Translating Climate Science into Policy Making in the Water Sector for the Vu Gia- Thu Bon River Basin

A DOCTORATE DISSERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF ENGINEERING

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ABSTRACT

Vu Gia- Thu Bon River Basin, located in the Central Coastal Zone of Viet Nam faces water shortage problems. This is expected to be further exacerbated in the future as a result of climate change. Previous attempts in addressing water shortage in the area followed a traditional top-down, predict-then-act approach. In such an approach, General Circulation Model outputs simulating future climate conditions are downscaled then adaptation measures proposed. This approach could produce optimal adaptation solution under an intended future. However, given the uncertainties related to GCMs, the approach fails to provide satisfactory information for adaptation measures. This study utilizes a combined top-down and bottom-up climate change impact assessment instead. A MIKE BASIN water balance model is used to analyze the water system response in the Vu Gia- Thu Bon River Basin under different rainfall and temperature ranges. Problematic conditions were then identified. Outputs from 25 GCMs were used to map the vulnerability space of the water system onto possible future climate conditions. A more detailed analysis of the system is thus performed only on problematic conditions suggesting both by the MIKE BASIN model and the GCM outputs. An analysis of the effects of current land use policy was performed to assist in the understanding of the changes in land policy and its effect on water usage. This was done through analyzing satellite images between the years 2011 and 2016 during the land use master plan period of 2011-2020. The results obtained in the study suggest that at a minimum, 66.36 km^2 of agricultural area would be facing water challenges in the future. Under more severe climate change conditions, up to 87.77 km^2 of crops would be facing water shortages. Overall, there is a water deficit of between approximately 11 million and 21 million m^3 of water for agricultural production. To meet the demand, the study proposes two lines of action, namely conserve/reduce use of water, and production of additional water. Conserving/reducing water usage could be achieved through changing crop types, irrigation practice, and introducing water efficient technologies. On the other hand, production of additional water includes the construction of more water reservoirs as well as to look into options such as seawater desalination.

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LIST OF ABBREVIATIONS

CDO	Climate Data Operators
CH_4	Methane
CMPI5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon Dioxide
DPSIR	Driving forces, Pressures, States, Impacts, Responses
DONRE	Department of Natural Resources and Environment
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
GHG	Greenhouse Gas
GIS	Geographic Information System
GCM	General Circulation Model/ Global Circulation Model
LWR	Long wave radiation
MONRE	Ministry of Natural Resources and Environment
IMHEN	Viet Nam Institute of Meteorology, Hydrology and Climate Change
IPCC	Intergovernmental Panel on Climate Change
NDBI	Normalized Difference Built-up Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NHMS	National Hydro-Meteorological Service
NO_2	Nitrous dioxide
RCHM	Regional Center for Hydrology and Meteorology
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SSP	Shared Socioeconomic Pathways
SWR	Short wave radiation
SWSI	Surface Water Supply Index
SO_2	Sulfur Dioxide
UTM	Universal Transverse Mercator
VGTB	Vu Gia- Thu Bon

1 INTRODUCTION

The motivation of the study is the realization that a traditional top-down climate change impact assessment have limitations in assisting adaptation policies both globally and in the VGTB River Basin. The first chapter of the report briefly states the problems related to climate change impact assessment and to illustrate the importance of a new approach. Research questions and research objectives are subsequently presented along with the structure of the report.

1.1 Background

Vu Gia- Thu Bon (VGTB) River Basin, located in the Central Coastal zone of Viet Nam, currently faces water shortages. Rainfall in the river basin is temporally variable with a distinct rainy season and a dry season. The rainy season, which begins in September and last until December, contributes approximately 70% to the total annual precipitation. On the other hand, the dry season spans the other 8 months within the year and contributes only 30% to total annual precipitation. Prolonged dry conditions with limited rainfall creates a huge challenge in water supply in the river basin.

As water resources will be the principal medium climate change impacts are felt (García, L.E. *et al.*, 2014), the challenges of water management in the VGTB River Basin is likely to be exacerbated in the future. Temperature and rainfall changes could reduce water availability in the river basin. Increase temperature could lead to increase evapotranspiration and increase air moisture holding capacity, i.e. more water losses and less rain. On the other hand, decrease rainfall directly reduces runoff in the river basin. The effects could be seen in an overall drier condition with a reduction in water availability. Other extreme weather events such as droughts, and heat waves are then expected to increase in both frequency and intensity (García, L.E. *et al.*, 2014; IPCC, 2012, 2013a).

There have been extensive studies into ways climate change impact the water systems in general and in the VGTB River Basin in particular. An increased understanding to recent date is the inertia of greenhouse gas (GHG) emissions in the past will likely accelerate climate change in the future. Hence, adaptation measures to climate change have gained increasing importance (Bhave *et al.*, 2014). In order to address the problem of climate change, traditionally a predict-then-act scheme is applied. Within this approach, future climate state is projected through downscaling outputs from climate models such as General Circulation Models (GCMs). The response of the system given the projected future climate state is consequently determined using hydrological models. The corresponding impacts to water resource are then evaluated and adaptation options determined (Brown *et al.*, 2012).

And while this approach produce optimal results for the intended future, its usability remains relatively limited in terms of decision support and policy design due to the uncertainties of climate change (Stéphane Hallegatte *et al.*, 2012; Brown *et al.*, 2012). Uncertainties in climate projection often come in the form of various climate change scenarios (e.g. RCPs) (IPCC, 2007a, 2013a) and socioeconomic scenarios (Shared Socioeconomic Pathways- SSP) (O'Neill *et al.*, 2014; van Ruijven *et al.*, 2014). Variability from different projections can be large and to plan for one projection could strictly be contradictory to the other (Brown, 2011). Furthermore, the process of downscaling outputs from GCMs entails large uncertainties. This creates a gap in translating climate information into adaptation policy (Dilling and Lemos, 2011).

Additionally, the importance of land cover on water usage has been well established (Calijuri *et al.*, 2015). Climate change affects the amount of water available while land cover change has an impact on the amount of water demanded. For this reason, there is also the need to provide land cover change information when addressing climate change impacts. This additional source of information would further benefit the adaptation process.

For the above mentioned reasons, this study seeks to adopt a different approach with less reliance on the use of GCMs and to omit the use of GCMs downscaling in climate change adaptation for the VGTB River Basin. Furthermore, the use of local information of land cover information is included. The result of the study includes better-tailored climate change information and providing policy makers with a list of proposed policies for climate change adaptation.

1.2 Research Questions and Objectives

The starting point that drives the motivation for the research is the knowledge that climate change will have an impact on the water system in the VGTB River Basin.

Although studies have focused on studying the impacts, a number of problem exists. *Firstly*, the reliability of climate change impacts predictions in the VGTB River Basin has not been fully assessed. Projections and predictions into the future carry a certain level of uncertainty, yet this level of uncertainty has not been fully explored and communicated in previous researches. *Secondly*, there is a difference between the knowledge of climate change impacts and the response to these impacts in an active way. Since the reliability of the various predictions on climate change impacts in the VGTB has not yet been fully explored, would it be possible to propose adaptation measures in the light of this uncertainty?

1.2.1 Research questions

In this context, the main challenge of the research is the uncertainties related to climate change in the VGTB River Basin. A specific list of research questions were asked prior to conducting the research. These include:

1. What is the status of water shortage in the VGTB River Basin?
2. How will climate change impact rainfall and temperature in the VGTB River Basin?
3. How will the status of water shortage change in the future as climate changes?
4. How does land use policy affect water usage in the VGTB River Basin?
5. What are adaptation policies to climate change for the VGTB River Basin?

To be able to answer the aforementioned questions, it is desirable to set up a list of objectives of research in which key findings would provide information and addresses the motivation of research.

1.2.2 Research objectives

The overall objective of the research is to be able to translate climate change information into adaptation policies for the VGTB River Basin. As part of the process, the gap between the understanding of climate change impacts and the development of adaptation measures and strategies would need to be overcome.

Climate information may be readily available yet the information has to be made useful to decision makers. Scientific impact analysis and planning pursue different goals when put into the context of climate change. The former adopts reductionist approach to find evidence by considering the essence of a cause-and-effect chain, the latter approach focuses on generating integrated solutions that cover all issues addressed. Hence, a better method of translating and/or utilizing science of climate change to the understanding of policy/ decision makers that bridges the gap between producers and users of knowledge needs to be sought for.

Specific objectives in the pursuant of the overall objectives include:

1. To develop a hydrological model to further understand the response of the river basin in different climate states
2. To identify the range of possible changes in temperature and rainfall in the VGTB River Basin using GCMs and the response of the system to those changes
3. To determine the potential effects of land use policy in the VGTB River Basin
4. To be able to utilize the best available information on climate change in the future to provide adaptation measures for policy makers

1.3 Structure of the Report

The report consists of 6 chapters. The first chapter introduces the topic and the structure of the report. Chapter 2 provides background theoretical basis that is useful in the study. Chapter 3 introduces the study area, the available data used in the study, and the justification for the study area selection. Chapter 4 introduces the methodology used. Chapter 5 discusses the results obtained and proposed adaptation measures based on the results. Chapter 6 provides conclusions and recommendations.

In chapter 2, conceptual basis in the context of climate change, hydrological modelling, and three climate change impact assessment approaches are provided. The chapter covers concepts that would be required to understand the research gap provided in the subsequent chapter 3.

Chapter 3 provides a detailed introduction into the research area of VGTB River Basin. Justification of the study area selection is provided together with previous relevant researches. Through the identification of past research efforts, research gap was identified. This research gap provides the foundation of the research questions and research objectives.

In order to fill the research gap, chapter 4 outlines the methods used in the study. The methodology consists of 5 parts. In the first part, the identification of climate hazards and threshold is described. This is performed using inputs from stakeholders and relevant experts, and analyzing the climate conditions of the VGTB River Basin. The second part describes the system model in use. In this case, the MIKE BASIN model is utilized. Various sub models are used namely the river basin model, the rainfall-runoff model, the water demand model, and the reservoir model. The fourth part establishes the method to discover climate risks. Climate variables, in particular temperature and precipitation are parametrically varied to simulate changing conditions in the river basin. Vulnerable climate space is then determined. In addition, output from General Circulation Models are utilized to map future temperature and precipitation conditions onto the vulnerability space identified earlier. The fourth component includes tailoring the information provided earlier to assist decision-making, i.e. combining the vulnerability space with possible future climate conditions in an easily understandable way. Lastly, the assessment of current land use policy is performed to provide further useful information for adaptation measures.

Chapter 5 presents and discusses the results obtained by using the methods proposed in chapter 4. The results are presented according to the components within chapter 4. Additionally, adaptation strategies are provided based on the results obtained from the analysis

Finally, chapter 6 refers back to the research objectives in chapter 1. Chapter 6 also discusses the shortcomings of the research and how this could be improved in the future. Other recommendations and future work are then presented.

2 THEORETICAL BASIS

Since the report deals with climate change impact assessment methods, this chapter provides an outline of the fundamental knowledge related to climate change. The cause of climate change and ways to predict climate change are further explained. Water shortage in the context of climate change is also discussed. In addition, hydrological modelling is introduced as a tool to study the impacts of climate change on water systems.

2.1 Climate Change Background

Earth's climate system has radically changed in the past. Over the last 700,000 years, glacial periods have occurred on average every 100,000 years due to the oscillation of both warmer and colder periods (García, L.E. *et al.*, 2014). Historical records of changes in the past reveal the high sensitivity of the climate system to relatively small changes in the atmosphere. This includes heat retention and atmospheric circulation, such as a shift in the concentration of greenhouse gasses (GHG) both due to human-induced activities and natural sources (IPCC, 2013a).

Yet the topic of climate change is becoming more important in public policy agendas around the world in recent decades (Dilling and Lemos, 2011). One important aspect of climate change now is the speed of change has been accelerated by human activities through the increase of GHG in general and carbon dioxide in particular. The evidence of human influence on climate change has increased since the Fourth Assessment Report (IPCC, 2007b). In fact, it is now virtually certain that human influence has been the dominant cause of warming since the mid-20th century (IPCC, 2013a). Unprecedented levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) within the last 800,000 years have been reached. Levels of carbon dioxide in the atmosphere today as compared to levels before the industrial-time have increased by 40% (IPCC, 2013a).

2.1.1 Climate and weather

In discussing climate change, the distinction between climate and weather has to be made. Weather describes the atmospheric condition at a certain location and time with indicators of temperature, pressure, humidity, wind and other parameters. Weather also includes the presence of cloud, precipitation and phenomenon such as thunderstorms, dust storms, tornados and the like. Climate on the other hand describes the mean and variability of variables such as temperature, precipitation and wind over a longer period ranging from months to thousands and millions of years. According to the World Meteorological Organization, a standard period of 30 years is used to determine the average value for climate (climate cycle). A broader definition of climate would further include associated statistics such as frequency, magnitude, persistence, trends (IPCC, 2013a).

Climate change, hence, refers to a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties and that persists for an extended period. The key aspects of changes in mean and/or variability for an extended period of time is highly crucial. Without these two components, it is less likely to attribute changes to changes in climate but rather to the normal fluctuation of weather. Therefore, discussions of climate change have to bare this in mind.

2.1.2 Causes of climate change

The Earth receives most of its energy from the Sun in the form of solar radiation. Solar radiation from the Sun, characterized by short wave length and high energy, drive the Earth’s climate system. Solar radiation provides heat to the Earth’s surface and atmosphere to sustain life. Roughly half of the solar radiation in the form of shortwave radiation (SWR) is absorbed by the Earth’s surface and stored as heat. The other half of SWR is either reflected back into space or absorbed by the atmosphere. The outgoing radiation from Earth in the form of longwave radiation (LWR, or infrared radiation) is mostly absorbed by certain atmospheric constituents such as water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other gasses, which are categorized as greenhouse gasses (GHGs), and cloud in the atmosphere. The downward directed component of the LWR adds heat to the lower layers of the atmosphere and to the Earth’s surface causing the greenhouse effect. The dominant energy loss of the infrared radiation from the Earth is from higher layers of the troposphere. The Sun provides its energy to the Earth primary in the tropics and subtropics; this energy is then partially redistributed to the middle and higher latitudes by atmospheric and oceanic transport process. The overall process of incoming and outgoing radiation is depicted in Figure 2-1.

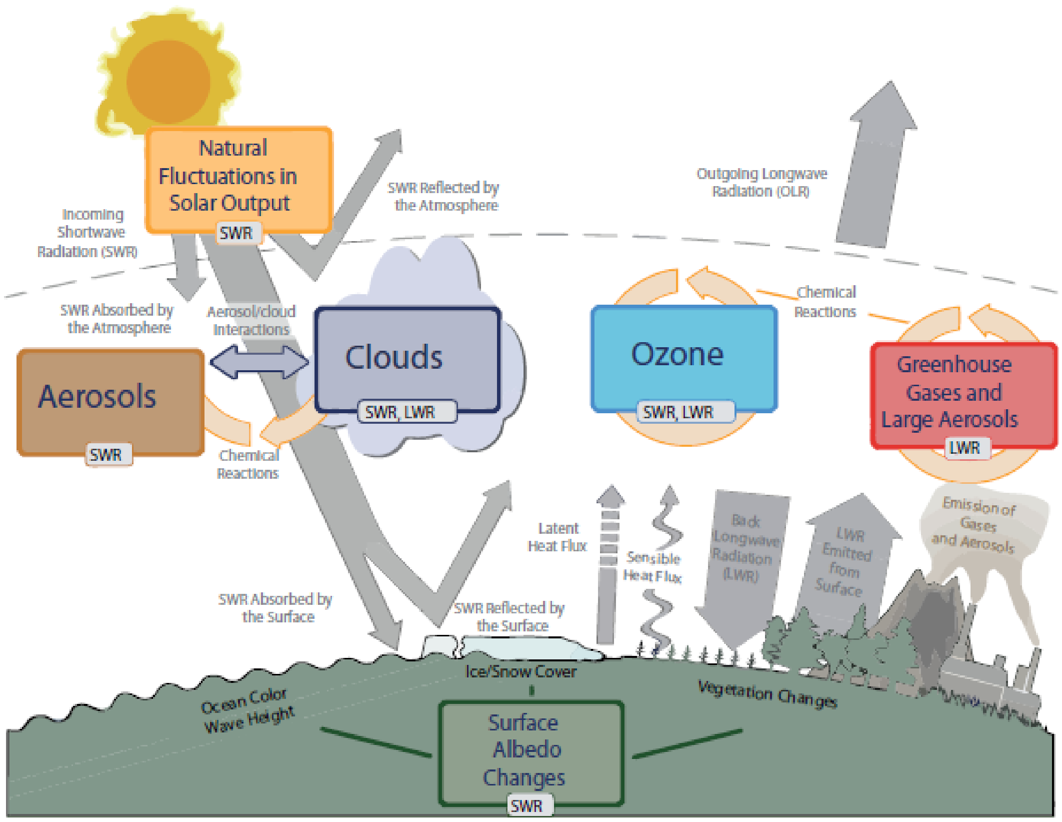

Figure 2-1: Main drivers of climate change (IPCC, 2007a)

As a result, changes in the global energy budget would come from either changes in the net incoming solar radiation or changes in the outgoing longwave radiation. Net incoming solar radiation changes comes from the changes in the Sun's output energy or the Earth's albedo. Changes in outgoing LWR can be a result of changes in the temperature of the Earth's surface or atmosphere, or changes in the emission efficiency of LWR from either the atmosphere or the Earth's surface. For the atmosphere, these changes in the emission efficiency are due predominantly to changes in cloud cover and cloud properties, GHGs and in aerosols concentrations. The Earth's energy budget is normally in equilibrium.

The influence of different aerosols on reflectivity of the Earth's atmosphere can be highly variable. Some aerosols increase atmospheric reflectivity while others are strong absorbers and modify SWR. Aerosol can also indirectly affect cloud albedo since some aerosols serve as cloud condensation nuclei or ice nuclei. Therefore, changes in aerosol types and distribution in the atmosphere can ultimately lead to changes in cloud albedo. Clouds play an important role in climate. Clouds can either increase albedo, thereby cooling the planet or increase warming through infrared radiative transfer. Depending on the physical properties of cloud such as level of occurrence, vertical extent, water path and effective cloud particle size, the net radiative effect of a cloud could be either cooling or warming. Human activities directly influence the greenhouse effect by emitting GHGs such as CO_2, CH_4, N_2O and CFCs into the atmosphere. In addition, GHGs in the form of pollutants such as CO, volatile organic compounds (VOC), nitrogen oxides (NO_x) and Sulphur dioxide (SO_2) produced by human activities also have an indirect effect on the greenhouse effect by altering, through atmospheric chemical reactions, the abundance of important gases to the amount of outgoing LWR such as CH_4 and ozone (O_3), and/or by acting as precursors of secondary aerosols.

The impacts of human activities is not limited to changing atmospheric concentration of gasses and aerosols. Human activities further change land surface. Conversion of forest to cultivated land causes an imbalance in the energy and water budget of the planet through changing the characteristics of the vegetation, color, seasonal growth and carbon content. By clearing a forest for other use, carbon storage in vegetation is released back into the atmosphere. By clearing a vegetated land, the reflectivity of Earth's surface, rates of evapotranspiration and long wave emissions changes.

The term radiative forcing (RF) refers to the measure of the net change in the energy balance in response to an external perturbation. The formation of radiative forcing is a direct result from changes in the atmosphere, land, ocean, biosphere and cryosphere both naturally and anthropogenically. These changes in the climate can include changes in the solar irradiance and changes in atmospheric trace gas and aerosol concentrations. However, the concept of RF does not include the interactions between anthropogenic aerosols and clouds. Therefore, to include the rapid response in the climate system, effective radiative forcing (ERF) is introduced. ERF is "the change in net downward flux at the top of the atmosphere after allowing for atmospheric temperatures, water vapor, clouds and land albedo to adjust, but with either sea surface temperature and sea ice cover unchanged of with global mean surface temperature unchanged" (IPCC, 2013a).

Once forcing is applied to the climate system, a system of complex feedback is triggered and determines the eventual response of the climate system. Feedback mechanisms in the climate system can be classified either as positive or negative. A positive feedback further amplifies the effects of the changes due to the forcing while a negative feedback has a diminishing effect. For example, an increase in surface temperature increases the amount of water vapor in the atmosphere; given that water vapor is an important GHG, an increase in water vapor would then further increases surface temperature and leads to further warming. Hence, surface temperature creates a positive feedback in reference to water vapor increase. Likewise, an increase in surface temperature or sea temperature causes ice caps to melt exposing darker and more absorbing surface beneath. While ice caps are more reflective surfaces, the removal of ice caps would then decrease the albedo leading to additional warming. Example of a negative feedback is the increased outgoing LWR as surface temperature increases (referred to as blackbody radiation feedback). It is important to note that the timescale in which different types of feedback operates can highly vary from hours through to decades and even centuries (IPCC, 2013a).

In short, the Earth has a natural mechanism of retaining energy and heat from solar radiation to support life. Since life on Earth is a highly dynamic system, the amount of energy and heat stored may fluctuate through time. However, given that the system on Earth is always in a dynamic equilibrium, the amount of energy and heat stored is also in a dynamic equilibrium. Human activities have released into the atmosphere an increased amount of GHG that increases the Earth’s ability to retain heat. A complex feedback system on Earth is then triggered leading to even further warming, causing the climate on Earth to change.

2.1.3 Climate Change Modeling and Projections

With the study of climate change, there are methods to predict the changes in climate variables such as temperature and rainfall due to changes in GHG concentrations and human activities. One approach that has been widely accepted in the past is the use of General Circulation Models (GCMs). This section introduces the core concept of GCMs and downscaling.

General circulation models

GCMs are numerical models that simulate the physical processes in the atmosphere, ocean, cryosphere and land surface in response to an increase in GHG emissions. While there are a broad range of models which are also capable of determining the climate response, only GCMs have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis (IPCC Data Distribution Center, 2013).

GCMs depict the climate using a three dimensional grid over the globe. A GCM typically has a horizontal resolution between 250km and 600km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans (IPCC Data Distribution Center, 2013). As a result, GCMs have relatively coarse resolution. A schematic of a GCM grid is shown in Figure 2-2.

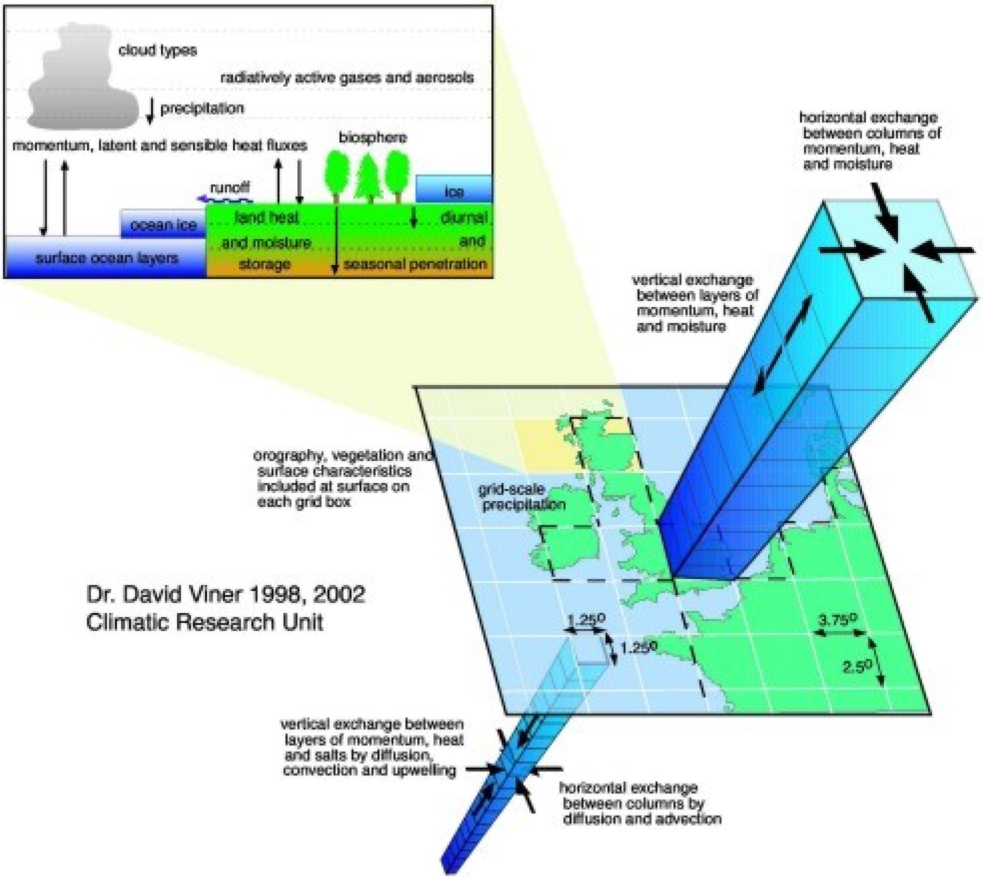

Figure 2-2: Schematic of a GCM grid (IPCC, 2013b)

Many physical processes, such as those related to clouds occur at smaller scales and cannot be properly modelled using GCMs. Instead, their known properties must be averaged over the larger scale in a technique called parameterization. This is one source of uncertainty in GCM-based simulations of future climate.

