Effects of Land Use Change on Groundwater Recharge

A Case Study in the Day River Basin, Vietnam

Master's Thesis

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05-12-2015

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Universiteit Utrecht

VNWATER Vietnam Netherlands Center for Water and Environment

TU Delft Delft University of Technology

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In fulfilment of the requirements for the Master's degree in Environmental Sciences, programme Water Science and Management, at Utrecht University.

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Summary

The Day River Basin In South East Asia, is characterized by rapid land use change processes reducing groundwater recharge rates and threatening groundwater resources. The main objective of this study was to “analyze the potential effects of different land use change scenarios on groundwater recharge in the Day River Basin in Vietnam”. The Soil Water and Assessment Tool (SWAT), a spatially distributed model able to predict the environmental impact of land use changes, was applied to the Day River Basin. Before the model was run, a land use classification and a land use map for the Day River Basin were made. The model is calibrated against measured daily discharge at 3 locations in the study area, Ba Tha, Phu Ly and Ninh Binh. For all 3 locations, daily R^2 values are above 0.5 indicating an acceptable model performance. The daily NSE values range between 0.2 and 0.7, which also indicate an acceptable model performance. Three land use change maps where created, representing three scenarios for the Day River Basin in 2035. Scenario I ’business as usual’ (BAU), scenario II ‘rapid economic growth’ (REG), and scenario III ‘sustainable policies’ (SUS).

The results show that each land use change scenario has different effects on groundwater recharge in the Day River Basin. The BAU scenario, which assumes no implementation of new policies and represents a continuation of current trends, shows decreasing groundwater recharge rates in almost all sub-basins. The same goes for REG scenario where even more rapid urbanization and deforestation processes are at hand, which drastically reduce the rainfall partitioning to groundwater recharge. The SUS scenario shows that sustainable policies, such as, reforestation practices can potentially influence the rainfall partitioning to groundwater recharge in a positive way.

Land use changes seem to have limited effects on the groundwater recharge rates when monthly values are evaluated. Cumulative trends over a longer periods of time, show a different pattern, which indicates that land use changes do in fact drastically effect groundwater recharge rates. Land use change can positively or negatively influence groundwater recharge rates, depending on the kind of land use changes. SWAT was used to rank the land use types from the ones generating the most to the least groundwater recharge. Results show that from the 13 land use types in the Day River Basin land use map, forest and grass generate the most groundwater recharge and residential areas (high density) generate the least. Paddy field also generates relatively small amounts of groundwater recharge.

Looking at a sub-basin scale, changes in groundwater recharge occur in areas where most land use changes are at hand. Similar land use changes do not have the same effects on groundwater recharge in all sub-basins. In lower areas with little slopes, land use changes reduce the rainfall partitioning to groundwater recharge more than in mountainous areas. It can be concluded that the sensitivity of groundwater recharge to land use changes is spatially distributed within the Day River Basin. As groundwater resources in the Day River Basin are depleting rapidly, policy effective measurement are needed to address the issue of reducing groundwater recharge as a result of land use changes. Since the effects of land use change on groundwater recharge are significant, land use planners should take into account the effects of their decisions on groundwater recharge, as it is one of the most valuable ecosystem services in the Day River Basin.

Preface

This thesis is written by Maik van der Wolf in fulfilment of the requirements for the Master's degree in Environmental Sciences, programme Water Science and Management, at Utrecht University. I am fortunate to have been given the opportunity to study the effects of land use change on groundwater recharge using the Day River Basin in Vietnam as a case study site. The idea for the study was initiated within the context of the MK27 project 'Inclusive development paths for healthy Red River landscapes based on ecosystem services'. The MK27 project is a collaboration of 9, Dutch and Vietnamese consortium partners, with TU Delft as the leading institute and was initiated in January 2015, running for a period of 2 years, ending in December 2016. Fortunately my personal interests in land use change processes, hydrology and hydrological modelling were in line with the contents of the MK27 project. Based on these common interests, I wrote a research proposal in accordance with Ir. M. Rutten from TU Delft, consistent with the challenges for the Mk27 project. After the proposal has been approved, I studied in Vietnam for a period of about 3 months starting June 1, 2015. I have experienced my stay in Vietnam as a once in a lifetime opportunity as I got the chance to work with both Dutch- and local experts, which are actively involved in topics related to ecosystem service assessment, hydrologic modelling and/or other water and sustainability related studies. Mostly I have been situated at the Water Resource University (WRU), the Hanoi University of Water Resources and Environment (HUNRE) and the Institute of Water Resources and Planning (IWRP). Rapid land use change processes and their effects on ecosystem services are a major challenge in the Day River basin for the coming years. In my opinion, analyzing the effects of land use change on groundwater recharge is one of the most urgent and important challenges for the Day River Basin, because groundwater is one of the most valuable resources in this region. Improved knowledge of these system dynamics could assist and/or guide land use planners and other decision makers as they manage future developments within the Day River Basin.

Acknowledgements

My deepest gratitude goes to the following persons who helped and supported me with this opportunity to study a topic of my personal interest abroad in Vietnam;

Ir. Martine Rutten from TU Delft for providing me the opportunity to do this research and supervising and guiding me along the way, Paul Schot from Utrecht University for his supervision, feedback, and advice, Ha Thanh Lan from IWRP for providing data and sharing his knowledge and experience on hydrological modelling, Thi von le Khoa from HUNRE for sharing his knowledge on SWAT and the Day River Basin water system, Son Tung Nguyen from HUNRE, for sharing his knowledge about ArcGIS and remote sensing and his efforts to produce a land use map. Trung Dũng Vũ, student at WRU and Thibaut Visser, graduate student from TU-delft, for their contribution on the production of a land use classification and land use map, Le Tranthah HUNRE sharing his knowledge on geohydrology in the Day River Basin, Duc Anh Nguyen WRU for sharing data and articles, G. Simons of Futurewater for sharing data and dr. Cong from Vinwater for providing me a working space at WRU.

Contents

List of abbreviations

ET	= Evapotranspiration
CMS	= Cubic meters per second
GWR	= Groundwater recharge
HUNRE	= Hanoi University for Natural Resources and Environment
IWRM	= Integrated Water Resources Management
IWRP	= Institute Of Water Resource Planning
LUC	= Land use change
MARD	= Ministry of Agriculture and Rural Development
NSE	= Nash Sutcliffe Efficiency
MONRE	= Ministry Of Natural Resources and Environment
NAWAPI	= National Center of Water Resource Planning and Investigation
RH	= Relative Humidity
WRU	= Water Resource University

1 Introduction

1.1 Land use and land cover change

All over the world, especially in the developing world, rapid population growth is at hand (United Nations, 2004). The world population of 7.2 billion in mid-2013 is projected to increase by almost one billion people within the next twelve years, reaching 8.1 billion in 2025, and to further increase to 9.6 billion in 2050 and 10.9 billion by 2100 (United Nations, 2013). At the same time, urban migration causes cities to grow and expand at fast rates. The World Bank recognizes the shift from rural to urban societies and predicts a massive impact on the economic, social, political, and environmental landscape of countries across the globe (World Bank Group, 2015). Population growth and the shift from rural to urban societies are both processes which drive changes in land use and land cover. Land cover is "the observed physical and biological cover of the earth's land, as vegetation or man-made features." In contrast, land use is "the total of arrangements, activities, and inputs that people undertake in a certain land cover type" (Choudhury et al., 1998). Land use- and hence land cover change, from here on addressed as 'land use change', is a general term for the human modification of Earth's terrestrial surface (Ellis, 2013). Current rates, extents and intensities of land use change are far greater than ever in history, driving changes in ecosystems and environmental processes at local, regional and global scales (Ellis, 2013).

In South East Asia, the Red River Basin is characterized by such rapid land use change processes (CGIAR, 2014). About 32.7 million people inhabit the Basin which covers an area of 169.000 km² covering parts of China, Vietnam and a small part of Laos (NAWAPI, 2015). In the Red River Basin the urban proportion of the population increased from 19.9% in 1999, to 29.2% in 2009 (Vietnam General Statistics Office, 2011). Urban growth In the Red River Basin has been most apparent in the capital Hanoi, which is located in the Day/Nhue River sub-basin, also known as the 'Day River Basin'. The Day River Basin (figure 1), located in the south-east of the Red River Basin, stretches from mountainous area to the coast and includes 5 provinces: Hanoi, Ha Nam, Ninh Binh, Nam Dinh and Hoa Binh, with a total area of 7665 km². Currently Hanoi accounts for 8.2 million inhabitants. From 1999 to 2009, the population of the capital increased by about 1.5 times. This rapid growth will continue if there are no changes in current trends (Vietnam General Statistics Office, 2011)

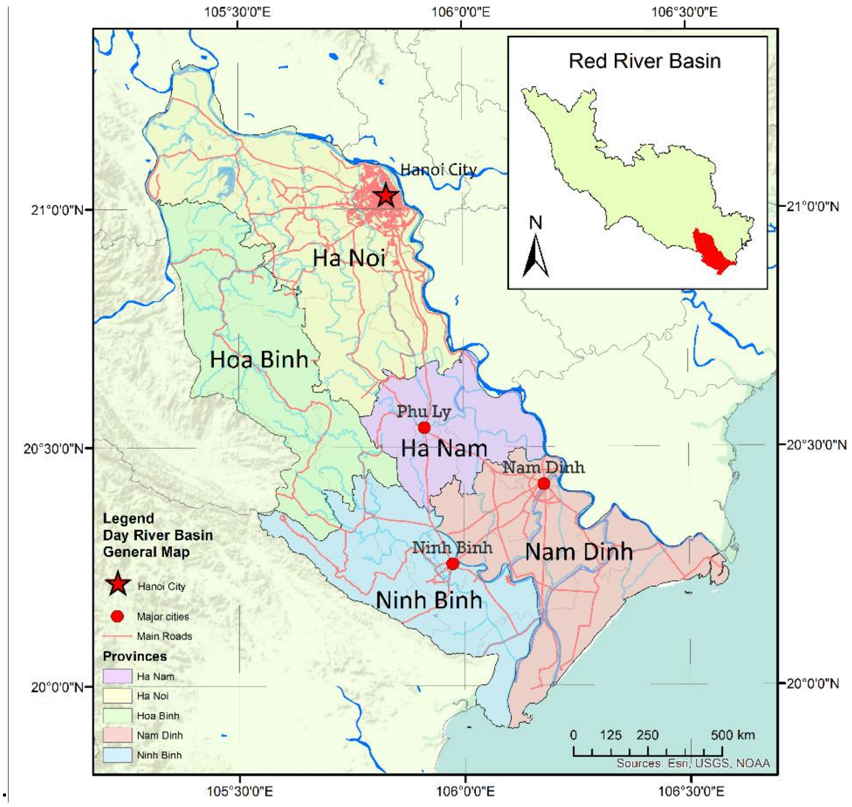


Figure 1. Day River Basin, provinces and major cities.

1.2 Problem description

For many people in the Day River Basin groundwater is a valuable resource as most surface waters are either absent or polluted (ICEM, 2007). Groundwater it is being used to provide fresh water to citizens and industry. Hanoi, is a good example of a quickly urbanized city in a developing country, where groundwater is the only resource of drinking water (Jusseret et al., 2010). In rural areas people also strongly rely on groundwater resources, as they use groundwater for many purposes like; drinking water for both themselves and their cattle, small scale irrigation and daily shores, such as washing clothes. Currently, within the Day River Basin groundwater resources are being threatened by rapid land use changes such as urbanization, deforestation, and intensive agriculture, as they reduce the amount of groundwater recharge from rainfall (Nhan, 2015). Groundwater recharge is defined as the ‘vertical downward water movement across the phreatic groundwater table’ (red arrows in figure 2) (Scanlon et al., 2002). Water movement differs per land use type, especially flow in the vertical direction (Bastiaanssen, 2015). When land use changes occur, hydrological processes (infiltration, evaporation, groundwater recharge) are also affected. Figure 2. shows some example land use types, forest(1), urban(2), agriculture(3) and bare land(4) and how they are interconnected with hydrological processes.

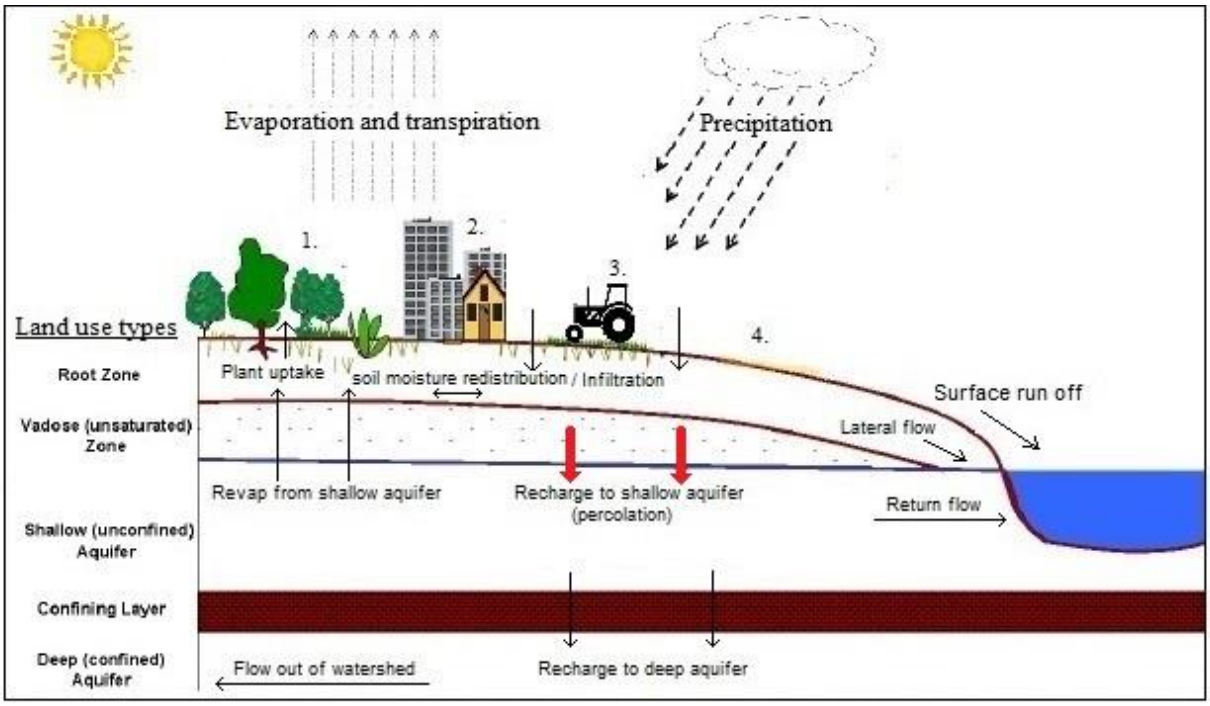


Figure 2. Hydrological processes and the interconnection with land use

The reduction of groundwater recharge as a result of rapid land use changes is a big challenge for the Day River basin as it involves many consequences. Reduced groundwater recharge leads to depleting groundwater resources and lowering of groundwater levels. The result is land subsidence, with a maximum observed yearly rate of 46 mm per year at Thanh Cong (Fischer et al., 2011), increasing flood risks within the Day River basin. At the same time, due to the lowering of groundwater levels, arsene- and salt intrusion from deep aquifers threaten groundwater quality (Postma et al., 2012). Furthermore, less groundwater recharge, leads to a less stable river discharge in terms of baseflow, which is considered to be a measure for the region’s water resource availability over time (Lawrence Dingman, 2002). Altogether, groundwater recharge is a valuable resource and for this reason it is recognized as one of the ecosystem services related to water within the Ecosystem Services and Resilience framework of the CGIAR (CGIAR, 2014). Understanding the dynamics between land use changes and hydrological processes, is a topic scientists have studied for several years. Yet, the challenge to quantify the effects of land use change on groundwater recharge remains, especially within the Day River Basin in Vietnam, where there is little knowledge on the effects of land use change on groundwater recharge (CGIAR, 2014).

1.3 Research objective

The main objective is to "*analyze the potential effects of different land use change scenarios on groundwater recharge in the Day River Basin in Vietnam"*. In regard to this objective, 'analyzing', does not only imply quantifying the potential effects of land use change scenarios on groundwater recharge in the Day River Basin, but also explaining the effects.

The objective fits within the context of the MK27 project. "Inclusive development paths for Healthy Red River Landscapes" funded under the CGIAR program WLE Greater Mekong (CGIAR, 2015). One of the objectives of this project is to support the Vietnamese Government in their decision making by providing access to improved (processed) data and to provide (land use) planners with tools to assess the impact of land use changes on ecosystem services (MK27, 2015). One of the challenges for the MK27 consortium partners, is to feed their knowledge into regional and national planning systems in order to manage the Day River Basin now and in the future. The outcome of this study may serve as a contribution to their objectives, by providing improved understanding of the effects of land use change on groundwater recharge within the Day River Basin.

1.4 Research questions

To meet the research objective one main research questions is proposed. Additionally, four sub-questions are formulated in order to answer the main question. How the sub-question contribute to answering to the two main research questions is explained in more detail under 'Methods'.

"What are the potential effects of different land use change scenarios on groundwater recharge in the Day River Basin and how can these effects be explained?"

A. What are possible land use change scenarios for the Day River Basin?
B. How much groundwater recharge is generated for each land use change scenario?
C. What is the rainfall partitioning to groundwater recharge for each land use type in the Day River Basin land use map and how can this be explained?
D. How is the sensitivity of groundwater recharge to land use changes spatially distributed within the Day River Basin and how can this be explained?

1.5 Research boundaries

To clarify the research objective some research boundaries are given. At first, groundwater resources can be refilled in a couple of ways such as; infiltration due to rainfall, lateral inflow from surface water bodies like lakes, rivers and streams, leakage from pipes in urban areas and artificial groundwater recharge (Yang et al., 1999). This research solely focusses on the groundwater recharge induced by rainfall, because land use change plays an important role in this process. Lateral inflow from surface water to groundwater resources and human induced groundwater recharge are not directly related to land use change processes and are therefore not within the scope of this study. Secondly, the aim is to quantify the effects of land use change on groundwater recharge, what happens after this process, for example, groundwater abstractions or other human interventions, are not within the scope of this study. Thirdly, even though, reduced amounts of groundwater resources have negative consequences for groundwater quality, this study solely focusses on water quantity and not the water qualitative consequences of reduced groundwater recharge. Fourthly, on purpose, the effects of climate change are not taken into account. This way it is clear what driving force induces the changes in the groundwater recharge and confusion is avoided about whether the changes in groundwater recharge are induced by land use- or climate change. Fifthly, within each hydrological year, many rainfall events occur with different characteristics in terms of duration, intensity and spatial distribution. The effects of a single rainfall event are not within the scope of this study, instead long term effects, yearly averages and seasonal variations of groundwater recharge are taken into account. Finally, the purpose of this study is to analyze and explain the effects of land use changes in the Day River Basin, in order to contribute to the objectives of the MK27 project. The aim is not to produce action plans or measurements strategies, but to provide land use planners with a tool to better understand the effects of land use change on groundwater recharge in the Day River Basin.

2 Site description Day River Basin

2.1 Climate

The Day River basin is situated in wet-hot tropical monsoonal climate with a pronounced maritime influence. Pfeiffer (1984) has classed its climate as seasonal, moist subtropical (Zhen et al., 2006). Annual average temperatures range from 24-27ºC. Summers are warm and very humid, with average temperatures ranging from 27ºC to 29ºC, with mean maxima of 31–33ºC. Winters are cool and dry, with mean monthly temperatures varying from 16.3ºC to 20.9ºC, and mean minimum temperatures from 14.4ºC to 19ºC (Zhen et al., 2006). Annual average rainfall is 1500-2200 mm, with peak rainfall occurring at Ba Vi Mountain in the upper catchment of the Tich River. Most of the annual rainfall falls during the summer rainy season (April-October), with the heaviest rainfall occurring in August and September (Zhen et al., 2006). The flood season (June-October) contributes 80% of the total annual flow, while the dry season contributes only 20% of the annual water volume (ICEM, 2007). A couple of meteorological stations (green dots in fig 2.), measure climatic related features such as rainfall and temperature.

