dams are not constructed as they are planned. In this study, costs are calculated by subtracting the income of scenarios from the income of baseline scenario. The income is from rice production, which is calculated as explained in Chapter 4.

To compare the costs in the present point among scenarios, net present value (NPV) should be calculated. Net present value can be calculated by discounting future value with discount rate. The social discount rate for discounting is referred from Boardman, Greenberg, Vining, and Weimer (2006)'s time-declining discount rates. This time-declining rate schedule is 3.5 percent from year 0 to year 50, 2.5 percent from year 50 to year 100, and 1.5 percent from year 100 to year 200.

5.2 Results of Future Estimation

In this chapter, the results of the model including total trapping sediment amount, changes in the Chiang Saen station which is the nearest station to the Upper Mekong Basin and the Pakse station which is the nearest station to the Mekong Delta, changes of delta area and corresponding agro-economic changes are examined. In 5.2.1, total trapping sediment amount of each scenario is analyzed. In 5.2.2, the results of 10 stations of scenario D are compared. In 5.2.3, changes of delta area and corresponding agro-economic changes are investigated.

5.2.1 Total trapping sediment amount

Total trapping sediment amount changes shown across four scenarios are described in figure 25. More sediments are deposited as additional dams are built. For example of 2100, in the case of scenario A, total trapping sediment amount is 1,130 million tons. In the case of scenario B, total trapping sediment amount in 2100 is 1,270 million tons. In the case of scenario C, total trapping sediment amount in 2100 is 1,280 million tons. In the case of scenario D, total trapping sediment amount in 2100 is 1,410 million tons. Additional six dams in the Lower Mekong Basin trap 140 million tons of sediments more in scenario B. Also, three more dams in scenario C trap 10 million tons of sediments more. At last, Sambor dam in scenario D traps 130 million tons of sediments more.

Figure 26 shows the ratios of 'status quo' scenarios to other additional dam scenarios. It shows the significance impacts of existing Chinese dams against planned dams of the Lower Mekong Basin according to each scenario. In the case of scenario B and C, ratios settle near 0.9. It means that cumulative sediment amount of existing six dams are ten times larger than other LMB mainstream dams in the scenario. In the case of scenario D, the ratio settles near 0.8. This is because of the Sambor dam, whose reservoir is so big that it can have an effect on the sediment system.