Other uncertainties related to GCM simulations include the simulation of feedback mechanisms. For example, the uncertainties in modelling the feedback between water vapor and warming, clouds and radiation, ocean circulation and ice and snow albedo. For this reason, GCMs may simulate different response to the same forcing, due to the way certain processes and feedbacks are modelled.

Downscaling

Despite the improvement of computing power in recent years, the horizontal resolution of GCMs are still too coarse to capture the effects of local climate change effects. Most GCMs have resolutions up to a few hundred kilometers while climate change impacts are normally felt and dealt with at the more local and regional scale. For this reason, significant progress has been made in applying downscaling techniques to obtain local climate change projections at finer resolution, this includes dynamic downscaling through the use of regional climate model and statistical downscaling.

The use of Regional Climate Model (RCM) is one widely used method to add detail to climate projections. The use of regional climate model is sometimes referred to as “dynamic downscaling” with a typical grid for climate change projection around 50 km, however, fine resolution up to 5km have been applied (IPCC, 2007a).

The regional climate model approach improves the resolution of climate projections through simulating at a sub GCM grid. In this approach, the RCM model is nested within the GCM grid and uses output from GCMs simulations to provide initial and driving lateral meteorological boundary conditions without accounting for the feedback from the RCM to the GCM. Therefore, the strategy in using RCM would be to first use the global model to simulate the response of global circulation to large scale forcing then use RCM to account for sub-GCM grid scale forcing and enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales (IPCC, 2001).

Dynamic downscaling relies on driving Regional Climate Models (RCM) using outputs obtained from GCMs. RCM have higher spatial resolution and can then hence, represent climate variables at the local scale of interest (Tofiq and Guven, 2014). Examples of highly successful researches in the past using the dynamical downscaling approach includes Maraun *et al.* (2010); Xue *et al.* (2014) and Castro *et al.* (2005).

There are two main theoretical limitation of RCMs including the effects of systematic errors in the driving fields provided by the global model and the lack of two-way interaction between regional and global climate. RCMs can also be computational demanding depending on the domain size and resolution hence limiting the ability to perform multi-model run. And finally, the temporal frequency of GCM fields (6 hours or higher) can mismatch that required by RCM, hence, careful consideration is needed when nesting RCM into GCM grids (IPCC, 2001).

Another approach in downscaling GCMs is through statistical downscaling. Statistical downscaling is based on the view that regional climate is influenced by large-scale climatic states and regional/local physiographic features (topography, land use, etc.). From this view point, statistical downscaling is mainly a two-step process including firstly develop a meaningful statistical relationship between climate variables at the local scale and the large scale predictors and then applying such a relationship to the output of GCM models to simulate local climate characteristics (IPCC, 2001).

The statistical downscaling approach seeks to establish a statistical relationship between large-scale variables such as atmospheric pressures and a local variable such as wind speed at a particular site of interest. Statistical downscaling facilitates the rapid development of multiple, low cost, single-site scenarios of daily surface water variables under current and future regional climate forcing (Tofiq and Guven, 2014). A number of studies were also successfully conducted by using statistical downscaling and different GCM scenarios to predict the runoff based on precipitation and rainfall-runoff models (Yonggang *et al.*, 2013; Chen *et al.*, 2012; Scmidli *et al.*, 2007).

A statistical downscaling approach has both advantages and disadvantages. The main advantage of a statistical downscaling method is computational efficiency. Since the majority of statistical downscaling model are able to produce results faster than regional climate models, a range of output from different GCM models could potentially be applied instead of using just one projection. The main disadvantage of a statistical downscaling method lies in the fundamental viewpoint of the method. In other words, a relationship between large-scale climatic state and regional physiographic feature does not necessarily hold true in the future under different forcing conditions.

2.2 Water Shortages and Climate Change

Climate change in both the context of natural variability and due to human activities can lead to changes in extreme weather and climate events. Extreme precipitation events leading to severe flooding or extreme dry spells leading to drought conditions can be excellent examples. By definition, an extreme weather event is “one that is rare at a particular place and/or time of the year” (IPCC, 2013a). Due to the misconception of weather and climate, there can be false classification of extreme events. At present, single extreme event is unlikely to be attributed to anthropogenic influence. Only when a pattern of extreme weather persists for at least some time, for instance a season or several months, then the event itself can be identified as an extreme event. For example, drought or heavy rainfall over a season long. Important factors contributing to an extreme event includes duration and intensity, especially in the case of drought and water shortage (IPCC, 2012).

In the context of climate change, there still exist high uncertainties in observing trends of drought on a global scale (IPCC, 2012). Evidence summarized in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change have shown that very dry areas have more than doubled in extent since 1970 globally. The assessment was made using the Palmer Drought Severity Index and based largely on the study by Dai *et al.* (2004). The results showed high sensitivity to changes in temperature rather than precipitation (IPCC, 2012).

Another study simulating soil moisture with an observation land surface model by Sheffield and Wood (2008) have determined that the trends in drought duration, intensity and severity being predominantly decreasing worldwide in the time period between 1950-2000. However, the study provided strong regional variation including strong increases in some regions. The study then concluded that the overall trend is moistening over the considered period with a switch starting from the 1970s to a drying trend, especially in the high northern latitudes.

Other regional studies have also arrive at a similar result that are consistent with the conclusion from Sheffield and Wood (2008), i.e. there is no widespread increase in drought trends globally as stated by Dai *et al.* (2004). A more recent study by Dai (2011) extended the record and found a widespread in drought based on PDSI values for the time period of 1950-2008 and output from soil moisture land surface model for the period of 1948-2004. For this reason, there are still large uncertainties in assessing global drought trends.

However, from the range of evidence, the AR4 concluded that it is more likely than not the increase of drought in the late 20th century is partially or substantially due to anthropogenic activities. Instrumental observations over the past 157 years show that temperature at the surface has risen globally. The increase is highly variable from region to region, yet globally occurred in two phases beginning from 1910 to the 1940s (Mishra and Singh, 2010). Consequently, drought extremes could also be expected to increase within the line of temperature. Additionally, a detection study identifying anthropogenic fingerprint in a global PDSI data set showed high significance (IPCC, 2012).

The more recent Fifth Assessment Report (AR5) agreed with AR4 that anthropogenic influence has contributed to the increased risk of drought in the second half of the 20th century. However, AR5 no longer supports the claim of increasing hydrological drought trends since the 1970s supported by AR4. In addition, due to the low confidence in observed large scale trends in dryness and variability of drought, there is now low confidence in the attribution of changes in drought over global land since the mid-20th century to human influence (IPCC, 2013a).

Given the range of different results, it can be seen that uncertainty exists on the overall water shortage and drought conditions due to climate change globally. Nonetheless, it has now been commonly accepted that droughts in the future pose a serious threat to human systems, especially in the case of agricultural production. Therefore, there is a large research demand into the possible impact of droughts and water shortage in the future to assist developing adaptation measures.

2.3 Hydrologic modeling

To assess the extent of water shortages in reality, different methods have been applied. This includes the use of hydrologic models. The objective of these models is to simulate the relationship between various variable within a river basin to produce outputs such as river flow from rainfall. Many of these models utilize advanced mathematical techniques and attempt to mimic the natural processes that occur within a basin level. However, there is still no consensus about the processes that occur in the natural system, therefore, this uncertainty has been represented by a many number of different models.

Three modeling approaches have generally been used in the development of hydrologic modeling. This includes a data-driven, a process-driven, and a conceptual model.

2.3.1 Process- driven modelling

Process-driven modeling is based on an understanding of the individual processes that occur within a basin. While in theory, the ability to use the processes to obtain outputs such as river flow and water level from rainfall should result in a wide range of applicability, this has not been the case in practice. This is because not all of the relevant processes that occur are fully understood, and some of the processes are not able to be represented mathematically. As Blöschl, G. and Sivapalan M. (1995) suggested, processes that are important at one scale may be irrelevant at another scale. Thus, the complexity embedded within a process-driven model may be superfluous. As a result, process-driven models often contain an excessive number of parameters. Consequently, an extensive amount of data is required in the development of process-driven models (Sivapalan, 2003).

2.3.2 Data- driven modelling

Data-driven modeling is concerned with the overall behavior of the system at a larger scale (Littlewood *et al.*, 2003). The selection and interaction of the relevant components of the model are dependent on an analysis of data obtained from the catchment, rather than from the processes that occur (Sivapalan, 2003). These data-driven models have been used with moderate success in predicting rainfall-runoff behavior (Chiew, F.H.S and Siriwardena, L., 2005). More importantly, data-driven models do not usually require as much data to develop as process-driven models, and are typically parametrically parsimonious (Littlewood *et al.*, 2003). In other words, they use fewer parameters without a loss in accuracy.

2.3.3 Conceptual hydrological models

In practice, the extreme idealized states of either data-driven or process-driven models are not often used, and an assimilation of the two approaches is adopted. This is mainly because process-driven models have to use data-driven procedures to establish the plausibility of the physical processes that occur. On the other hand, most data-driven models assume a form of underlying relationship which is the principle underlying process-driven models. Therefore, a combination of the two is usually used instead. These combination models based on both data-driven and process-driven models are termed conceptual models.

While the equations and the solution procedures may vary depending on the model used, all hydrological models have the following common components (US Army Corps of Engineers, 2000):

- State variables represent the state of a system at a particular time and location.
- Parameters which are numerical measures of the properties of the real world system. They control the relationship of the system input to system output. Parameters can have physical significance or may be purely empirical.
- Boundary conditions of the system input which forces the system to change
- Initial conditions which are values of the output given before computation

Conceptual hydrological models describe how a basin responds to a precipitation event and flows of water from upper stream. The general hydrologic processes represented by models is shown in Figure 2-3. The processes illustrated begin with precipitation. In the simple conceptualization shown, the precipitation can fall on the watershed’s vegetation, land surface, and water bodies (streams and lakes).

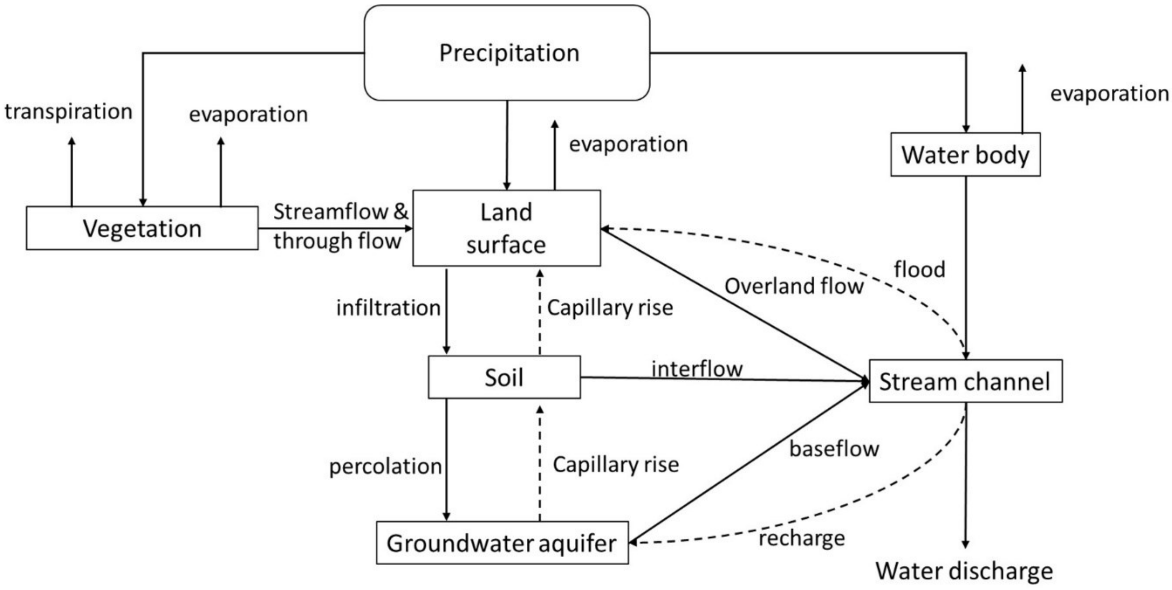

Figure 2-3: Runoff processes (US Army Corps of Engineers, 2000)

In the natural hydrologic system, much of the precipitation water returns to the atmosphere in the form of evaporation from vegetation, land surfaces, and water bodies and through transpiration from vegetation. During a storm, the amount of evaporation and transpiration is small.

Further precipitation on vegetation could avoid interception and fall through the leaves or run down stems, branches and trunks and reach land surface. At the land surface, water may pond, and depending on the soil type, ground cover, antecedent soil moisture and other watershed properties, a portion may infiltrate. This infiltrated water is stored temporarily in the upper, partially saturated layers of soil. From there, it rises to the surface again by capillary action, moves horizontally as interflow just beneath the surface, or it percolates vertically to the groundwater aquifer. The interflow eventually moves into the stream channel. Water in the aquifer moves slowly, but eventually, some returns to the channels as baseflow.

Water that does not pond or infiltrate moves by overland flow to a stream channel. The stream channel is the combination point for the overland flow, the precipitation that falls directly on water bodies in the watershed, and the interflow and baseflow. Thus, resultant streamflow is the total watershed outflow.

Conceptual hydrologic models mimics this natural cycle and to an extent simplify these processes into mathematical formulations. Hydrologic models could further incorporate other components of the hydrologic system that are beyond the natural system. This includes the operation and storage of water from hydrological structures such as reservoirs and dams, and the usage of water for domestic and agriculture purposes. The main purpose of this additional capability is to assess the water balance within a watershed with precipitation as the main input and various competing uses.

Hydrologic modeling can either be continuous modeling or event based. Continuous modeling involves predicting runoff as a result of rainfall of a desired continuous time series. Event based choses from the time series of historical data a rainfall event that is of interest. The selection of rainfall event for the purpose of engineering design is common through the analysis of rainfall frequency. The approach starts by fitting a probability distribution function to the annual rainfall data. After a distribution has been fitted to the historical data, the probability of exceedance and/or the return period of the rainfall depth can be calculated. A design rainfall can then be selected based on the type of structures or objectives of engineering, e.g. a design rainfall with exceedance probability of 20% for urban drainage systems.

There is a range of different hydrological models available. Commercial models such as the MIKE family model developed by the Danish Hydraulic Institute are excellent example of powerful tools for both hydrological and hydraulic models. MIKE by DHI are powerful tools with separate modules. In the study of water shortages and drought, one module is of extreme importance, the MIKE BASIN model. MIKE BASIN is a hydrological model which incorporates Geographic Information System (GIS) into its calculation abilities. On a basin wide scale, MIKE BASIN is useful in modeling water balance from different users. MIKE BASIN is widely used in Viet Nam and within the research area (Chau *et al.*, 2013; Viet, 2014; Mai, 2009; Lan and Son, 2013).

HEC-HMS is developed by the United States Army Corps of Engineering (USACE) and is a freely available software with a user-friendly interface. Since the model is developed in the United States of America, most applications in the past have been for locations within the United States of America. Nonetheless, applications of HEC-HMS outside of the United States have also been performed with relative success. Kafle *et al.* (2010) used HEC-HMS in a flood forecasting application for a basin in Nepal with a predicted peak discharge of 98% of the observed value, showing the ability of successfully calibrating HEC-HMS to basins outside of the US. The study further suggested that HEC-HMS could be applied to other river basins. Likewise, Abushandi and Merkel (2013) compared the performance of HEC-HMS to another hydrological model for a single rain event for a basin in Jordan and concluded that the calibrated HEC-HMS hydrograph fit well within the observed data. J.A. Kaatz (2014) used HEC-HMS as a tool to inform river gauge placement for a flood early warning system in Uganda and arrived at promising results.

2.4 Climate Change Impact Assessment Approaches

The study of climate change is mostly concerned with assessing the impacts of changes in climate variables on both natural and human systems. This could include the study of, for example, impacts on water system in a river basin, or the socio-economic implications of climate change to a city. There are three broadly categorized approaches in climate change impact assessment, namely the top-down, bottom-up, and combined top-down bottom-up approach. This section reviews the different approaches.

2.4.1 Top-down climate change assessment

Early impact and adaptation studies of climate change adopted a scenario-based approach under given GCM scenario of the future climate. Within each scenarios, risks and vulnerability in future climate states are identified and adaptation responses proposed. Earlier impact and adaptation studies of climate change normally followed a formal systematic approach. The approach was presented as an analytical framework by the first United Nations Framework Convention on Climate Change Conference of the Parties in 1995 (Carter and Mäkinen, 2011).

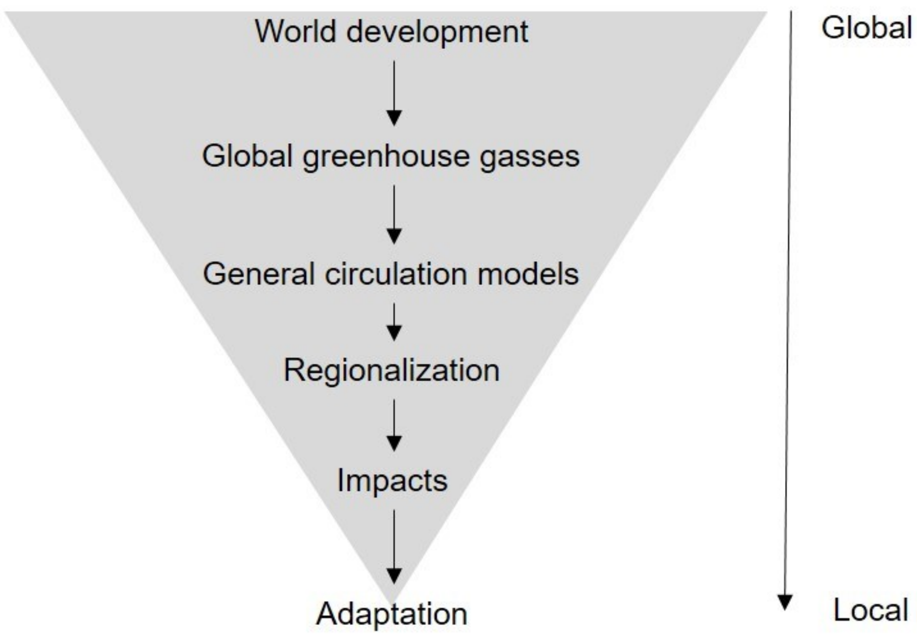

Figure 2-4: Top- down approach (Dessai and Hulme, 2004)

This type of approach is more commonly referred to as a top-down approach to climate impact assessment because it relies on top-down information of global climate projections (Carter and Mäkinen, 2011). The analysis starts with climate change projections from a single or a range of GCMs. The projections from GCMs are normally coarse in resolution (several hundred kilometers). To make use of these projections, downscaling techniques needs to be applied so that the results could be represented at the similar temporal and spatial scale with the hydrologic projections of climate change to drive water resources systems models (Brown *et al.*, 2012). Vulnerabilities components of the system are then assessed and adaptation policy proposed. The schematic of a top-down climate impact assessment approach is as shown in Figure 2-4.

One key component in the top-down climate adaptation studies, as mentioned above, are the GCMs. GCMs are based on mathematical representations of the atmosphere, ocean, ice cap and land surface processes. To date, GCMs are still considered to be the only credible tools available for simulating global climate system response to increasing GHG concentrations (Tofiq and Guven, 2014).

Scientific literature of the past decade contains a large number of studies regarding the development of downscaling methods and the use of hydrological models to assess the potential effects of climate change on a variety of water resource issues.

Hydrological models provide a framework to conceptualize and investigate the relationship between climate and water resources (Xu, 1999). The most relevant meteorological variables for hydrological impacts studies are temperature and precipitation (Maraun *et al.*, 2010).

2.4.2 Bottom-up climate change assessment

Another approach to the studies of climate change shifts the focus away from impact assessment to adaptation. This is due to an increased understanding that the inertia of climate change will necessitate adaptation measures in the long term (Bhave *et al.*, 2014). An important implication of such a shift includes relying less on GCM models. The shift resulted in the use of a bottom-up approach.

In contrast to top-down approaches, bottom-up climate assessments start with the vulnerability domain (instead of GCMs). A bottom-up approach analyzes the important system characteristics, local capacities before testing the sensitivity and robustness of adaptation options (García, L.E. *et al.*, 2014). The difference between a top-down and a bottom-up approach can be best understood using the equation describing risk by Plate (2002):

$$R(x) = \int_{0}^{\infty} C(x) f(x) dx \tag{1}$$

where R(x) describes risks, f(x) is the probability density function of the event (e.g. the occurrence of a future climate state) and C(x) is the consequences of the event. The consequence can be listed either as positive or negative. A negative consequence would be a case where damage to lives and property is done, on the other hand, a positive consequence is where benefit from the event is yielded. The top-down approach to climate change impacts assessments emphasizes estimating f(x), that is, the future distribution of climate or hydrologic variables. It should be noted that climate change entails deep uncertainty. This is because climate change is characterized by multiple possible future worlds without known relative probabilities (Stéphane Hallegatte *et al.*, 2012). For this reason, emphasizing the estimation of f(x) is fundamentally flawed. Thus, the top-down probabilistic approach is highly unsuitable for climate change impact assessment. With a bottom-up approach, the focus is on C(x), the response of the system to all the possible values of x, without regard to f(x) (Brown *et al.*, 2011).

The bottom-up approach allows low-regret adaptation measures as well as promotes robust adaptation for a wide range of future climate conditions. The schematic of a bottom-up approach as compared to a top-down approach is shown in Figure 2-5.

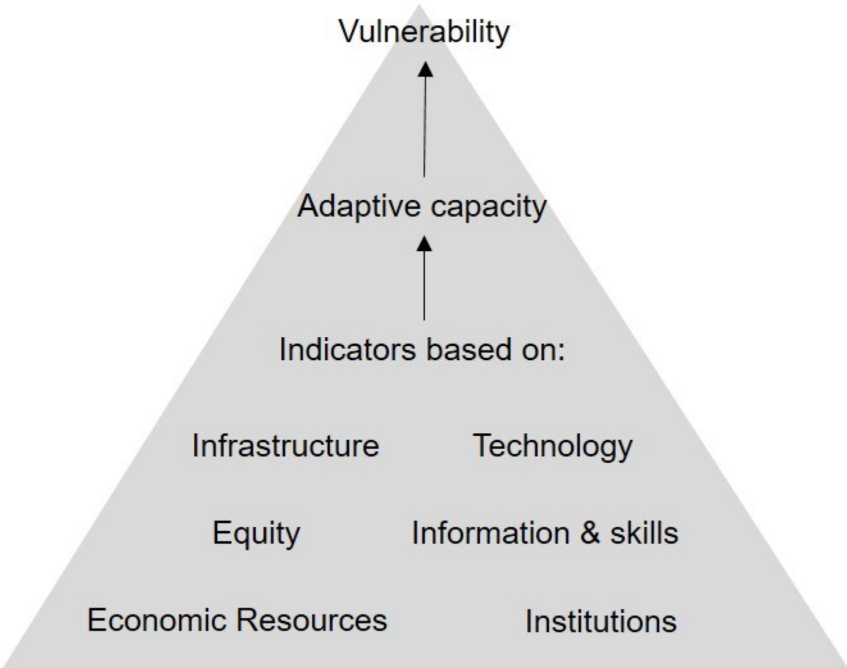

Figure 2-5: Bottom-up approach (Dessai and Hulme, 2004)

A robust decision process implies the selection of a project or plan which meets its intended goals, e.g. increase access to safe water, reduce floods, and upgrade slums, or many others- across a variety of plausible futures. As such, the approach starts by looking into the vulnerabilities of a plan (or set of plans) to a field of possible variables. A set of plausible futures are then identified, incorporating sets of the variables examined, and evaluate the performance of each plan under each future. Finally, plans that are robust to the futures deemed likely or otherwise important to consider could be identified (Stéphane Hallegatte *et al.*, 2012).