2.2 Surface water

The Day River basin has a rather complicated hydrology due to the many diversions and flow alterations. The natural systems have been fundamentally altered and controlled by engineering interventions and management regimes (ICEM, 2007). It is a system with an annual flow of approximately 28.8 billion m³. The mainstream of the Day River basin, is the Day River (figure 3. red line) with a total length of 240 km, from the river mouth at the Red River, all the way to the sea. The Day River used to be a regular distributary of the Red River, diverting water of the Red River at Hat Mon, about 25 km upstream of Hanoi. Nowadays the Day river does not receive any water from the Red River anymore and partly turned into a 'dead river' from the river mouth to approximately 71 km downstream near Ba Tha (ICEM, 2007). From here on the Day River receives surface water from a couple tributaries starting with the Tich river, followed by the Nhue, Hoang Long, Chau, and Dao rivers. In the upstream area, the lack of surface water increases the value and importance of groundwater resources (Le Tranthanh, personal communication, July 12, 2015). Hydrological stations (figure 3. red dots) measure either water level or discharge. Three hydrologic stations, Ba Tha, Phu Ly and Ninh Binh, are situated along the Day River.

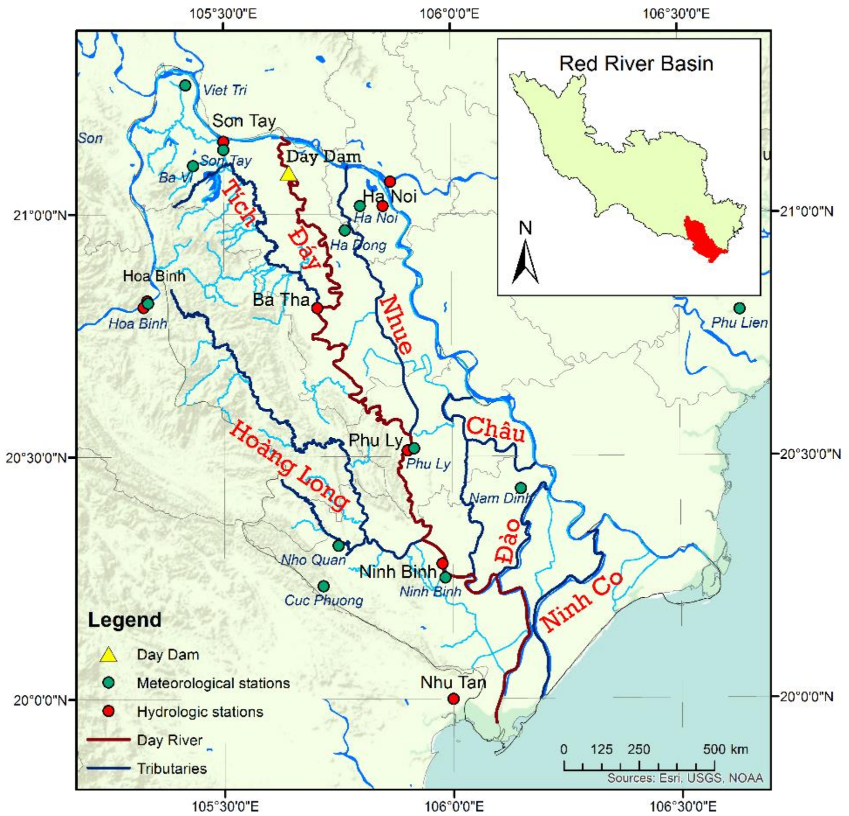


Figure 3. Day River (dark red) and tributaries (dark blue)

2.3 Groundwater

There are 6 soil layers in the Day River Basin (figure 4). Groundwater resources are stored in 2 layers. Groundwater extractions in both layers, are expected to grow in the coming years, increasing the value of groundwater resources and thereby the importance of groundwater recharge even more (Le Tranthanh, personal communication, July 12, 2015).

Firstly, groundwater is stored in the relatively undeep Holocene layer, an unconfined/semi-unconfined aquifer. Households in suburban districts extract drinkable water from this layer using shallow drilling wells. The number and extraction amounts are impossible to estimate (Tong et al., 2001). Water entering this layer is known as 'recharge to the shallow aquifer' (figure 2). Land use changes have a direct influence on this process. A fraction of the water in the Holocene layer can seep deeper into the ground to the Pleistocene layer, which is a confined aquifer.

From this Pleistocene layer, centralized extractions are managed by governmental organizations, such as the Hanoi Water Supply Company (Hawaco) in the Hanoi area with 11 well fields and 7 small stations accounting for a total of 200 wells. The average withdrawal from these well fields has been monitored, showing continuous rising of groundwater extraction over the last decades for domestic and industrial demand and for public services in urban districts (Dang et al., 2014). Decentralized extraction are being done by factories and companies, which drill from their own wells. They also directly extract groundwater from the confined Pleistocene aquifer. Land use change processes have an indirect effect on 'recharge to the deep aquifer' (figure 2. p10) (Le Tranthanh, personal communication, July 12, 2015).

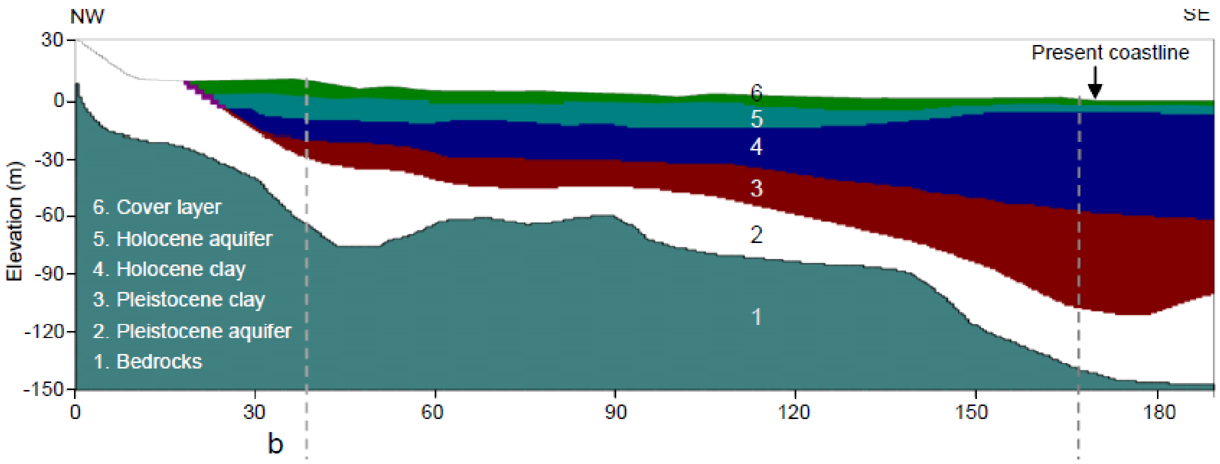
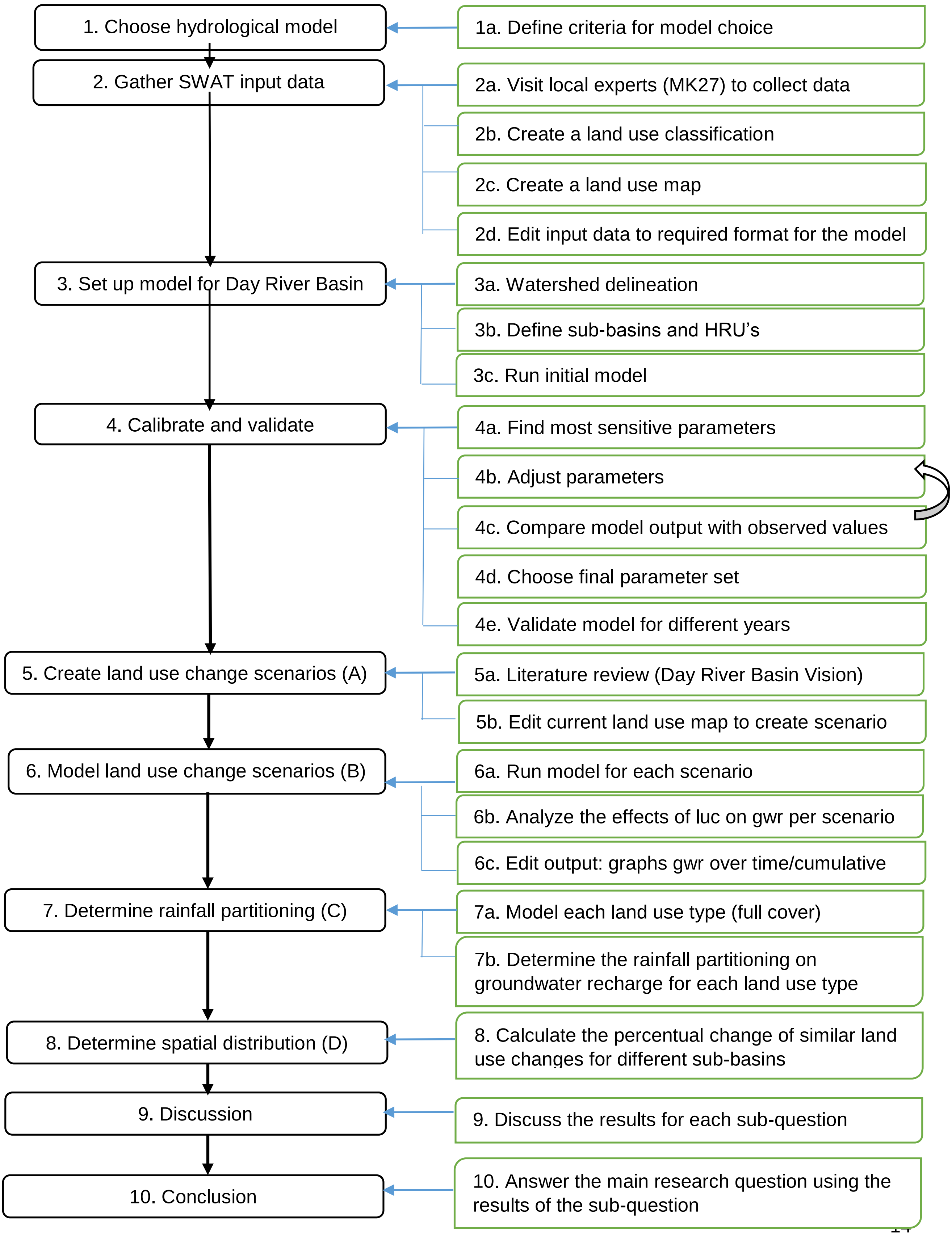


Figure 4. Geohydrological setting: Day River Basin cross section (Source: HUNRE, 2015)

3 Method

3.1 General approach

The general approach to answer the main research question, is presented in a flow diagram. The letters A, B, C and D indicate which steps relate to the sub-questions.



3.2 Research steps

3.2.1 Choose hydrological model

The effects of land use change on groundwater recharge are analyzed using the Soil Water and Assessment Tool (SWAT) (Arnold et al., 1998) (Arnold & Fohrer., 2005). The selection for the SWAT model is based on the following criteria;

- Able to estimate groundwater recharge rates over a large range of scales. SWAT is able to model from small watershed to river basin-scale up to 500,000 km² (Arnold et al., 2000).
- A spatially distributed model. SWAT enables spatially distributed simulations to predict the environmental impact of land use changes (Neitsch et al., 2011).
- Able to do long−term continuous simulations with daily- monthly- and yearly output. SWAT output includes evapotranspiration, surface runoff, lateral- or baseflow and groundwater recharge over time.
- A physically based model. SWAT simulates the physical characteristics and processes related to land use and groundwater recharge (Neitsch et al., 2011).
- Ability to use different kind of data (measured data, point source data, remote sensing data)
- Possibility to model scenarios by using land use maps with spatially displayed input/output.
- Earlier studies have been done with fair results, such as: Sun et al. (2005) who simulated 30 years of bore data in SWAT for a 437 km² watershed, in order to estimate recharge in the headwaters of the Liverpool Plains in New South Wales, Australia.

SWAT operates together with the Geographical Information System (GIS). Figure 5 gives an overview of all SWAT model components (Neitsch et al., 2011). The green arrows show which model components are related to the generation of groundwater recharge. The red arrow indicates the 'groundwater recharge to the shallow aquifer', which specifically is the focus of this study. Model components such as 'snowmelt', 'irrigation', and the 'pond and reservoir water balance' are not being used.

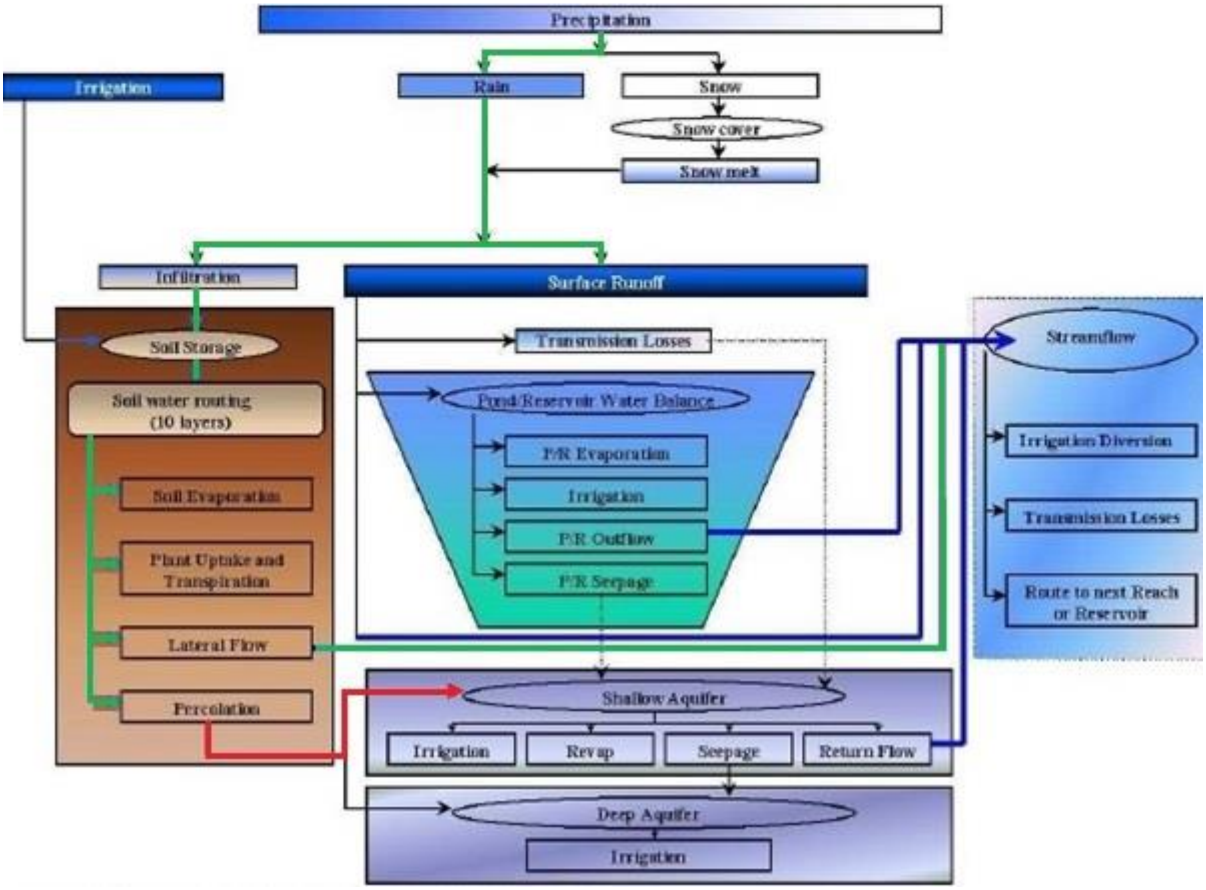


Figure 5. Schematic overview of processes (rectangles) and storages (circles) in SWAT, adopted from (Neitsch et al., 2011)

3.2.2 Gather SWAT input data

Input data for the SWAT model was gathered by visiting local experts in Vietnam working for the MK27 project and additionally on-line databases were used. An overview of the input data and sources is given in Appendix I. Not all data was readily available. In order to set up a SWAT model for the Day River Basin, a 'land use map' for the Day River Basin current situation was required. A 'land use map classification' was made in cooperation with Sơn Tùng Nguyễn (HUNRE) and Thi Văn Lê Khoa (HUNRE), who have in-depth knowledge of the study area. The Day River Basin 'land use map' was created in cooperation with Sơn Tùng Nguyễn (HUNRE), Trung Dũng Vũ (WRU) and Thibaut Visser (TU Delft).

3.2.2.1 Create a land use classification for the Day River Basin.

A selection was made from the total list of 100+ land use types in the SWAT database, to exclude land use types irrelevant for the Day River Basin such as snow, ice cover, tundra, etc. After this step, 53 land use types were left. A second selection was made by removing land use types from the list which are very small in size and cannot be recognize using remote sensing, for example, a single eggplant or tomato plant in a back yard. Due to their limited effect on hydrology, these land use types were removed from the list, resulting in 39 land use types for the Day River Basin land use classification (Appendix II).

3.2.2.2 Create a land use map for the Day River Basin.

A 'level 1 classification' was made based on a classification from Tsinghua University (2014). It contains 8 classes: Crop, forest, grass, shrub, impervious, soil, water and wetland. These 8 classes for the Day River Basin land use map were identified using Landsat images in ArcGIS. The 39 SWAT land use types were divided over these 8 classes. All crops were placed under 'crop', al urban and industrial areas under 'impervious' etc. In the end, T. Visser and Sơn Tùng Nguyễn used satellite images and field trips to further improve and finalize the land use map, resulting in a land use map with 13 land use types (Appendix V).

3.2.3 Set up model for Day River Basin

SWAT incorporates a number of methods to simulate the hydrological processes. The surface runoff/infiltration process can be modelled using the empirically derived SCS curve number method (USDA Soil Conservation Service, 1972) or the Green and Ampt method (Green and Ampt, 1911). The latter requires sub-daily rainfall data, which was not available, and canopy storage must be modelled separately which requires additional data sets. Therefore, the SCS curve number method is used to model the surface runoff/infiltration process, with the amount of infiltration determined implicitly as the difference between the amount of rainfall and surface runoff. For the potential evapotranspiration, the calculation methods in SWAT include the Penman-Monteith (Monteith, 1965), the Priestley Taylor method (Priestley and Taylor, 1972) or the more simple Hargreaves method (Hargreaves et al., 1985). The Penman-Monteith method, which is the default method in SWAT, is used because it is the most physically based method and is therefore universally accurate (Wang et al., 2009). Furthermore it is the most commonly used method when a full complement of weather data is available (Allen et al., 1987) which yields good results under different climatic conditions (Droogers & Allen, 2002). In SWAT a kinematic storage model is used to predict lateral subsurface flow (Sloan et al., 1984). The method SWAT uses to calculate actual groundwater discharge is derived from the steady-state response of groundwater flow to recharge as described by Hooghoudt (Hooghoudt, 1940). Manning's equation is used by SWAT to define the rate and velocity of flow. Water is routed through the channel using the variable storage routing method (Williams, 1969).

During the watershed delineation process the Day River Basin was divided into 75 sub-basins with on average 11 Hydrological Response Units (HRU's) per sub-basin, 817 HRU's in total. SWAT automatically creates HRU's based on, geological conditions (soil map), land use characteristics (land use map) and elevation/slope (digital elevation map). When modelling land use scenarios, land use changes need to be recognized by the model. Therefore the threshold for land use is set to 2%, meaning that each land use type covering an area of more than 2% of a sub basin is recognized by the model. Therefore 99/100% of the land use change will be noticed by the model while running land use change scenarios. The thresholds for soil and slope are higher, 17%. These thresholds require less detail because soil and slope maps have less detail and do not change when the scenarios are run.

3.2.4 Calibration

Calibration of the SWAT model is done using the ‘manual calibration tool’ from SWAT (Inchell et al., 2013). This tool provides the most dominant parameters in SWAT (appendix III) and enables modifications. These parameters are also referred to in many other SWAT studies such as (Miller et al., 2002), (Sawyer, 2010) and also in the SWAT theoretical documentation (S.L Neitsch et al., 2011) and the SWAT Input/Output Documentation (Arnold et al., 2012).