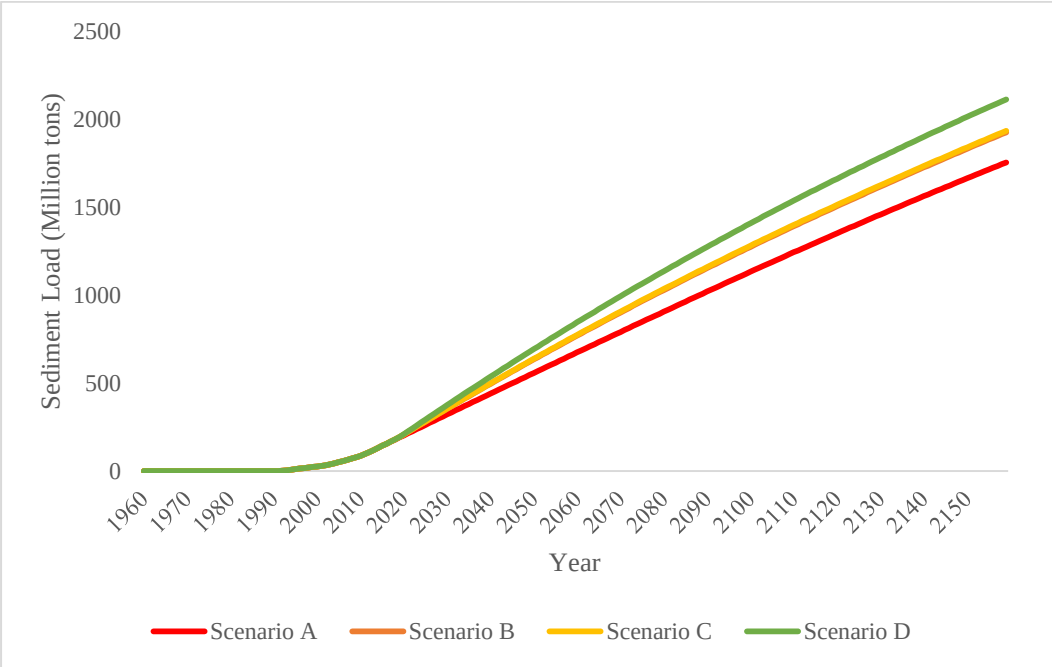

Figure 25 Cumulative Trapped Sediment of 4 scenarios

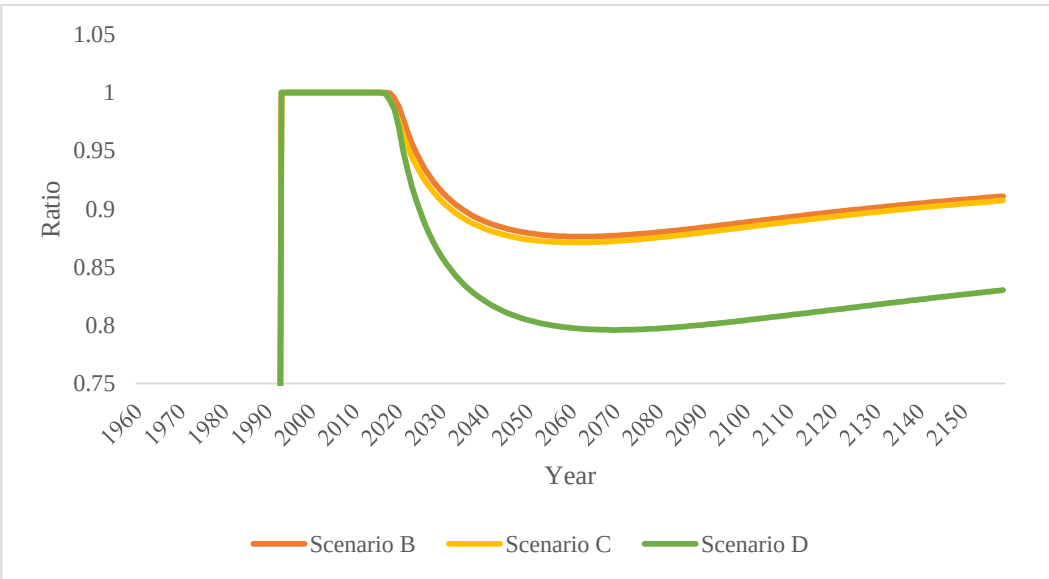

Figure 26 Ratio of Status Quo Scenario to Scenarios

5.2.2 Comparison among stations

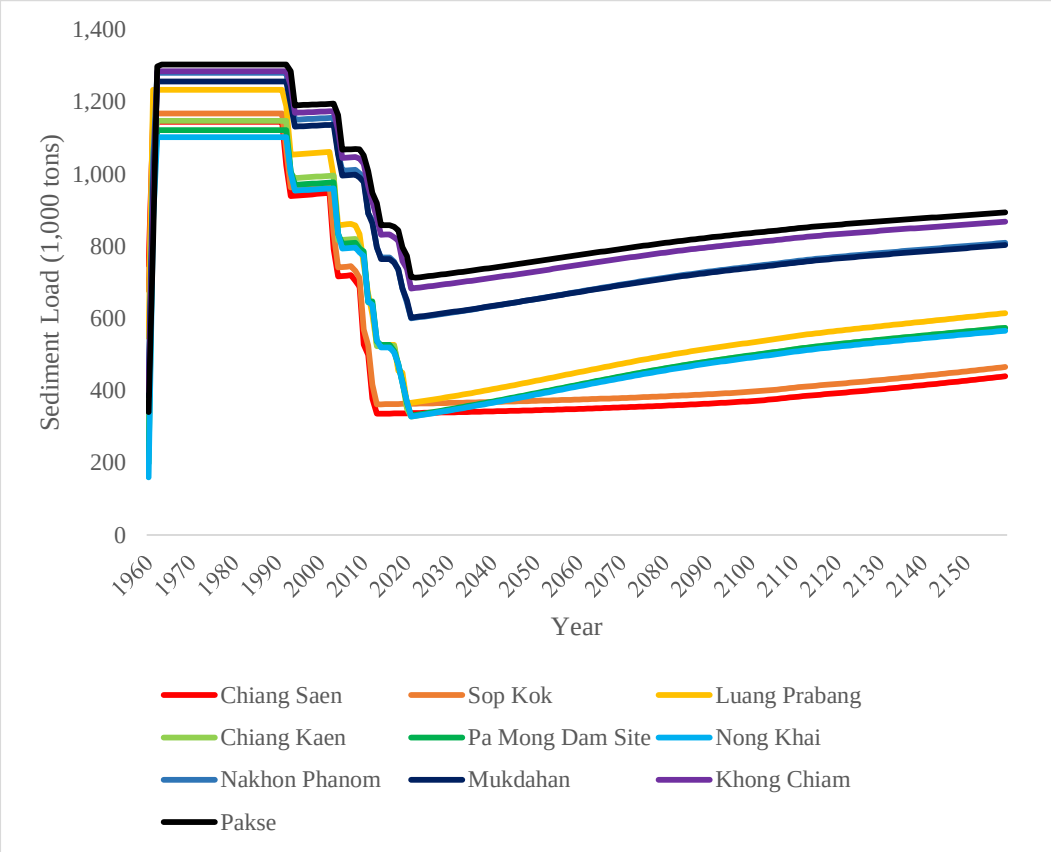

Figure 27 Change of the Sediment Load at Each Station in Scenario D

Figure 27 demonstrates change of the sediment load of at each station in scenario D. At Chiang Saen station and Sop Kok station, we can identify the effects of Chinese dams on the sediment load. Between Sop Kok and Luang Prabang station, Pakbang dam and Luang Prabang dam are planned to be constructed in 2018 and 2020, having an effect on sediment load of Luang Prabang station. Between Luang Prabang and Chiang Kaen station, three dams are planned to be built, which are Xayaburi, Paklay, and Sanakham. Between

Chiang Kaen station and Pa Mong Dam site station, Santong-Pakchom dam is planned to be built in 2017. Among Pa Mong Dam site station, Nong Khai station, Nakhon Phanom station and Mukdahan station, no dam is planned to be built on the Mekong mainstream, so the slopes of each graph seem similar. Between Mukdahan station and Khong Chiam station, Ban kum dam is planned to be built in 2020. Between Khong Chiam station and Pakse station, Latsua dam is planned to be built in 2018. After Pakse station, Don Sahong, Stung Treng, and Sambor dams are planned to be built.

The graphs are not ordered by the order of the station, because it is assumed that sediments are trapped in the channel with channel trapping ratio of 0.05% by 1 km. Therefore, downstream station can have lower sediment load than upstream station in this model.

5.2.3 Agro-economic impact on rice production

In this study, changes in delta area due to sediment flux change and corresponding income change from rice production are modelled as a representative variable reflecting socioeconomic impacts of dam construction. Figure 28 shows comparison of delta area changes between different scenarios. Area of delta of each scenario drops from 2018 to 2020, and shows recovering trend.