As robust processes imply the acceptance of uncertainty through the use of a vulnerability space that is representative of a wider range of possible climate futures, they also demand a process of dialogues to determine which vulnerabilities to consider, which performance metrics suggest success, acceptable levels of risk, and which possible scenarios to evaluate. The stakeholder process is an opportunity to further fortify the project against uncertainty, as a variety of viewpoints and concerns can simultaneously be addressed in distinct scenarios. Incorporation of multiple scenarios builds consensus on the outputs (the project) despite differing inputs (Dotsis and Makropoulou, 2005).

2.4.3 Combination of top-down and bottom-up approaches

While the bottom-up approach has shifted away from the heavy reliance on GCMs, it still requires top-down information to inform the likelihood of future climate conditions. The scientific understanding of physical climate mechanisms informs the experiments performed using bottom-up techniques. Without these inputs from the physical climate modeling community, the bottom-up approach would lack a basis for selecting the range of climate conditions test the vulnerability of the system. The vulnerability exploration would be imprecise and unbounded, and of limited decision-making value (García, L.E. *et al.*, 2014). For this reason, a number of researches have tried to integrate the top-down and bottom-up approaches.

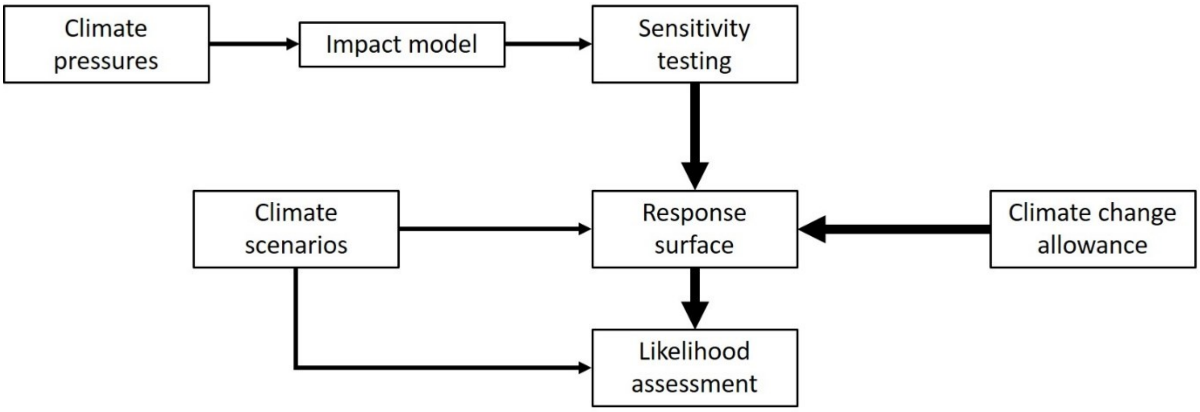

Figure 2-6: Scenario-neutral conceptual framework (Prudhomme et al., 2010)

Prudhomme *et al.* (2010) proposed a scenario- neutral approach in assessing flood risks in two river catchments located in the UK (Figure 2-6). The study differs from the top-down approach in the way climate change risks (the hazard) is separated from the catchment responsiveness (the vulnerability). The approach proceeds in three steps. *Firstly*, a reference climatology period for the region of interest was determined. *Secondly*, the absolute or percentage changes in the equivalent variable are calculated for the GCM grid-box closest to the target site using projections for a specified period in the future. *Thirdly*, the change suggested by the GCM is simply added to the reference climatology and the resulting time series is used for impacts modeling. Four main information sources are used in the framework: (1) the climate change allowance or safety margin, (2) a mathematical model of the climate response system, (3) an ensemble of climate change projections, and (4) metrics to show the likelihood that the safety margin is robust to the available sample of climate change projections.

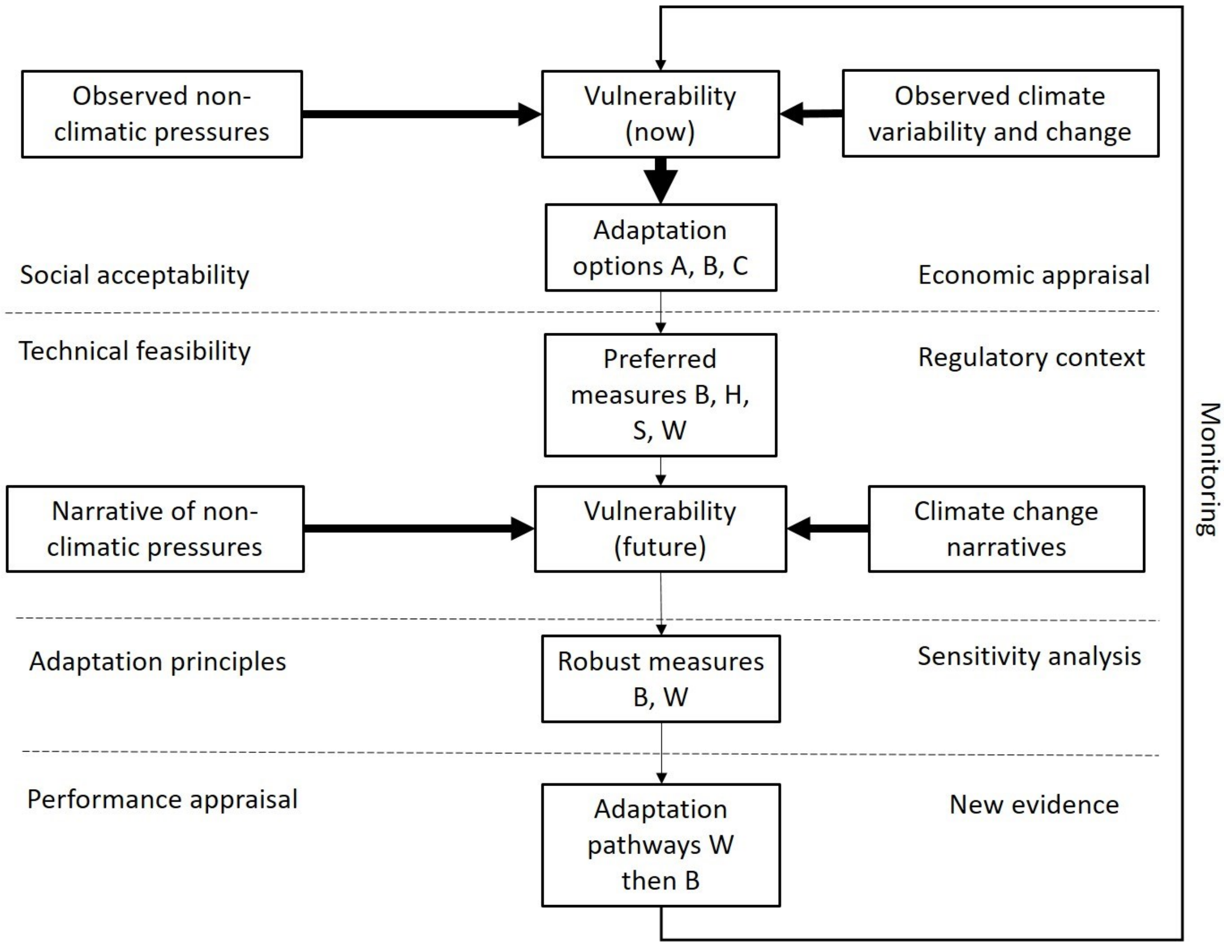

Figure 2-7: Conceptual framework used by Wilby and Dessai (2010)

Wilby and Dessai (2010) described a process that examines robust adaptation, measures that are low regret or reversible, incorporate safety margins, employ soft solutions, are flexible and mindful of actions being taken by other to either mitigate or adapt to climate change (Figure 2-7). The first step includes constructing an inventory of adaptation options containing both hard-engineering as well as soft-solutions. Through screening, adaptation measures that reduce vulnerability in current climate regime could be identified. For shorter lifetime projects for a few years or less, the measures could be sufficiently tested using current climate schemes. However, if the lifetime of a project exceeds multiple decades (such as irrigation systems and reservoirs), performance of the adaptation projects would need to be evaluated across a range of scenarios. The use of Regional Climate Downscaling is then utilized for such cases.

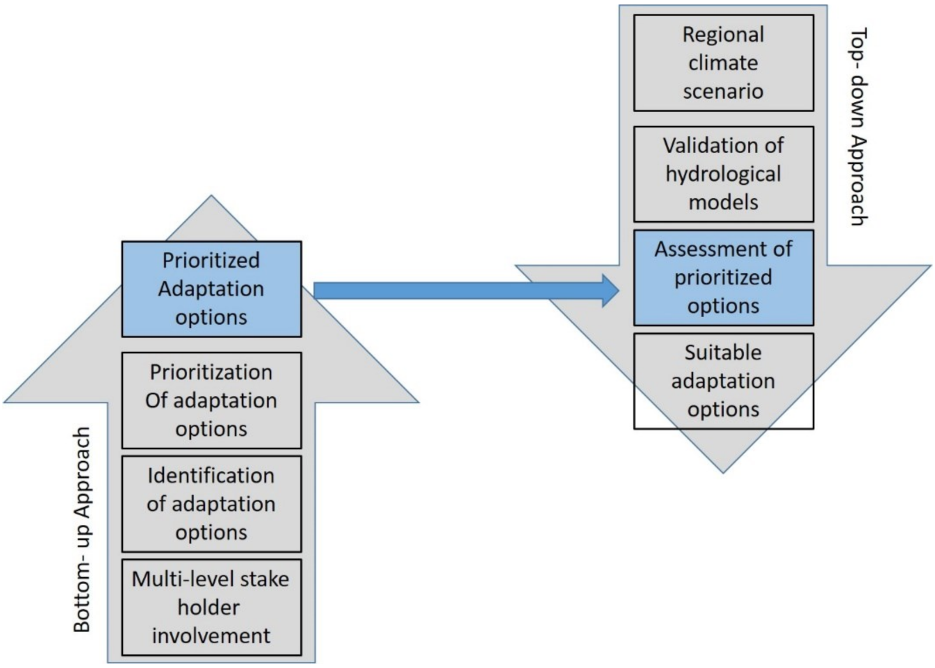

Figure 2-8: Framework from Bhave et al. (2014)

Bhave *et al.* (2014) combined the two aspects of bottom-up and top-down climate change adaptation via the use of hydrological models to assess the effect of stakeholder prioritized adaptation options for the Kangsabati River catchment in India (Figure 2-8). A series of 14 multi-level stakeholder consultations are used to ascertain locally relevant no-regret adaptation options using Multi-Criteria Analysis (MCA) and scenario analysis methods. A validated Water Evaluation and Planning (WEAP) model is then used to project the effect of three options; option 1 check dams (CD), option 2 increasing forest cover (IFC) and option 3 combined CD and IFC, on future (2021–2050) streamflow. High-resolution (roughly 25 km) climatic projections from four Regional Climate Models (RCMs) and their ensemble based on the SRES A1B scenario for the mid-21st century period are used to force the WEAP model.

Shaw *et al.* (2009) and Sheppard *et al.* (2011) adopted a combination of top-down and bottom-up approach through a future visioning process. (Sheppard *et al.*, 2011). The studies identified that uncertainties of a top-down approach with heavy reliance on GCM complicate the process of raising public awareness and policy making in climate change adaptation. The studies propose a future visioning process, a conceptual framework that generates alternative, coherent, holistic climate change scenarios and visualization at the local scale, in collaboration with local stakeholders and scientists. In essence, a range of future climate scenarios that is deemed relevant through scenario development workshops with stakeholders was chosen so that local impacts could be determined. Local visualization is then determined showing the effects of the climate change scenarios with and without adaptation measures. The future visioning process framework is as shown in Figure 2-9.

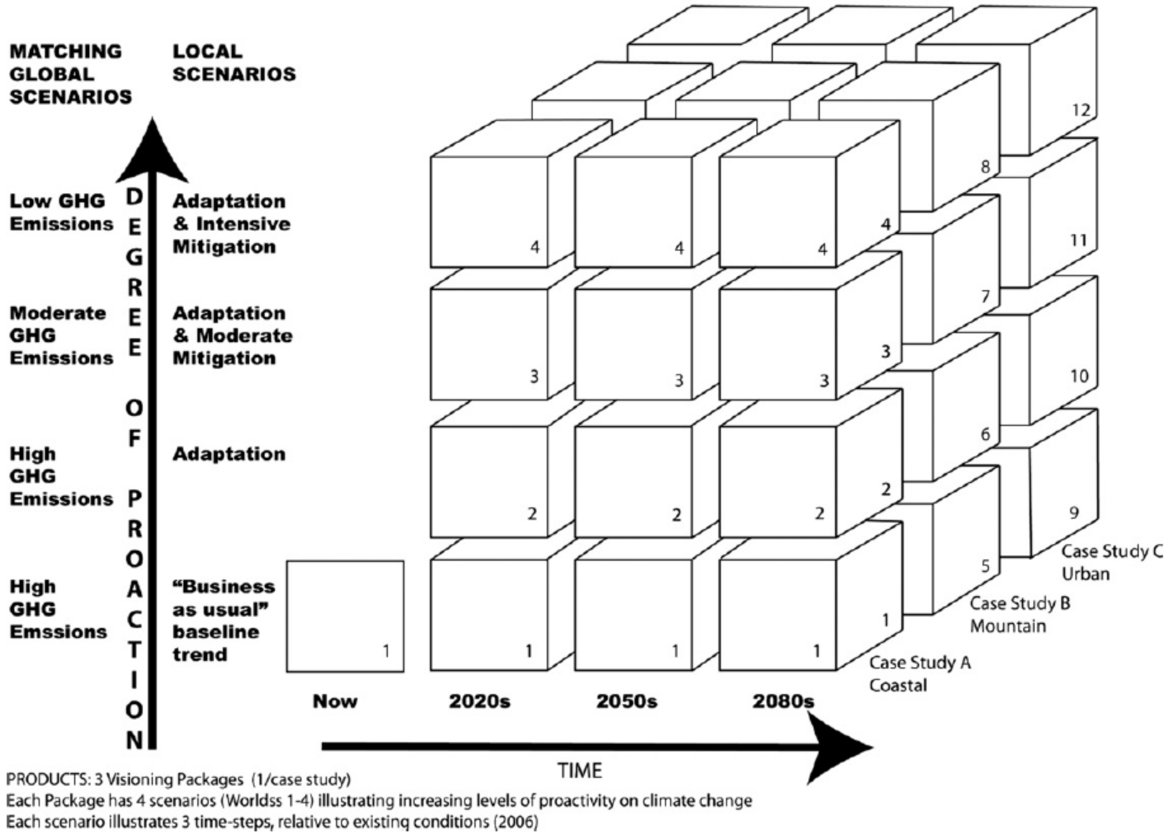

Figure 2-9: Future Visioning Process (Shaw et al., 2009; Sheppard et al., 2011)

Another framework that has gain much attention to date is the decision scaling approach (Brown *et al.*, 2012; Brown, 2011; Brown *et al.*, 2011; García, L.E. *et al.*, 2014; Grijsen, 2014). The approach links bottom-up, stochastic vulnerability analysis with top-down use of GCMs. In simple terms, the decision scaling process first identify the kind of climate change that are problematic to the system before turning to climate models to determine whether those changes are likely. Three different steps would be required to be undertaken in order to perform the stress test. *Firstly*, the vulnerabilities of the system to changes are evaluated in a large climate space using weather generators. *Secondly*, the climate domain is mapped onto the vulnerability domain. *Thirdly*, the risks to project performance are determined. Adaptation measures are then evaluated to reduce the risks associated with the project. The strength in the approach lies in the combination use of methods from the other previous approaches presented above. The decision scaling framework is visualized in Figure 2-10.

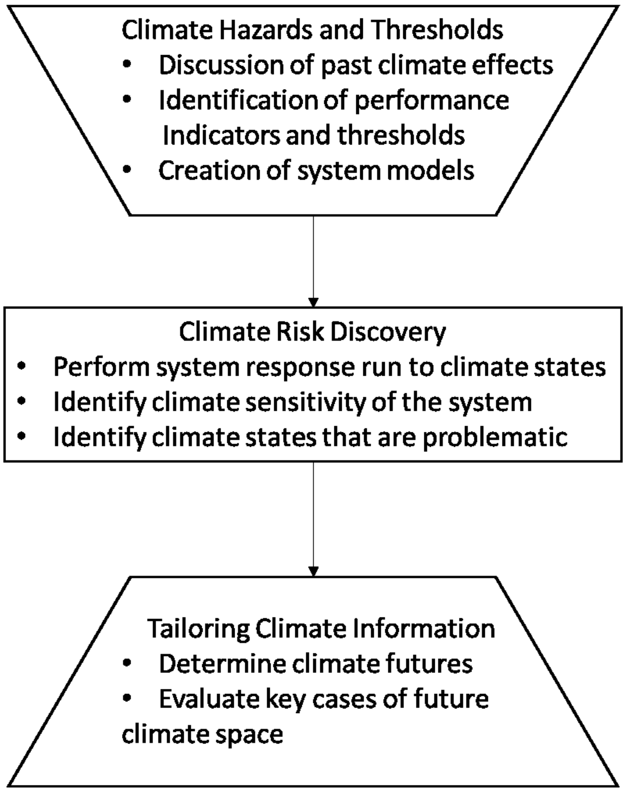

Figure 2-10: The Decision Scaling Framework (Brown et al., 2012)

3 STUDY AREA AND SELECTION JUSTIFICATION

This chapter introduces the Vu Gia- Thu Bon River Basin study area, the selection justification, and provides a literature review of climate change impact assessment in the study area. The main goal is to highlight the research gap that the study seeks to address. In addition, available data that are used for the study is also discussed in detailed.

3.1 Overview of Study Area

The VGTB River System consists of two major river including the Vu Gia and the Thu Bon Rivers. The two rivers cross-link 36km upstream from the coast of the East Sea, Viet Nam. Total catchment area of the river basin is approximately 10,350km^2 and spans an area from the Truong Son Mountain Ranges to the coast of the East Sea (Figure 3-1). More precisely, the river basin extends from 14^{o}90’ to 16^{o}20’ latitude North and 107^{o}20’ to 108^{o}40’ longitude East and includes 4 provinces namely Quang Nam, Quang Ngai and Kon Tum Provinces and Da Nang City. However, the majority of the river basin is within Quang Nam Province and Da Nang City. For the purpose of the study, only the portion of the river basin within Quang Nam Province and Da Nang City is considered. The VGTB River Basin in this context is thus referred to be the basin area within these province and city unless otherwise stated.

The natural topography of the basin divides the area into three major landscape namely highland, midland and lowland (Figure 3-2). The mountainous highland characterizes the area west of Da Nang including Hoa Vang district and parts of Quang Nam Province (Tay Giang, Nam Giang, Phuoc Son and Nam Tra My District). The midland covers major parts of the Dong Giang, Nam Giang, Dai Loc, Nong Son, Hiep Duc and Bac Tra My District in the Quang Nam Province. Lowlands preside over the area close to the coast of Da Nang City as well as Dien Ban, Hoi An, Duy Xuyen, Que Song, Thang Binh, Phu Ninh, Tam Ky and Nui Thanh District of Quang Nam Province.

The highland area presents steep sloping topography with narrow riverbeds. This leads to a short flow time and retention time in streams and rivers. Elevation in the highland area reaches 2000m. The area has the highest vegetation coverage yet have low agricultural activity. Agriculture, due to the low population that resides in the area and the remote accessibility, is rather sparse in the area (DONRE, 2012)

Figure 3-1: Location of the study area

The midlands have lower hills ranging from 150m to up to 1000m in comparison to the highlands. However, the area is highly suited for hydropower dams as is the case where a large number of structures have been constructed. Agricultural practice in the area is dominant by slash and burn and rice is cultivated on slopes. The large hillside area, on the other hand, is characterized by production forests, mainly *Acacia mangium* and *Acacia auriculiformis* for paper production (DONRE, 2012).

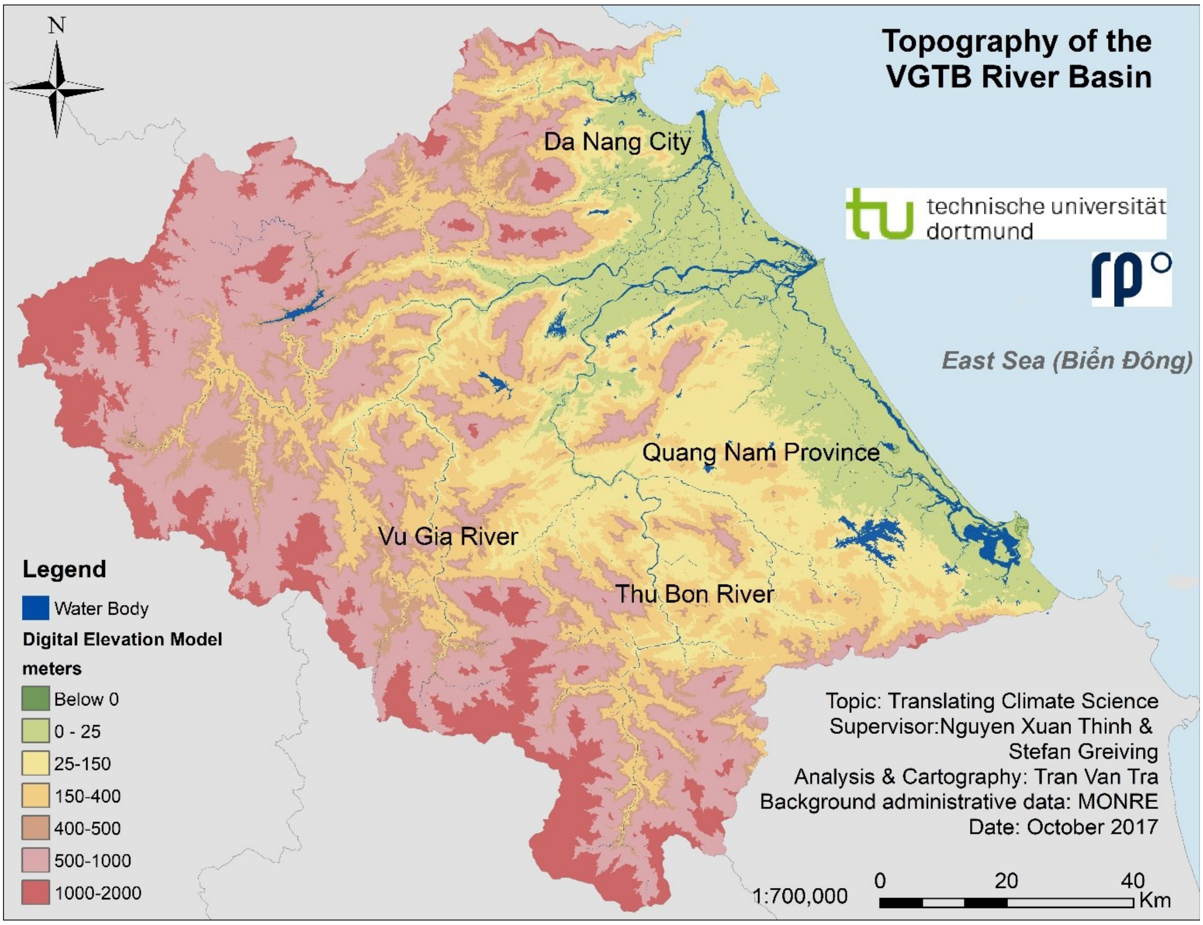

Figure 3-2: Topography of the study area

The lowlands are characterized by areas lower than 25m and sand dunes close to the shoreline ranging from 0 to 10m in height. Riverbeds are shallow in the region, leading to a slower flow time and increase water retention time. Paddy rice fields and a complex network of irrigation channels dominate the area. Nonetheless, the area stretching from Da Nang City to the township of Hoi An presents sandy beaches and has been used as tourist attraction (DONRE, 2012). The lowland along the coastline is the most densely populated area in the basin.