The aim was not to get a fully calibrated model, but to improve model performance to an acceptable level. Two statistical methods are used to assess model performance during the calibration. The coefficient of determination (R^2) and the Nash Sutcliffe mode efficiency coefficient (Nash & Sutcliffe, 1970) are used to assess the model performance. The ‘coefficient of determination’ or R^2, describes the proportion of the variance in measured data vs modelled output. R^2 ranges from 0 to 1, where values closer to 1 indicate less error variance (Moriasi et al., 2007). Values greater than 0.5 are considered to indicate ‘acceptable model performance’ (Moriasi et al., 2007). The NSE describe the degree of collinearity between simulated and measured discharge data (Moriasi et al., 2007). NSE values range from - ∞ to 1 where values between 0 and 1 indicate an acceptable model performance.

The model is calibrated by iteratively changing parameters in SWAT while comparing the modelled- and measured daily discharge in 2006 at 3 locations Ba Tha, Phu Ly and Ninh Binh. Discharge measurements at these 3 locations were not readily available, because only waterlevel measurements are being done at these stations. Therefore, Q-h relations for the Day River Basin from a study by Luu et al. (2010) are used to convert water level measurements to discharge rates. These derived daily discharge rates are compared with the daily discharge rates in SWAT for calibration. Table 1 presents in column 1; the parameters used for calibration, column 2; the range for the parameter values, 3. the final parameter values after calibration.

PARAMETER DESCRIPTION	RANGE	CALIBRATED VALUE
CH_N2	0.01-0.3	0.3
ESCO	0.01 to 1.0	1
CNCOEFF	0.5 to 2.0	1
ALPHA_BF	0.01 to 1.0	0.1

Table 1 (adjusted) parameter values for calibration of SWAT.

3.2.5 Validation

The model is validated by comparing the modelled- and measured daily discharge for 2008 at 3 locations Ba Tha, Phu Ly and Ninh Binh, without further adjustments to the SWAT model. A second validation for the water balance was done by comparing the monthly evapotranspiration rates for 2006 presented in Luu et al., (2010), a study on water circulation patterns for the Red River system, with the SWAT model output.

3.2.6 Create land use change scenarios (sub-question A)

Future land use changes cannot be predicted, as it is a process driven by social- economic developments and changes in society. In developing countries like Vietnam, due to a lack of policies, land use change is a relatively uncontrolled process compared to developed countries such as the Netherlands (Nguyen, personal communication, June 2015). To take into account the uncertainty of land use changes, three land use change scenarios are made for the Day River Basin. The scenarios are based on a study from Niapp et al. (2012), ‘Land use, food security, and climate change’, which aimed to provide better insights about future land use change in Vietnam and the relation towards food security and climate change. The land use types in Niapp et al., (2012) are not completely similar to the land use types in the Day River Basin land use map. Therefore a personal interpretation was given to the Day River Basin scenario maps. The scenarios were continuously discussed with two Vietnamese experts, Sơn Tùng Nguyễn (HUNRE) and Thi Văn Lê Khoa (HUNRE), who have indebt knowledge of the study area. The scenarios are created by editing the Day River Basin land use map of the current situation into new hypothetical land use maps using ArcGIS.

3.2.7 Model land use change scenarios (sub-question B)

The scenarios are applied to the model to analyze the potential effects on groundwater recharge. The analysis focusses on, 1; the effects on groundwater recharge over time and 2; the annual 'cumulative effects' of land use change scenarios on groundwater recharge. The analysis is done by comparing the output per sub-basin and not the HRU's. The HRU definition is different for each scenario and therefore the boundaries of the HRU's also change. For this reason the HRU's cannot give a fair comparison. The sub-basin boundaries remain the same when running the scenarios. The following 2 steps are done to gain a better understanding on the effects of the scenarios on groundwater recharge.

3.2.8 Determine rainfall partitioning on groundwater recharge for each land use (sub-question C)

To better understand the effects of the different land use changes scenarios on the groundwater recharge in the Day River Basin the rainfall partitioning to groundwater recharge is analyzed. To estimate the rainfall partitioning to groundwater recharge for the land use types present in the Day River Basin land use map, a full cover for each land use type was given to the model. SWAT does not allow a full cover of the land use type 'water', so this land use type is not taken into account. For the other 12 land use types, the range for average minimum- and maximum rainfall partitioning to groundwater recharge is determined. This range is determined for both the dry- (November-March) and wet (April-October) season, using rainfall data from 2014. First, a full cover is given to the Day River Basin land use map for land use X. Secondly. For each month the rainfall [mm] and the amount of groundwater recharge [mm] are averaged over the sub-basins. Finally, the percentage of rainfall becoming groundwater recharge is calculated for the driest- (January) and wettest month (November), giving the range for land use type X in the dry season. For the wet season the range is determined similarly using the driest month (May) for the lower- and the wettest month (August) for the upper limit.

3.2.9 Assess the spatial distribution of sensitivity (sub-question D)

When land use changes occur at location A, they effect the amount of groundwater recharge which is generated at 'location A'. Due to differences in soil type, elevation and slope steepness, the same land use change at 'location B' might have a different effect on groundwater recharge as in 'location A'. From here on this is referred to as the 'spatial distribution of the sensitivity of groundwater recharge to land use changes'.

To find the spatial distribution of the sensitivity of groundwater recharge to land use change within the Day River Basin' the result of sub-question C is used. First, the SWAT model was given a full cover of a land use type generating little groundwater recharge. For this land use type, the amount of groundwater recharge per sub-basin is calculated using rainfall input from 2014. Secondly, a full cover of the land use type generating the most groundwater recharge is given to the model. Also, for this land use type the amount of groundwater recharge per sub-basin is calculated using the same rainfall input. Finally, for each sub-basin the percentual change in the amount of groundwater recharge between both situations is calculated. The percentual change shows for each sub-basins, the sensitivity of groundwater recharge to land use changes.

4 Results

4.1 Model performance

The model performance is assessed after calibration using coefficient of determination (R^2) and Nash-Sutcliffe methods. The results for the model performance after calibration are presented in Table 2. Table 3. shows the validation results. Appendix IV contains the calibration and validation curves for the 3 stations. The high peaks in the modelled discharge are caused by extreme rainfall events. SWAT is not a hydraulic- or flood model and higher discharge peaks can occur during intense rainfall events. The R^2 values are sensitive to these high values which have a negative effect on the R^2 values (Legates, 1999). Nevertheless, for all 3 locations, the daily R^2 values are above 0.5 and indicate an acceptable model performance. The daily NSE values are between 0 and 1, which also indicate an acceptable model performance.

Both the R^2 and the NSE indicate that model performance increases further downstream, from Ba Tha to Ninh Binh. This improved model performance downstream can be explained by surface water flow, exfiltration from the Red River, adding to the total Day River Basin discharge. The SWAT model only takes into account rainfall input and does not take into account surface and groundwater inflow from surrounding upstream areas. For this reason the discharge in the SWAT model might be underestimated in the upstream areas, where Ba Tha station is situated.

Calibration (2006)		Mean (cms)	Std. deviation	R^2	E_{ns}
Ba Tha	Measured SWAT	53 25	42 42	0.6	0.3
Phu Ly	Measured SWAT	121 61	93 90	0.7	0.2
Ninh Binh	Measured SWAT	146 117	115 153	0.7	0.7

Table 2. Calibration statistics for discharge at 3 locations Ba Tha, Phu Ly and Ninh Binh

Validation (2008)		Mean (cms)	Std. deviation	R^2	E_{ns}
Ba Tha	Measured SWAT	70 54	60 124	0.2	0.2
Phu Ly	Measured SWAT	158 136	128 283	0.4	0.4
Ninh Binh	Measured SWAT	194 213	173 406	0.5	0.5

Table 3. Validation statistics for discharge at 3 locations Ba Tha, Phu Ly and Ninh Binh

The SWAT model output is compared with monthly evapotranspiration from Luu et al., (2010) to validate the water balance. Figure 6 shows the results from Luu et al., (2010) (left) and the SWAT model output (right). The SWAT water balance seems to produce similar evapotranspiration patterns over the year with similar rainfall input.

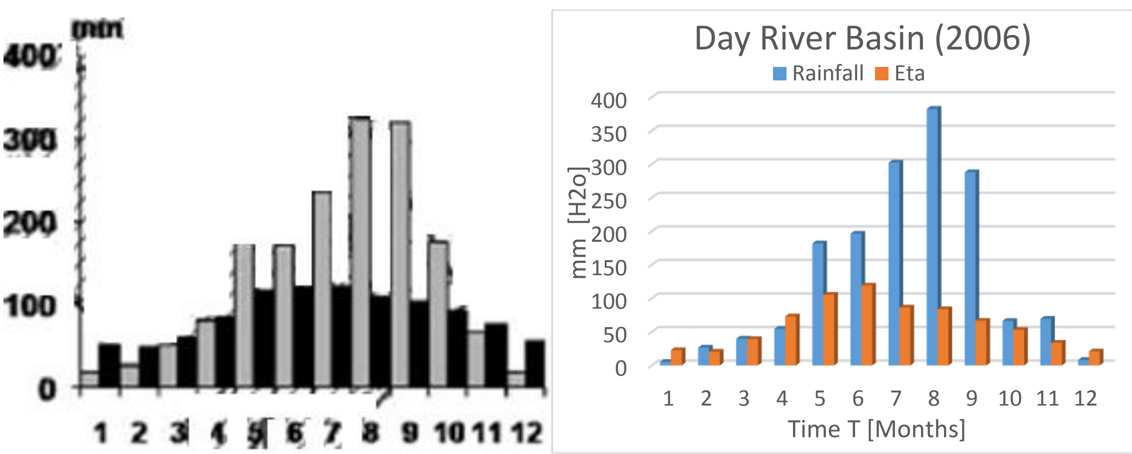


Figure 6. Rainfall and evaporation for the Day River Basin adopted from Luu et al., (2010) *vs. SWAT model.*

4.2 Land use change scenario's

Three land use change scenarios are created for the Day River Basin. Including the land use in the 'current situation' 2015, there is a total of 4 land use maps. The three scenarios are described below. Table 4 shows for each scenario the percentual land use changes compared to the current situation.

4.2.1 Scenario I

The first scenario is the most realistic scenario for 2035. It is the baseline scenario reflecting the 'Business As Usual' (BAU) and simulates an economic growth path for the Day River Basin assuming no implementation of new policies. Urban growth, industrial growth and production forest land replace paddy fields, non-production (evergreen) forest and other crops. The land use changes are not distributed evenly over the Day River Basin. Urban- and industrial growth is concentrated in the sub-urban areas resulting a decrease in paddy rice area and other crops. In non-urbanized areas, paddy fields and non-production forest are replaced by production forest. The land use map for scenario I is given in appendix VI.

4.2.2 Scenario II

The second scenario involves 'Rapid Economic Growth' (REG) without implementation of new policies. To some extend similar patterns as in scenario I occur, but in scenario II some land use changes are more extreme and additional land use changes occur. Economic development and structural change will lead to considerable land use changes. Production forest land and built up land will expand at the expense of paddy rice area, non-production forest, and shrub land (Niapp et al., 2012). Structural change and economic growth is accompanied by an increase in the demand for wood resources at the expense of forest. Rising demands can lead to opening of National parks, nature reserves and World Heritage sites for commercial logging and agriculture (Niapp et al., 2012). This means that forests in these areas will be negatively affected. Additionally, the economy becomes increasingly oriented towards services and manufacturing while the agricultural sector becomes less important. At the same time, changing diets and an increase in yields leads a decrease of paddy rice land and other agricultural land, which are replaced by urban and industrial areas (Niapp et al., 2012). The land use map for scenario II is given in appendix VII.

4.2.3 Scenario III

Scenario III involves a policy effective or so called 'Sustainable Scenario' (SUS). Investments are made to increase agro forestry and reforestation activities combined with natural forest protection. Land use policy trade-offs are implemented to mitigate conflicts, for instance reducing land use for rice and increasing forest areas so as to reduce greenhouse gas emissions (Niapp et al., 2012). This will affect food security negatively unless rice yields or rice imports increase. Increasing demands for food is adapted to by investments in other agricultural activities besides paddy, causing increasing land use practices for fruit trees and other crops. The land use map for scenario III is given in appendix VIII.

land use type	current situation	% change	scenario I BAU	% change	scenario II REG	% change	scenario III SUS
1. Water	*3.97*	*0*	*3.97*	*0*	*3.97*	*0*	*3.97*
2. Wetland	*0.01*	*0*	*0.01*	*0*	*0.01*	*0*	*0.01*
3. Mangrove	*0.08*	*0*	*0.08*	*0*	*0.08*	*0*	*0.08*
4. Barren land	*1.37*	*0*	*1.37*	*0*	*1.37*	*0*	*1.37*
5. Industrial	*3.86*	*+0.28*	*4.14*	*+2.53*	*6.39*	*+0.13*	*3.99*
6. Res-High	*1.87*	*+0.3*	*2.17*	*+1.11*	*2.98*	*+0.31*	*2.18*
7. Res-Med/Low	*15.92*	*+1.3*	*17.22*	*+4.94*	*20.86*	*+0.76*	*16.68*
8. Grass	*6.32*	*-0.19*	*6.13*	*0*	*6.32*	*-0.19*	*6.13*
9. Shrub	*1.04*	*0*	*1.04*	*0*	*1.04*	*0*	*1.04*
10. Evergreen forest	*20.36*	*-1.19*	*19.17*	*-9.28*	*11.08*	*+3.23*	*23.59*
11. Paddy field (rice)	*26*	*-2.19*	*23.18*	*-6.85*	*19.15*	*-9.32*	*16.68*
12. Fruit trees	*4.93*	*+1.18*	*6.11*	*+3.89*	*8.82*	*+2.22*	*7.15*
13. Other crops	*14.28*	*+0.5*	*14.78*	*+3.66*	*17.94*	*+2.85*	*17.13*
Total	*100*		*100*		*100*		*100*

Table 4. Current land use, land use change per scenario, new land use per scenario (all in % of total)

4.3 Groundwater recharge rates per scenario

4.3.1 Current situation

For the current situation (2014) the rainfall partitioning to groundwater recharge in percentages of the total rainfall, is presented in figure 7. The average annual rainfall in 2014 is 1621 mm, ranging from a local minimum of 1377.9 mm per year in sub-basin 7 and a maximum of 1944 mm per year in sub-basin 65. The average annual groundwater recharge over the sub-basins is 248 mm, ranging from minimal rates of 37 mm per year with lowest values in sub-basins 9, 2, 6 and 15 up to a maximum of 601 mm per year with highest values in sub-basins 41, 53 and 55.

Low groundwater recharge values occur in sub-basins with impervious areas such as Hanoi in sub-basin 9, which accounts for 35% high- and 16% med/low residential areas in the land use map. Also sub-basins with abundant paddy fields seem to generate relatively little groundwater recharge compared to the average, for example sub-basin 6, with 26% paddy field area and only a rainfall partitioning of 5% to groundwater recharge.

High groundwater recharge rates occur in sub-basins in the south west, such as sub-basin 55, where evergreen forest is with 54% the most common land use. High groundwater recharge rates can also be linked to the elevation levels which show that the sub-basins with high groundwater recharge rates lie in a valley. Water can travel from surrounding mountainous areas with steep slopes to this area as surface runoff. When slope steepness and flow velocity reduces it gets a chance to infiltrate.

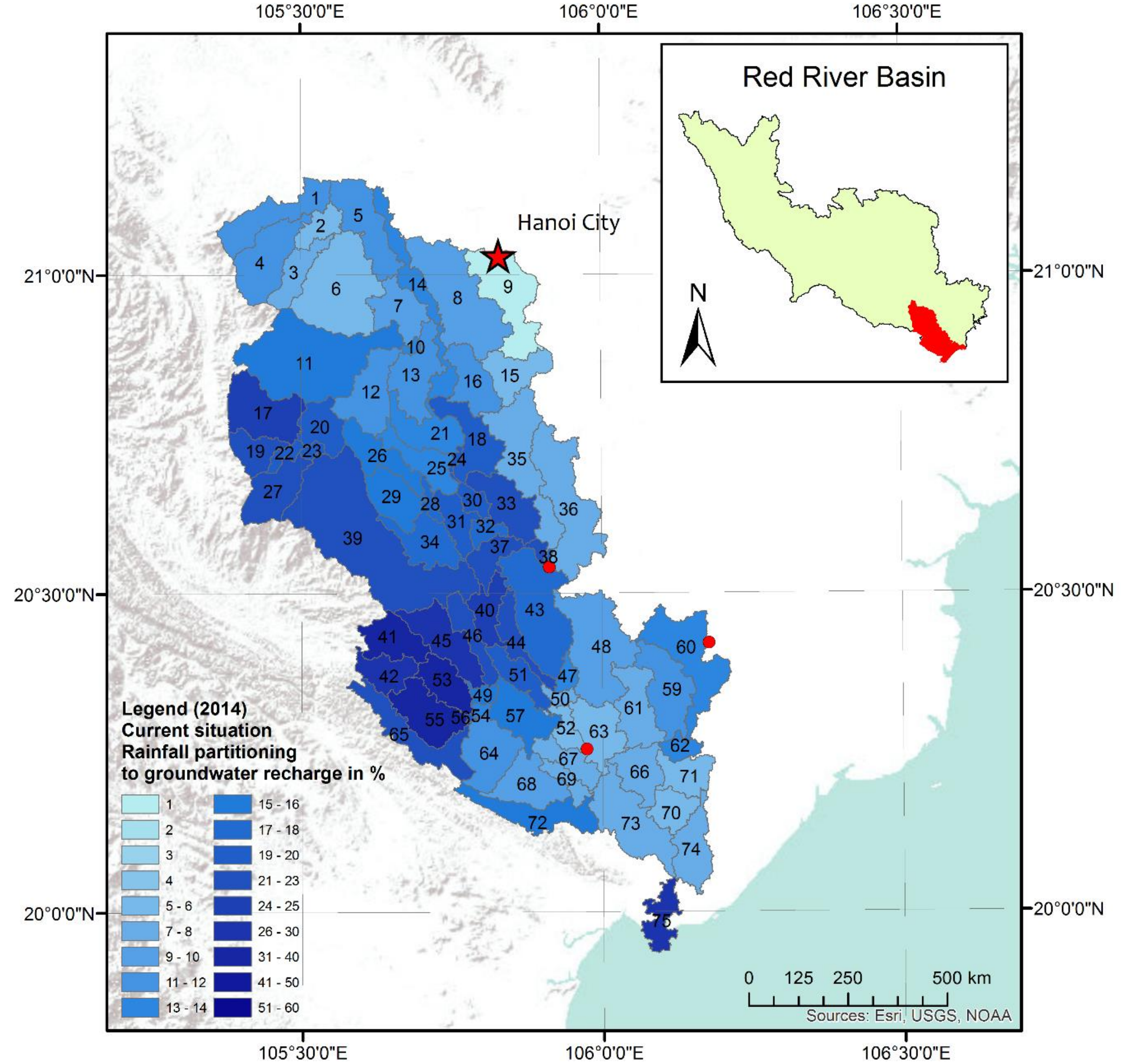


Figure 7. Rainfall partitioning to groundwater recharge in % of total rainfall per sub-basin

4.3.2 Scenario I 'business as usual'

The effects of the land use changes in scenario I compared to the current situation are presented in Figure 8. The map shows the percentual change of the rainfall partitioning to the groundwater recharge, after the land use changes have occurred. The climatic conditions and the rainfall input is the same as in the current situation. The average annual groundwater recharge over the sub-basins is 242 mm, ranging from minimal rates of 19 mm per year with lowest values in sub-basins 9, up to a maximum of 595 mm per year with highest values in sub-basins 41, 53.

The darker red colors in the sub-basins show where the land use changes have affected the rainfall partitioning to the groundwater recharge the most. These are the sub-basins 49 and 68, where the rainfall partitioning to groundwater recharge is reduced by more than 2.5%. Also in sub-basins where urbanization is at hand, such as sub-basin 8 and 9 in the surrounding area of Hanoi city, relatively less rainfall partitions to groundwater recharge. Overall, the rainfall partitioning seems to have reduced over the whole Day River Basin due to the land use changes.