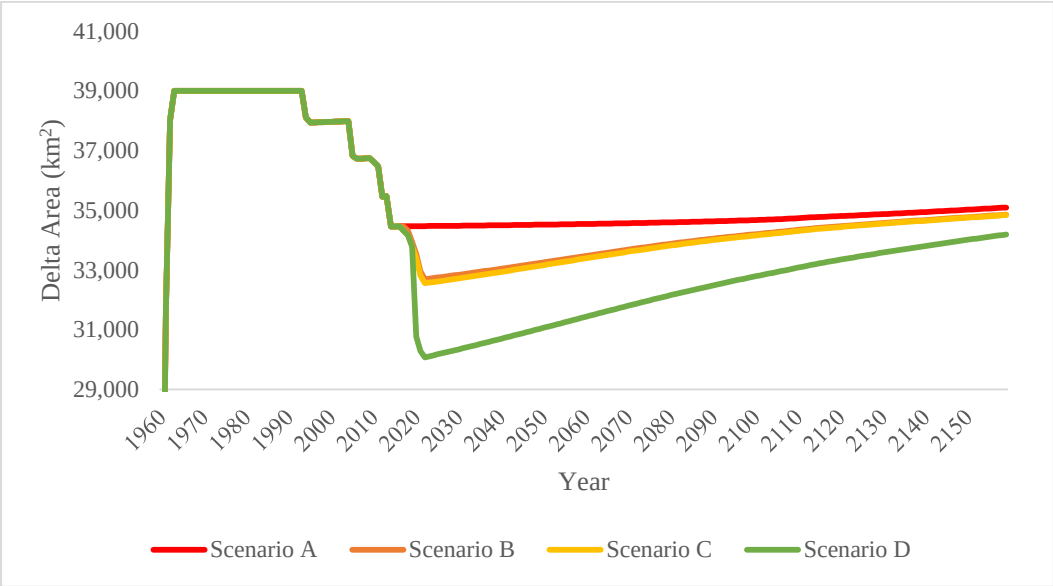

Figure 28 Comparison of Delta Area Change between Scenarios

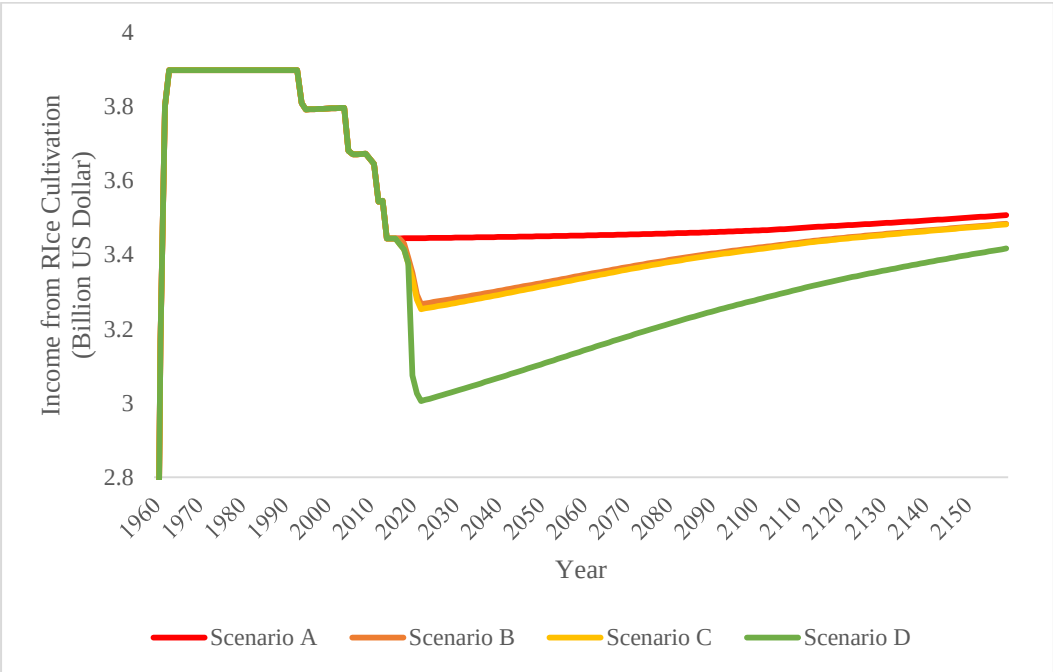

Figure 29 Comparison of Income from Rice Production between Scenarios

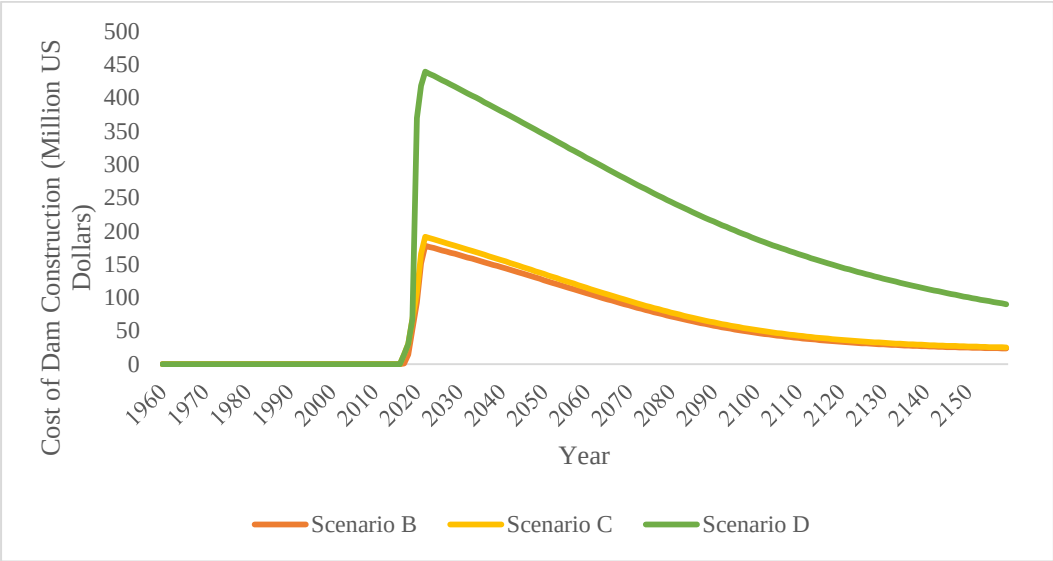

Figure 30 Cost of Cascade Dam Construction

Figure 29 and figure 30 show comparison of agro-economic impacts on rice production of the Vietnam delta. Impact on rice production shows a similar trend to the reflecting impact on the delta area. Rice productions drop in every scenario, but the degree of reduction and recovery is different according to scenarios. Scenario D, which is with additional Sambor dam compared to scenario C, shows the largest decrease among four scenarios. It is because huge reservoir and the distance between Mekong delta and Sambor dam is the closest among dams.

In order to compare each scenario to the status-quo scenario A, the difference in income is computed for each scenario as the opportunity cost of dam construction. The cost of dam construction sharply increases right after the construction, but decreases in a different speed according to each scenario. The costs of scenario B and E rises up to 200 million dollars, meanwhile the cost of scenario D skyrockets up to 450 million dollars.

The NPV of the cost of each scenario is shown in Table 15. Scenario D shows the highest cost among the scenarios with 4,726 million dollars, and scenario B shows the lowest cost among the scenarios with 1,574 million dollars. The results show that Sambor dam costs about 3 billion dollars if it is built.

Since only mainstream dams are considered in this study, actual costs will be higher if tributary dams are considered.

Table 15 Net Present Value of Cost of Each Scenario (Million dollars)

Scenario	NPV of Cost
A	-
B	1,574
C	1,707