Roughly half of the inhabitants in the river basin rely on agricultural production (2013 census) (Viet, 2014). The dominant crop in the area is paddy rice with up to 70% of irrigated agriculture area. As paddy rice is a water intense crop, water demand is high. Hence, agriculture production is one of the main vulnerable systems in the river basin in relation to water resource availability. In drier months, insufficient water supply can lead to droughts affecting yield and economic output.

3.2 Climate Variability and Extreme Weather Events

The selection of the VGTB River Basin as the study area is due to the natural climate variability in the region as well as the potential vulnerability of the population living in the area under both present and future conditions. Natural climate variability presents in the form of low precipitation during the drier months that leads to water shortages. In addition, variation in temperature and precipitation due to climate change further exacerbates dry conditions and is responsible for extended period of dry spells and drought conditions in the basin area.

Precipitation in the area is spatially variable. Areas of low precipitation include the northern part of the river basin with an average annual precipitation less than 2,000mm. In contrast, the upper reach of the Thu Bon River southwest of the basin receives a relatively high precipitation annually up to 4,000mm. It should be noted that this region is steep with narrow river bends, thus, most of the rainfall here are not retained upstream, but flows downstream and to the estuaries.

On the other hand, precipitation in the area is also temporary variable. The rainy season in the region begins in September and lasts until December while the dry season spans the length of January through to August. Precipitation during the rainy season accounts for up to 70% of the region’s precipitation. Only roughly 30% of annual precipitation is accounted for during the dry season with less than 6% of annual precipitation accounted for in the driest three months (DONRE, 2012). In addition, conditions during the dry season normally include higher temperature. Highest average monthly temperatures for March until August are constantly measured to be well above 30^0C. The higher temperature during the dry season leads to an increase potential evapo-transpiration.

Figure 3-3 depicts the variability in precipitation and evaporation in the river basin. As can be seen, from February to April, potential evaporation exceeds precipitation. Thus, potentially creating drought and water shortage risks.

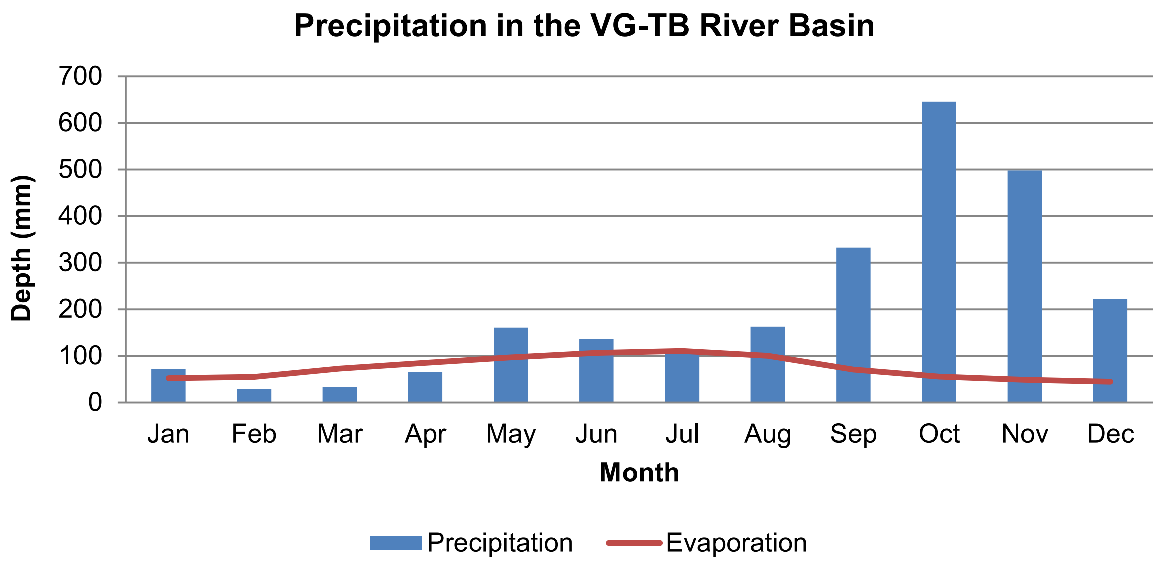

Figure 3-3: Average monthly rainfall and evaporation (data source: IMHEN)

It should be noted that only average values for 30 years of data were utilized for the brief analysis. Therefore, in more extreme cases, precipitation could be lower, or evaporation higher or both resulting in a lower precipitation compounded on a more extreme evaporation, ultimately leading to a dire water shortage situation. In fact, major natural disaster of hydrological origin has been reported in the river basin since 1980 where more reliable data have been accumulated. In that, 10 drought events have been reported in the years of 1982, 1983, 1984, 1985, 1988, 1993, 1998, 2001, 2008, 2009 (QNHMC, 2012).

The impacts of both drought and water shortage are likely to be increased in the region. This is due to an expected changes in rainfall and temperature in the future as a result of climate change (MONRE, 2012). While temperature and precipitation are not all relevant climate variables to natural disasters of hydrological origins in VGTB River Basin, they are dominant ones (Maraun *et al.*, 2010). Changes in these variables could indicate more extreme drought events in the future.

3.3 Previous Relevant Research in the Area

The hydrological component of the VGTB River Basin has been extensively studied in the past. There is a general agreement that climate change will have an impact on the water system in the basin. These researches call for adaptive measures to be taken to reduce the impacts of climate change. The results provided useful information on the extent of possible climate change conditions and impacts, yet fall short on providing useful information for adaptation. In other words, there are room for improvement to bridge the gap between science and decision-making.

The first two important studies includes the official Climate Change and Sea Level Rise Scenario for Viet Nam by the Viet Nam Ministry of Natural Resources and Environment (MONRE, 2012, 2016). The second official scenario by MONRE (2012) included the SRES scenarios from IPCC (2007b) whereas the third official scenario by MONRE (2016) used the Representative Concentration Pathway (RCP). Both studies performed climate change downscaling to obtain detailed climate scenarios for regions of Viet Nam including the VGTB River Basin.

MONRE (2012) included the low emission scenario (B1), the medium emission scenario (B2, A1B) and high emissions scenario (A2, A1FI). Statistical downscaling method, the MRI and PRECIS dynamic downscaling models were adopted in producing the temperature, seasonal, annual mean rainfall under low, medium and high emissions scenario throughout Viet Nam. The spatial resolution of the result is 25km by 25km grid cell and included both Da Nang City and Quang Nam Province. An increase of up to 2.7^0C by the end of the century was projected for the region together with an increase of 3.6% to 5% of precipitation by 2100.

MONRE (2016) used 5 RCMs to dynamically downscale 6 GCM outputs for entire Viet Nam. This includes using AGCM/MRI, PRECIS, CCAM, RegCM, and clWRF RCMs to downscale the NorESM1-M, CNRM-CM5, GFDL-CM3, HadGEM2-ES, ACCESS1-0, CCSM4 GCM models. The results showed that as compared to the baseline period of 1986-2005, average annual temperature in the VGTB River Basin is likely to increase 1.8^0C under RCP 4.5 and 3.2^0C under RCP 8.5 by the period 2080-2099 (Thuc *et al.*, 2016). Likewise, annual average precipitation is also expected to increase. More specifically, annual average precipitation could increase up to 30% under RCP 4.5 scenario by the end of the century. Under RCP 8.5, annual average precipitation could increase some 26% (Thuc *et al.*, 2016).

From the study of MONRE (2012) and MONRE (2016) it can be drawn that differing techniques and methods in climate change downscaling and scenarios selection could lead to varying results. This further reiterates the uncertainties in GCM downscaling. In addition, given the downscaling effort, only a limited number of available scenarios could be selected. Thus, the wider range of information on the condition of the climate in the future was not fully utilize.

An earlier attempt to study the impacts of climate change on water systems in Viet Nam and in the VGTB River basin was made by IMHEN (2010). Three emissions scenarios from IPCC (2007b) were adopted to develop the climate change scenarios including the low (B1), the medium (B2) and the high emissions scenario (A2) with a baseline period from 1980 to 1999. Statistical downscaling methods were then adopted to develop the climate change scenarios. The study concluded that dry season will see further water shortages. One important limitation of the study is the range of possible future climate conditions evaluated. Only three scenarios were used for the downscaling process therefore not fully utilizing a wider range of available information from GCMs. The limitation of the statistical downscaling technique used in the study have also been discussed earlier.

DONRE (2012) studied the impacts of climate change on drought risks in Quang Nam Province which covers the majority of the VGTB River Basin. The study initially determined the current status of drought in the study area through different pre-established drought indices. The trend of drought using historical data was also analyzed. From the analysis, an average drought index for the present was established. Through the use of climate change scenarios, projected temperature in the future was then used to directly determine the drought coefficient so that drought indices in the future can be determined as a product of present drought coefficient and indices. The study concluded that future drought conditions are expected to be more severe especially during dry season where there is an increase in temperature. Given that the main objective of the study was only on climate change impact assessment, no linkage to adaptation measures are proposed. Thus, the information provided from the study is of little use for adaptation.

Streamflow under the condition of future climate change conditions in VGTB were also studied by Institute of Geography (2011). Temperature and precipitation changes according to the scenarios developed by MONRE (2012) were utilized. The study concluded that dry season flow is expected to last 10 to 15 days longer as compared to the baseline period of 1980-1999. The approach used in the study is similar to that carried out by IMHEN (2010). In particular, the same climate change projections were used to drive hydrological models. Given the uncertainties in the statistical downscaling approach and the limited consideration of the wider range of climate conditions, the reliability of the analysis could thus be questioned.

Nam *et al.* (2011) presented a more detailed analysis of the impacts of climate change on the water systems for the Thu Bon River, part of the VGTB River system, through downscaling GCM outputs. The precipitation projection under A1B scenario simulated by CGCM model (MRI & JMA of 300km resolution) was statistically downscaled to the scale of the basin and used as input for the super-tank model for runoff analysis. The authors determined that by the middle and the end of the century, annual rainfall would increase slightly, together with a rising temperature; potential evapotranspiration is also expected to increase. As a result, total annual runoff in the dry season will likely decrease. The delay tendency of the low river flow period was observed where the timing shifts from the current January-August period to January-September period in the future. The strength in the study lies in its ability to dynamically downscale future climate conditions. However, given the large dynamical downscaling effort, only one RCM and one emissions scenario was considered. As there is no guarantee that the emission scenario is the best depiction of future conditions and the RCM used could provide the best simulation of conditions locally, reliability is thus limited.

Nga *et al.* (2013) focused on the coastal zone of Quang Nam Province, which forms part of the VGTB River Basin. The authors agreed that the issue of climate change in the area is highly complex and that little research is available in assessing the influences of climate change on the disaster vulnerability. Through a modified **D**riving forces- **P**ressures- **S**tates- **I**mpacts- **R**esponses (DPSIR) framework, the study attempted to apply an integrated assessment approach to determine the natural disaster impacts in the future climate state. The approach produced tailor made set of vulnerability indicators defining the socio-economic, environmental and physical impacts related to climate change. However, the approach falls short on the applicability when data is limited especially in the case for the VGTB river basin. In addition, the process of selecting the indicators used for the vulnerability assessment is highly subjective in nature, and only uses expert knowledge from the researchers.

Lan and Son (2013) studied the effects of climate change on the different hydrological extremes including floods and droughts. The research utilized the MIKE 11 hydraulics model from the Danish Hydrological Institute coupled with ArcGIS. Overall, drought periods are expected to increase in between 7 to 65 days from 2020 to 2100 depending on the climate change scenario (either medium emission scenario of high emission scenario). The main focus of the study, however was on the issue of flooding. This is mostly due to the availability of data and the time period of simulation for flood is shorter. Droughts and water shortage simulation would require decades of data and simulation. Thus, insufficient attention has been paid to the issue of drought and water shortage.

Viet (2014) explored the impacts of salinity intrusion at the downstream estuaries of the VGTB River Basin. Four different scenarios were used for the analysis including a current condition, sea level rise due to climate change condition, sea level rise due to climate change and human interventions condition, and salinity intrusion after adaptation measures were performed. Under the impact of sea level rise due to climate change as well as due to human interventions, salinity was seen to increase at all investigated sites. However, when complex human interactions and water regulation was analyzed, the trend in salinity intrusion is far more complex. Thus, the scenario-approach is relatively insufficient in translating science information into adaptation policies.

The Viet Nam Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation also included the analysis of climate change impacts in the Central Coastal zone (IMHEN and UNDP, 2015). The report summarized a number of researches and studies in the field of climate change impacts in Viet Nam and concluded: (1) extreme rainfall event showed an increasing trend within the period 1961- 2010 for the Central Coastal area, (2) the number of consecutive dry days have increased over the same period. In the Central Coastal zone, the number of drought events is not expected to increase yet the duration can be further prolonged in the future (IMHEN and UNDP, 2015), (3) analysis of past flooding events showed an increase in annual flood peak steadily in the last 30 years. Given the scope of the study was to summarize the overall trend of extreme events, no real adaptation responses were proposed.

A more recently published research by Vo *et al.* (2016) studied the impacts of climate change on river flow in the VG-TB River Basin. A MIKE SHE model was used to determine river flow in present day climate conditions over the time period of 1991-2010. Future conditions were obtained from dynamically downscaling the global climate models CCSM3.0, MIROC-medres, and ECHAM5 under the A2 scenario. The study concluded that river flow under scenario A2 could increase up to 200% during rainy season and decrease to roughly 7-30% during dry season. The study improved from other downscaling approaches in the selection of different RCMs. Given that different RCMs have different underlying assumptions, using more than one RCM could potentially provide output to determine the sensitivity of the downscaling technique. However, only the A2 emission scenario was considered. It is more likely than not that the future emission would not be similar to the scenario considered. Hence, the uncertainty of future climate condition is left unaddressed.

3.4 Research Gap and Justification

Previous research effort in the VGTB River Basin have provided information on the potential impacts of climate change, however, they share a common approach where a top-down framework was used. This includes the usage of downscaling of GCM results and either directly use climate variables for impact assessment or drive the climate variables through hydrological/hydraulics models. The limitation of a top-down approach has been well documented in the literature (García, L.E. *et al.*, 2014; Stéphane Hallegatte *et al.*, 2012; Wilby and Dessai, 2010; Dessai and Hulme, 2004). Figure 3-4 summarizes the propagation of uncertainty within a top-down approach.

The first source of uncertainty lies in the future economic development and emissions scenario. Emissions of greenhouse gasses in the future is highly dependent on socio-economic development and demographic change in the future, technology advances, and policies (García, L.E. *et al.*, 2014). The SSP approach could provide to be useful in linking climate scenarios with socioeconomic scenarios. However, the approach still suffers from uncertainty due to its scenario nature approach.

Scientific uncertainty is another factor within the cascade of uncertainty. This is a result of the imperfect knowledge of the functioning of the climate system and of the affected systems. For instance, one can clearly state that there are uncertainties related to the response of the global mean temperature to a given quantity of GHGs together with the uncertainty in the regional effects of climate change (Stéphane Hallegatte *et al.*, 2012).

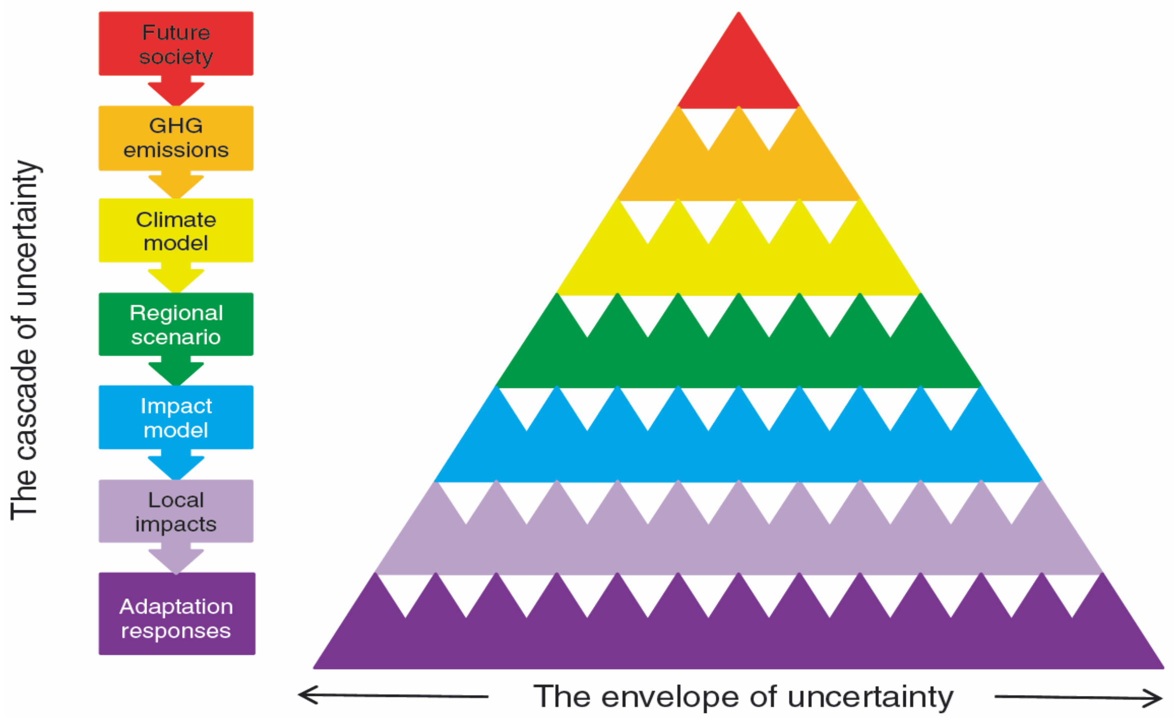

Figure 3-4: Uncertainties in a top-down approach (Wilby and Dessai, 2010)

Natural variability contributes further to the lists of uncertainties in the top-down approach. The uncertainty arises due to the natural dynamics of the climate system, linked to the chaotic behavior of the system that has been observed in the past. In that, climate models can estimate statistical nature (averages, variance, likelihood to exceed threshold) but not forecasts, i.e. deterministic prediction of the future. In other words, climate models can estimate average number of rainy days in a particular year but cannot provide further detail as to a specific day of a specific season (Stéphane Hallegatte *et al.*, 2012).

The top-down climate impact assessment approach provides a useful tool to assist the process of adaptation. However, it fails to deliver the required information that may be useful to decision makers. This is mostly due to the heavy reliance on GCM models. *Firstly*, by relying heavily on GCMs, the approach only assesses a number of scenarios. This is because downscaling of GCMs is demanding. *Secondly*, there are large uncertainties in GCMs as discussed previously (García, L.E. *et al.*, 2014). In utilizing GCMs, there is a risk of having a cascade of uncertainty starting with hard-to-predict human behavior to derive emissions scenario, uncertainties in model parameters and structures, natural climate variability, and the underlying science that is being used to develop GCMs. The uncertainty is represented in a range of projected futures by different GCMs. Variability in projections from different models can be so large that to plan for one projection will strictly be contradictory to the other. In cases where there is a consensus between a broad range of models and scenarios, the implication is that there exists a consensus between the assumptions in the different range of models (García, L.E. *et al.*, 2014).

Traditional decision making processes work through the prediction of a future state, and the design of plans or projects for the conditions of that state. This approach produces optimal results for the intended future; however, its applications may be increasingly limited as there are large uncertainties. The approach is represented by a “loading-dock” situation where scientific information is continuously provided without the real objective of providing adaptation responses. Given the uncertainties related to a top-down approach for climate change impact assessment in the VGTB River Basin and the lack of adaptation response, the research demand is justified. A different approach where useful information to policy makers has to be adopted. The methodology has to combine the strengths and reduces the weaknesses of a top-down and a bottom-up climate change assessment methods. In other words, downscaling should be avoided and a wider range of climate information and their uncertainties should be included. Through such an approach, better climate information could be provided to stakeholders to propose adaptation measures.

3.5 Data

The study utilizes a range of data in quest for the research demand. This includes hydrological and meteorological data, GCM outputs, socio-economic data, and satellite image data. The following section describes the data used in further detail.

3.5.1 Hydrological and meteorological data

The hydrological and meteorological monitoring network within the VGTB River Basin is relatively sparse. For the entire river basin, there are only 2 river flow gauges and 25 rain gauges. Historical data record begins as early as 1975 after the country’s reunification with missing gaps at certain stations and certain years. As part of the research, data for the flow gauges and rain gauges were collected from the beginning of monitoring up until the end of 2013. More recent data could be obtained, however, would not significantly affect the analysis. The focus of the study lies on the average long-term effects of climate conditions rather than short-term phenomena (see section 2.1.1).

The two river flow gauges measure flow in the Vu Gia and the Thu Bon main river branches. The Thanh My river gauge monitors flow in the Vu Gia branch of the river system while the Nong Son river gauge monitors flow in the Thu Bon branch. Unlike rain monitoring data, flow data are only available from 1976 onwards.

The rain gauge network in the river basin consists of 25 independent stations. The quality of rainfall records in the gauging stations are, however, not consistent. There exist data gaps in certain stations, some up to a decade, thus limiting their usability. Upon a detailed analysis of all historical rainfall record, it was deemed that only data from 21 rain gauges would be utilized. This would ensure a consistency in duration and quality of the rainfall record.

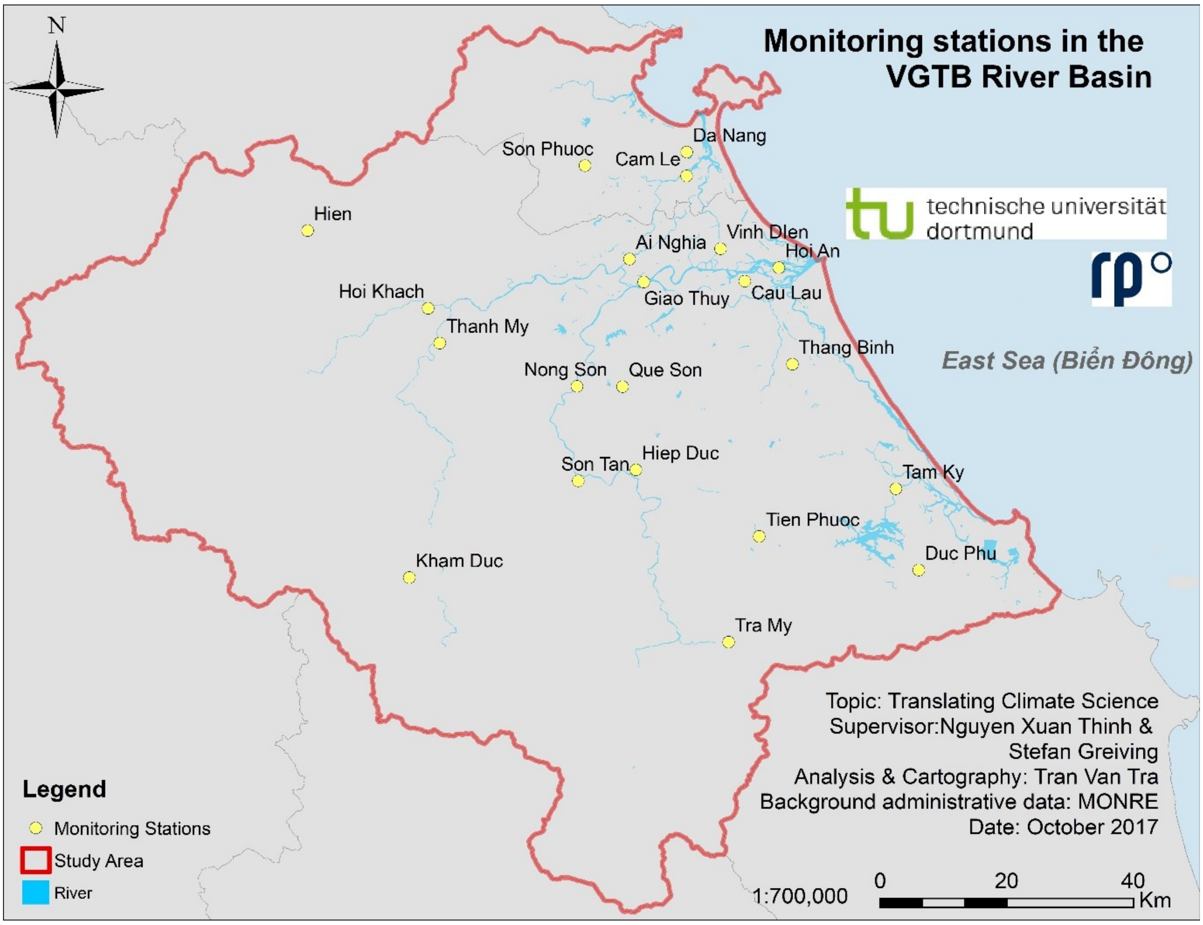

Figure 3-5: Monitoring stations in the Vu Gia- Thu Bon River Basin

The names and locations of the 21 monitoring stations used are as shown in Figure 3-5. Note that Thanh My and Nong Son stations monitor both river flow and rainfall. In addition, Da Nang, Tam Ky, and Tra My rain gauging stations also monitor climate parameters such as humidity, sunshine hours, wind, temperature, etc. It could be seen that monitoring stations in the river basin are not evenly distributed. There is a high density of stations downstream of the river basin whereas a limited number of stations upstream. This could be partially due to the limited access to remote mountainous areas upstream.