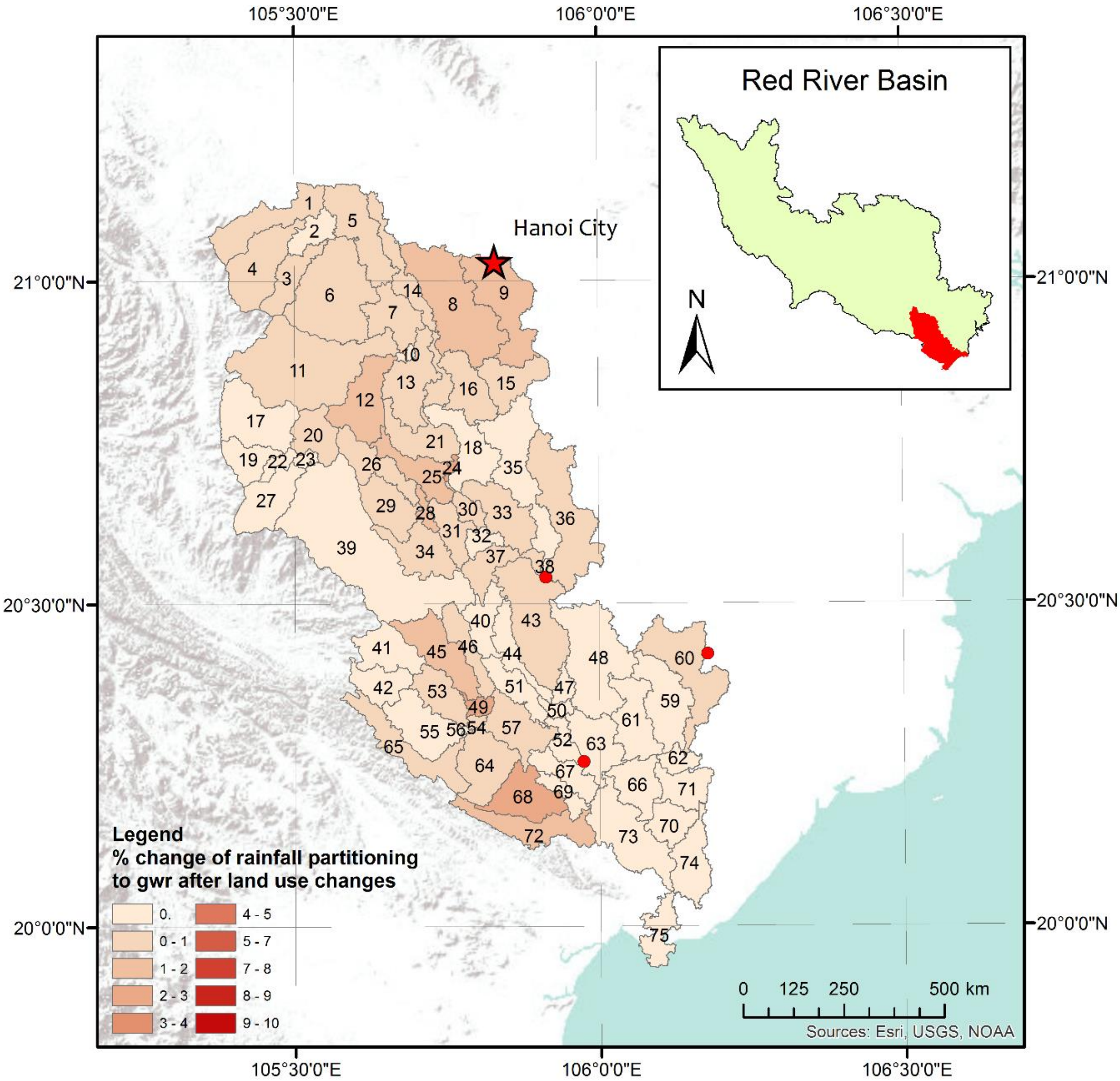


Figure 8. The change in groundwater rainfall partitioning in scenario BAU vs current situation

4.3.3 Scenario II 'rapid economic growth'

The effects of the land use changes on the rainfall partitioning to groundwater recharge in scenario II, compared to the current situation are shown in figure 9. The climatic conditions and the rainfall input are the same as in the current situation. The average annual groundwater recharge over the sub-basins is 205 mm, ranging from minimal rates of 17 mm per year with lowest values in sub-basins 9, up to a maximum of 581 mm per year with highest values in sub-basins 75.

Looking at the effects of the land use changes on groundwater recharge, sub-basins 41, 53 and 55 show the biggest changes. Rainfall partitioning significantly dropped by more than 10% in these sub-basins. Looking at the scenario II land use map, these changes are induced as a result of the development of med-low density residential areas at the expense of forest. Also sub-basins 20, 26, 28 and 31 show significant reductions. These reductions can be linked to deforestation. These sub-basins are located at the border between agricultural lands and natural forest. In this scenario, deforestation processes are at hand reducing the rainfall partitioning to groundwater recharge drastically in those specific areas.

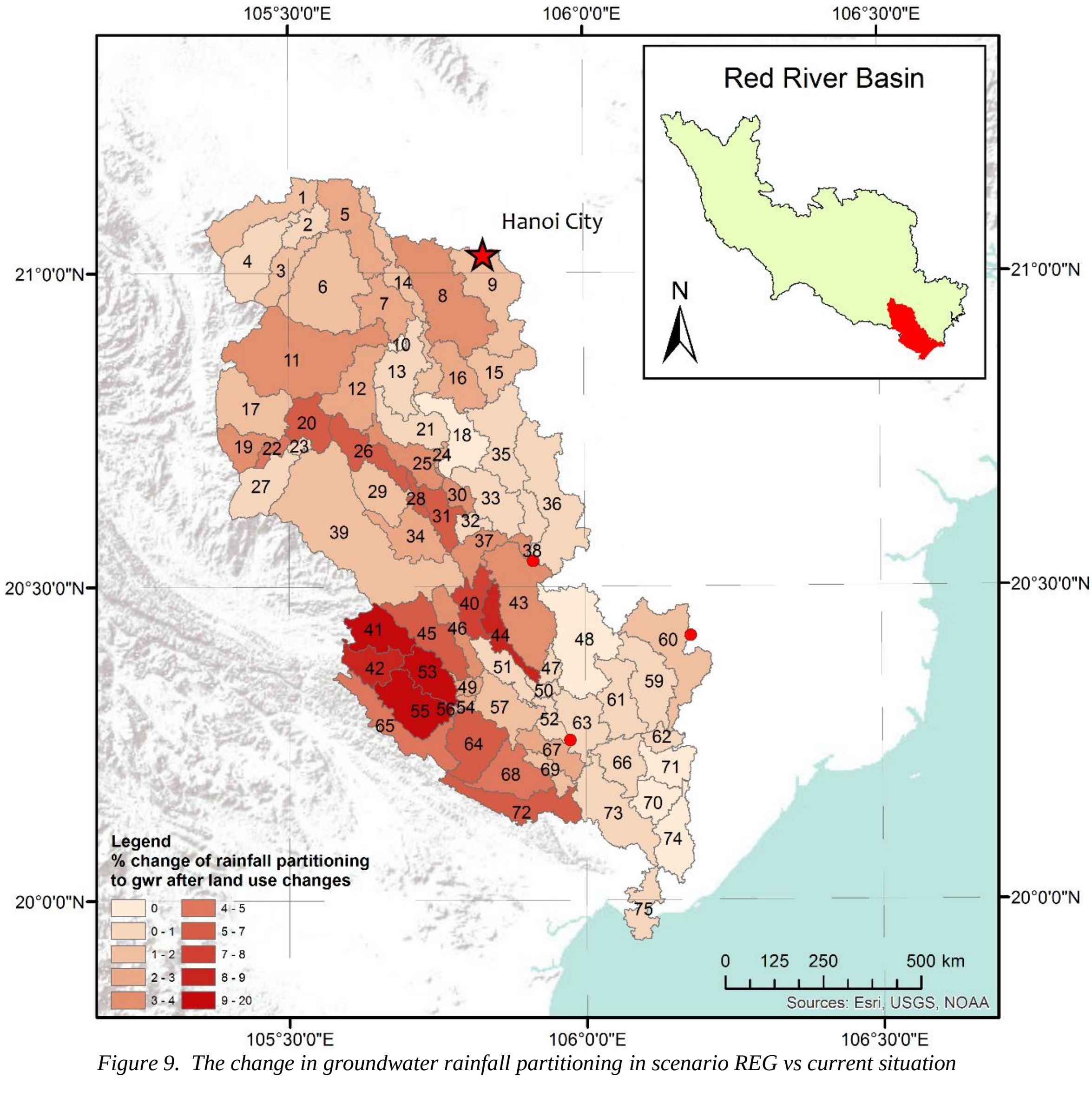


Figure 9. The change in groundwater rainfall partitioning in scenario REG vs current situation

4.3.4 Scenario III 'sustainable policies'

The effects of the land use changes on the rainfall partitioning to groundwater recharge for scenario III compared to the current situation are shown in figure 10. Again the climatic conditions and the rainfall input are the same as in the current situation. The average annual groundwater recharge over the sub-basins is 249 mm, ranging from minimal rates of 19 mm per year with lowest values in sub-basins 9, up to a maximum of 629 mm per year with highest values in sub-basins 58.

In contrast with the other two scenarios, this map contains green colors which represent an increase of the rainfall partitioning to the groundwater recharge for those specific sub-basins. At the same time, the red colors indicate, that other sub-basins are still characterized by decreasing groundwater recharge rates as a result of land use changes. It can be concluded that based on the specific land use changes in each sub-basin the rainfall partitioning to groundwater recharge is affected. The result of scenario III shows that reforestation processes locally, have a positive effect on groundwater recharge processes.

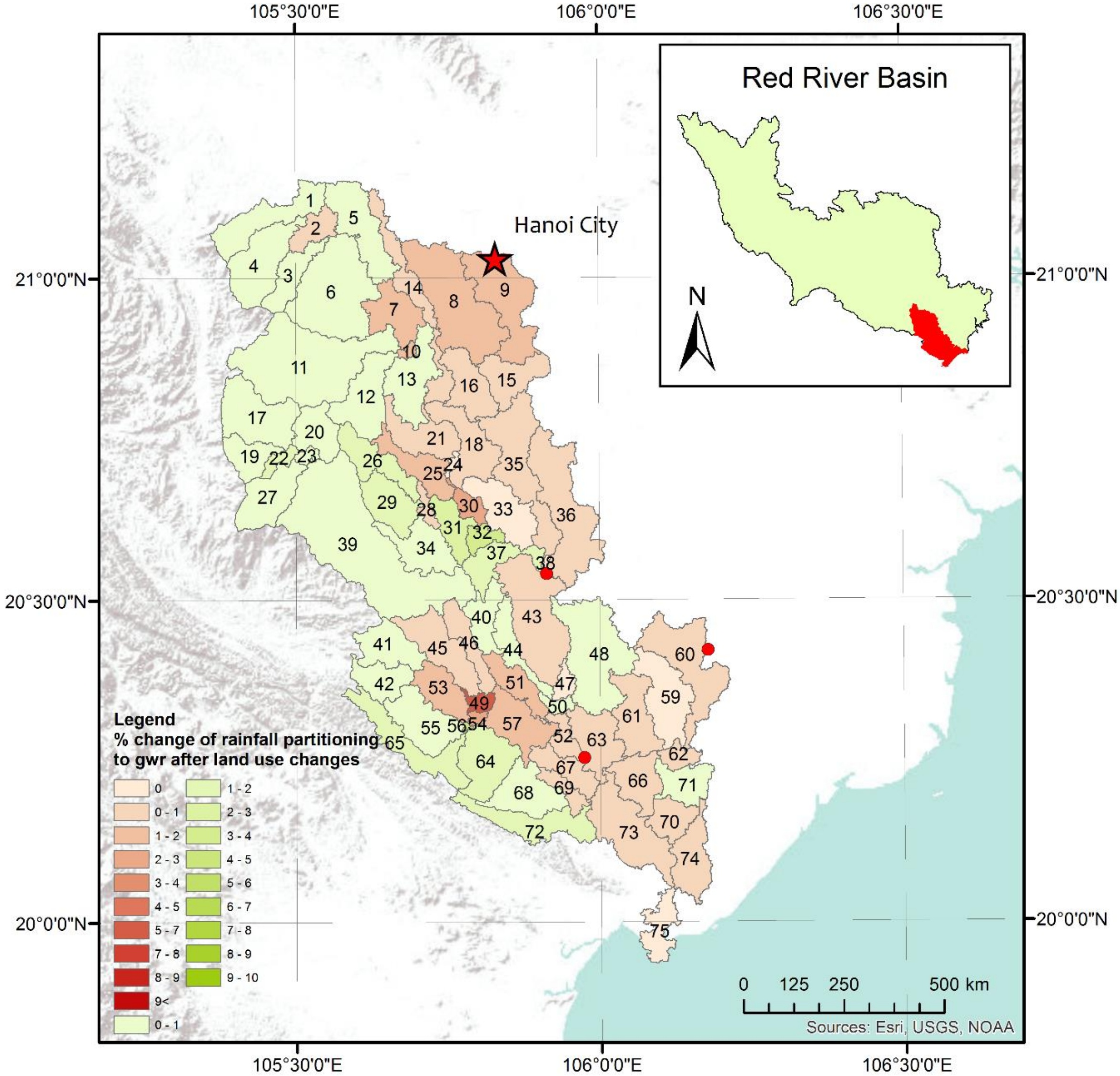


Figure 10. The change in groundwater rainfall partitioning in scenario SUS vs current situation

4.3.5 Comparing scenarios

The groundwater recharge and rainfall for a 5 year period using rainfall input data from 2005-2009 are presented in figure 11. Both the rainfall and the groundwater recharge are averaged over the sub-basins. The result indicates that the averages show little difference between the groundwater recharge rates for the different scenarios over time. For the current situation 24 mm groundwater recharge is generated each month, averaged over the 5 year period. For the BAU scenario, the averaged groundwater recharge equals 23 mm per month, for the REG scenario 20 mm and the SUS scenario 24 mm.

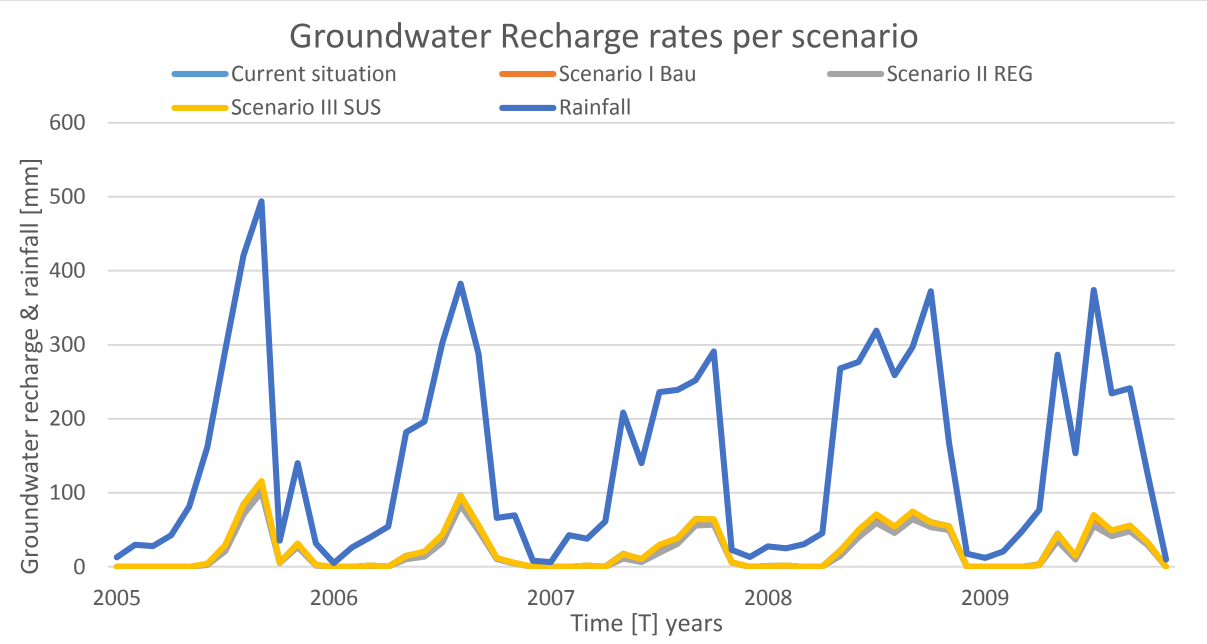


Figure 11. Groundwater recharge vs rainfall over time for all scenarios

Figure 12 presents the groundwater recharge over the same 5 year period, but in this case the groundwater recharge rates are cumulated. The results show that on the long term differences become visible between the scenarios. After a 5 year period, for the current situation 1407 mm groundwater recharge has been generated. The BAU scenario has generated 1374 mm groundwater recharge for the same period. The REG scenario only generated 1175 mm and the SUS scenario 1417 mm.

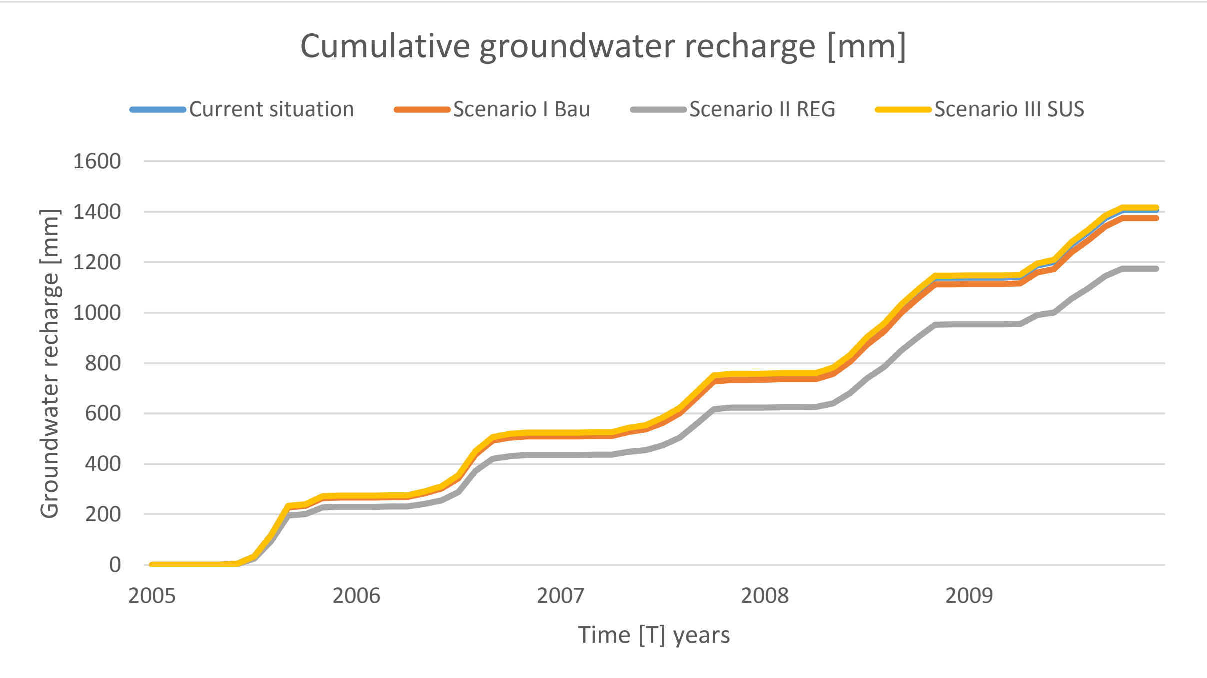


Figure 12. Cumulative groundwater recharge per scenario

4.4 Rainfall partitioning per land use type

The rainfall partitioning to groundwater recharge for each land use type in the Day River Basin land use map is given in table 5. The range for the rainfall partitioning to groundwater recharge is given in percentages of the total rainfall for the dry season (November - April). The standard deviation indicates the variation of the rainfall partitioning to groundwater recharge among the different sub-basins.