D	4,726

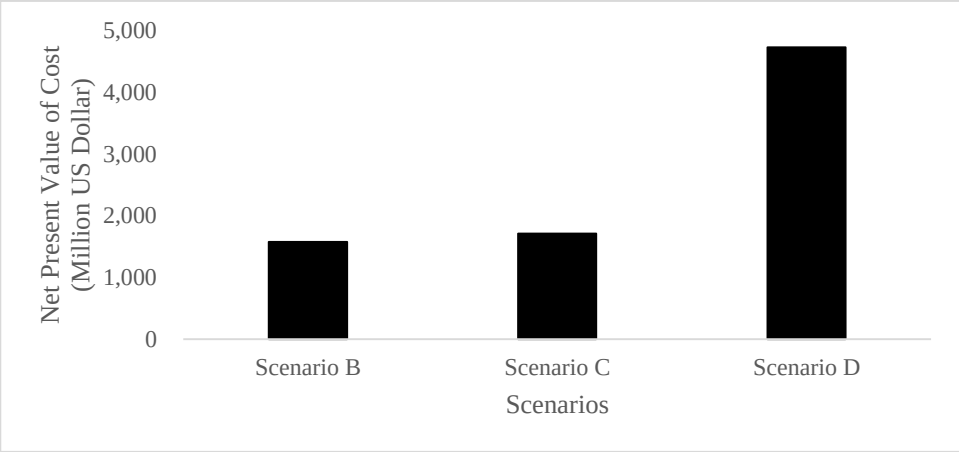

Figure 31 Net Present Value of Cost of Each Scenario

5.3 Discussions

Possible future impacts of mainstream dams on the Mekong River are estimated using Integrated System Dynamics in the previous chapter. With other variables being constant, this model can examine pure effects of mainstream dams. The extent of the effects of Chinese dam, difference between the effects of Chinese dam and of dams in the Lower Mekong Basin on the Mekong Delta, and costs of dam construction are discussed in this chapter.

The results shows that dams can reduce downstream sediment flux significantly. In particular, Chinese dams have an impact on Mekong delta, which is contrasting result to previous studies. Fu et al. (2006) and Fu et al. (2008) suggested that the effects of Chinese dam on sediment flux are limited in the Chinese boundary by comparing sediment flux of Chinese stations and Chiang Saen station statistically. Lu and Siew (2006) suggested that suspended sediment concentration has decreased significantly in Chiang Saen, Luang Prabang and Can Tho and sediment load has changed significantly only in Chiang Saen by statistical analysis. The results of the model suggest that the effects of Chinese dams can reach the Mekong estuary. This results can be because only pure dam effects are considered in this study. Other factors such as anthropogenic impacts or climatic impacts can have an impact on soil erosion, making the portion of the actual dam impacts on suspended sediment data lessen. Lu and Siew (2006) also suggested that the insignificance of change of suspended sediment load after Chiang Saen station might be because the areas surrounding Vientiane and Luang Prabang station are possibly contributing substantial amounts of sediments into the Mekong River.