3.5.2 General circulation model outputs

GCM outputs based on IPCC Fifth Assessment Report Representative Concentration Pathway (RCP) Scenarios were also utilized for the river basin. More specifically, output for RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 scenarios were utilized. In total, 25 GCM outputs were extracted. However, not all scenario results from all 25 GCMs were utilized. In total, 55 combination of scenarios were used. The list of model used is attached in Appendix A: List of CMIP5 models used.

3.5.3 Socio-economic data

The study further utilized socio-economic data for the VGTB River Basin. Since socioeconomic data are issued based on administrative jurisdiction, data for Quang Nam Province and Da Nang City were collected separately. For this purpose, Statistical year book from Quang Nam and Da Nang were obtained. Information such as population, gross domestic products, share of economic sectors, etc. were obtained.

Additionally, land use planning documents and legal documents made by authorities were collected. This includes documents issued both by local governments in Quang Nam Province and Da Nang City as well as the Central government of Vietnam. In particular, land use master plan for the period 2011-2020 for both Quang Nam and Da Nang were obtained, decisions on land prices from Quang Nam and Da Nang, and relevant laws from the central government of Vietnam such as the Land Law were also utilized.

3.5.4 Satellite image data

Satellite image data for the VGTB River Basin are also utilized for the study. This includes the use of high-resolution SPOT 7 image from AIRBUS and the widely used Landsat mission data from the United States Geological Survey. The SPOT image has a base resolution of 6mx 6m accommodating only 4 basic spectral bands of Red, Green, Blue, and Near Infrared. On the other hand, the Landsat satellite image has a base resolution of 30mx 30m while accommodating a larger number of spectral bands (11 bands).

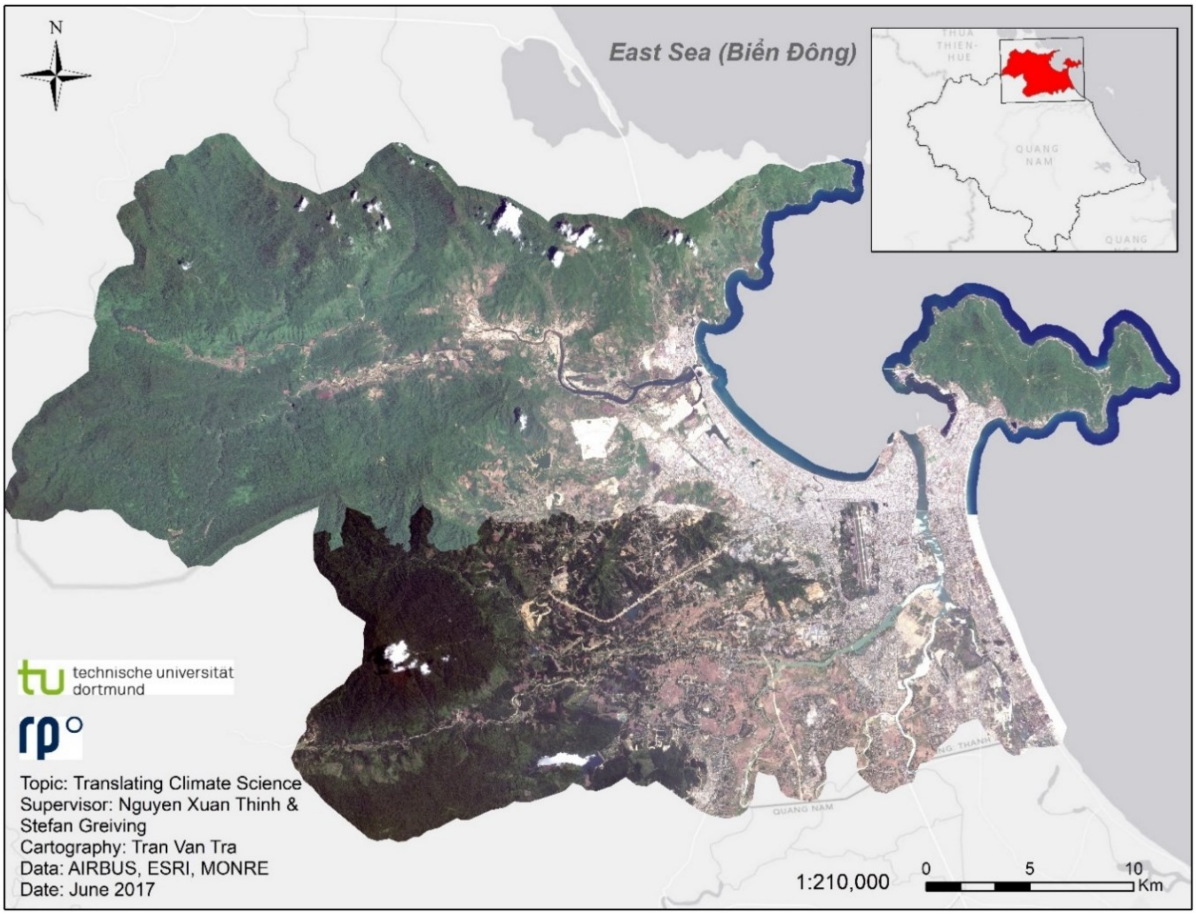

Figure 3-6: High Resolution SPOT image for Da Nang City

The SPOT image used in the study includes two separate scenes that cover the entire boundary of Da Nang, roughly 1000 km^2. The northern scene which covers approximately half of Da Nang City from the Northern border through to the division line at the city airport, and includes the Son Tra peninsula is taken on 7th March 2014. The southern scene of the image covers the remaining part of Da Nang and is taken on 3rd May 2015 (refer to Figure 3-6). Cloud coverage in the SPOT image is minimal and deemed to have no significant impact on any analysis.

Due to financial constraints, similar SPOT image for Quang Nam Province could not be procured. Instead, the study utilizes Landsat images including both the LANDSAT5 and the more recent Landsat 8 data from the United States Geological Survey. In total, there are 10 Landsat scenes used including 5 Landsat 8 scenes and 5 Landsat 5 scenes. The Landsat 8 scenes provide images for 2016 and 2017 while Landsat 5 scenes provide images for 2010 and 2011. The Landsat 5 data was used in place of the Landsat 7 due to the Landsat 7 mission sensor error (Scan Line Error). The list of scenes used in the study is shown in Table 3-1. The reason for such a large selection of scenes is for the purpose of performing multi-temporal NDVI.

Table 3-1: Landsat satellite images used for the study

Data	Date	Scene names
Landsat 8 OLI (30x 30m)	8th March 2016	LC81240492016068LGN00
	8th March 2016	LC81240502016068LGN00
	25th April 2016	LC81240492016116LGN00
	2nd May 2016	LC81250492016123LGN00
	11th March 2017	LC81240492017070LGN00
Landsat 5 TM (30x 30m)	7th February 2011	LT51240492011038BKT00
	7th February 2011	LT51240502011038BKT00
	5th July 2010	LT51250492010186BKT01
	11th May 2010	LT51240492010131BKT01
	12th June 2010	LT51240492010163BKT01

3.5.5 Input from stakeholders and experts

The study further utilizes information from local and national stakeholders as well as experts in the study area. Information from stakeholders and experts were obtained through multiple informal meetings and interview. The objective of such activities were to gather information on the types of hazards that the river basin faces, the level of impacts that would require immediate actions, and to quantify the threshold value for the performance of the system under analysis that would trigger adaptation options. The list of stakeholders and experts involved in the study is attached in Appendix C: List of stakeholders and experts involved.

4 METHODOLOGY

In order to meet the research objective, the methodology selected would need to address the problems associated with top-down climate change impact assessment. To overcome the limitation of the traditional approach, a combined top-down and bottom-up approach would need to be utilized.

A slightly modified decision scaling framework is adopted for the study. The decision scaling framework- being of a combined top-down and bottom-up nature have several advantages over the traditionally used climate change impact assessment. *Firstly*, the decision-scaling framework omits the need to use downscaling techniques that entails large uncertainties. *Secondly*, through limiting the efforts in downscaling and allowing an analysis on a wider range of GCM scenarios, the framework considers the uncertain future climate prediction themselves. *Thirdly*, through focusing on the vulnerable area of the system in question, the analysis focuses only on climate conditions that are relevant. *Lastly*, the framework make use of stakeholder exchange dialogue from the early stage and make room for constant information exchange throughout the process. This allows the research to tailor information that are both relevant and meaningful to stake holders.

A detailed workflow of the research is shown in Figure 4-1. Initially hydrological data, meteorological data, socioeconomic data, GCM outputs, satellite images, and ground truthing points in the river basin were collected. Through a series of stakeholder meetings together with analysis of historical data record, climate hazards, performance indicators and performance threshold could be established. Hydrological data, meteorological data, socioeconomic data, performance indicator, and performance threshold are then used in the MIKE BASIN hydrological model. Through parametrically varying annual average temperature and rainfall, problematic conditions leading to water shortage could be established. Combining the problematic conditions of temperature and rainfall from the MIKE BASIN simulation with output from GCM models, a vulnerability space of the water system in the face of climate change could be drawn. Satellite images were further utilized to establish land cover classification for two time periods of 2011 and 2020. The land cover classification then acts as the input for land cover change detection within the same period. The information from the land cover change is thus related back to the water demand components in the established MIKE BASIN model. Finally, adaptation measures are proposed on the basis of the problematic conditions from the MIKE BASIN simulation and the land cover change detection results.

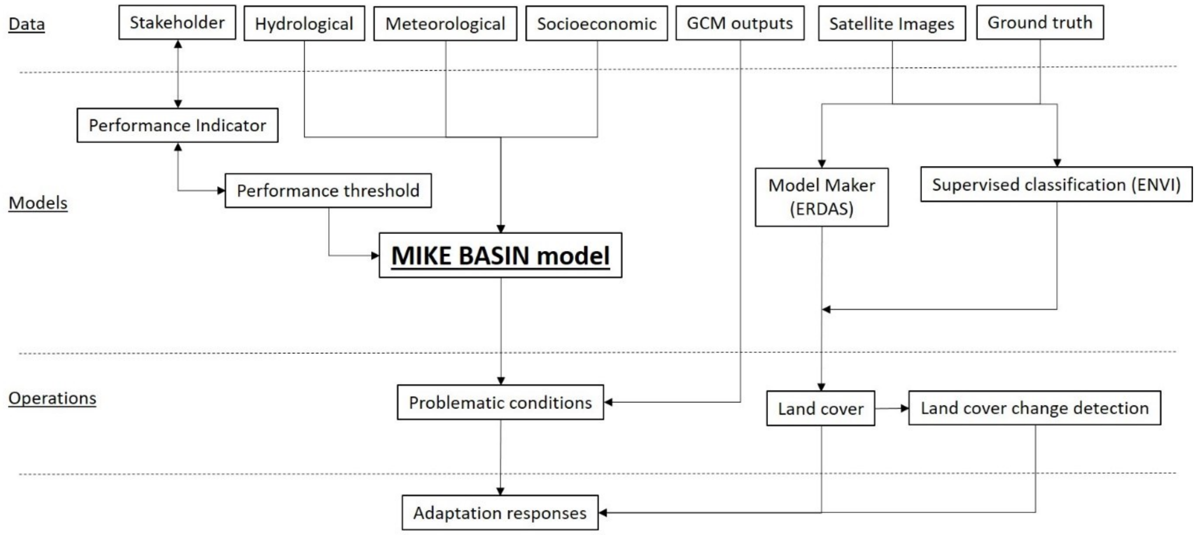

Figure 4-1: Overall Workflow of the research

4.1 Identification of Climate Hazard and Threshold

The initial step involves determining the climate hazards relevant to the study area. This includes identifying the climate conditions that have caused problems historically and that are of concern. Exchange with local stakeholders and policy makers were performed initially to obtain the overview of water resource problems in the area. General summaries of climate change projections from the literature on the regional impacts are also used as guidelines. For the purpose of the study, the aspect of water shortage would be analyzed in detailed.

The assessment of water shortage and drought in the VGTB River Basin is performed based on analyzing water supply and demand within the basin. Supply in the basin includes rainfall and water storage from reservoirs. On the other hand, demand in the basin includes domestic, industrial and agricultural demands.

To assess the problematic conditions in the context of water supply in the VGTB River Basin, reliability is chosen as the system performance indicator. Reliability (%) is the measure of time where demand is met, i.e. reliable. For example, a water supply system of 70% reliability means that out of the period analyzed, only 70% of the time the water supply system met its demand, the remaining 30% of the time, the system faced water shortages. A threshold of system performance (reliability) would also need to be established to reflect conditions unacceptable to stake holders.

In the original decision scaling approach, the threshold level should be determined based solely on stakeholder meetings and expert knowledge. However, as stakeholder and expert meetings were conducted during the first phase of research, it was clear that a one common threshold level was difficult to be obtained from the various stakeholders. It is for this reason, a different approach is required. In this approach, media and official technical report on water shortage and drought were analyzed. This is based on the assumption that severe water shortages in the past would give an indication of to what level of hazard would be deemed unacceptable to the river basin. The performance of the water supply system during such water shortage events are then recommunicated with the stakeholders to confirm that the event in the past served the purpose of setting a threshold.

However, instead of solely relying on one source of information, a cross check scheme is adopted. Drought and water shortage events reported in both media and official technical reports were thoroughly studied using meteorological and hydrological data. More specifically a monthly Surface Water Supply Index (SWSI) was used to validate the information provided in the literature together with information from stakeholders. The assumption is that SWSI values would be able to pick up water shortage events. The SWSI values were determined using gauging data from Nong Son and Thanh My flow gauges.

The SWSI is a predictive drought index commonly used in the United States of America, however, widely applicable to other areas in the world. The index measures the total surface water availability within a river basin. The main criticisms of the SWSI in the past has been its subjective assignment of values to coefficient and obscured statistical properties of the index (Garen, 1993). For this reason, instead of using the SWSI from Shafer and Dezman (1982), an earlier version which only includes reservoir and streamflow component taken from Gumbel (1963) is adopted. The revised SWSI is calculated as follows:

$$SWSI = \frac{(P - 50)}{12} \qquad \textbf{\textit{(2)}}$$

where P is the non-exceedance probability in percent for the stream flow and reservoir release component. During the period of October to March, the value of P is determined from 1st April reservoir storage adding April to September stream flow. On the other hand, during the months from April to September, P is determined for the first-of-month reservoir storage adding the month to September streamflow.

4.2 System Models

To assess the effects of climate conditions and water shortage in the study area, it is imperative to develop a system model that is capable of simulating hydrological processes. A MIKE BASIN model is adopted for the area. The selection of the model is due to its previous applications in Viet Nam, thus allowing exchange with local experts to improve the model and transferability to other users once the research is completed. The licensed version from the Viet Nam Institute of Meteorology, Hydrology and Climate Change was used in the study.

MIKE BASIN is an extension of the ESRI ArcGIS software. The program allows simulation of water allocation, conjunctive water uses, and reservoir operation (DHI, 2012). The development of the MIKE BASIN model in the VGTB River Basins includes the development of the basin model, rainfall-runoff model, water demand model, and the reservoir model.

4.2.1 River basin

The initial step in setting up the MIKE BASIN model is to delineate the sub-basins. The river basin was delineated using the SRTM Digital Elevation Model (DEM) with a resolution of 90mx 90m. Although a 30mx30m higher resolution DEM is available, this version was not used. This is due to a number of reasons. *Firstly*, within the study area, there were anomalies in the 30mx30m DEM that needs reprocessing. However, to process these anomalies would require in-situ field data, none were available at the time of the study. *Secondly*, for the sole purpose of delineating river basins, a 90mx90m would be sufficient, reducing the unnecessary computational strain. A total of 182 sub-basin was obtained (Figure 4-2). It should be noted that due to the coarse resolution and the quality of the DEM, not all parts of the VGTB River Basin could be properly covered. This however, should not affect the accuracy of the model.

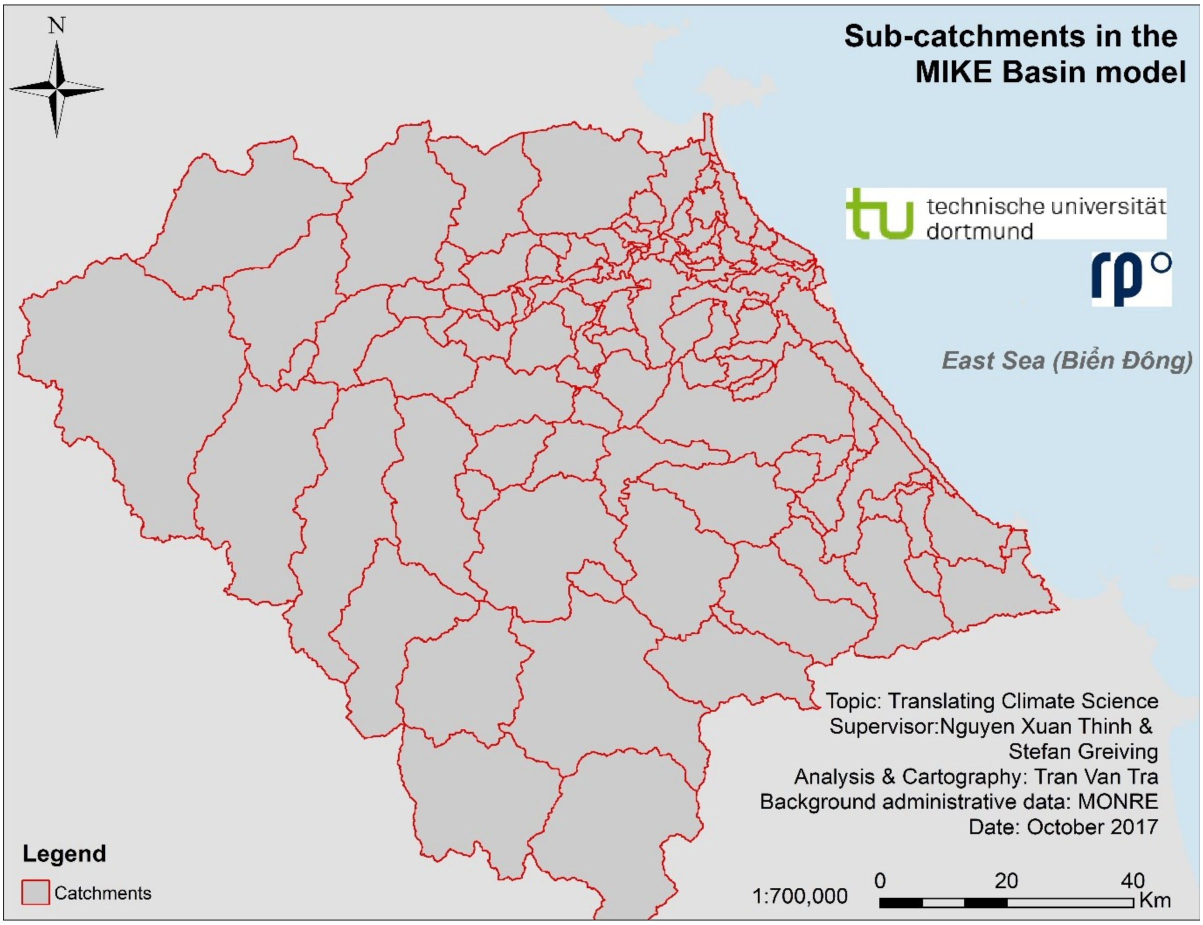

Figure 4-2: MIKE BASIN sub-basin delineation

4.2.2 Rainfall-runoff model

The second step in the MIKE Basin model development involves developing the rainfall-runoff model in the sub-basins. For this purpose, the rainfall-runoff module MIKE NAM was used. MIKE NAM is a lumped, conceptual rainfall-runoff model. The model calculates runoff from precipitation through determining the processes that occur at the catchment level vertically. In particular, three layers are divided in the model including the above ground layer, the unsaturated zone and the saturated zone.

A 13-model parameter version of MIKE NAM is used. The model parameters and the description of each parameter is shown in Table 4-1. The parameters can be divided into two groups describing processes at the surface-root zone and processes at the groundwater zone. There are 7 parameters describing processes at the surface-root zone. This includes Umax, Lmax, CQOF, CKIF, CK1,2, TOF, and TIF. The remaining 6 including TG, CKBF, Carea, Sy, Cqlow, and Cklow describe processes at the groundwater level.

Table 4-1: Model parameters in MIKE NAM

Parameter	Unit	Description
Umax	mm	Maximum water content in surface storage
Lmax	mm	Maximum water content in root zone storage
CQOF	dimensionless	Overland flow runoff coefficient
CKIF	hours	Time constant for routing interflow
CK1,2	hours	Time constant for routing overland flow
TOF	dimensionless	Root zone threshold value for overland flow
TIF	dimensionless	Root zone threshold for interflow
TG	dimensionless	Root zone threshold value for groundwater recharge
CKBF	hours	Time constant for routing baseflow
Carea	dimensionless	Change ratio of groundwater- area to catchment area
Sy	dimensionless	Change specific yield of groundwater reservoir
Cqlow	dimensionless	Lower baseflow, recharge to lower reservoir
Cklow	hours	Time constant for routing lower baseflow

A visual depiction of the rainfall-runoff processes and model parameters is shown in Figure 4-3. The input of the model includes precipitation whereas the final output of the model includes the water discharge. Intermediate calculations includes the determination of evaporation E_a, net rainfall P_n, infiltration I, overland flow QOF, interflow QIF, interflow and overland flow routing CK, groundwater recharge G, groundwater storage and baseflow q_g, and capillary flux C (Agrawal and Desmukh, 2016).