DRY SEASON **Land use Type**	Minimum average of all sub-basins	Standard deviation	Maximum average of sub-basins	Standard deviation
1. *Water*	x	x	x	x
2. Wetland	2.5	19.8	9.4	6.9
3. Mangrove	3.0	21.4	10.6	8.1
4. Barren land	1.1	9.8	8.0	6.8
5. Industrial	0.0	0	0.2	0.1
6. Res – high density	0.0	0	0.1	0.1
7. Res – med/low	1.2	10.7	4.6	4.6
8. Pasture (grass)	4.3	27.5	23.1	13.8
9. Shrub-land	2.5	19.5	11.0	8.1
10. Evergreen forest	4.0	26.5	19.4	11.6
11. Paddy field	1.5	12.8	5.3	4.4
12. Fruit trees	0.9	8.4	2.2	2.9
13. Other crops	0.8	7.7	2.0	2.8

Table 5. Rainfall partitioning to groundwater recharge per land use type [all in % of the annual rainfall]

The land use types are ranked in chronological order, from the land use type with highest- to lowest rainfall partitioning, in figure 13.

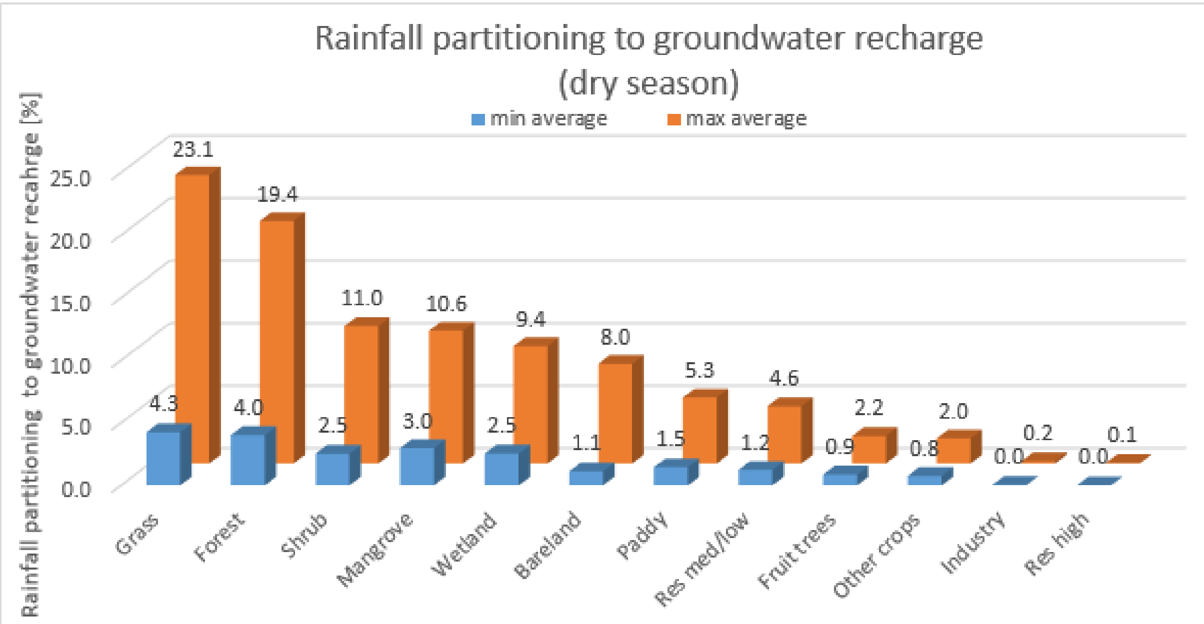


Figure 13. Range for rainfall partitioning per land use type

For the land use types grassland, forest and shrub the rainfall partitioning is the highest in the dry season. High density residential areas and industries have the lowest range for rainfall partitioning. The diagram presents the rainfall partitioning to groundwater recharge 'averaged over the sub-basins', therefore local extremes of rainfall partitioning, both high and low, might not be within this range. Also the range is based on rainfall measurements from 1 year (2014). In other years the absolute amount of rainfall might vary, but the rainfall partitioning will be within the same range because it is a percentage of the total rainfall.

Table 6, gives for the wet season (May – October) the range for the rainfall partitioning to groundwater recharge for each land use type in the Day River Basin land use map.

DRY SEASON **Land use Type**	Minimum average of all sub-basins	Standard deviation	Maximum average of sub-basins	Standard deviation
1. *Water*	x	x	x	x
2. Wetland	7.1	6.9	27.9	10.5
3. Mangrove	9.3	8.4	30.0	10.5
4. Barren land	13	9.7	30.8	9.9
5. Industrial	0.2	0	0.7	0.1
6. Res – high density	0.6	0	1.8	0.1
7. Res – med/low	4.7	4.6	19.2	12.6
8. Pasture (grass)	20.3	11.1	42.6	9.2
9. Shrub-land	11.3	10.3	34.8	10.9
10. Evergreen forest	13.4	11.6	42.1	10.6
11. Paddy field	7.9	7.3	25.5	9.4
12. Fruit trees	3.6	3.5	17.2	10.7
13. Other crops	2.7	2.8	16.4	10.3

Table 6. Rainfall partitioning to groundwater recharge per land use type [all in % of the annual rainfall]

Also for the wet season, the land use types are ranked in chronological order, from the land use type with highest- to lowest rainfall partitioning, in figure 14.

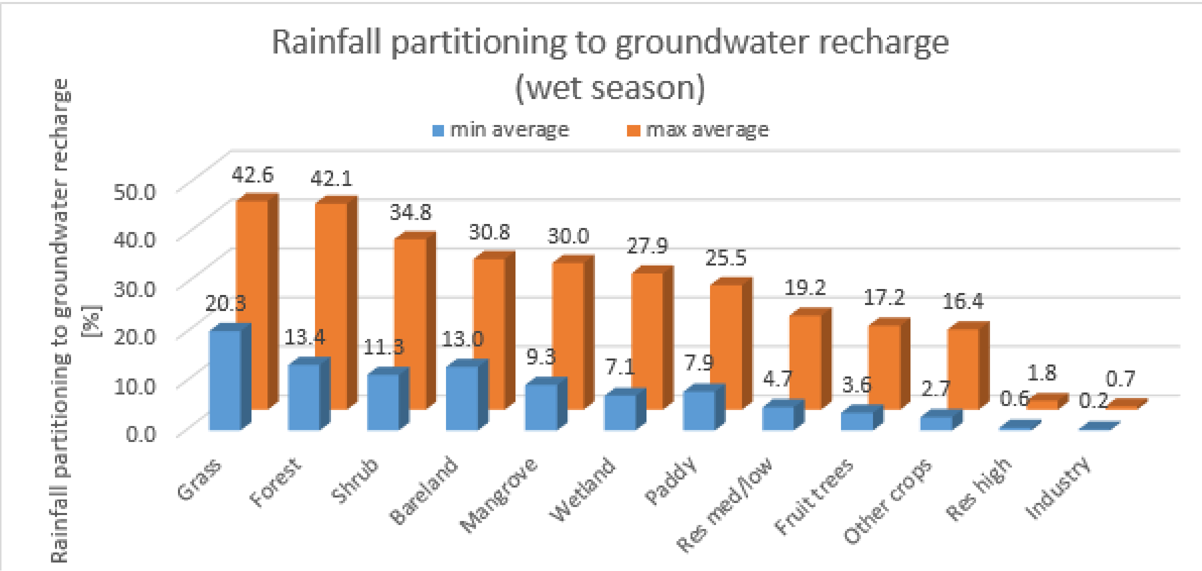


Figure 14. Range for rainfall partitioning per land use type

In the wet season the rainfall partitioning is higher than in the dry season. This difference can be explained by the duration, frequency and intensity of the rainfall events. During a rainfall event the top soil layers become more saturated over time. When a soil layer is fully saturated, the excessive water will percolate to lower soil layers eventually becoming groundwater recharge. In the wet season, longer rainfall events will more often lead to full saturation of the soil, and therefore generate more groundwater recharge. When two or more rainfall events occur in a short amount of time, the soil can have a high soil moisture content from the first rainfall event. When, in a short amount of time a second rainfall event occurs, the soil can still be saturated and the soil will lose excessive water to lower layers faster.

4.5 Spatial distribution of sensitivity

Similar land use changes were made in all sub-basins, from fruit trees to grass. The percentual change of the rainfall partitioning to groundwater recharge for each sub-basin is presented in figure 15. The results show that the sensitivity of groundwater recharge to land use changes is spatially distributed within the Day River Basin. In the sub-basins with dark red, groundwater recharge rates are highly sensitive to land use changes. One of the most extreme sub-basins is sub-basin 14 where land use changes caused a reduction of the rainfall partitioning to groundwater recharge of 37%. Similar land use changes have relatively lower effects on the rainfall partitioning to groundwater recharge in other sub-basins. These are the sub-basins with lighter colors such as, sub-basin 70 and 71.

The sensitivity of groundwater recharge seems to have a similar structure as the elevation map (appendix I). Sensitivity is highest in areas with lower elevation levels, which are also more flat. In these flat areas, land use changes are more dominant to groundwater recharge than in hilly and mountainous areas. This result shows that the slope in the mountainous areas is also a dominant factor effecting the groundwater recharge rates. Additionally, the lower areas are characterized by loam and clay loam soil structures which have a relatively low hydraulic conductivity compared to sandy loam soils. Groundwater recharge rates are initially lower in areas with loam and clay loam soils. When land use changes occur both soil structure and land use limit the infiltration capacity, resulting in local reductions of the rainfall partitioning up to 30%.

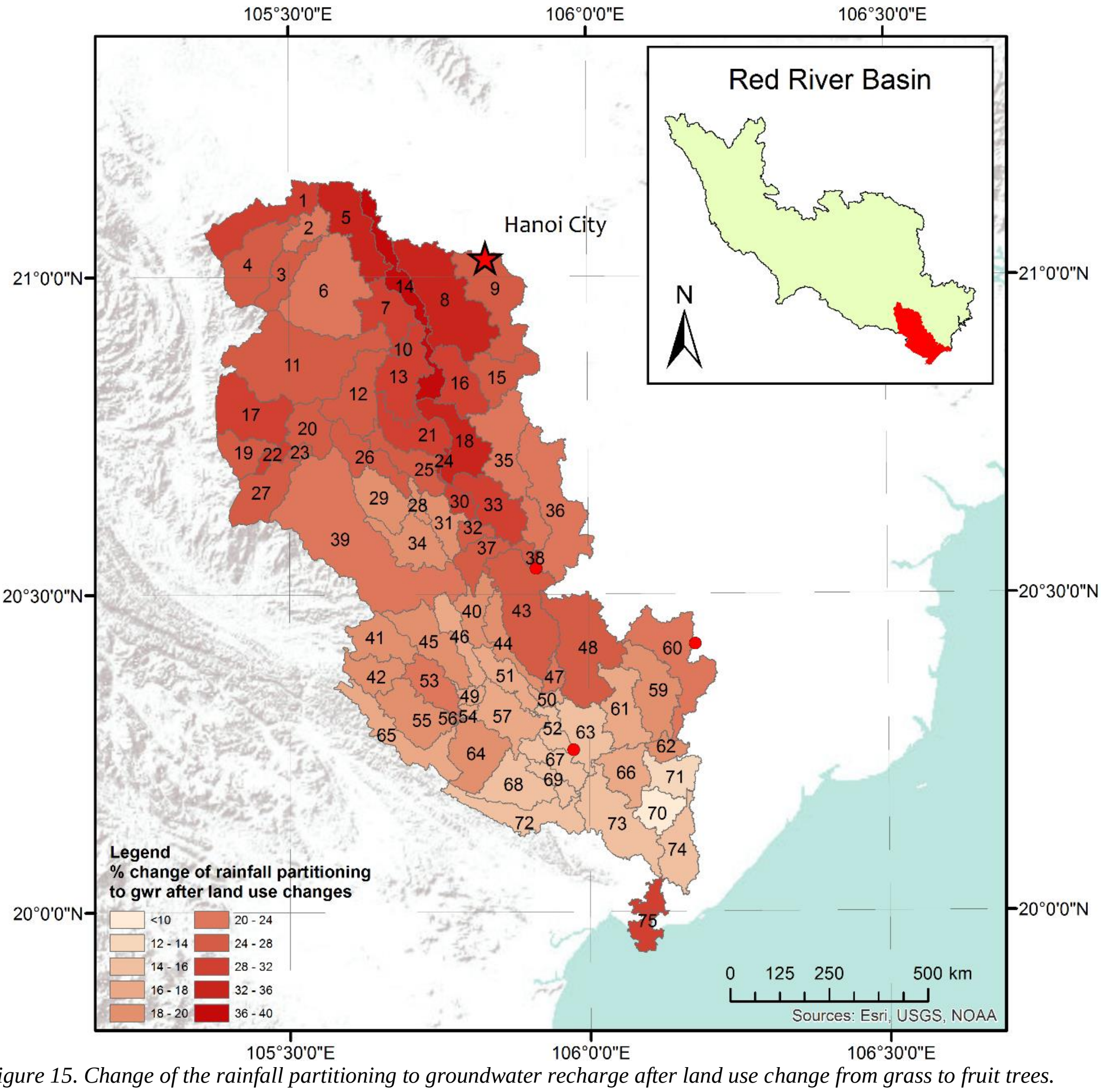


Figure 15. Change of the rainfall partitioning to groundwater recharge after land use change from grass to fruit trees.

5 Discussion

5.1 Reliability of results

Watershed-modeling approaches may be more accurate in humid regions, where perennial surface-water flow can be used for model calibration, than in arid- semi-arid regions (Scanlon et al., 2002). The Day River basin is situated in wet-hot tropical monsoonal climate and is therefore watershed modelling tools such as SWAT tend to generate accurate results. Also for this study surface water flow is used to calibrate the model. A drawback of the SWAT model is the fact that it considers the Day River Basin watershed boundaries as real boundaries. Within the SWAT model there is no interaction between the watershed under consideration and the surrounding area while in reality, many flow alterations and exfiltration causes water to flow into the Day River Basin in the upstream areas. This drawback of the model specifically showed during model calibration where the modelled discharge values in the upstream area of the Day River Basin where significantly underestimated compared to the observed discharge values. At downstream locations (Ninh Binh station) SWAT simulated discharge improved compared to the observed discharge because the upstream area receiving rainfall had increased.

Calibration for the SWAT model is done using q-h relationships from a study by Luu et al., (2010). Luu et al., (2010) describes the role of tidal influence on the measured waterlevels in the Day River. The tidal influence on daily variations on waterlevel where not taken into account for the q-h relationships. The SWAT model does not take tidal influence into account either.

Demessie (2015) concluded that land use change, in time will also change soil properties. The long term effects of land use changes on soil properties is not taken into account in this study. It would require a much more detailed soil map, soil data, and a lot of field measurements, to take this long term effect into account. The effects of land use changes on groundwater recharge would be more significant if soil properties also change.

Besides land use, other factors might also influence the amount of groundwater recharge such as lateral inflow from streams, lakes and rivers, pipe leakage in urban areas and non-diffused groundwater recharge by artificial recharge wells. These factors are not incorporated in the SWAT model, so in urban areas SWAT might underestimate the amount of groundwater recharge to some extend as other sources for groundwater recharge might be present in real urban areas.

5.2 Possible improvements

The runoff-infiltration process in SWAT is simulated using the SCS curve number method which is a function of as function of hydrologic group, hydrologic condition, cover type, and antecedent moisture condition (Miller et al. 2002). The other method to simulate the runoff-infiltration process in SWAT is the Green and Ampt method which models the infiltration process and considers excessive water as runoff. The Green and Ampt method requires a lot more input data such as sub-daily rainfall measurements, improved soil data and additionally data on the maximum canopy storage. It is arguable that the Green and Ampt method provides a better physically representation of the runoff-infiltration process, but for large scale watersheds such as the Day River Basin the curve number method provides acceptable results. For studies on a smaller scale with abundant data available, the Green and Ampt method might improve model performance to some extent.

The performance of the SWAT model is dependent and limited by the level of detail in the land use map. Some classes in the current land use map, such as ‘forest’ or ‘other crops’ can further be reclassified to obtain more detailed model input. An improved land use map would also result in more detailed output for the SWAT model. Improving the detail level of the land use map would probably not significantly change the overall model output or water balance. The boundaries of the 13 classes currently present in the land use map will not change, only within each class a more detailed division of land uses can be made. ‘Forest’ can be reclassified to different types of forest, but the level 1 classification will remain and the land use type will always be forest. For this reason an improved land use map can be made but would only be advisable in case there is a specific interest in the hydrological effects on groundwater recharge for specific land use types. An improved land use map would also improve the model performance in terms of estimating evapotranspiration. Improved data and knowledge on plant growth and harvest cycles in the Day River Basin would also improve the evaporation component in the model.

For the Day River Basin daily rainfall measurements were available from 11 metrological stations. Occasionally extreme local rainfall events occur in the Day River Basin. When having a limited amount of rainfall measurement point, SWAT risks overestimation of extreme rainfall events. If only one measurement station is in the center of an extreme rainfall event, the model cannot estimate the spatial distribution and areal coverage of the extreme event. This might lead to temporal high run off rates in the model. These peaks are also observed in the daily discharge values in SWAT. SWAT is not able to simulate extreme run off events and floods, and therefore occasionally high discharge peaks might be observed, especially in humid areas with extreme rainfall events.

5.3 Further research

This study estimated the effects of land use change on groundwater recharge on a watershed scale. It would be interesting to estimate groundwater recharge rates at a smaller spatial scale, to obtain comparative data for the SWAT model. When the swat model (watershed scale) results are compared to a smaller scale model/simulations on groundwater recharge in a sub-catchment in the upper day river basin (local scale), new conclusions can be drawn on the SWAT model performance. Besides expert knowledge on groundwater recharge processes in the Day River Basin there are no comparative study results available for the Day River Basin which specifically focus on groundwater recharge.

6 Conclusion

The main research question is **"what are the potential effects of different land use change scenarios on groundwater recharge in the Day River Basin and how can these effects be explained?"**

Three land use change scenarios show different effects on groundwater recharge in the Day River Basin. The BAU scenario, which assumes no implementation of new policies and represents a continuation of current trends, shows decreasing groundwater recharge rates in almost all sub-basins. The same goes for REG scenario where even more rapid land use changes such as urbanization and deforestation are at hand, drastically reducing the rainfall partitioning to groundwater recharge. The SUS scenario shows that sustainable policies, such as, reforestation practices can potentially influence the rainfall partitioning to groundwater recharge in a positive way.

The land use changes seem to have limited effects on the groundwater recharge rates when monthly values are evaluated. Cumulative trends over a longer time period, show a different pattern which indicates that land use changes do in fact drastically effect groundwater recharge rates. Land use change can positively or negatively influence groundwater recharge, depending on the kind of land use changes. Forest and grass generate the most groundwater recharge, impervious areas the least. Also paddy field has a small groundwater recharge rate.

Looking at a sub-basin scale, changes in groundwater recharge occur in areas where most land use changes are at hand. But similar land use changes do not have the same effects in all sub-basins. In lower areas with little slopes, land use changes reduce the rainfall partitioning to groundwater recharge more than in mountainous areas. The sensitivity of groundwater recharge to land use changes is spatially distributed. It can be concluded that land use changes have a strong correlation to the groundwater recharge the Day River Basin. As groundwater resources in the Day River Basin are depleting rapidly, policy effective measurement are needed to address the issue of reducing groundwater recharge as a result of land use changes. Since the effects of land use change on groundwater recharge are significant, land use planners should take into account the effects of their decisions on groundwater recharge, as it is one of the most valuable ecosystem services in the Day River Basin.

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Appendix I Input data

Input data for SWAT was gathered by visiting local experts in Vietnam working for the MK27 project. Additionally on-line databases were used to gather input data. SWAT requires a variety of input data such as, a digital elevation map, soil map, land use map and weather data input. Data on water system regulations, and meteorological- and hydrologic measurements were also gathered for model calibration. Table 7. Gives an overview of the local experts which were visited and which data was gathered during the visits. Figure 16-17 on the following pages show the FAO soil- and digital elevation map used as input for SWAT.