In this study, the effects of Chinese dams are relatively larger than dams of the Lower Mekong Basin because of their larger reservoirs. Kummu et al. (2010) also calculated trapping efficiency for the planned reservoirs on the Mekong mainstream. This study also showed different trapping efficiency between dams of the Upper Mekong Basin and of the Lower Mekong Basin. Mean of trapping efficiency of reservoirs in the Upper Mekong Basin is 0.435, while mean of trapping efficiency of reservoirs in the Lower Mekong Basin is 0.085. The effects of dams on the Lower Mekong Basin are relatively smaller, because most of the dams' structures in the Lower Mekong Basin are run-of-river type, which stores a little sediment. In the case of trapping suspended sediment concentration by the run-of-river dam, trapping efficiency is known as near 0 (Csiki & Rhoads, 2014).

In spite of large reservoirs of Chinese dams, the effects of them on the Mekong Delta are diminished by the distance. The effects are measured by the change of the Delta area. Delta area may be reduced because of reduced sediment supply from the Mekong Basin, which can in turn affect the pattern of land use. Six dam construction in the Upper Mekong Basin makes delta area reduced about 4,000km^2. In contrast, Sambor dam which is located nearest to the Mekong Delta makes delta area reduced about 5,000km^2 solely (scenario D). Even the effects of dam reservoirs are reduced by the distance, Chinese dams still have an impact on the Mekong Delta.

Regarding socioeconomic impacts, negative impact of dam constructions on agro-economic aspects is mainly covered in this study. After every Chinese dams are constructed, the income from rice cultivation of the Mekong Delta drops 460 million dollars, from 3,900 million dollars to 3,440 million dollars. The cost of dam construction can be increased up to 450 million dollars per year if all

planned dams in the Lower Mekong Basin are constructed. The net present value of the cost of dam construction is 4.726 billion dollars in case of scenario D. Today's rice exports of Vietnam is 4 billion dollars, which accounts for more than a fifth of the global total. The costs of dam construction in this study accounts for 10% of the rice exports of Vietnam, and the net present value of total cost is almost same as the rice export of Vietnam. Vietnam has strong linkages between agricultural sector and their processing counterpart sectors, the effects of reduction of rice yield can have a substantial damage on Vietnam economy (Rutten, van Dijk, van Rooij, & Hilderink, 2014). The costs show decreasing trends in all scenarios, because dam reservoirs lose its trapping capacity as time goes by.

In this study, the agricultural land use type is selected as a representative land use type in delta area. Also, distribution of land use and cover type are assumed equal. Based on this assumptions, the income of each scenario and corresponding cost are calculated. Additional study related with land cover type and distribution of the Mekong Delta area, and related impacts of sediment supply change can make the analysis of the impacts of dam construction more elaborate.

This model can capture pure effects of dam constructions as a kind of laboratory experiment. It is in the purpose for the model to examine only dam effect without any disturbance. In this sense, dam effects on sediment flux in this study might seem exaggerated. However, only suspended sediments are considered to affect the area of delta in this study, so the effects of dam construction can be underestimated in this study. Moreover, only the sediment yield from the Mekong Basin and entering the channel are considered in order to

model the large scale of basin. Re-suspension and channel erosion are not included, which also can make the effects of dam construction underestimated. Also, the effects of dam constructions on Cambodian floodplain are not included in this study, where is also important rice field in the Mekong Basin. Further studies related with daily precipitation data and changes of land cover data, the effects of the bed load, and the impacts of sediment flux change on the Cambodian floodplain can help to understand the situation of sediment transportation in the Mekong Basin with dam construction.

6. Conclusion

Many hydropower projects are ongoing in the Mekong river basin, and scientific research is needed for suitable policy making. There have been two ways in scientific research on sediment flux change due to dam construction on the Mekong River: studies using statistical methodologies based on statistical data and studies using theoretical equation based on the information of each dams. However, those studies have limitations, and the integrated system dynamics used in this study can overcome those limitations. The purpose of this study has attempted to estimate the possible impacts of cascade dam constructions on sediment flux and to assess the corresponding socio-economic impacts on the Mekong River. For this purpose, statistical analysis and integrated system dynamics are employed as methodologies.

In order to understand dam effects on the Mekong River in the past and create variables for model validation, t-test, ANOVA test, and multiple regression analysis are used. Suspended sediment concentration data is grouped by the season variable which represents dry season and wet season, the Chinese cascade dam variable which represents dam construction of China, and station variable. The significance of those grouping variables are tested by t-test and ANOVA test. The results of t-test and ANOVA test are all significant, which means that all variables are effective enough to be put into the multi regression model. From the results of the model, it is shown that Chinese dam construction has a significant effect on suspended sediment concentration in the Lower Mekong Basin with other variables controlled. With the equation from the analysis, suspended sediment concentration for each station is estimated.

In chapter 4, possible impacts of dams on the Mekong mainstream are modelled using system dynamics approach. Potential erosion is modelled by The Universal Soil Loss Equation. The amount of trapped sediments by dam reservoirs is modelled using Brune (1953)'s equation. To calibrate and validate the model, sediment system with two dam model is built and calibrated with data produced in chapter 3. The model shows same trend with actual sediment load data. The impacts of Chinese cascade dams on sediment flux are modelled with the validated model. Sediment load shows decreasing trend after Chinese dam construction, but the rate of decrease is 10%, which is smaller than that of previous studies. It can be because this study reflects dynamic feature of trapping capacity of dam reservoirs.

Using the model, the impacts of dam constructions on sediment flux and corresponding socio-economic impacts are modelled and discussed in chapter 5. Four scenarios with different number of dams in the Lower Mekong Basin are built and compared. According to the results of the model, additional six dams in the Lower Mekong Basin trap 140 million tons of sediments more in scenario B. Also, three more dams in scenario C trap 10 million tons of sediments more. At last, Sambor dam in scenario D traps 130 million tons of sediments more. The effects of dam constructions in the Upper Mekong Basin seem larger than the effects of dams in the Lower Mekong Basin, but the effects of Chinese dams mitigated by the distance. The net present value of costs of cascade dam construction is estimated from 1.57 to 4.72 billion US dollars. These results only considered mainstream dams on the Mekong River. Therefore, the costs will be higher if the costs of tributary dams are additionally considered.