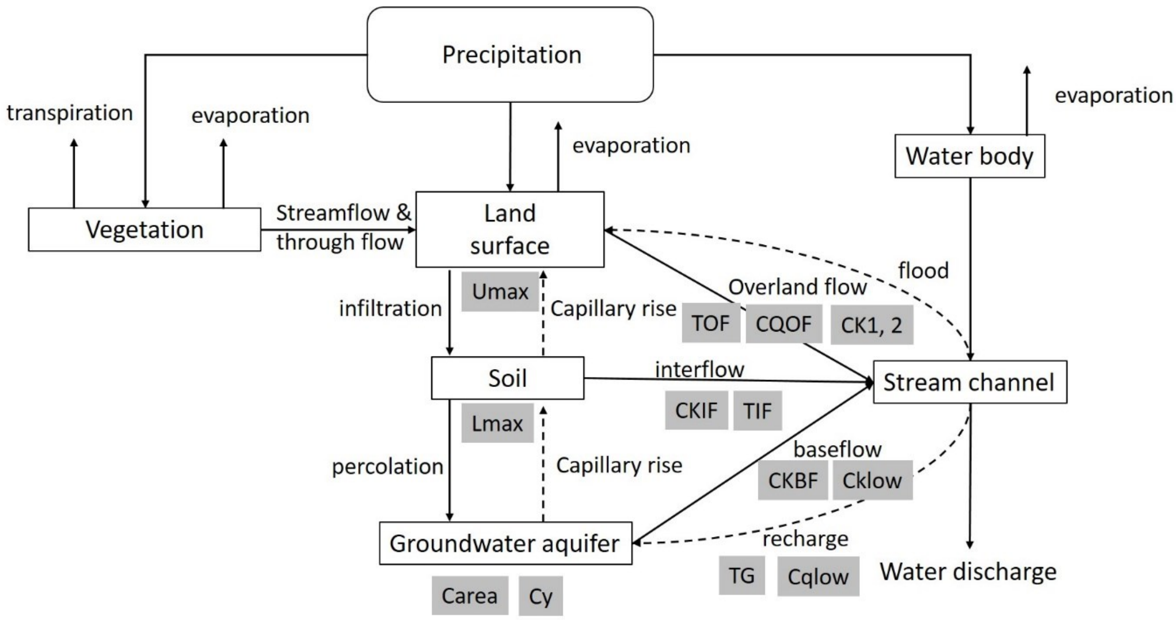

Figure 4-3: MIKE NAM processes and parameters

Potential evapotranspiration E_a is a direct function of the relative soil dampness content and is determined by:

$$E_a = \begin{cases} L & U \geq E \\ U + \frac{L}{L_{max}}(E - U) & otherwise \end{cases} \quad \textbf{(3)}$$

Net rainfall and infiltration processes in MIKE Nam are dependent on the precipitation, evaporation, overland flow, and interflow. Net rainfall P_n and infiltration I are described as:

$$P_n = \max(0, P - E_a - QIF - (U_{max} - U)) \quad \textbf{(4)}$$

$$I = P_n - QOF \quad \textbf{(5)}$$

At the point where the water content in the surface storage zone exceeds the maximum storage capacity, the surface storage spills. At this point, the overabundance of water from P_n contributes to overland stream and infiltration. *QOF* is the part of P_n that is added to overland flow. Overland flow only occurs when the saturated fraction of the lower zone exceeds the threshold value *TOF* and is determine by:

$$QOF = \begin{cases} CQOF\ P_n \left[\frac{\frac{L}{L_{max}} - TOF}{1 - TOF}\right] & \frac{L}{L_{max}} > TOF \\ 0 & otherwise \end{cases} \quad \textbf{(6)}$$

The interflow component *QIF* is dependent on the relative dampness of the lower zone storage *L*. Interflow only occurs when the critical saturation fraction of the lower zone exceeds the threshold value *TIF* and is determined by:

$$QIF = \begin{cases} CQIF \left[\frac{\frac{L}{L_{max}} - TIF}{1 - TIF}\right] & \frac{L}{L_{max}} > TIF \\ 0 & otherwise \end{cases} \quad \textbf{(7)}$$

The interflow is directed through two straight reservoirs in arrangement with the same time consistent $CK_{1,2}$. The overland stream routing is also based on the linear reservoir idea but with a variable time consistent. To hold a linear response for nearly surface flows and kinematic response for above surface flows at higher discharges, the time constants is modified as:

$$CK = \begin{cases} CK_{1,2} & OF < OF_{min} \\ CK_{1,2}\left[\dfrac{OF}{OF_{min}}\right]^{-\beta} & otherwise \end{cases} \quad \textbf{\textit{(8)}}$$

OF	overland flow (mm/hour)
OF_{min}	upper limit for linear routing (0.4 mm/hour)
β	0.4

The amount of ground water recharge *G* depends on the soil moisture content in the root zone. Ground water recharge *G* only occurs when the saturated fraction exceeds the threshold *TG*:

$$G = \begin{cases} I\left[\dfrac{\dfrac{L}{L_{max}} - TG}{1 - TG}\right] & \dfrac{L}{L_{max}} > TG \\ 0 & otherwise \end{cases} \quad \textbf{\textit{(9)}}$$

Groundwater capacity allows base flow in two distinct ways. The first is through an assumption of a linear reservoir concept whereas the second uses the concept of a shallow reservoir. The simple base flow process assumes a linear reservoir concept such that:

$$q_g = \begin{cases} CKBF & S_g > 0 \\ 0 & otherwise \end{cases} \quad \textbf{\textit{(10)}}$$

S_g	water in groundwater storage above zero reference

The second base flow process is directly related to water table depth above the maximum drawdown of groundwater zone and is estimated by:

$$q_g = \begin{cases} CKBF & S_y(D_g^{max} - D_g)D_g^{max} \geq D_g \\ 0 & otherwise \end{cases} \quad \textbf{\textit{(11)}}$$

D_g	depth of water table below zero datum
D_g^{max}	depth of water table attaining a maximum value

Water between ground water storage and lower zone storage could be transferred upwards due to capillary rise. Capillary flux *C* is determined as:

$$C = \left(1 - \frac{L}{L_{max}}\right)\left(\frac{D_g}{D_g^1}\right)^{-\alpha} \tag{12}$$

With $\alpha = 1.5 + 0.45D_g^1$ and D_g^1 being the depth of the groundwater table at which capillary flux =1mm/day when L=0.

There are only two gauging stations with historical flow data. This includes Nong Son and Thanh My gauges. Consistent flow data were available from 1/1/1978-31/12/2013. For this reason, the MIKE NAM model could only be calibrated using flow data from these two stations for the stated time period.

In terms of the meteorological input for the MIKE NAM model, precipitation and evaporation data is required. A Thiesen polygon method was used to calculate the weight of each precipitation station (by area) on the overall precipitation in Nong Son and Thanh My basins (Table 4-2). A Thiessen polygon define individual areas of influence around each of a set of points. Thiessen polygons are polygons whose boundaries define the area that is closest to each point relative to other points. They are mathematically defined by the perpendicular bisectors of the lines between all points. Precipitation data input of Nong Son and Thanh My would then be the weighted average sum from the Thiessen polygon areas. In particular, precipitation in Thanh My catchment would be the weighted average sum of precipitation in Kham Duc (0.791), Thanh My (0.174), Hoi Khach (0.008), and Tra My (0.026) stations. Likewise, precipitation in Nong Son catchment would be the weighted average sum of Kham Duc (0.106), Thanh My (0.22), Tra My (0.468), Tien Phuoc (0.138), Hiep Duc (0.178), Nong Son (0.084), and Tam Ky (0.004) stations. For the purpose of calibration and validation, the historical record of rainfall has to match the record of river flow gauge. For this reason, rainfall record between 1/1/1978-31/12/2013 is used. Evaporation data for the nearby Tra My monitoring station for the period of 1/1/1978-31/12/2013 was also used. This is due to the vicinity of Tra My meteorological station to Nong Son and Thanh My gauging station suggesting its representativeness of the evaporation conditions.

Table 4-2: Weight of precipitation data used in Nong Son and Thanh My precipitation calculation

No.	Station	Thanh My	Nong Son
1	Kham Duc	0.791	0.106
2	Thanh My	0.174	0.022
3	Hoi Khach	0.008	0.000
4	Tra My	0.026	0.468
5	Tien Phuoc	0.000	0.138
6	Hiep Duc	0.000	0.178
7	Nong Son	0.000	0.084
8	Tam Ky	0.000	0.004

Both model calibration and model validation was conducted. For both monitoring stations of Nong Son and Thanh My, calibration period is between 1/1/1978-31/12/1994 and validation period between 1/1/1995-31/12/2013. The length of data used for calibration and validation is approximately the same to ensure calibration and validation are equally considered. The location of Nong Son and Thanh My catchments are shown in Figure 4-4.

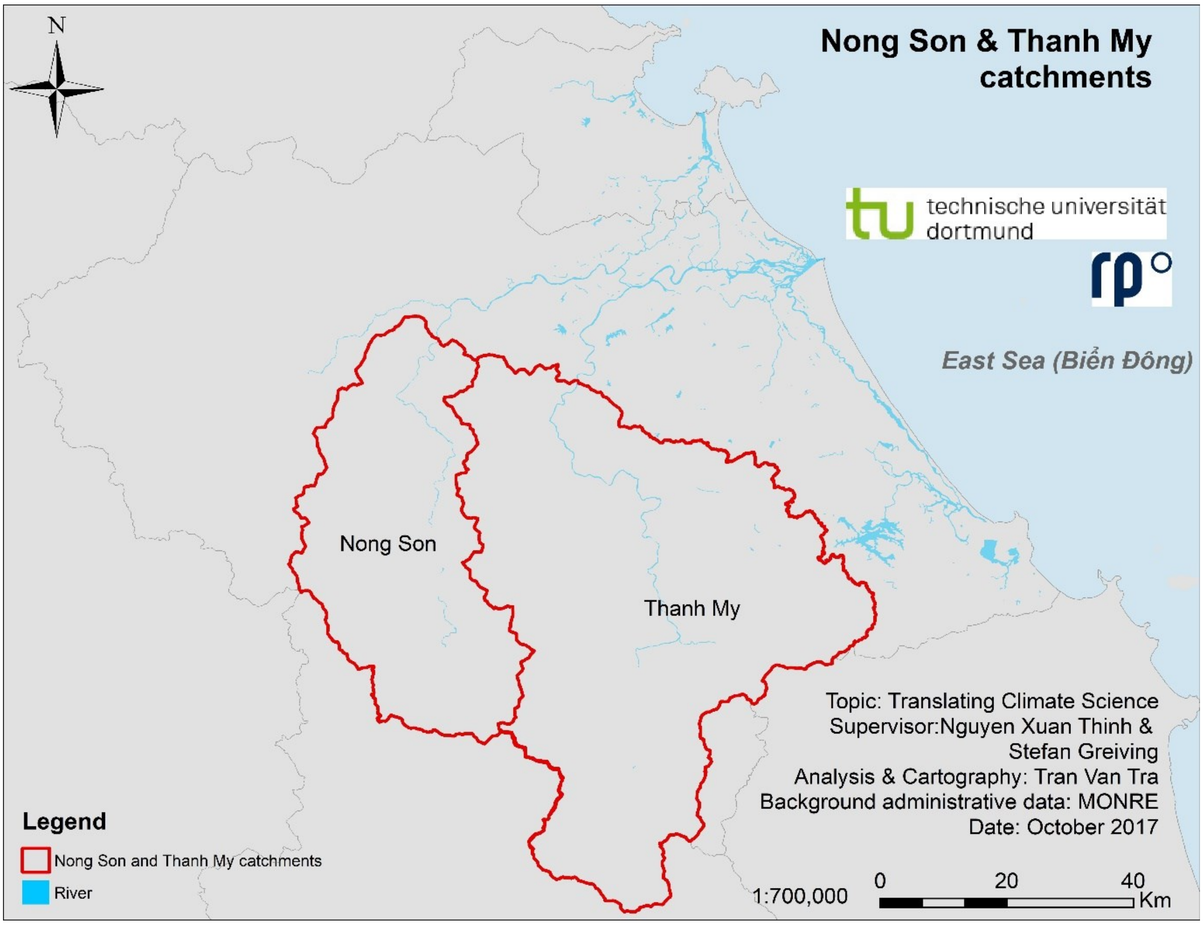

Figure 4-4: Location of Nong Son and Thanh My catchments

The calibration and validation criterion used is the Nash-Sutcliffe model efficiency coefficient. The coefficient is calculated as:

$$Nash - Sutcliffe\ efficiency\ (E) = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \quad \textbf{\textit{(13)}}$$

where $\overline{Q_o}$ is the mean of observed discharges, Q_m^t is modelled discharge at time step t, Q_o^t is the observed discharge at time step t. The value of the Nash-Sutcliffe efficiency coefficient ranges from -∞ to 1. A value of 1 indicates a perfect match of the modelled discharge to the observed discharge. A value of 0 indicates that the model predictions are as accurate as the mean of the observed discharge. A value less than 1 indicates that the observed mean discharge is a better predictor of the model, meaning the model has little usefulness. A value closer to 1 indicates higher level of accuracy. In practice, a level equal to or above 0.8 is generally accepted.

After the MIKE NAM model has been fully developed for the Nong Son and Thanh My catchments, averaged parameters of Nong Son and Thanh My catchments were used for other sub-basins. This is based on the donor catchment method where nearby catchments are assumed to share similar physical properties, hence, share model parameters. Runoff could then be calculated for the other sub-basins using the average parameters from Nong Son and Thanh My. The calculation period chosen is between 1/1/1985 and 31/12/2005. The main reason behind a limited calculation period is to coincide with the baseline period in IPCC Fifth Assessment Report (1986 to 2005). The similar period has also been accepted by the Ministry of Natural Resources and Environment as the baseline period in the Climate Change and Sea Level Rise Scenario projections. Through parametrically varying rainfall and temperature within the same period, policy makers who are already familiar with the assessment period could easily understand the results. The additional calculation of runoff in 1985 served as a warm-up period to remove the possible effects of the initial condition selection in the model, and results in 1985 were not further utilized in the study.

4.2.3 Water demand model

The water demand in the MIKE BASIN model consists of two components: domestic and industrial water demand, and irrigation water demand. The domestic and industrial demand was calculated using socio-economic data of Quang Nam and Da Nang from a compilation of sources including the Statistical Year Book. Irrigation demand in theory could be determined using the irrigation demand module within MIKE BASIN. Nonetheless, due to the limitation of the module to determine crop water requirement for rice, a different model was utilized, namely the CROPWAT 8.0 by the Food and Agriculture Organization. Water demand is represented in the MIKE BASIN in the form of water user nodes.

Table 4-3: MIKE BASIN node corresponding to domestic water users

Node in MIKE BASIN	Township	City/District Name	Urban Population (people)
WSP_VG01	Kham Duc	Phuoc Son	6,407
WSP_VG02	Thanh My	Nam Giang	7,398
WSP_VG03	P'rao	Dong Giang	4,444
WSP_VG04	Ai Nghia	Dai Loc	17,060
WSP_VG05	Da Nang	Da Nang	992,800
WSP_TB01	Tra My	Bac Tra My	6,723
WSP_TB02	Tien Ky	Tien Phuoc	7,184
WSP_TB03	Tan An	Hiep Duc	3,335
WSP_TB04	Ha Lam	Thang Binh	16,291
WSP_TB04	Dong Phu	Que Son	8,525
WSP_TB05	Vinh Dien	Dien Ban	8,350
WSP_TB05	Nam Phuoc	Duy Xuyen	22,757
WSP_TB05	Hoi An	Hoi An	84,588
WSP_TK01	Tam Ky	Tam Ky	279,851
WSP_TK01	Phu Thinh	Phu Ninh	4,050
WSP_TK02	Nui Thanh	Nui Thanh	10,345

In respect to domestic and industrial water demand, a total of 12 water demand nodes were established. For domestic water demand calculation, it is assumed that only inhabitants living in the urban area have access to a water mains supplying scheme. Communities living in the rural area relied on wells, and local, small water supply schemes. For this reason, only domestic water demand for urban area was accounted for as water users (from reservoirs). The assumption holds largely true in reality. The total number of people and the corresponding node represented in MIKE BASIN is shown in Table 4-3. An average of 120 liters/person/day demand was used to estimate domestic demand with an exception for the city of Da Nang where an average water demand per person per day is set at 200 liters/day. These values are based on the standards set by the Ministry of Construction for the Central Coastal Zone of Viet Nam at the time of the study (Vietnam Ministry of Construction, 2006).

For industrial water demand, the similar set of standards by the Ministry of Construction on water consumption was used, in which, water demand was a function of the area of the industrial zone. According to the standard, water demand in 2010 is set at $50m^3/day/m^2$ and demand in 2020 set at $60m^3/day/m^2$. An average value of $55m^3/day/m^2$ was taken for the time of the study.

Irrigation demand was determined through the establishment of irrigation zones in the MIKE Basin model. The river basin was divided into 7 irrigation zones (Figure 4-5) with 43 irrigation nodes. These irrigation zones were determined based on the information provided by the relevant Irrigation Company of Quang Nam and Da Nang, and irrigation reservoir data as well as irrigation infrastructure (pumping stations, dams, etc.). Irrigation water demand for each node was then determined using the CROPWAT 8.0 model from the Food and Agricultural Organization (Allen *et al.*, 1998).

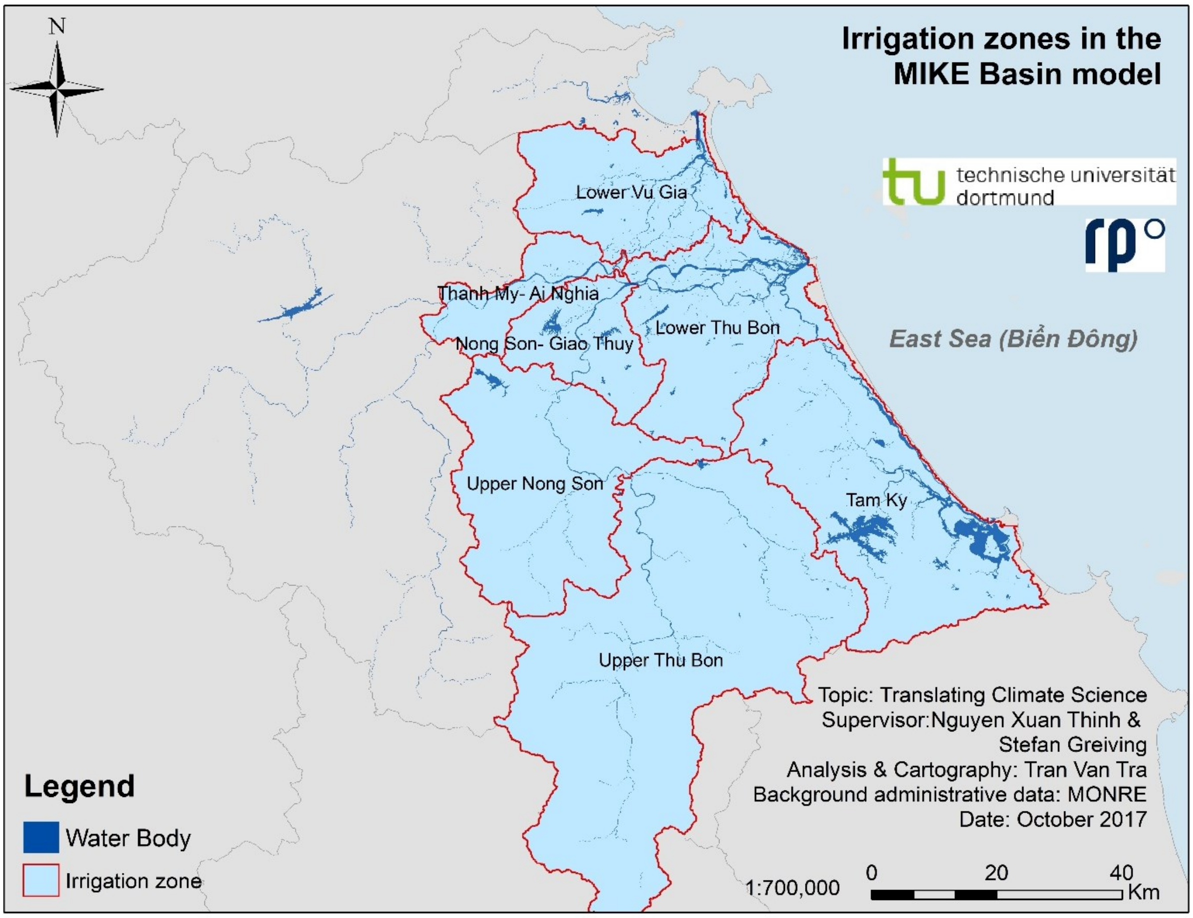

Figure 4-5: Irrigation zones in the MIKE BASIN model

Irrigation water demand in Cropwat is estimated in two steps. The first step is to determine the reference evaportranspiration while the second step is to determine the crop water demand. Initially, the reference evapotranspiration ET_0 is estimated using the Pennman-Moneteith equation:

$$E_{T_0} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{14}$$

ET_o	reference evapotranspiration (mm/day)
R_n	net radiation at the crop surface (MJ/m^2/day)
G	soil heat flux density (MJ/m^2/day)
T	mean daily air temperature at 2 m height (^{0}C)
u_2	wind speed at 2 m height (m/s)
e_s	saturation vapor pressure (kPa)
e_a	actual vapor pressure (kPa)
e_s- e_a	saturation vapor pressure deficit
Δ	slope vapor pressure curve (kPa/^{0}C)
γ	psychrometric constant (kPa/^{0}C).

Secondly, the crop water demand is determined through multiplying the reference evapotranspiration with an empirical crop coefficient K_c to produce an estimate of crop evapotranspiration:

$$ET_C = ET_0 \times K_c \tag{15}$$

K_c	empirical crop coefficient

Only water demand for rice was determined due to the limitation of available data. This however, represents the majority of irrigation demand in most case due to the cropping area (well over 70% agriculture area) (Viet, 2014) and intense water demand of paddy rice. A two-cycle crop pattern was used. The winter-spring crop cycles begins on 15th December each year whereas the summer-autumn crop starts on 10th May each year.

Rainfall data used in the CROPWAT are design rainfall for dry years. The selection of dry years includes first fitting the total annual runoff into a Pearson type III distribution model (three-parameter gamma distribution). The selection of a Pearson type III distribution was due to its established used in Vietnam in hydrological calculations

(Doan *et al.*, 2014; Le *et al.*, 2006). A random variable x has a Pearson type III distribution when it has the probability density function (pdf) of:

$$f(x) = \frac{(x-\gamma)^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} exp\left(\frac{-(x-\gamma)}{\beta}\right) \quad \textbf{\textit{(16)}}$$

where Γ is the Gamma function α, β, and γ are the three parameters of the distribution. The mean, variance, and skewness of the Pearson type III distribution are:

$$\mu = \gamma + \alpha\beta \quad \textbf{\textit{(17)}}$$

$$\sigma^2 = \alpha\beta^2 \quad \textbf{\textit{(18)}}$$

$$\kappa = 2/\sqrt{\alpha}f \quad \textbf{\textit{(19)}}$$

Annual precipitation with an exceedance probability of 80% is considered as a dry year. The selection of assessments only in dry years is due to a number of reasons. *Firstly*, by selecting a dry year, it is expected that the crop water requirement will be higher than a normal or a wet year, hence, gives an indication of water shortage problems. *Secondly*, the ability of CROPWAT limits the amount of rainfall per month to be no more than 999 mm. However, in the VGTB River Basin, more often than not, during normal years (50% exceedance probability) and wet years (20% exceedance probability), precipitation can be as high as 1300mm. Therefore, this limits the ability of assessment.

Precipitation data for each irrigation node was selected based on the location of the irrigation node such that precipitation data from a nearby monitoring station is used. The precipitation station data used for each node is shown in Table 4-4. An 80% effective rainfall method was used to determine the amount of effective precipitation for crop. In other words, only 80% of the rainfall that falls onto cultivated land can be utilized by the crop, the remaining are considered as loss (runoff, interception, etc.).

Meteorological data input includes minimum temperature, maximum temperature, humidity, wind speed, sunshine hours, radiation and evaporation. Average monthly values from three stations at Tam Ky, Tra My and Da Nang were used for this purpose. Irrigation nodes corresponding to meteorological station data are shown in Table 4-4. The averaging period of meteorological data is between 1976 and 2013.

The total irrigation water demand for one node is the product of the crop water requirement determined from the CROPWAT model with the total irrigation area. An additional irrigation efficiency factor was included. Upon consultation with the head of the Quang Nam Irrigation Company, an irrigation efficiency of 70% is used, i.e. only 70% of water provided by the pumping station reaches the field. The remaining 30% is lost both in irrigation canals and in field (conveyance efficiency and field application efficiency). This is in line with the recent research by Rui Pedroso *et al.* (2016).

All demands were determined in units of m^3/s.