Institute	**contact**	**data**
IWRP	Thanhlan Ha	Digital Elevation Map (Japan Space Systems 2014 (J-spacesystems), 2015) Evapotranspiration estimates based on Landsat images (SEBS, 2015)
HUNRE	Le Tranthanh	Groundwater recharge observations in the upper Day River Basin
HUNRE	Thi von le Khoa	Soil database
HUNRE	Sơn Tùng Nguyễn	Land use classification/Land use map
Vinwater	Nguyễn Quang Đức Anh	Locations and details of head regulators
Vinwater	Le Duc Dung	Meteorological stations: rainfall/temperature measurements Hydrologic stations: waterlevel measurement
Futurewater	Gijs Simons	Topographic maps Shapefiles for Day and Red River Basin
On-line database		Rivernetwork Basin (Hydrosheds, 2015) FAO soil map (FAO, 2015) Weather data (The National Centers for Environmental Prediction (NCEP), 2015) Mekong data SWAT (Mekong River Commision, 2004)

Table 7 Overview of local experts and the obtained data during visits

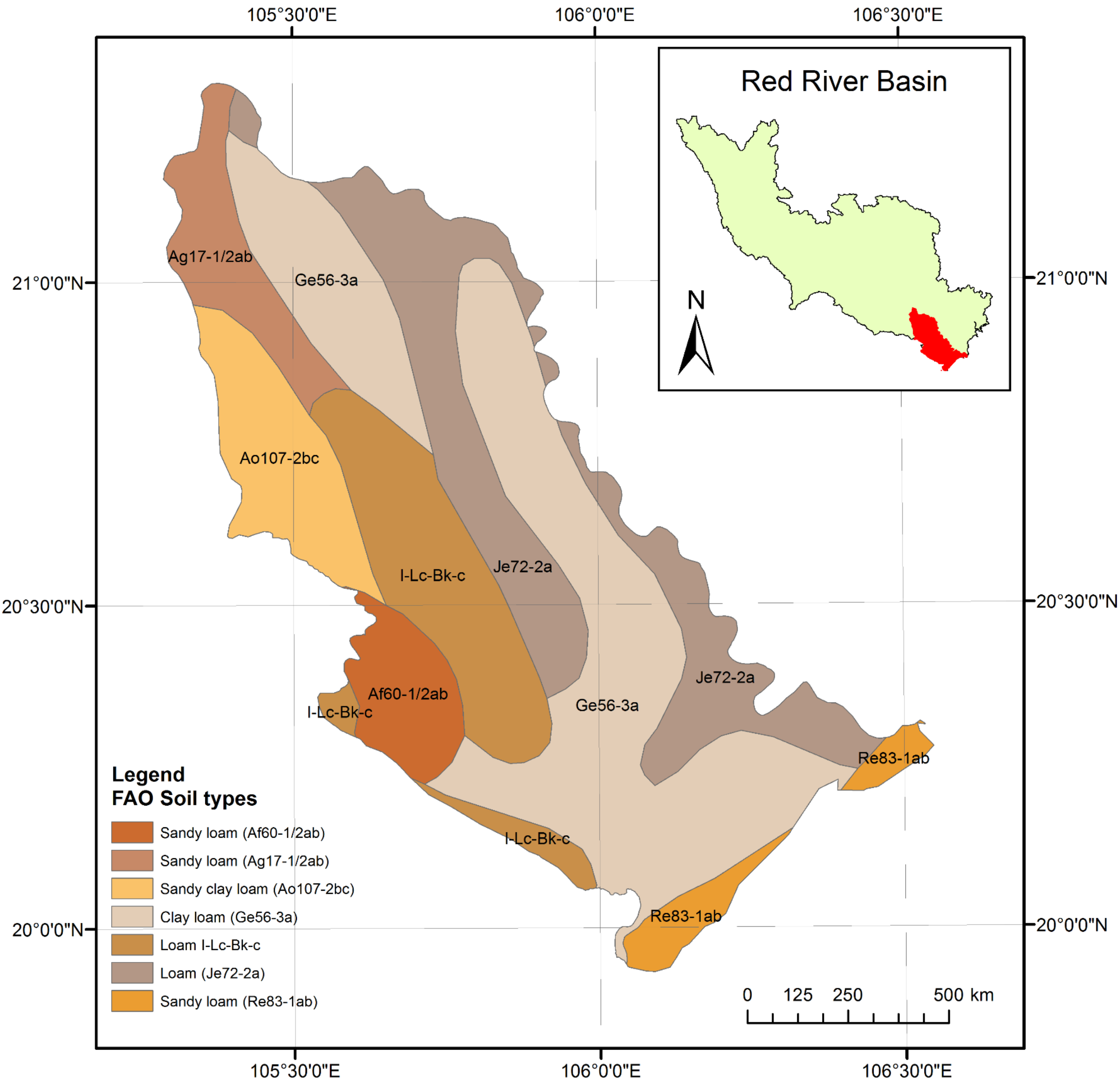


Figure 16. FAO soil map (FAO, 2015)

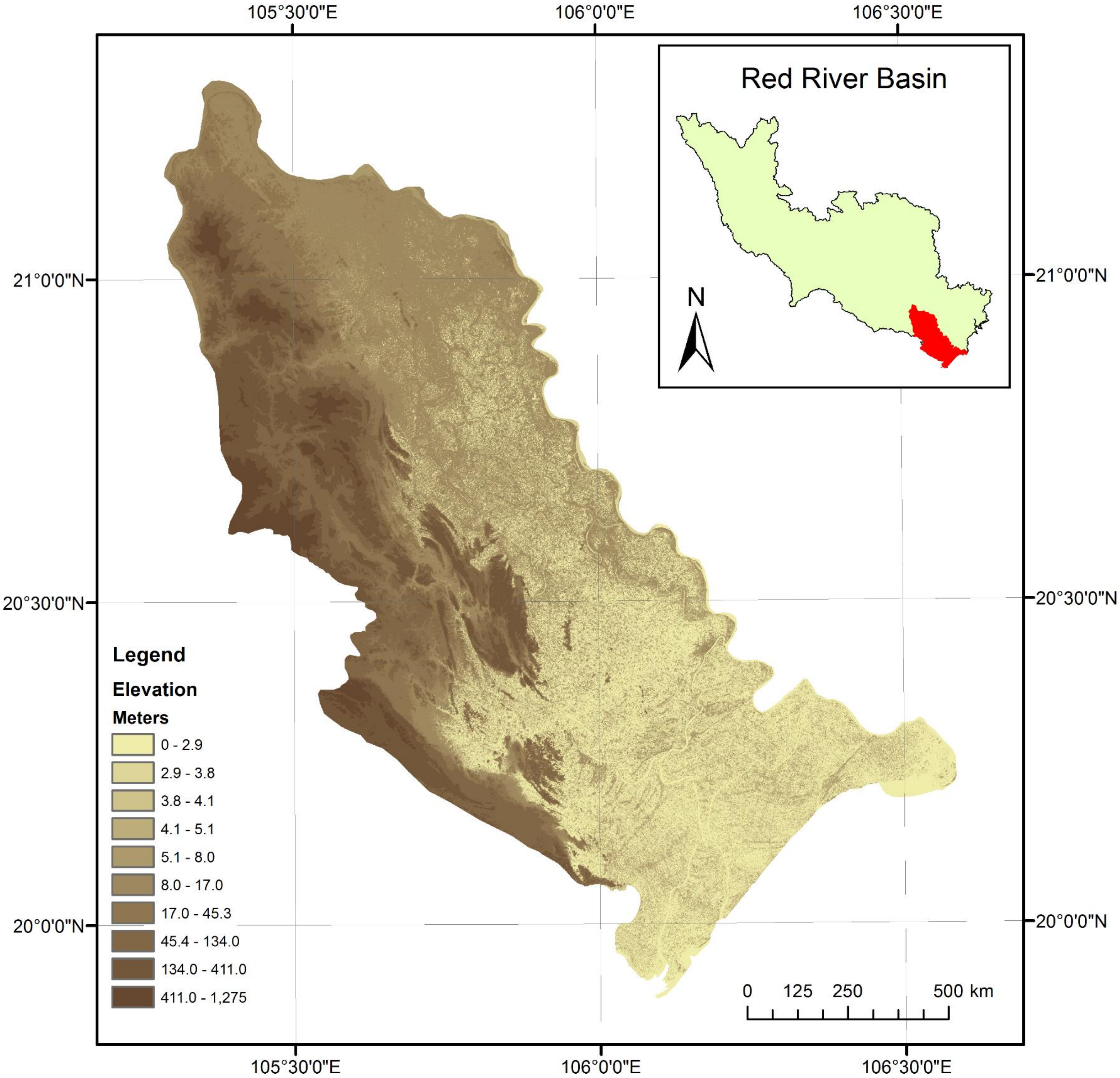
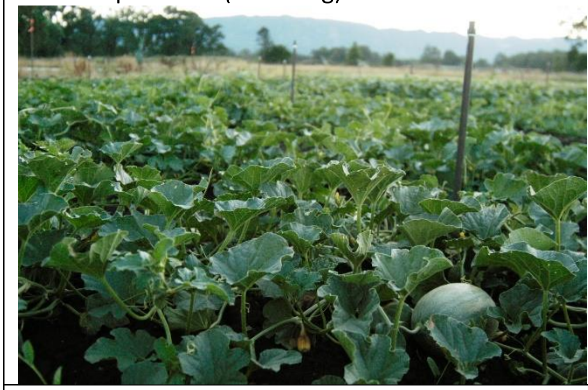


Figure 17. Digital Elevation Map (DEM) in meters above sea-level (Japan Space Systems, 2015)

Appendix II Land use classification Day River Basin

1. Crops

Cantaloupe melon (Dưa vàng) **1.1**	Carrot (Cà Rốt) **1.2**
	
Corn (Ngô) **1.3**	Cowpeas (Đậu đũa, Đậu dải) **1.4**
	
Field peas (Đậu hà lan) **1.5**	Garden (Vườn rau) **1.6**
	
Green beans (Đậu co ve) **1.7**	Honeydew Melon (Dưa bở) **1.8**
	

Mulberry tree (Dâu tằm) **1.9** 	LMB Tea (Chè) **1.10** 
Mung Beans (Đậu xanh) **1.11** 	Orange (Cam) **1.12** 
Orchard (Vườn cây ăn quả) **1.13** 	Paddy field (Ruộng lúa) **1.14** 
Peach tree (đào) **1.15** 	Pineapple (Dứa) **1.16** 

Plaintains (Asian bananas) (Chuối mễ) **1.17**

Potato (Khoai tây) **1.18**

Soybean (Đậu tương) **1.19**

Sugarcane (Mía) **1.20**

Sweetclover (Nhãn hương) **1.21**

Sweetpotato (Khoai lang) **1.22**

Watermelon (Dưa hấu) **1.23**

2. Forest

Disturbed forest (Rừng bị phá) **2.1**

Evergreen forest (Rừng thường xanh) **2.2**

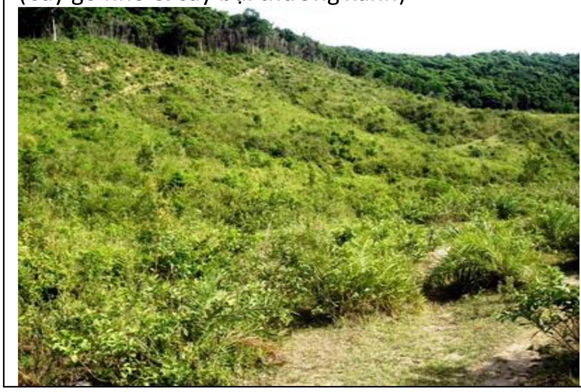
Mixed Forest (Rừng hỗn hợp) **2.3**

3. Grass

Pasture (Đồng cỏ) **3.1**

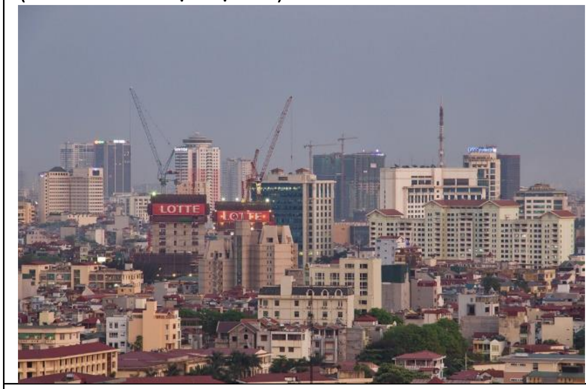
4. Shrub

Wood- and shrubland, evergreen (Cây gỗ nhỏ & cây bụi thường xanh) **4.1**



5. Impervious

Residential-High Density
(Khu dân cư mật độ cao) **5.1**



Residential-Medium Density
(Khu dân cư mật độ trung bình) **5.2**

Residential-Low Density
(Khu dân cư mật độ thưa) **5.3**

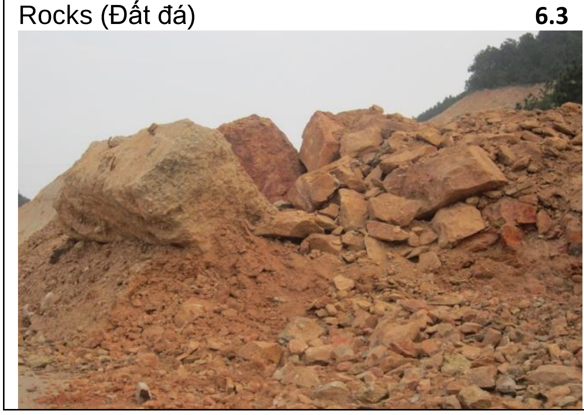
Industrial
(Khu công nghiệp) **5.4**

6. Soil

Barren land (Đất trống) **6.1**

Miscellaneous land (Đất trống nhiều đích) **6.2**

Rocks (Đất đá) **6.3**



7. Water

Aqua-culture (Vùng nuôi trồng thủy sản) **7.1**	Water (Mặt nước) **7.2**
	

8. Wetland

Mangrove (Rừng ngập mặn) 8.**1**	Wetland (Đất trũng, đầm lầy) **8.2**
	

Appendix III SWAT parameters description

The ‘Manual calibration tool’ from SWAT allows the user to change parameters settings to improve model performance. Table 8 gives an overview and description of the available parameters and the ranges for the parameter values.

Parameter	Description	Ranges/Values
Alpha_bf	Baseflow alpha factor (1/days).	Values vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with rapid response.
Biomix	The redistribution of soil constituents as a result of the activity of biota in the soil (earthworms etc.).	Swat allows bio mix to occur to a depth of 300 mm. If no value is entered swat puts value on 0.20.
Canmx	Maximum canopy storage. Plant canopy can significantly affect infiltration, surface run off and evapotranspiration. As rain falls canopy interception reduces the erosive energy of the droplets and traps a portion of the rainfall within the canopy.	When calculating surface run-off, the SCS curve number method lumps canopy storage in the term for initial abstractions. This ‘initial abstractions’ variable also includes surface storage and infiltration prior to run off and is estimated as 20% of the ‘retention parameter value’ for a given day.
CH_cov	The Channel erodibility factor, channel coverage.	0 = non erosive channel 1 = no resistance to erosion
Ch_erod	The Channel erodibility factor.	A set value between 0 and 1 non erosive to no resistance to erosion.
Ch_N2	Manning’s N-value for the main channel. Manning’s roughness coefficient.	Typical values for Ch_N2 for channel flow are given in SWAT-IO-documentation-2012.pdf table 25-1 page 332.
Ch_K2	Effective hydraulic conductivity in tributary channel alluvium (mm/h). This parameter controls transmission losses from surface run off as it flows to the main channel in the sub-basin.	Typical values for Ch_K2 for various alluvium materials are given in SWAT-IO-documentation-2012.pdf table 25-2 page 334.
Cn2	Initial SCS curve number method for moisture condition II.	Typical curve numbers for moisture condition II are listed in (SCS Engineer Division, 1986) for various land cover and soil types. These values are appropriate for a 5% slope.
Epco	Plant uptake compensation factor. If upper layers in the soil profile do not contain enough water to meet the potential water uptake, users may allow lower layers to compensate.	Can range from 0.01 to 1.00. As epco approaches 1 the model allows more of the water uptake demand to be met by lower layers in the soil, as it approaches 0.01 the model allows less variation from the original depth distribution to take place.
Esco	Soil evaporation compensation factor. This coefficient allows the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks.	Range 0.01 to 1.00 As the value for esco is reduced, the model is able to extract more of the evaporative demand from lower levels.
Gw_delay	Groundwater delay time (days). Water that moves past the lowest depth of the soil profile by percolation or bypass enters and flows through the vadose zone before becoming shallow aquifer recharge. The lag between the time that water exits the soil profile and enters the shallow aquifer will	The gw_delay time cannot be directly measured. It can be estimated by simulating aquifer recharge using different values for gw_delay and comparing the simulated variations with observed values. Sangrey et al. (1984) notes that monitoring wells in the same area had similar values for gw_delay.

	depend on the depth to the water table and the hydraulic properties of the geologic formations in the vadose and groundwater zones.	
Gw_revap	Groundwater revap coefficient. Water in the capillary fringe will evaporate and diffuse in periods when the material overlying the aquifer is dry. Once removed it is replaced by water from the underlying aquifer. Deep rooted plants can also uptake water directly from the aquifer, thus gw_revap varies per land use type.	Revap = water in the shallow aquifer returning to the root zone. As gw_revap approaches 0, movement of water from the shallow aquifer to the root-zone is limited. If gw_revap approaches 1 the rate of transfer from the shallow aquifer to the root zone approaches the rate of potential evapotranspiration. The value should be between 0.02 and 0.20.
Gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur. (mm)	Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than gwqmn.
Rchrg_Dp	Deep aquifer percolation factor. The fraction of percolation from the root zone which recharges to the deep aquifer.	The value should be between 0.0 and 1.0.
Revapmn	Threshold depth of water in the shallow aquifer for 'revap' or percolation to the deep aquifer to occur. (mm)	Movement of water in the shallow aquifer to the unsaturated zone is allowed if the volume of water in the shallow aquifer is equal or greater than revapmn.
Slsubbsn	Slope length.	Rule of thumb 90m is considered to be a very long slope length. Default is 50m.
Sol_Awc	Available water capacity of the soil layer. (mm/mm soil)	AWC = FC – WP AWC = plant available water content FC = water content at field capacity WP = water content at wilting point
Sol_K	Saturated hydraulic conductivity (mm/h). Relates soil water flow rate to the hydraulic gradient.	A measure of the ease of water movement through the soil.

*Table 8. Description of SWAT parameters present in the 'SWAT Manual Calibration Tool' (*Arnold et al., 2012)

Appendix IV Calibration and Validation

Figure 18, 19 and 20 present the measured- and modelled discharge after calibration (2006) at 3 locations along the Day River. From upstream to downstream, Ba Tha, Phu Ly and Ninh Binh.