Dam construction is the transnational issue in the Mekong River Basin, which needs cooperation of member countries and appropriate policy based on scientific information. When building policy, scientific knowledge and corresponding socioeconomic impact should be considered together when building policy, and this study is an attempt to account for not only environmental impact but also agro-economic impact related to dam constructions. Integrated system dynamics can act as an effective tool to integrate various knowledge so that make stakeholders understand and take into account transnational impact of dam construction.

This study cannot fully consider trends and changes of sediment flux due to precipitation. Also, land cover change is not considered in the integrated system dynamics model, remained as static. These treatment is suitable for the purpose of this study which examine the pure dam effects on the Mekong river mainstream and for the study region such as the Mekong Basin where data accessibility and quality is low. However, inclusion of precipitation dynamics and land cover dynamics can reflect the reality more. Therefore, it is helpful to understand sediment flux change in the Mekong Region to study variables which can have an effect on sediment flux and incorporate these variables in the model. Further study of the effects of the bed load, and the impacts of sediment flux change on the Cambodian floodplain also can help to understand the situation of sediment transportation in the Mekong Basin with dam construction.

References

Ahmad, S., & Simonovic, S. P. (2004). Spatial system dynamics: new approach for simulation of water resources systems. *Journal of Computing in Civil Engineering, 18*(4), 331-340.

Arnoldus, H. (1977). Methodology used to determine the maximum potential average annual soil loss due to sheet and rill erosion in Morocco. *FAO Soils Bulletins (FAO).*

Biggs, D., Miller, F., Hoanh, C. T., & Molle, F. (2009). The delta machine: water management in the Vietnamese Mekong Delta in historical and contemporary perspectives. *Contested waterscapes in the Mekong region: Hydropower, livelihoods and governance*, 203-225.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2006). Cost-Benefit Analysis: Concepts and Practice.

Borshchev, A., & Filippov, A. (2004). *From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools.* Paper presented at the Proceedings of the 22nd international conference of the system dynamics society.

Brune, G. M. (1953). Trap efficiency of reservoirs. *Trans. AGU, 34*(3), 407-418.

Chang, Y., Hong, F., & Lee, M. (2008). A system dynamic based DSS for sustainable coral reef management in Kenting coastal zone, Taiwan. *Ecological Modelling, 211*(1), 153-168.

Chen, C., Son, N., Chang, L., & Chen, C. (2011). Classification of rice cropping systems by empirical mode decomposition and linear mixture model for time-series MODIS 250 m NDVI data in the Mekong Delta, Vietnam. *International Journal of Remote Sensing, 32*(18), 5115-5134.

Csiki, S. J. C., & Rhoads, B. L. (2014). Influence of four run-of-river dams on channel morphology and sediment characteristics in Illinois, USA.

Geomorphology, 206, 215-229. doi: 10.1016/j.geomorph.2013.10.009

Fernández, J. M., & Selma, M. A. E. (2004). The dynamics of water scarcity on irrigated landscapes: Mazarrón and Aguilas in south-eastern Spain. *System Dynamics Review, 20*(2), 117-137.

Ferro, V., & Minacapilli, M. (1995). Sediment delivery processes at basin scale. *Hydrological Sciences Journal, 40*(6), 703-717.

Forrester, J. (1958). Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review, 36*(4), 37-65.

Forrester, J. (1961). W.(1961). Industrial Dynamics: Cambridge: MIT Press.

Forrester, J. (1964). *Modeling the dynamic processes of corporate growth*. Paper presented at the Proceedings of the IBM Scientific Symposium on Simulation Models and Gaming.

Forrester, J. (1968). *Market growth as influenced by capital investment*: Industrial Management Review.

Fu, K., & He, D. (2007). Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River. *Chinese Science Bulletin, 52*(2), 134-140.

Fu, K., He, D., & Li, S. (2006). Response of downstream sediment to water resource development in mainstream of the Lancang River. *Chinese Science Bulletin, 51*(22), 119-126.

Fu, K., He, D., & Lu, X. (2008). Sedimentation in the Manwan reservoir in the Upper Mekong and its downstream impacts. *Quaternary International, 186*(1), 91-99.

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research, 35*(4), 1305-1311.

Gray, J. R., & Simões, F. J. (2008). Estimating sediment discharge. *Sedimentation Engineering–Processes, Measurements, Modeling, and*

Practice, Manual, 110, 1067-1088.

Gupta, A., Hock, L., Xiaojing, H., & Ping, C. (2002). Evaluation of part of the Mekong River using satellite imagery. *Geomorphology, 44*(3), 221-239.

Gupta, A., & Liew, S. C. (2007). The Mekong from satellite imagery: a quick look at a large river. *Geomorphology, 85*(3), 259-274.

Hanxiong, Z., & Mingjan, S. (1999). A simulation of the dynamics of soil erosion in the loess hills of Shaanxi and Shanxi provinces. *Acta Geographica Sinica, 54*(1), 42150.

Hassanzadeh, E., Zarghami, M., & Hassanzadeh, Y. (2012). Determining the main factors in declining the Urmia Lake level by using system dynamics modeling. *Water Resources Management, 26*(1), 129-145.

He, D., Feng, Y., Gan, S., Magee, D., & You, W. (2006). Transboundary hydrological effects of hydropower dam construction on the Lancang River. *Chinese Science Bulletin, 51*(22), 16-24.