Table 4-4: Irrigation nodes with corresponding irrigation area, precipitation, and meteorological station data

Zone	MIKE BASIN node	Designed irrigation Area (km^2)	Actual Irrigation Area (km^2)	Precipitation station	Meteorological station
Thanh My- Ai Nghia	IRR_VG01	0.65	0.65	Thanh My	Tra My
	IRR_VG02	1.26	0.71	Thanh My	Tra My
	IRR_VG03	5.86	5.86	Ai Nghia	Da Nang
	IRR_VG04	1.20	1.20	Ai Nghia	Da Nang
	IRR_VG05	4.25	4.25	Ai Nghia	Da Nang
	IRR_VG06	2.00	2.00	Ai Nghia	Da Nang
	IRR_VG07	3.87	3.87	Ai Nghia	Da Nang
	IRR_VG08	20.10	20.10	Ai Nghia	Da Nang
Lower Vu Gia	IRR_VG09	1.50	1.50	Ai Nghia	Da Nang
	IRR_VG10	1.47	1.47	Ai Nghia	Da Nang
	IRR_VG12	2.35	2.35	Ai Nghia	Da Nang
	IRR_VG13	47.66	47.66	Ai Nghia	Da Nang
	IRR_VG11	3.80	3.80	Cam Le	Da Nang
	IRR_VG14	8.35	8.35	Cam Le	Da Nang
Lower Thu Bon	IRR_TB11	23.11	23.11	Cau Lau	Da Nang
	IRR_TB12	13.05	13.05	Cau Lau	Da Nang
	IRR_TB13	6.66	6.66	Cau Lau	Da Nang
	IRR_TB14	3.80	3.80	Cau Lau	Da Nang
	IRR_TB15	7.35	7.35	Cau Lau	Da Nang
	IRR_TB17	19.10	19.10	Cau Lau	Da Nang
	IRR_TB18	1.55	1.55	Cau Lau	Da Nang
	IRR_TB19	14.07	14.07	Cau Lau	Da Nang
	IRR_TB20	9.70	8.23	Cau Lau	Da Nang
	IRR_TB21	5.15	5.15	Cau Lau	Da Nang
	IRR_TB22	1.40	1.40	Cau Lau	Da Nang

Zone	MIKE BASIN node	Designed irrigation Area (km²)	Actual Irrigation Area (km²)	Precipitation station	Meteorological station
	IRR_TB16	6.85	6.85	Hoi An	Da Nang
	IRR_TB23	2.33	2.33	Hoi An	Da Nang
	IRR_TB24	0.80	0.80	Hoi An	Da Nang
Upper Nong Son	IRR_TB03	24.02	0.528	Hiep Duc	Da Nang
	IRR_TB04	7.95	3.84	Hiep Duc	Da Nang
	IRR_TB05	0.90	0.90	Nong Son	Da Nang
Nong Son-Giao Thuy	IRR_TB06	1.20	1.20	Nong Son	Da Nang
	IRR_TB07	9.60	6.80	Giao Thuy	Da Nang
	IRR_TB08	35.00	16.16	Giao Thuy	Da Nang
	IRR_TB09	10.90	10.90	Giao Thuy	Da Nang
	IRR_TB10	1.00	1.00	Giao Thuy	Da Nang
Upper Thu Bon	IRR_TB01	240	80	Tien Phuoc	Da Nang
	IRR_TB02	155	62.6	Tien Phuoc	Da Nang
Tam Ky	IRR_TK01	15.85	10.75	Tam Ky	Tam Ky
	IRR_TK02	2.80	2.80	Tam Ky	Tam Ky
	IRR_TK03	4.36	4.36	Tam Ky	Tam Ky
	IRR_TK04	230.00	145.00	Tam Ky	Tam Ky
	IRR_TK05	15.30	2.95	Tam Ky	Tam Ky

4.2.4 Reservoir model

Reservoirs in the VGTB River Basin would further be required in hydrological calculations. This involves providing the location of the reservoir and the corresponding powerhouse of the hydropower structure. It should be noted that, however, not all powerhouse are located at the dam but some several kilometers downstream to take advantage of the potential power. Hence, care was taken to include the powerhouse of the reservoirs.

Further reservoir operational data were required. This includes: characteristics levels time series, flood control input, level-area-volume table, losses and gains time series, minimum operation data, and priority for downstream users, maximum release data, and minimum release data. To better understand the important processes and data that are used as inputs for an individual reservoir Figure 4-6 could be used. Characteristic levels time series provide information on the bottom level of the reservoir (meters), the top of dead storage (meters), and the dam crest level (meters). Flood control inputs involves providing the flood control level (meters) that would require releasing of water storage in reservoir. The level-area-volume table provides the relationship between the area and the volume of the storage reservoir according to the storage depth (meters). The losses and gains time series includes data for precipitation, evaporation, and dam infiltration. Minimum operational level data is the level which the reservoir is allowed to be operating, this is normally higher than the dead water level in the reservoir. Priority for downstream users set the priority for water user nodes in the model. Lastly, maximum and minimum release (m^3/s) involves providing the upper boundary and lower boundary of volume in which the reservoir is allowed to release.

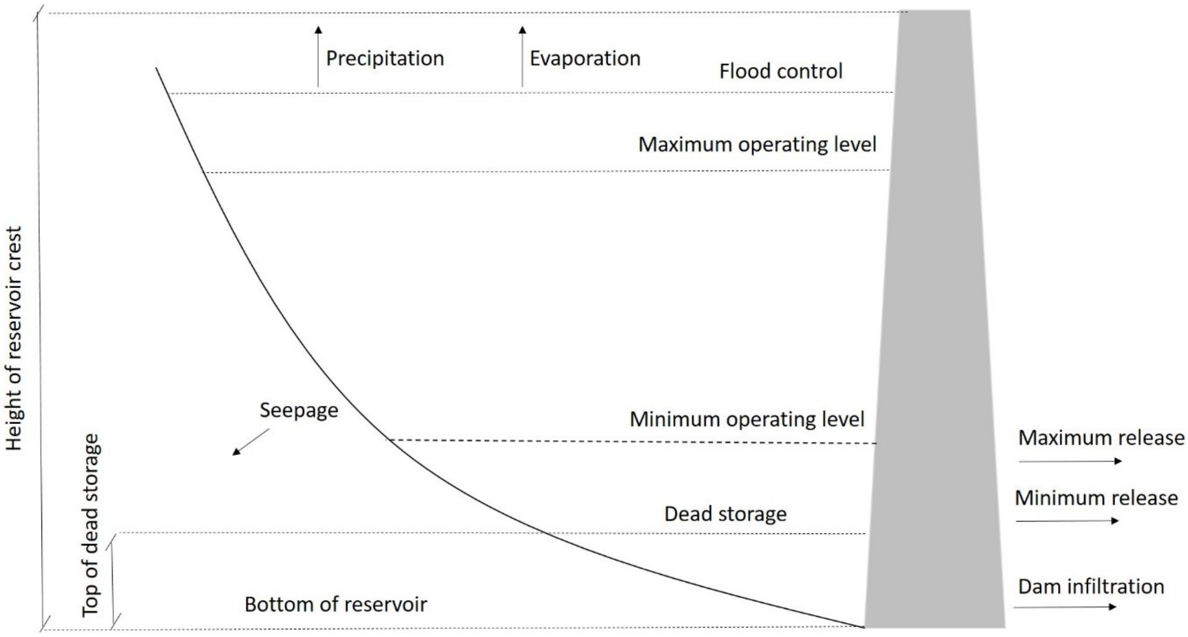

Figure 4-6: Schematic of important reservoir inputs

Due to the large amount of irrigation reservoirs, inputting all existing irrigation infrastructure would require large calculation efforts, deeming inefficient for the purpose of the study. Instead, two groups of reservoirs are created within the model. The first group of reservoirs includes major upstream reservoirs in the river basin. This includes: A Vuong, Dak Mi 4, Song Bung 2, Song Bung 4, Song Bung 5, Song Con 2, Song Tranh 1, and Song Tranh 2 reservoirs. This group of reservoirs have large storage volumes and are located upstream of the river basin, thus mostly regulate water downstream. The second group of reservoirs are representative reservoirs rather than actual reservoirs. Representative reservoirs were created by summing the characteristics of individual reservoirs along the same branch of river stream that serves the same irrigation area. In irrigation areas where only one reservoir exists, the representative reservoir is then the existing reservoir.

4.3 Climate Risk Discoveries

From the developed system model, climate states related to decision outcomes are identified and characterized. The risk discoveries step includes identifying problematic conditions based on a classic sensitivity analysis of the system performance due to changes in rainfall and temperature. The sensitivity analysis was carried out in two separate steps. The first is to establish a baseline set of results of 1/1/1986-31/12/2005 compatible with that established by the Fifth Assessment Report of IPCC. Within the baseline simulation, two scenarios were analyzed namely one with upstream reservoirs and one without upstream reservoirs. The second step includes determining performance of the system through changing system variables. The analysis is carried out at the annual scale since reservoir operations are normally more meaningful under the annual scale (Brown *et al.*, 2011; Grijsen, 2014).

Rainfall and temperature are parametrically varied and the response of the system analyzed. Through varying temperature and rainfall, the possible effects of climate change to the water system could be simulated. The effect of a changing precipitation is related directly to the flows in tributaries. A change in temperature however, is reflected in both the change in tributary flows as well as crop water requirements and/or water demand in general. This is due to the implied effects of changing evaporation as a result of changing temperature. The change in evaporation is determined assuming all other climate variables such as wind speed and humidity remains unchanged with only temperature as the changing factor. In other words, evaporation due to climate change is determined using the Pennman- Monteith equation similar to equation (14) with a changing temperature variable while keeping all other climate variables constant. This assumption, however, is not entirely true since a change in temperature leads to a complex change in atmospheric conditions, hence, could change these other climate variables.

4.4 Tailoring Climate Information to Assist Decision Making

The next step includes tailoring climate information to provide climate risks information and assist adaptation responses. In the previous step where problematic climate states have been identified, effort can focus on GCM climate projections that are relevant. The decision space is then simplified into two alternative decisions whether to take action (adapt) or no action (no adaptation).

There is a need to establish the likelihood of occurrence for a particular climate state that may poses problems. Nonetheless, estimating the true likelihood of a climate state is impossible due to the uncertain nature of climate change. For this reason, it has to be assumed that the results provided by the climate models (GCMs) may be informative for estimating the relative probability of the climate states (Brown *et al.*, 2012).

A similar approach using the consensus among multiple GCMs has been developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia (Clarke *et al.*, 2011) to studies both in Viet Nam and Australia. Within the approach, key scenarios of GCM projections are analyzed. This could include for example, a maximum consensus case where there is a highest number of GCM projections predicting the same range of climate variable change.

For the study, output from 25 GCMs were used to establish a possible future climate space. The list of used GCMs are attached in Appendix A: List of CMIP5 models used. There is a total of 47 models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5), however not all were selected for the study. The selection of models in this research was mainly due to the easy accessibility and the ability to store a large amount of data on limited storage capacity. In addition, the selected 25 GCMs have been widely used in applications in Viet Nam as well as being thoroughly tested for their performances and skills (Hidalgo and Alfaro, 2015; Miao *et al.*, 2014; Rupp *et al.*, 2013; Jury *et al.*, 2015; Mehran *et al.*, 2014; Supharatid, 2016; Lutz *et al.*, 2016).

The extraction of GCM data for precipitation and temperature values after acquiring GCM outputs were undertaken in four steps using the Climate Data Operator (CDO) tool offered by the Max Planck Institute of Meteorology (Max-Planck Institute for

Meteorology, 2017). The first step involves converting the GIS data of the river basin into a recognizable format by CDO. The second step involves interpolating to obtain data from GCM outputs. The third step is to combine the GCM outputs with the GIS data of the river basin. Finally, climate projections for the river basin is re-formatted to meet the analysis need.

Initially, the spatial GIS data of the river basin needs to be converted from a shapefile into a Network Common Data Form (NetCDF) file that is supported by CDO. As the river basin information is converted from a shapefile to a NetCDF file, the basin information is stored in grids with cells containing river basin spatial information having a value 1 and cells without this information having a 0. It should be noted that the resolution of cells containing the river basin spatial information is finer than that of the GCM outputs, thus, leading to the second step.

The second step of the GCM output extraction involves performing a bilinear interpolation of the GCM data. The process could be visualize using Figure 4-7. In this example, x_1, x_2, y_1, y_2 are predefined points with known value of $Q_{11}(x_1, y_1)$, $Q_{21}(x_2, y_1)$, $Q_{12}(x_1, y_2)$, and $Q_{22}(x_2, y2)$. The bi-linear interpolation process intends to solve for P(x,y).

	x_1	x	x_2
y_1	Q_{11}		Q_{21}
y		P	
y_2	Q_{12}		Q_{22}

Figure 4-7: Visualization of bi-linear interpolation

This is performed using the following function:

$$P(x,y) \approx \frac{(x_2-x)(y_2-y)}{(x_2-x_1)(y_2-y_1)}Q_{11} + \frac{(x-x_1)(y_2-y)}{(x_2-x_1)(y_2-y_1)}Q_{21} + \frac{(x_2-x)(y-y_1)}{(x_2-x_1)(y_2-y_1)}Q_{12} + \frac{(x-x_1)(y_2-y_1)}{(x_2-x_1)(y_2-y_1)}Q_{22} \qquad \textbf{\textit{(20)}}$$

The third step is to simply multiply the value of the interpolated cells from the GCMs with the NetCDF file containing river basin spatial information. The result would return values only for cells that contain river basin spatial information (since the cells values are 1) while the remaining cells that are beyond the boundary of the river basin would be discarded (multiplied by 0). A simple arithmetic average is then performed on the cells within the river basin to obtain an overall value for the river basin for both precipitation and temperature values.

As different GCMs have different data format, reformatting is required to ensure consistency. This is performed in the fourth step where a simple FORTRAN 90&95 program was created to reformat the data.

Key cases from the GCM outputs would then be further analyzed. The key cases includes “maximum consensus” where there is a maximum number of model agreement, a “best-case” where there is a minimal change of both temperature and precipitation, and a “worst-case” where there is the most increase in temperature and decrease in precipitation.

4.5 Current Status and Effects of Land Use Policies

A key component in assessing climate change impacts on water resources is the determination of land cover status. This stems from the knowledge that land cover and land use have a significant impact on water usage. Thus, through studying land cover and land use, further information could be obtained for the purpose of climate change adaptation. GIS and remote sensing technologies are used to determine land cover.

The effectiveness of land policy in the river basin is determined through assessing the land use master plan. This involves comparing land cover for two different time period: one before the current land use master plan and another after. Since the current master plan is for the 2011-2020 period, land cover beyond the date of the research is not possible. For this reason, a land change detection was conducted between 2011 and 2016. Land cover in 2011 represents the status prior to the land use master plan while 2016 land cover results represents the current status of land cover.

Changes detected for the time period of 2011-2016 is then compared to the expected changes during the time period 2011-2020 from the master plans for Quang Nam and Da Nang. This shows the relative effectiveness and impacts of policies of land use change in the study area. Two land cover objects would be the focus of the analysis. This includes paddy rice area (representative of agricultural area) and built-up area that are well represented in the MIKE BASIN model. In particular, water demand from agricultural area is represented by irrigation nodes while water demand from built-up area is represented by domestic and industrial nodes.

According to the land use master plan for Quang Nam Province and Da Nang City (Government of Viet Nam, 2013a, 2013b), by the year 2020, the main changes to be executed for agriculture and built-up areas are summarized in Table 4-5. The effects of informal development and those not adhering to the plan is neglected in the analysis due to its complex nature.

Table 4-5: Land planning changes in Quang Nam and Da Nang until 2020

Land use type	Quang Nam (km^2)	Da Nang (km^2)	Total change (km^2)
Agriculture (rice)	- 33.12	- 13.48	- 44.6
Built-up	+ 242.03	+ 50.54	+ 292.57

To assess the effectiveness of land use policy, land cover classification is performed on Landsat images. Land cover classification in the study area is based on the IPCC's recommendation of 6 land cover types (Penman *et al.*, 2003). The original IPCC land cover recommendation includes grassland, agriculture, forest, water, built-up, and others. However, for the purpose of the study, only 5 types of land cover was used including: water, vegetation, agriculture, empty land, and built-up classes.

The major component of a grassland in the definition of IPCC including rangelands and pasture land does not exist in the study area. For this reason, the vegetation class is a lumped class of forest, bushes, and other types of vegetation that does not fall into the category of agricultural land. The lumped of the two types of land cover does not impact the accuracy on the classification scheme since the two main objects of the classification is the agricultural area and the built-up area.

In addition, given that the majority of the agricultural area in the river basin is paddy rice, agricultural land cover would thus be assumed to be paddy rice unless otherwise stated. A detailed description of the various land cover class are shown in Table 4-6.

The method for land cover classification is based on two approaches, namely a supervised classification and an index-based classification method. A supervised classification is performed using the ENVI software package whereas the index based approach is performed using the Model Maker tool from the Erdas Imagine software package.

Table 4-6: Description of land cover class classification

Land use type	Description
Water	Similar to wetland class from IPCC's classification and includes permanent open water, lakes, reservoirs, and streams
Vegetation	Lumping of forest and grassland from IPCC's classification. The land cover includes: production forest, natural forest, special use forest, protected forest, grassland, perennial crops, annual crops
Agriculture	Paddy rice
Empty land	Similar to other land class from IPCC. Includes bare soil, and sandy beaches
Built-up	Similar to settlement class from IPCC. This includes: residential, commercial, industrial, and other urban land

Supervised classification was performed using the Envi software package. The method includes selecting sample training points that represent the spectral signals of the different land cover classes. An overview visual inspection of the satellite image is required to determine the possible number of different spectral signal combinations. If there are more than one combination signal for one type of land cover, the training samples would then be selected for two sub classes belonging to one super land cover class. For example, should the visual inspection of the image shows that spectral signals for urban area for two types of urban cover is highly different, urban area 1 and urban area 2 sub classes would be established to select training sample points. A simple maximum likelihood classifier algorithm is utilized.

The second method of land cover classification is based purely on three indices, namely the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and the Normalized Difference Built-up Index (NDBI). The indices calculation was performed in the ERDAS Imagine software package.

NDVI is a measure of vegetation cover and is determined using the near infrared and the red spectral band from satellite images. The calculation for NDVI is as follows:

$$NDVI = \frac{Near\ Infrared\ Band - Red\ Band}{Near\ Infrared\ Band + Red\ Band} \qquad \textbf{(21)}$$

$$NDVI_{Landsat\ 8} = \frac{Band\ 5 - Band\ 4}{Band\ 5 + Band\ 4} \qquad \textbf{(22)}$$

$$NDVI_{Landsat\ 5} = \frac{Band\ 4 - Band\ 3}{Band\ 4 + Band\ 3} \quad \textbf{(23)}$$

NDVI is used to separate vegetation in the image. NDVI value ranges between -1 and 1. Areas of barren rock, sand normally show low values of NDVI with typical ranges of 0.1 or less. Sparse vegetation exhibit higher NDVI approximately between 0.2 and 0.5. Dense vegetation could have NDVI as high as 0.6 to 0.9. Thus, through the calculation of NDVI, vegetation together with agricultural area could be identified.

Additionally, a multi-temporal NDVI approach is used to separate between the other types of vegetation and agriculture areas (rice). Crops in the area exhibit a seasonal pattern, i.e. agricultural land would be green during the growing phase and becomes bare land once crops are harvested. Through combining the information of NDVI in these areas in different stages of crop growth, agricultural area could be determined. For example, satellite image for the months of March would provide agricultural areas with high NDVI values while images in May would show lower values since crops have already been harvested.

NDBI is a measure of the reflectance of built-up surfaces from satellite images and utilizes the short wave infrared band and the near infrared band. The formula for the calculation of NDBI is as follows:

$$NDBI = \frac{Short\ Wave\ Infared\ Band1 - Near\ Infrared\ Band}{Short\ Wave\ Infared\ Band1 + Near\ Inrfared\ Band} \quad \textbf{(24)}$$

$$NDBI_{Landsat\ 8} = \frac{Band\ 6 - Band\ 5}{Band\ 6 + Band\ 5} \quad \textbf{(25)}$$

$$NDBI_{Landsat\ 5} = \frac{Band\ 5 - Band\ 4}{Band\ 5 + Band\ 4} \quad \textbf{(26)}$$

NDBI allows the separation of built-up and empty land areas in the images. Built-up and empty land normally exhibit higher NDBI values, ranging from -0.5 to 1. Through selecting an initial threshold, built-up and empty land could be separated from the other remaining types of land cover. A second round of thresholding would further separate built-up and empty land since built-up areas exhibit a lower range of NDBI values than empty land.

NDWI is used to monitor changes related to water content in water bodies. The calculation of NDWI is based on the green spectral band and the near infrared band as follows:

$$NDWI = \frac{Green\ Band - Near\ Infrared\ Band}{Green\ Band + Near\ Infrared\ Band} \tag{27}$$

$$NDWI_{Landsat\ 8} = \frac{Band\ 3 - Band\ 5}{Band\ 3 + Band\ 5} \tag{28}$$

$$NDWI_{Landsat\ 5} = \frac{Band\ 2 - Band\ 4}{Band\ 2 + Band\ 4} \tag{29}$$

The use of NDWI would allow the separation of water bodies in the images. Pixels with value above 0 represents water cells and could be extracted from the original image, and classified as water bodies.

The three different indices were then coded in a model maker in Erdas Imagine Software package. The three indices and thresholding were performed simultaneously providing the first level of classification of vegetation and agriculture, water, and empty land and built-up. A second level of classification would involve performing multi-temporal NDVI through using a number of Landsat images. This would allow the separation between vegetation and agriculture. Thresholding was also performed to separate empty land and built-up area in the NDBI. A classification decision tree is shown in Figure 4-8:

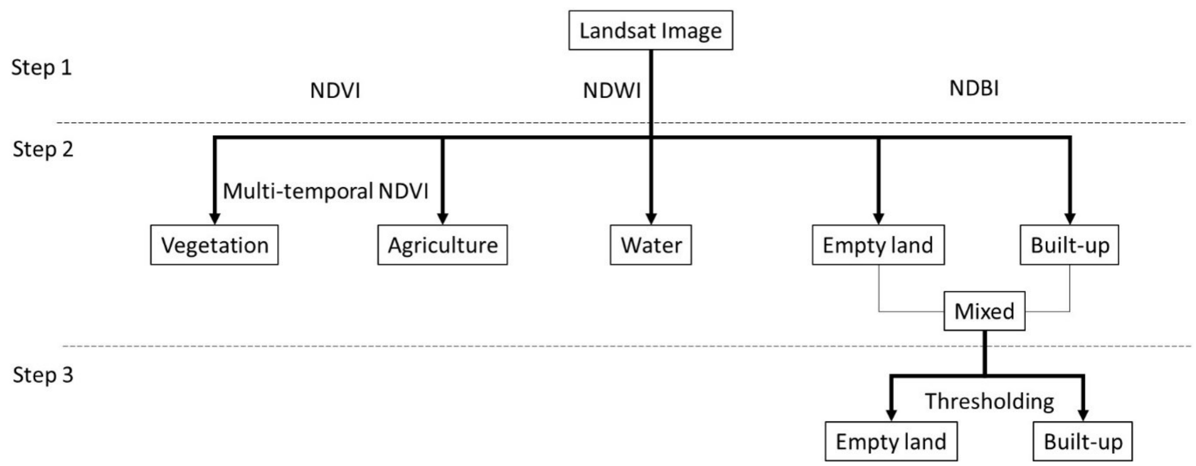

Figure 4-8: Hierarchy classification scheme for land cover mapping

Accuracy assessment of the land cover classification schemes are performed using both the overall accuracy index and the Kappa coefficient. Overall accuracy is the sum of the correctly classified points in each class divided by the total number of sampling points. Overall accuracy formula is described as follows:

$$Overall\ accuracy = \frac{\sum Correctly\ classified\ pixels\ in\ each\ class}{Total\ number\ of\ pixels\ (samples)} \tag{30}$$

A Kappa coefficient is used to measure the agreement between the prediction and the reality, i.e. to determine whether the values contained in the error matrix represent a result significantly better than random.