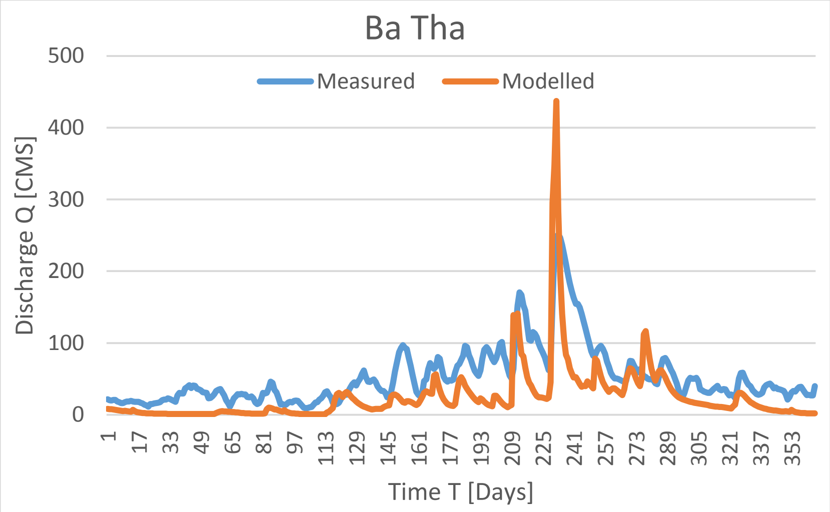


Figure 18. Measured vs. modelled discharge at Ba Tha (2006)

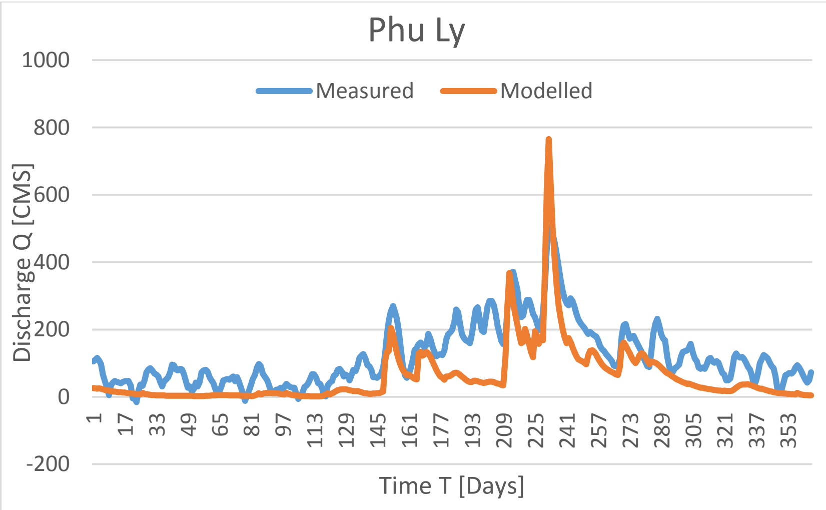


Figure 19. Measured vs. modelled discharge at Phu Ly (2006)

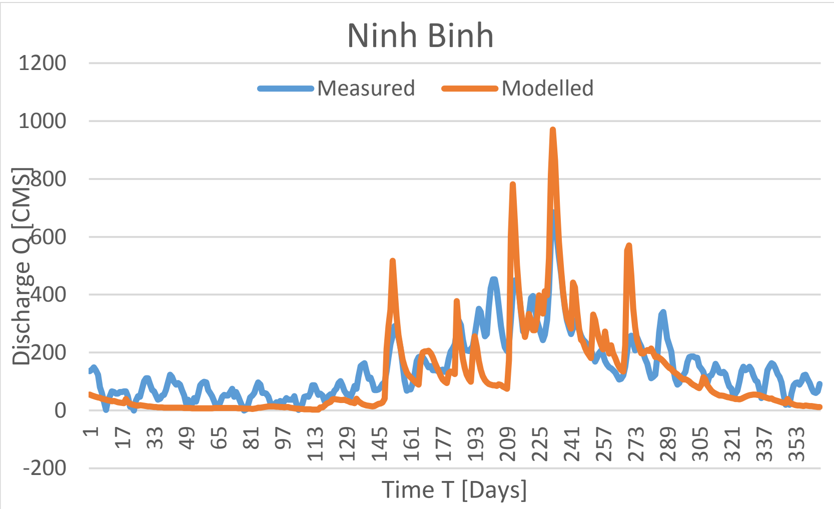


Figure 20. Measured vs. modelled discharge at Ninh Binh (2006)

Figure 21, 22 and 23 present the cumulative measured- and modelled discharge after calibration (2006) at the same 3 locations. From upstream to downstream, Ba Tha, Phu Ly and Ninh Binh.

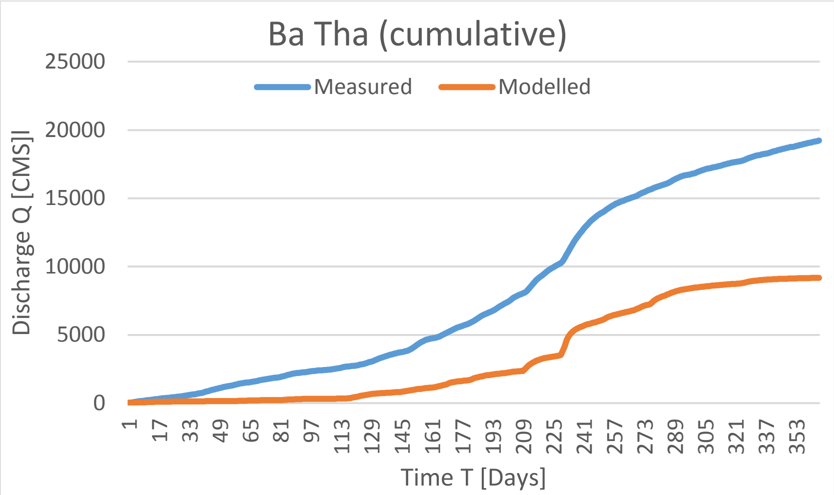


Figure 21. Cumulative measured vs. modelled discharge at Ba Tha (2006)

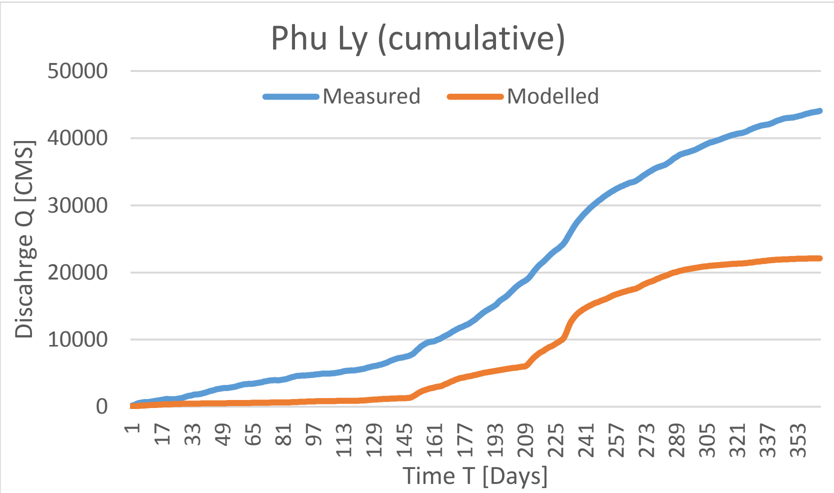


Figure 22. Cumulative measured vs. modelled discharge at Phu Ly (2006)

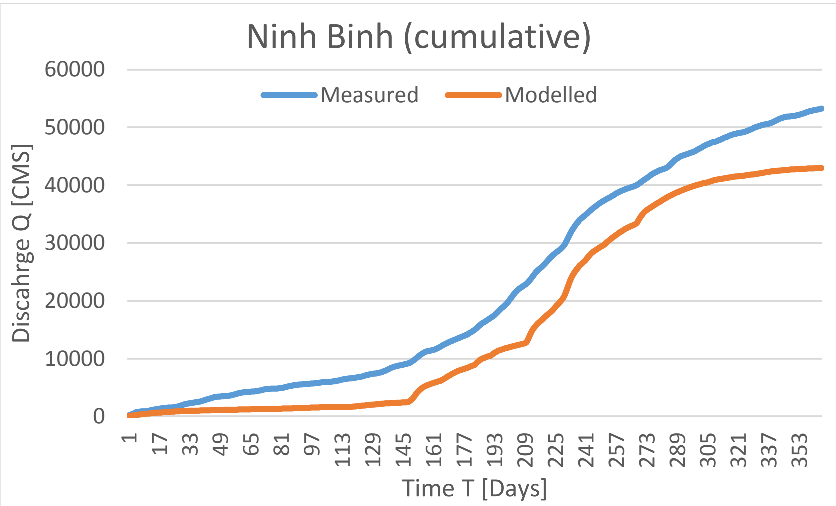


Figure 23. Cumulative measured vs. modelled discharge at Ninh Binh (2006)

Figure 24, 25 and 26 present the coefficient of determination for the measured- and modelled discharge after calibration (2006) at the same 3 locations.

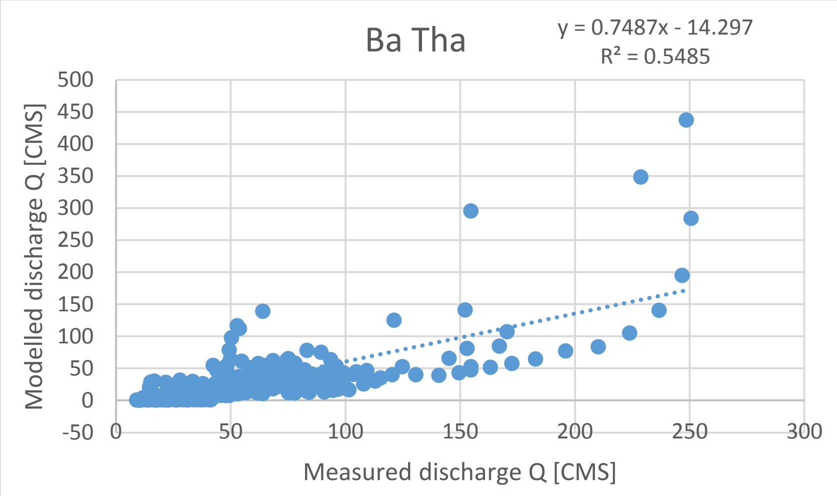


Figure 24. Coefficient of determination, Ba Tha (2006)

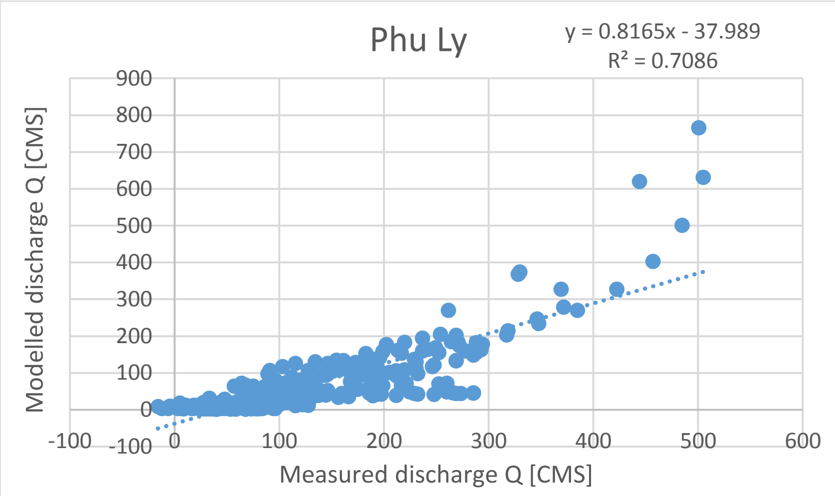


Figure 25. Coefficient of determination, Phu Ly (2006)

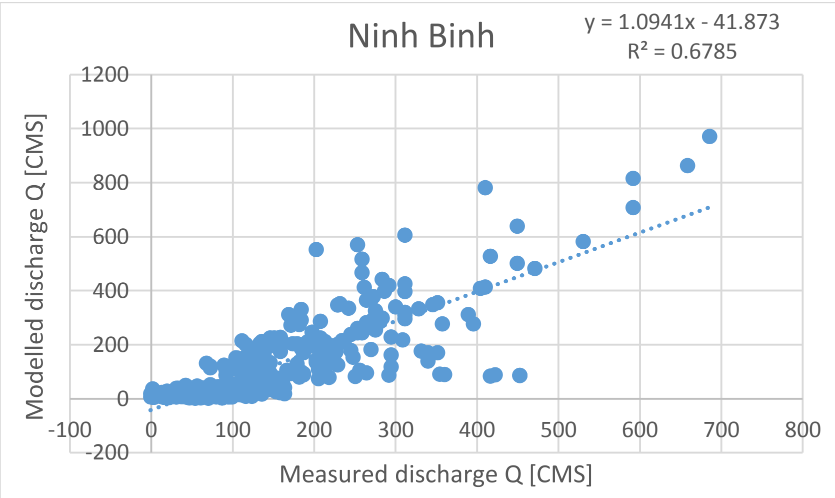


Figure 26. Coefficient of determination, Ninh Binh (2006)

Figure 27, 28 and 29 present the measured- and modelled discharge used for validation (2008) at 3 locations along the Day River. From upstream to downstream. Ba Tha, Phu Ly and Ninh Binh.

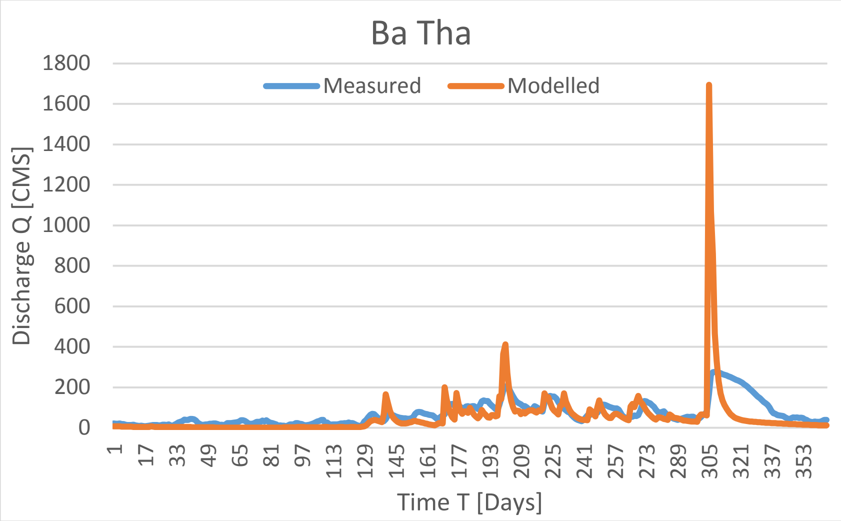


Figure 27. Measured vs. modelled discharge at Ba Tha (2008)

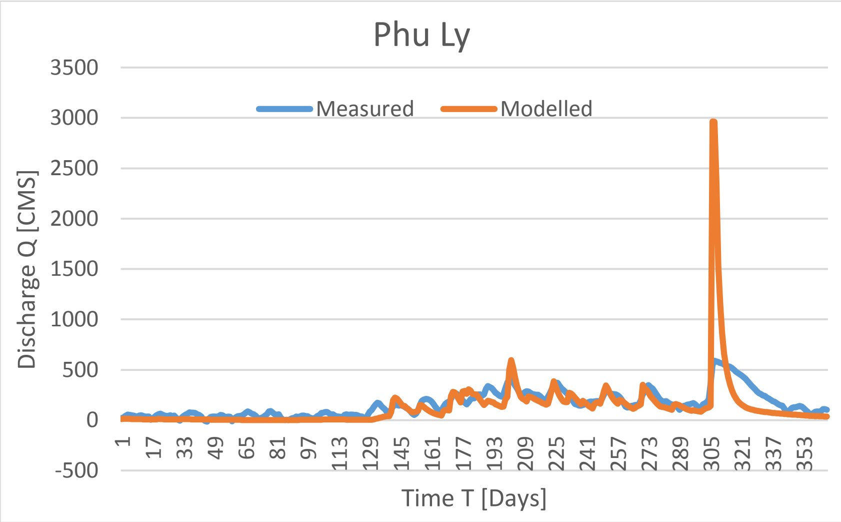


Figure 28. Measured vs. modelled discharge at Phu Ly (2008)

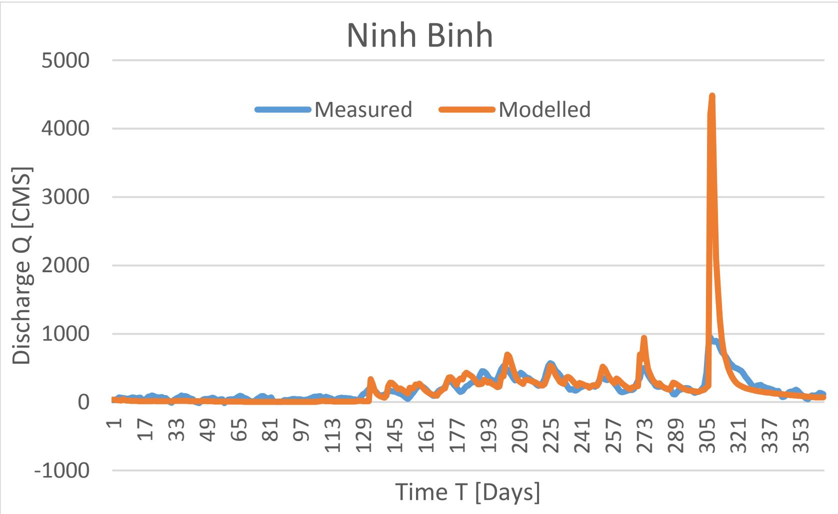


Figure 29. Measured vs. modelled discharge at Ninh Binh (2008)

Figure 30, 31 and 32 present the cumulative measured- and modelled discharge for validation (2008) at the same 3 locations. From upstream to downstream, Ba Tha, Phu Ly and Ninh Binh.

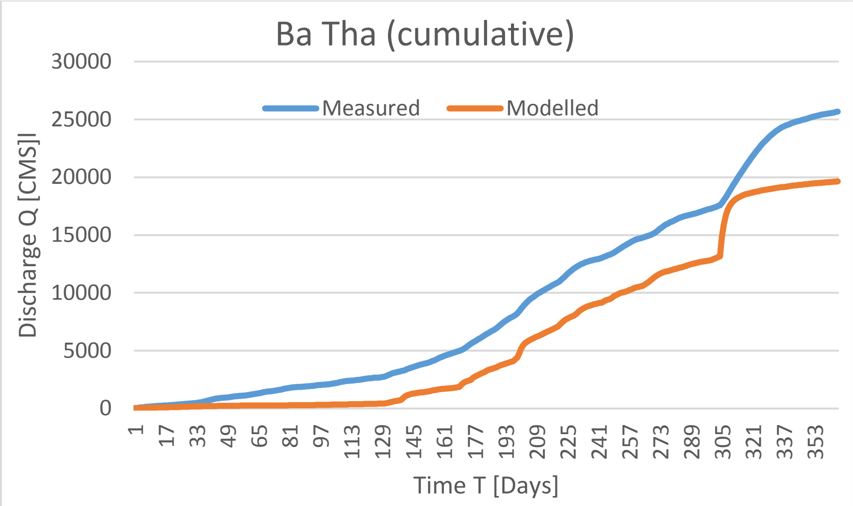


Figure 30. Cumulative measured vs. modelled discharge at Ba Tha (2008)

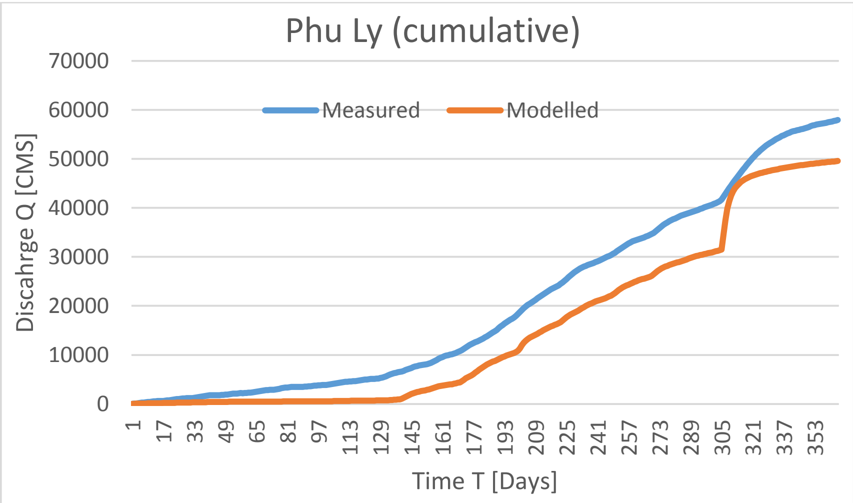


Figure 31. Cumulative measured vs. modelled discharge at Phu Ly (2008)

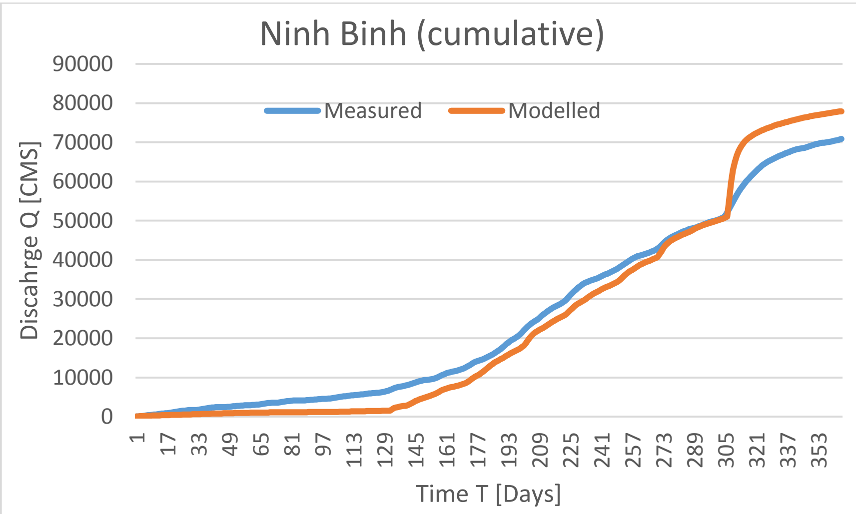


Figure 32. Cumulative measured vs. modelled discharge at Ninh Binh (2008)

Figure 33, 24 and 35 present the coefficient of determination for the measured- and modelled discharge for validation (2008) at the same 3 locations.