Hirsch, P. (2010). The Changing Political Dynamics of Dam Building on the Mekong. *Water Alternatives, 3*(2).

Ibàñez, C., Prat, N., & Canicio, A. (1996). Changes in the hydrology and sediment transport produced by large dams on the lower Ebro river and its estuary. *Regulated Rivers: Research & Management, 12*(1), 51-62.

ICEM. (2010). Strategic Environmental Assessment of Hydropower on the Mekong Mainstream: Summary of the Final Report.

Jakeman, A. J., Barreteau, O., Borsuk, M. E., Elsawah, S., Hamilton, S. H., Henriksen, H. J., . . . Van Delden, H. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software, 47*, 159-181.

Kubiszewski, I., Costanza, R., Paquet, P., & Halimi, S. (2013). Hydropower development in the lower Mekong basin: alternative approaches to deal with

uncertainty. *Regional Environmental Change, 13*(1), 3-15.

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V. Q., & Dech, S. (2013). Understanding the impact of hydropower developments in the context of upstream-downstream relations in the Mekong river basin. *Sustainability Science, 8*(4), 565-584. doi: 10.1007/s11625-012-0195-z

Kummu, M., Lu, X., Wang, J., & Varis, O. (2010). Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. *Geomorphology, 119*(3), 181-197.

Kummu, M., & Varis, O. (2007). Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology, 85*(3), 275-293.

Kuper, M., Mullon, C., Poncet, Y., & Benga, E. (2003). Integrated modelling of the ecosystem of the Niger river inland delta in Mali. *Ecological Modelling, 164*(1), 83-102.

Lee, S. (2013). Hydropower Development in the Mekong River Basin -Analysis through the Hydro-Hegemonic Approach. *동남아연구, 23*(1), 223-259.

Li, J. P., Dong, S. K., Peng, M. C., Yang, Z. F., Liu, S. L., Li, X. Y., & Zhao, C. (2013). Effects of damming on the biological integrity of fish assemblages in the middle Lancang-Mekong River basin. *Ecological Indicators, 34*, 94-102. doi: 10.1016/j.ecolind.2013.04.016

Li, J. P., Dong, S. K., Yang, Z. F., Peng, M. C., Liu, S. L., & Li, X. Y. (2012). Effects of cascade hydropower dams on the structure and distribution of riparian and upland vegetation along the middle-lower Lancang-Mekong River. *Forest Ecology and Management, 284*, 251-259. doi: 10.1016/j.foreco.2012.07.050

Lu, X., & Higgitt, D. L. (1999). Sediment yield variability in the Upper Yangtze, China. *Earth Surface Processes and Landforms, 24*(12), 1077-1093.

Lu, X., & Siew, R. (2006). Water discharge and sediment flux changes over the past decades in the lower Mekong River: possible impacts of the Chinese dams. *Hydrology & Earth System Sciences, 10*(2).

Lu, X., Wang, J.-J., & Carl, G.-W. (2008). Are the Chinese dams to be blamed for the lower water levels in the Lower Mekong? *Modern Myths of the Mekong*, 39.

Matthews, N. (2012). Water Grabbing in the Mekong Basin-An Analysis of the Winners and Losers of Thailand's Hydropower Development in Lao PDR. *Water Alternatives, 5*(2).

Molle, F., Foran, T., & Kakonen, M. (2009). *Contested waterscapes in the Mekong region: Hydropower, livelihoods and governance*: Earthscan.

MRC. (2011). Assessment of Basin-wide Development Scenarios: Cumulative impact assessment of the riparian countries' water resources development plans, including mainstream dams and diversions.

Nguyen, T. M. H., Kawaguchi, T., & 川口雅正. (2002). Overview of rice production system in the Mekong Delta-Vietnam. *九州大学農学部紀要, 47*(1), 221-231.

Nguyen, T. T. H., De Bie, C., Ali, A., Smaling, E., & Chu, T. H. (2012). Mapping the irrigated rice cropping patterns of the Mekong delta, Vietnam, through hyper-temporal SPOT NDVI image analysis. *International Journal of Remote Sensing, 33*(2), 415-434.

Phillips, J. D., Slattery, M. C., & Musselman, Z. A. (2004). Dam-to-delta sediment inputs and storage in the lower Trinity River, Texas. *Geomorphology, 62*(1), 17-34.

Qin, H.-P., Su, Q., & Khu, S.-T. (2011). An integrated model for water management in a rapidly urbanizing catchment. *Environmental Modelling*

& Software, 26(12), 1502-1514.

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D., & Yoder, D. (1997). Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). *Agriculture Handbook (Washington)*(703).

Richter, B. D., Postel, S., Revenga, C., Scudder, T., Lehner, B., Churchill, A., & Chow, M. (2010). Lost in Development's Shadow: The Downstream Human Consequences of Dams. *Water Alternatives, 3*(2).

Rutten, M., van Dijk, M., van Rooij, W., & Hilderink, H. (2014). Land Use Dynamics, Climate Change, and Food Security in Vietnam: A Global-to-local Modeling Approach. *World Development, 59*, 29-46.

Sahai, S. (2005). *The Mekong River: Space and Social Theory*: BR Publishing Corporation.

Saysel, A. K., Barlas, Y., & Yenigün, O. (2002). Environmental sustainability in an agricultural development project: a system dynamics approach. *Journal of Environmental Management, 64*(3), 247-260.

Stone, R. (2011). Mayhem on the Mekong. *Science, 333*(6044), 814-818.