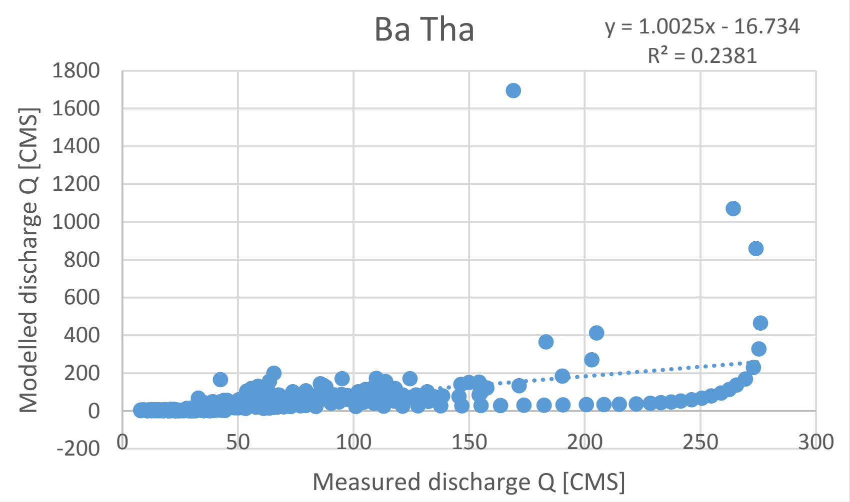


Figure 33. Coefficient of determination, Ba Tha (2008)

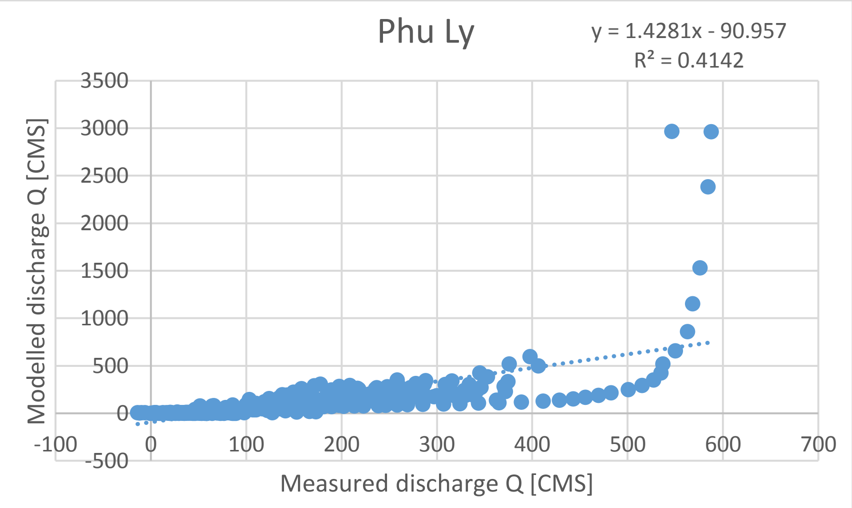


Figure 34. Coefficient of determination, Phu Ly (2008)

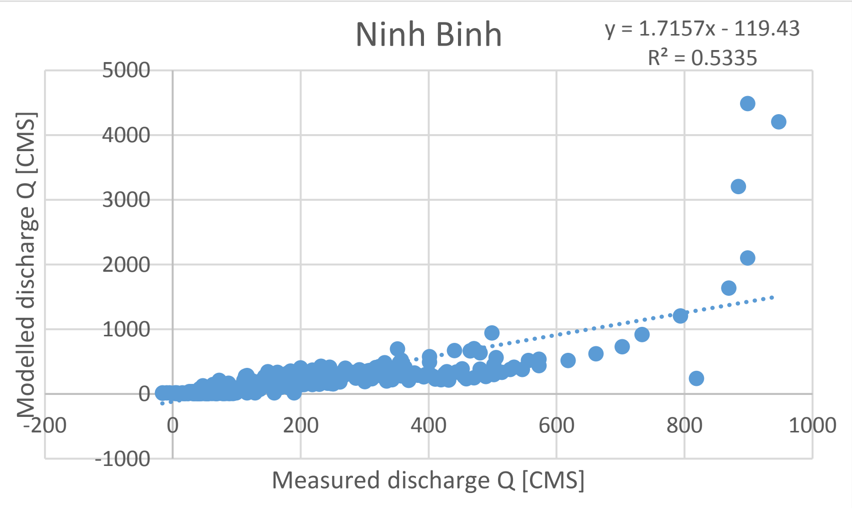


Figure 35. Coefficient of determination, Ninh Binh (2008)

Appendix V Land use map, current situation

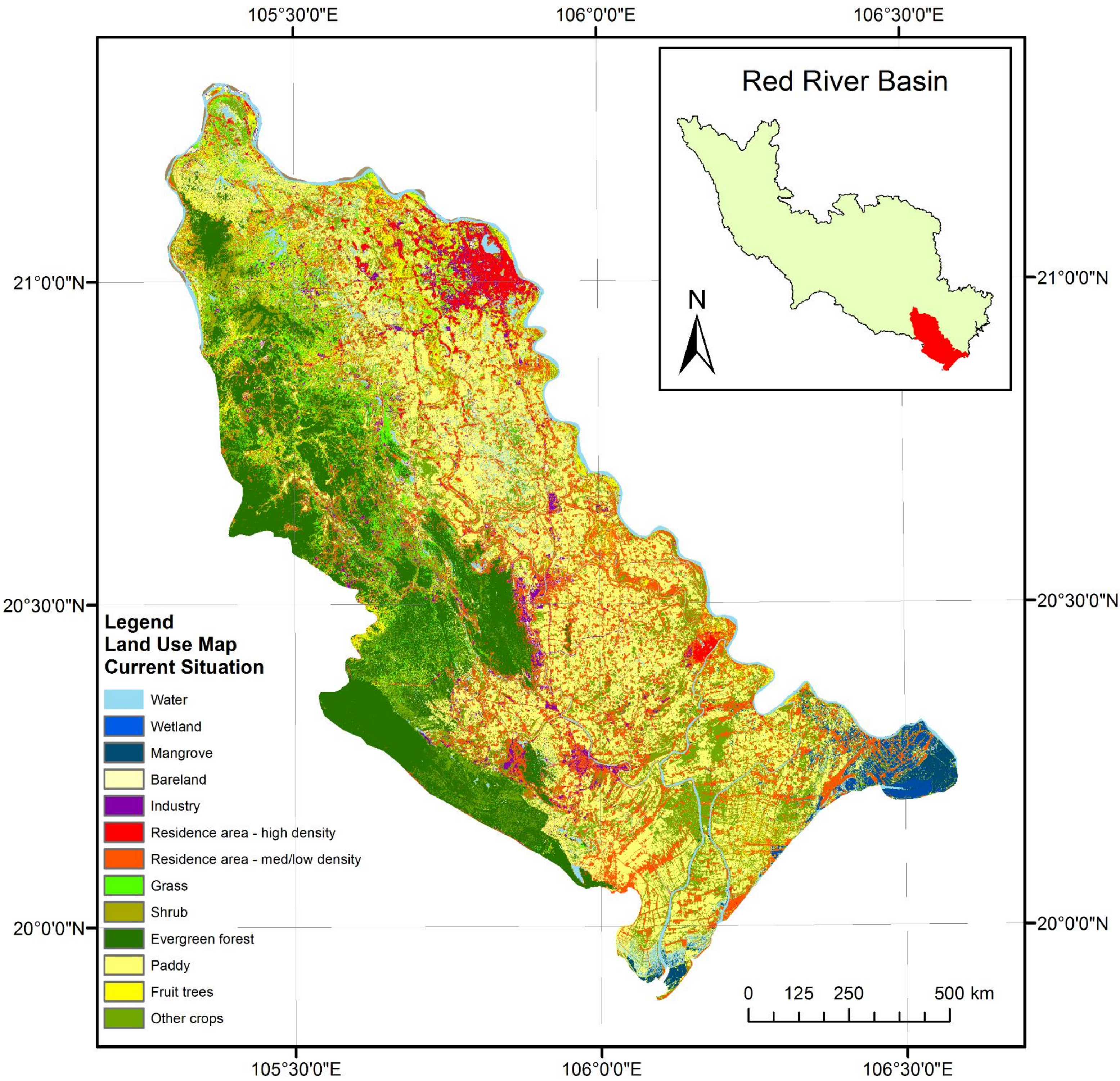


Figure 36. Land use map Day River Basin, current situation

Appendix VI Land use map scenario I

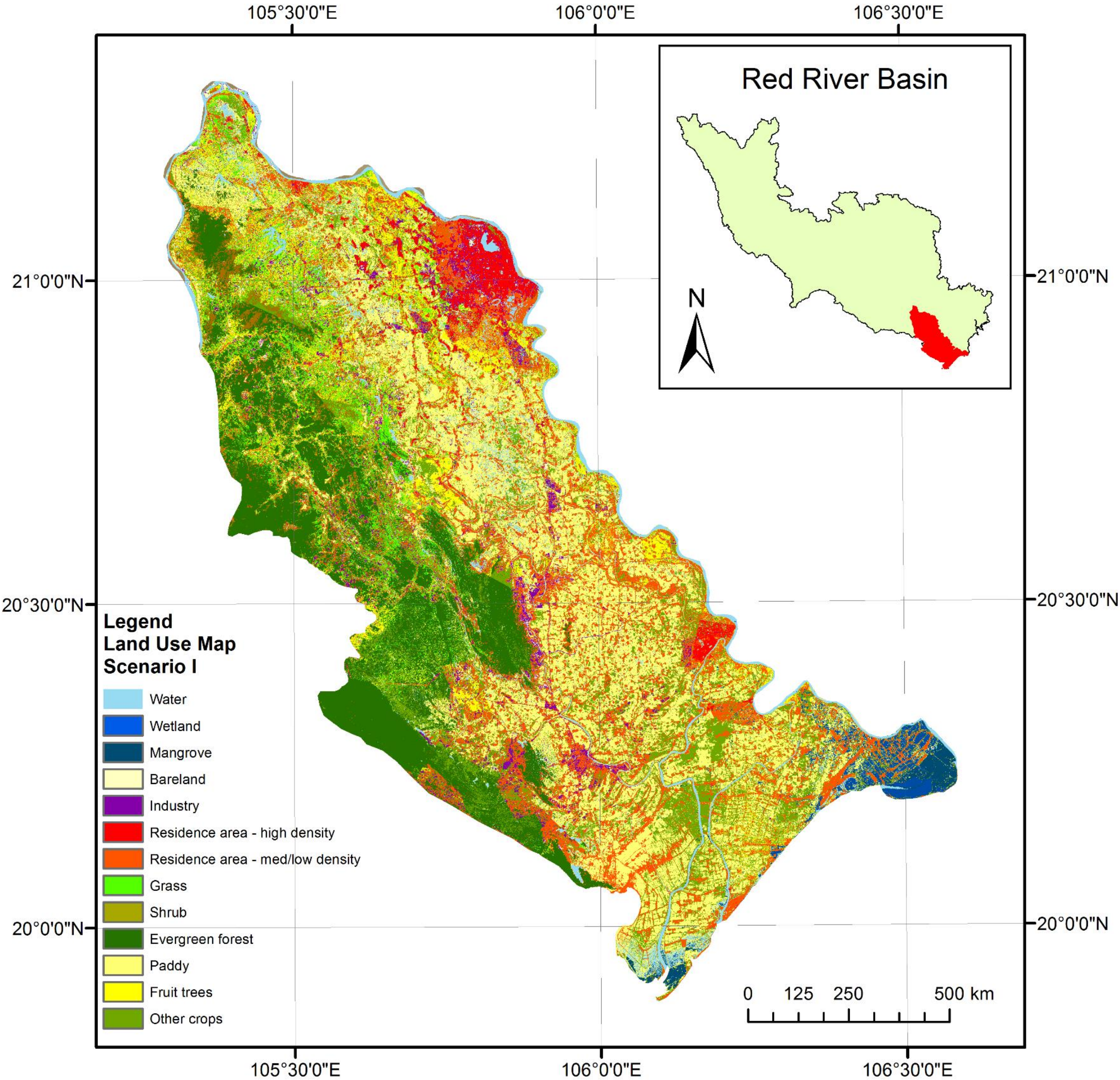


Figure 37. Land use map scenario I

Appendix VII Land use map scenario II

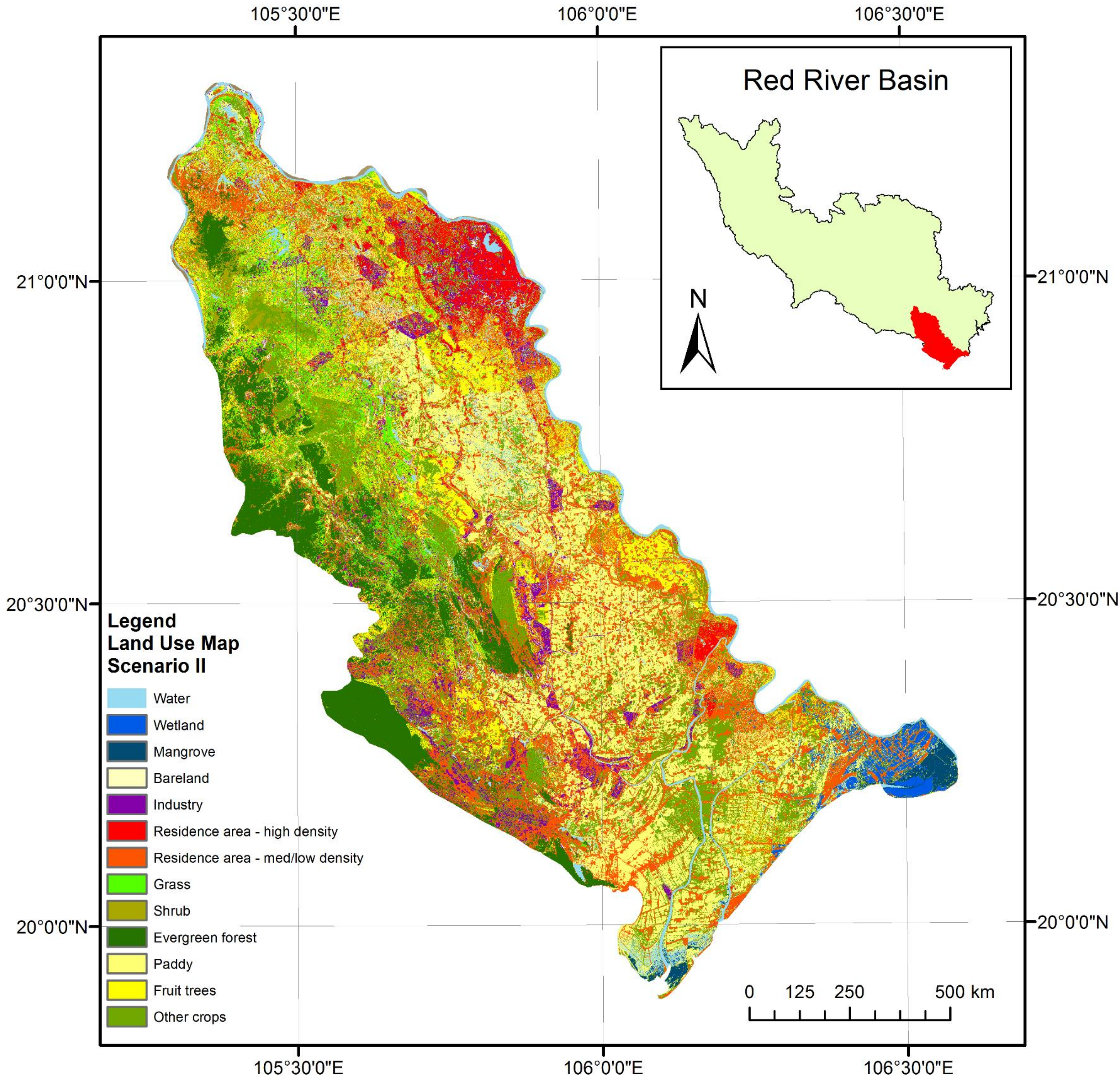


Figure 38. Land use map scenario II

Appendix VIII Land use map scenario III

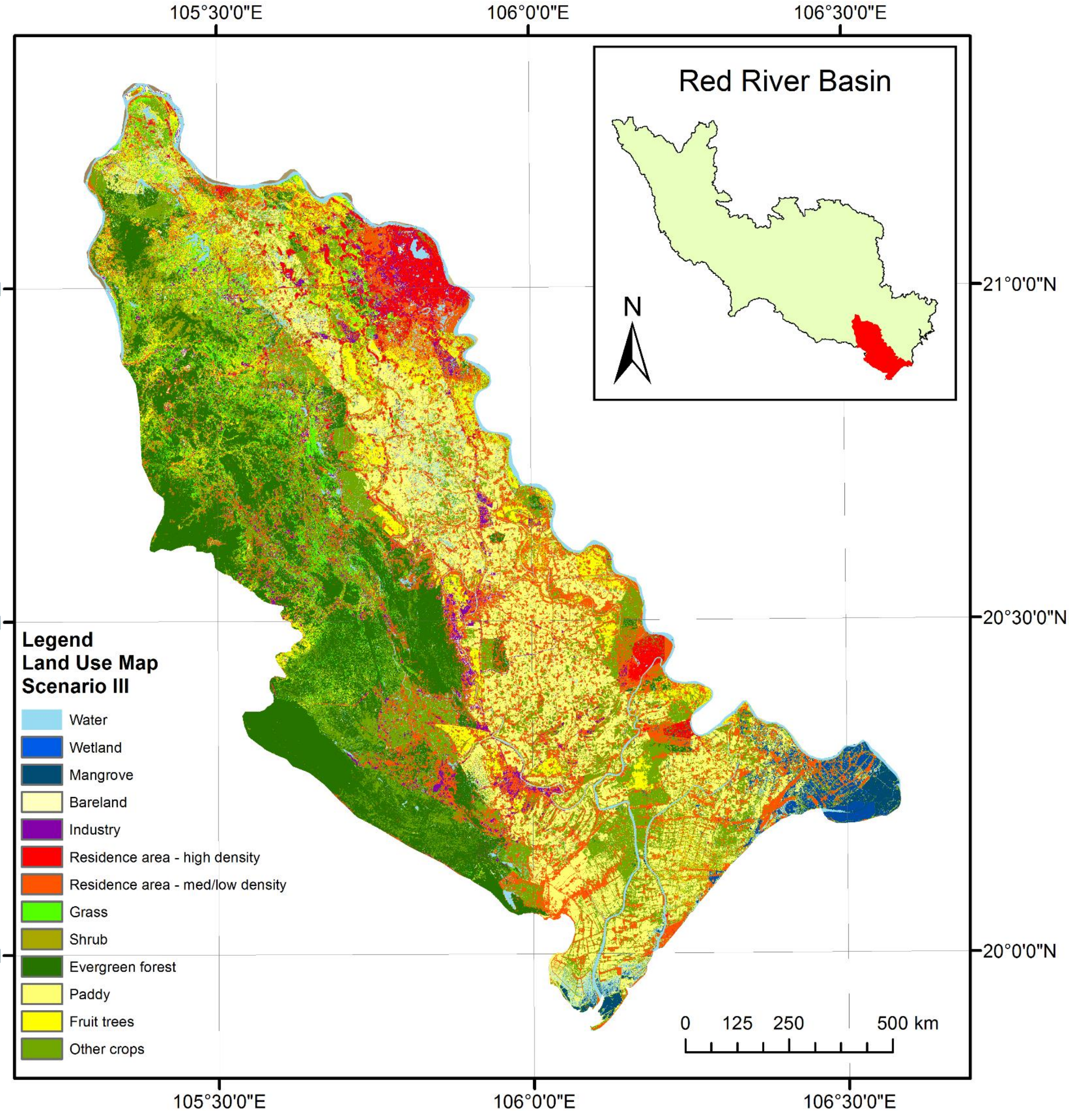


Figure 39. Land use scenario III