Suif, Z., Yoshimura, C., Valeriano, O. C. S., & Seingheng, H. (2013). *Spatially Distributed Model for Soil Erosion and Sediment Transport in the Mekong River Basin*. Paper presented at the Seventeenth International Water Technology Conference, IWTC17, Istanbul.

Syvitski, J. P., & Saito, Y. (2007). Morphodynamics of deltas under the influence of humans. *Global and Planetary Change, 57*(3), 261-282.

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., & Syvitski, J. P. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change, 39*(1), 169-190.

Vaidyanathan, G. (2012). Remaking the Mekong. *Nature, 478*, 305-307.

Walling, D. (1977). Assessing the accuracy of suspended sediment rating curves for a small basin. *Water Resources Research, 13*(3), 531-538.

Walling, D. E. (2008). The changing sediment load of the Mekong River. *AMBIO: A Journal of the Human Environment, 37*(3), 150-157.

Wang, J. J., Lu, X. X., & Kummu, M. (2011). Sediment load estimates and variations in the Lower Mekong River. *River research and applications, 27*(1), 33-46. doi: 10.1002/rra.1337

Williams, G. P., & Wolman, M. G. (1984). *Downstream effects of dams on alluvial rivers*: US Government Printing Office Washington, DC.

Williams, J., Renard, K., & Dyke, P. (1983). EPIC: A new method for assessing erosion's effect on soil productivity. *Journal of Soil and water Conservation, 38*(5), 381-383.

Yang, D., Kanae, S., Oki, T., Koike, T., & Musiake, K. (2003). Global potential soil erosion with reference to land use and climate changes. *Hydrological Processes, 17*(14), 2913-2928.

Yeh, S.-C., Wang, C.-A., & Yu, H.-C. (2006). Simulation of soil erosion and nutrient impact using an integrated system dynamics model in a watershed in Taiwan. *Environmental Modelling & Software, 21*(7), 937-948.

Zhou, Q., Yang, S., Zhao, C., Cai, M., & Ya, L. (2014). A Soil Erosion Assessment of the Upper Mekong River in Yunnan Province, China. *Mountain Research and Development, 34*(1), 36-47.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., & Levin, S. A. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences, 109*(15), 5609-5614.

국문 초록

통합 시스템 다이나믹스를 이용한 메콩강 댐 건설의 사회경제적 영향 추정

댐 건설은 식수, 관개, 기후 변화 적응, 전기 생산 등의 방식으로 강을 이용하는 방식 중의 하나이다. 6개의 유역 국가 중 5개의 국가를 댐이 없는 채로 흐르고 있는 유일한 하천인 메콩강도 최근 유역 국가의 급격한 발전과 함께 수력 발전이 진행되고 있다. 이 연구의 목적은 메콩강 본류에 연속적으로 건설되고 있는 댐으로 인한 퇴적물 양의 변화와 이에 따르는 사회경제적 영향을 추정하는 것이다. 이를 위한 방법론으로 통계적 분석과 통합 시스템 다이나믹스가 사용되었다.

과거 메콩강에 건설된 댐의 영향을 이해하고 모형의 타당성 검증을 위한 변수를 생성하기 위해, t-test, ANOVA test, 다중회귀분석이 사용되었다. 계절 변수, 중국 댐 건설 변수, 각 스테이션과 관련된 변수들이 모두 다중회귀분석에 사용되기에 유효한 것으로 검증되었다. 다중회귀분석을 통해, 다른 변수들을 통제하였을 때 중국 댐 건설이 여전히 메콩 하부 유역에 유의한 영향을 미치는 것으로 나타났다. 다중회귀분석으로부터 도출된 관계식을 바탕으로 각 스테이션의 부유 하중 농도 데이터가 추정되었다.

시스템 다이나믹스 접근법을 이용하여 메콩강 본류에 건설된 중국 댐 건설이 미치는 영향을 모델링하였다. 이 모델의 결과는 실제 퇴적물 자료와 같은 경향을 보였다. 퇴적물의 양은 중국 댐 건설 후에 감소하는 경향을 보였다.

퇴적물의 감소율은 10%로 기존 연구보다 낮은 감소율이며, 이는 이 연구에서 댐 저수지가 퇴적물을 가두는 것의 동적인 측면을 고려하였기 때문이다.

미래 댐 건설의 영향을 4개의 시나리오를 통해 모델링하였다. 4개의 시나리오는 메콩 하부 유역에 건설 예정인 댐의 숫자를 다르게 하여 수립되었다. 모델 결과에 따르면, 현상 유지인 시나리오 A에 비해 시나리오 B의 경우 1억 4천만 톤, 시나리오 C의 경우 1억 5천만 톤, 시나리오 D의 경우 2억 7천만 톤의 퇴적물을 더 가두게 되는 것으로 나타났다. 또한 상류 메콩 유역에 건설되는 댐의 영향이 하류 메콩 유역에 건설되는 댐의 영향보다 크게 나타났으며, 상류 메콩 유역에 건설되는 댐의 영향은 거리에 따라 감소되는 것으로 나타났다. 댐 건설의 사회적 비용의 현재 가치는 15억 7천 달러에서 47억 2천 달러로 추정되었다.

이 연구는 댐 건설의 환경적 영향뿐만 아니라 사회경제적 영향을 함께 설명하려는 시도였다는 데 의의가 있다. 통합 시스템 다이나믹스 방법론은 다양한 지식을 통합하는 데 효과적인 도구로 작동할 수 있으며 이를 통해 다양한 이해관계자들의 현상에 대한 이해를 증진시키고 댐 건설의 초국가적 영향을 고려하는 데 사용될 수 있다.

주요어: 메콩강, 퇴적물, 댐, 통합 시스템 다이나믹스, 세디먼트

학 번: 2012-20120