	Class 1 reference	Class 2 reference	…	Class r reference	Total
Class 1 classified	x_{11}	x_{12}	…	x_{1r}	x_{1+}
Class 2 classified	x_{21}	x_{22}	…	x_{2r}	x_{2+}
…	…	…	…	…	…
Class r classified	x_{r1}	x_{r2}	…	x_{rr}	x_{r+}
Total	x_{+1}	x_{+2}	…	x_{+r}	

Figure 4-9: Confusion matrix post classification

Given a confusion matrix as shown in Figure 4-9, the value of x represents the number of points within a classified class that falls within a reference class. The subscript represents the combination. For example, x_{12} represent the number of points classified as class 1 while having a reference class of 2. The generalized Kappa coefficient formula is determined as follows:

$$k = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} * x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} * x_{+i})} \tag{31}$$

with: N being the total number of sites in the matrix, r is the number of rows in the cross correlation matrix, x_{ii} is the number of combinations along the diagonal of the matrix, x_{+i} is the total observations in row i of the matrix, and x_{+i} is the total observations in column i of the matrix.

Reference points for accuracy assessment are selected from Landsat images with the aid of high resolution Google Earth images. This method has been attempted by other studies (Rwanga and Ndambuki, 2017; Senf *et al.*, 2015; Akinyemi, 2017). Both random points and points that could potentially be misclassified were selected.

The minimum number of reference points followed the rule established by McCoy (2005), where:

$$N = Z^2(p)(100 - p)/E^2 \qquad \textbf{\textit{(32)}}$$

with N being the number of sample points, Z=2 (standard normal deviate for a 95% confidence interval), p is expected accuracy, and E is allowable error (100- confidence interval). For this study, an accuracy of 85% is expected, therefore, a minimum of 204 samples would be required.

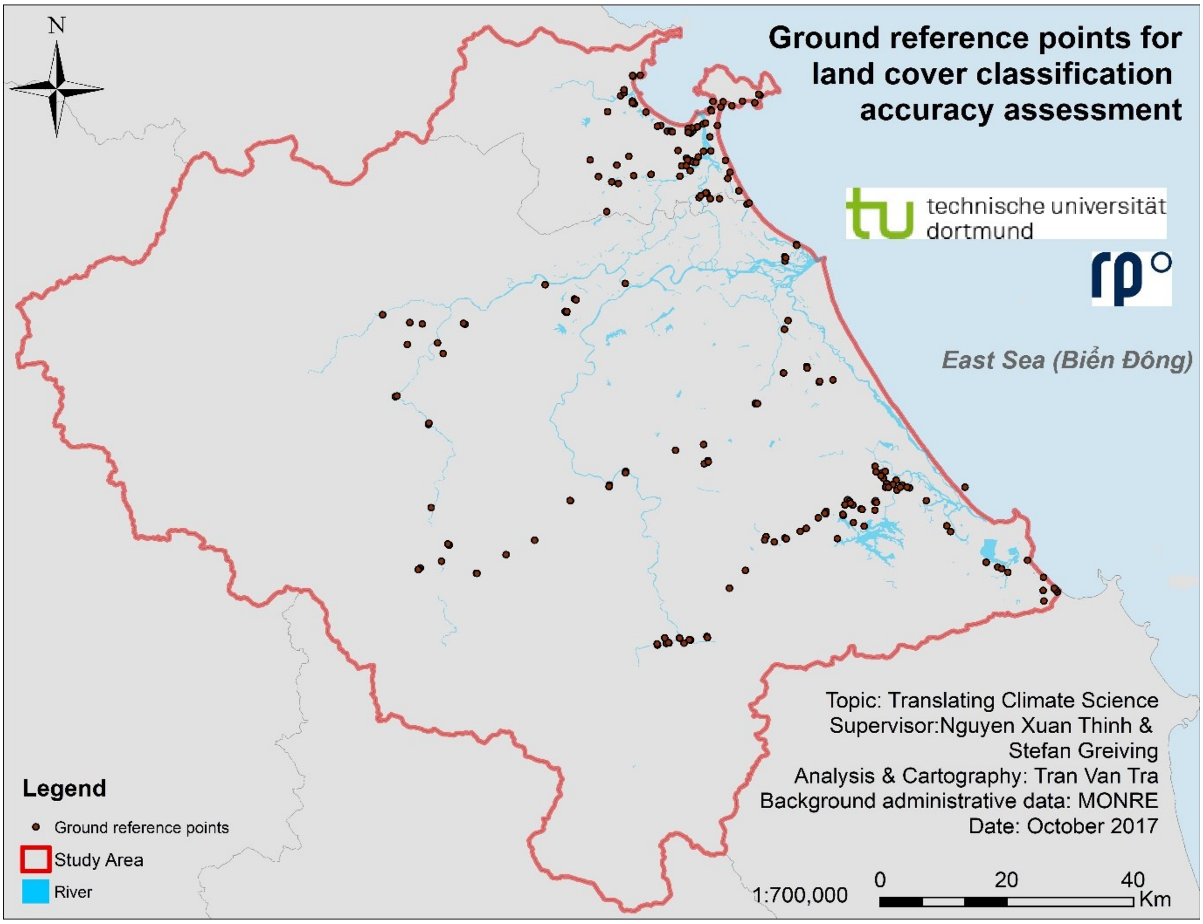

Figure 4-10: Ground reference points for accuracy assessment

Additionally, ground truthing was performed in early 2017 to reassess and validate the choice of ground reference points chosen for the classification scheme in 2016. The reassessment of ground reference points in 2011 could not be carried out through ground truthing and since there are no other available data, was not carried out. The location of ground reference points for the classification of land cover is as shown in Figure 4-10.

The classified images are further compared with land use statistics in the river basin. This involves comparing the total land area of the different classes of land cover established in the classification scheme with the land use inventory data from the Vietnam Ministry of Natural Resources and Environment. Two available land use inventory for 2010 and 2015 were used in the comparison. The main objective of the inter-comparison between the land cover and the land use inventory is to further establish the relative accuracy of the land cover classification scheme. It should be noted, however, that there is a mismatch of timescale between the land cover classification and the land use inventory. In particular, land cover classification was performed for 2011 and 2016 while the land use inventory was available for 2010 and 2015. Hence, there could be discrepancies between the two.

5 RESULTS AND DISCUSSIONS

In the previous chapters, the importance of a combined top-down and bottom-up approach for climate change impact assessment has been established. Through this approach, uncertainties from a heavy reliance on GCM could be avoided. Hence, the results obtained from the new approach would be able to provide more useful information for adaptation measures. This chapter discusses the results of the study.

5.1 Climate Hazards and Thresholds

Through the information provided from local stakeholders, review of available literature and cross validation with available data, it was determined that water shortage during 1998 is representative for an extreme water shortage event that requires adaptation action. Hence, reliability of the water supply system in the year 1998 could serve as a threshold for the performance of the system.

Table 5-1: Drought and water shortage years from literature

Year	Source
1982 1983	Kim (2005), Quang Nam Hydromet Center (2011), Quy (2011)
1984	Quy (2011)
1985 1988 1993	(Kim, 2005), Quy (2011), Thuc (2012), Viet Nam Institute of Meteorology, Hydrology, and Climate Change (2005)
1998	Quang Nam Hydromet Center (2011), Kim (2005), Quy (2011),Thuc (2012) Viet Nam Institute of Meteorology, Hydrology, and Climate Change (2005)
2001 2008 2009	(DONRE, 2012)

The review of relevant literature on droughts in the VGTB River Basin is summarized in Table 5-1. The media report and literature suggested qualitatively that in 1998 severe water shortage occurred. The information provided in the literature review was then used as a foundation for further discussion with stakeholders and experts in the area. Local experts and stakeholders agreed to the selection of 1998 to be a representative year of an extreme water shortage event.

Drought in 1988 was further validated using SWSI to be a heavily drought year. Water shortages occurred basin-wide from the months between January through to October with the exception of November and December. In other words, the dry season in the river basin in 1998 experienced significantly less than average river flow, while the rainy season experienced somewhat wetter condition. SWSI for January through to August in 1998 were lower than the -3.0 benchmark, classifying these months in 1998 as extremely dry. SWSI for September and October is classified as near average and moderately dry respectively (refer to Table 5-2).

Table 5-2: SWSI value in year 1998 for Nong Son and Thanh My catchments

	Nong Son	Thanh My	Average	Drought classification
January	-3.9	-3.7	-3.8	Extremely dry
February	-3.9	-3.7	-3.8	Extremely dry
March	-4.2	-3.9	-4.0	Extremely dry
April	-3.9	-3.9	-3.9	Extremely dry
May	-3.7	-3.7	-3.7	Extremely dry
June	-4.2	-4.2	-4.2	Extremely dry
July	-3.7	-4.2	-3.9	Extremely dry
August	-4.2	-3.9	-4.0	Extremely dry
September	0.8	-0.8	0.0	Near Average
October	-2.3	-2.0	-2.1	Moderately dry
November	3.5	3.5	3.5	Extremely wet
December	2.7	3.0	2.9	Moderately wet

The extremely wet and moderately wet classification for November and December in 1998 can be partly attributed to the El Nino Southern Oscillation (ENSO) active in 1998. As ENSO involves a warm phase (El Nino) and a cold phase (La Nina). During the warm phase of ENSO, El Nino, water shortage occurred due to increase temperature and drier conditions. However, as El Nino phase out and La Nina phase in, the opposite condition occurred where wetter condition is observed. The warm phase of ENSO occurred late 1997 and early 1998, leading to dry conditions in early 1998. However, as El Nino phase out at the end of 1998 and La Nina phase in, the higher than normal water abundance in late 1998 could be explained.

A quick comparison of the SWSI in 1998 and other reported drought years of 1982, 1983, 1984, 1985, 1988, 1993, 2001, 2008, and 2009 is shown in Figure 2-1. For the dry season from January through August, the SWSI value of 1998 is consistently within the first quartile of the distribution of SWSI values; with August baring the minimum SWSI- indicating the most severe water shortage. When viewing the SWSI for each month, SWSI values for other years indicate more severe water shortage conditions. However, when viewing the SWSI for each year, there is no other year having a consistently low SWSI throughout the year similar to 1998. Thus, for other reported drought years in comparison, there is no prolonged dry condition as observed in 1998. Calculated SWSI values are attached in Appendix B: SWSI values for drought years.

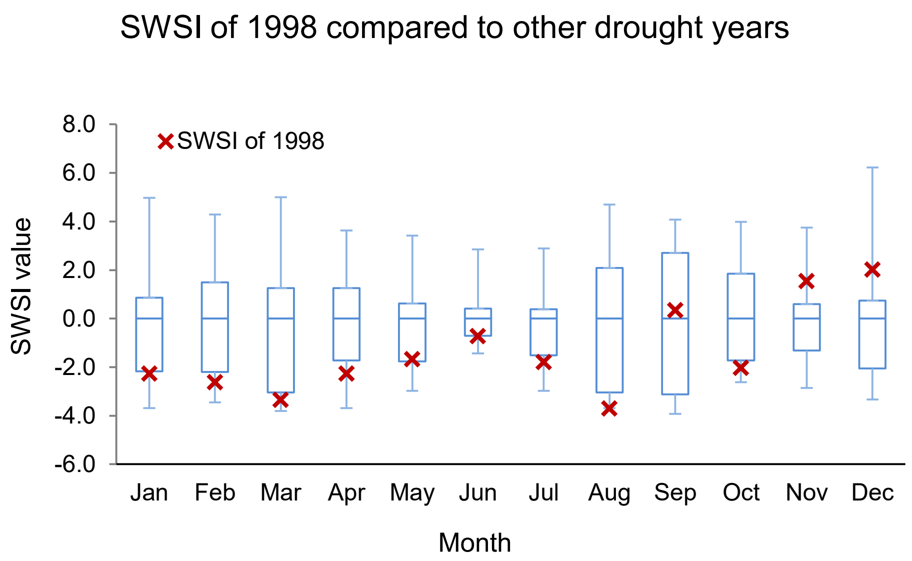

Figure 5-1: SWSI of 1998 in comparison with other drought years

The SWSI results validated the selection of the year 1998 as a representative water shortage event. Thus, reliability of the water supply system in 1998 could be used as a threshold in the approach. Performing the MIKE BASIN run for 1998 gives a lowest reliability level of 92%. In other words, 92 out of 100 times, the water supply system would be able to fulfill its demand. The remaining 8 times the water system would be under water stress and water shortage. Previous study by Brown *et al.* (2012) and Brown *et al.* (2011) also had a similar reliability value range of 95%. Thus, the 92% reliability threshold value is deemed reasonable and justifiable.

5.2 System Models

This section provides the results and discussion for the various system models used. This includes results from the rainfall-runoff model, the water demand model and the schematic of the reservoir model within the MIKE BASIN model.

5.2.1 Rainfall-runoff model

Runoff following calibration and validation plot for Nong Son river flow gauge are shown in Figure 5-2 and Figure 5-3. Runoff following calibration and validation plot for Thanh My flow gauge are shown in Figure 5-4 and Figure 5-5.

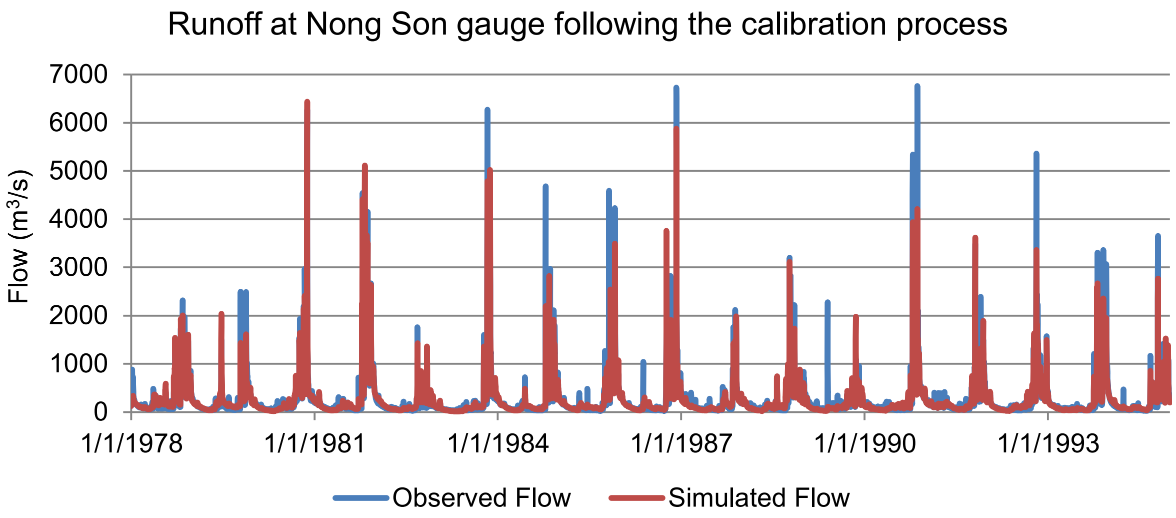

Figure 5-2: Runoff at Nong Son gauge following the calibration process

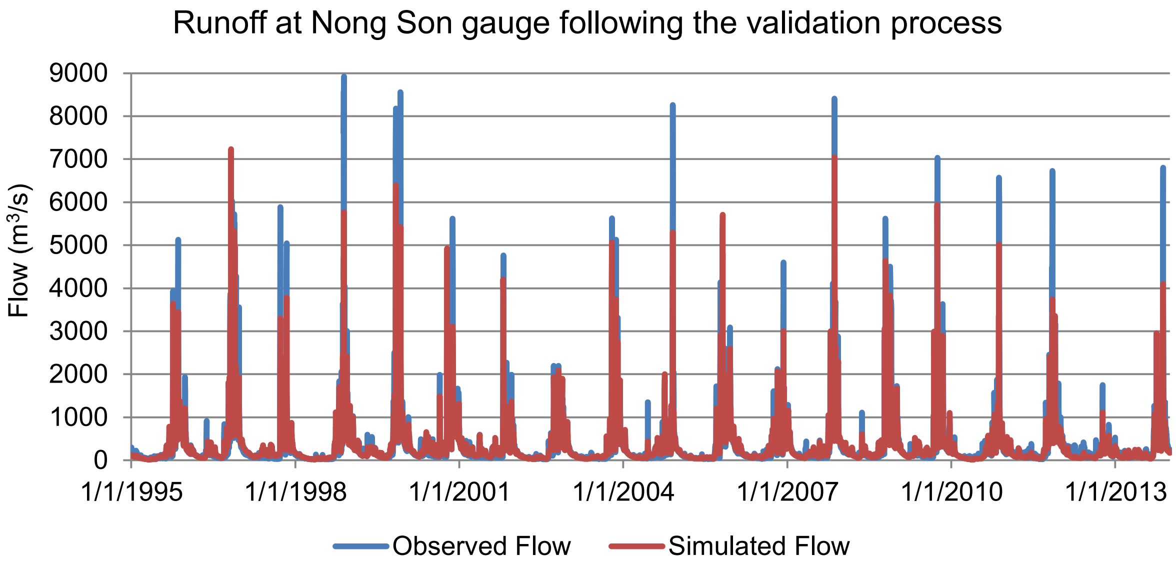

Figure 5-3: Runoff at Nong Son gauge following the validation process

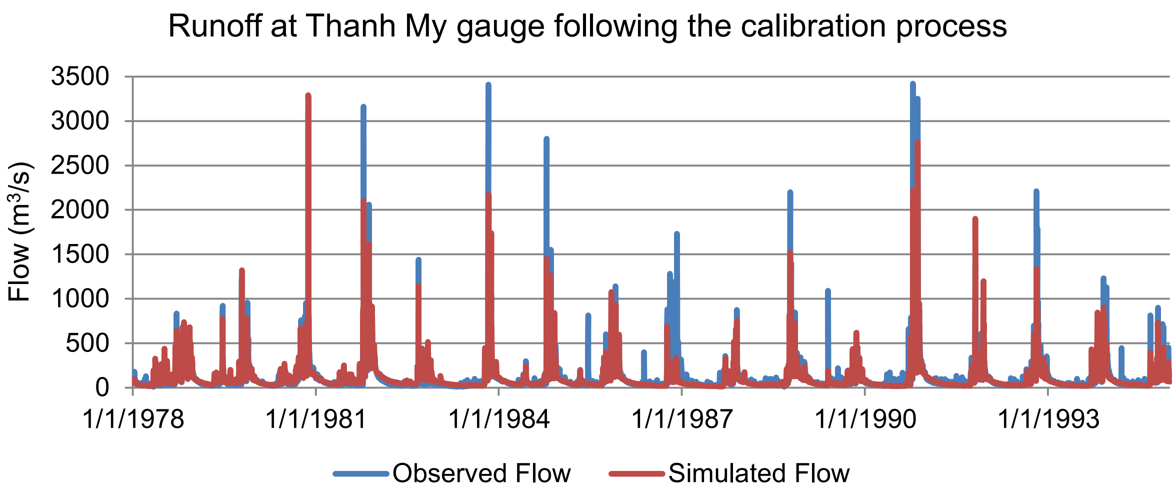

Figure 5-4: Runoff at Thanh My gauge following the calibration process

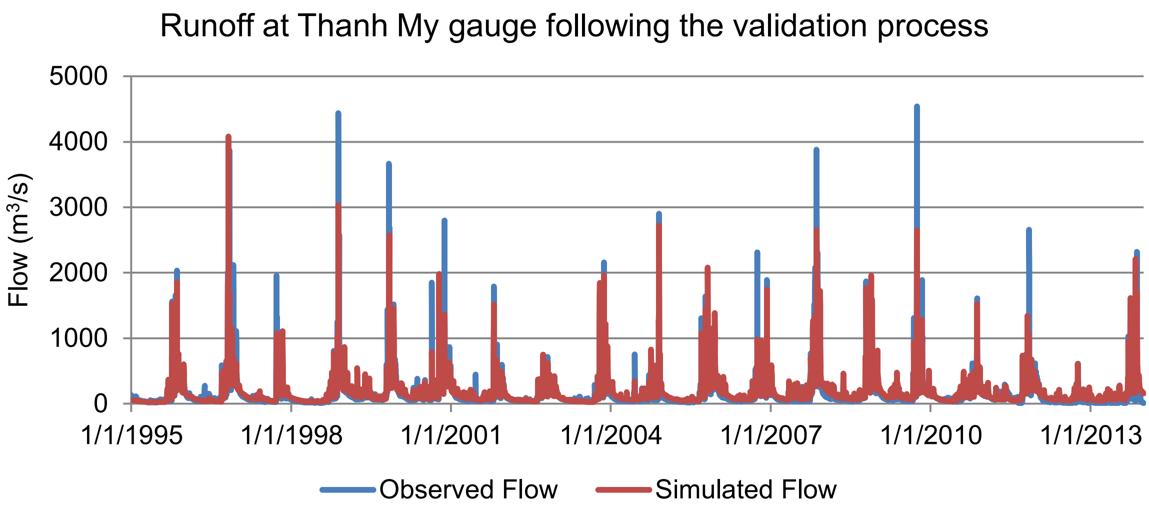

Figure 5-5: Runoff at Thanh My gauge following the validation process

Overall, the calibrated MIKE NAM model for the Nong Son and Thanh My catchments were able to predict the trend of observed flow. Nonetheless, the peak flow predicted in both Nong Son and Thanh My gauges are consistently lower than peak observed flow. Since the objective of the study is not to study flooding conditions, i.e. the highest peak, capturing the peak is not a paramount objective in calibration and validation of the MIKE NAM model. The main objective of the model is to simulate the trend of flow, and this has been relatively successful.

The corresponding Nash-Sutcliffe value for both validation and calibration of the MIKE NAM model is shown in Table 5-3. In Nong Son basin, a Nash-Sutcliffe value of 0.87 and 0.85 was recorded for calibration and validation respectively. In Thanh My basin, a lower Nash-Sutcliffe value of 0.8 and 0.81 respectively for calibration and validation was obtained. In good hydrological practice, a Nash-Sutcliffe value of 0.8 and above is highly desirable and normally accepted. Hence, the calibrated MIKE NAM model was used to further predict specific runoff in nearby basins.

Table 5-3: MIKE NAM corresponding NASH-Sutcliffe value

Station	Period		Nash	
	Calibration	Validation	Calibration	Validation
Nong Son	1978 - 1994	1995-2013	0.87	0.85
Thanh My	1978 - 1994	1995-2013	0.80	0.81

The 13 calibrated model parameters for Nong Son and Thanh My catchments are listed in Table 5-4. Average parameter values in Nong Son and Thanh My catchments were determined. This average parameter value was then adopted to the entire river basin. In other words, sub-catchments developed in the MIKE-BASIN model would utilize the average value to determine runoffs.

Table 5-4: Calibrated MIKE NAM parameters

Parameter	Unit	Description	Nong Son	Thanh My	Average
Umax	mm	Maximum water content in surface storage	10.5	10.3	10.4
Lmax	mm	Maximum water content in root zone storage	180	130	155
CQOF	dimensionless	Overland flow runoff coefficient	0.63	0.468	0.549
CKIF	hours	Time constant for routing interflow	570	747	658.5
CK1,2	hours	Time constant for routing overland flow	32	24.6	28.3
TOF	dimensionless	Root zone threshold value for overland flow	0.878	0.765	0.822
TIF	dimensionless	Root zone threshold for interflow	0.16	0.246	0.203
TG	dimensionless	Root zone threshold value for groundwater recharge	0.115	0.167	0.141
CKBF	hours	Time constant for routing baseflow	1248	1700	1474
Carea	dimensionless	Change ratio of groundwater- area to catchment area	0.99	0.84	0.915
Cy	dimensionless	Change specific yield of groundwater reservoir	0.2	0.2	0.2
Cqlow	dimensionless	Lower baseflow, recharge to lower reservoir	30	30	30
Cklow	hours	Time constant for routing lower baseflow	20000	20000	20000

Through averaging the model parameters, a more simplistic approach could be performed in determining flow in sub-catchments within the MIKE BASIN model. This removes the need to apply separate parameter sets for a huge number of sub-basins making computation less time consuming. However, the accuracy of the results could be affected. Without the data to compare the effect of using average parameter values from Nong Son and Thanh My catchment and estimating parameter sets for individual sub-catchment, little could be said about the overall impact of the chosen approach.

5.2.2 Water demand model

The three components of water demand including domestic, industrial and agriculture demand are provided in this section.

Domestic and industrial water demand

Industrial water demand is shown in Table 5-5. The highest industrial demand node is from Tam Hiep Industrial Area with an estimated demand of 0.515 m^3/s. The industrial node with the least demand is Go Hoang Industrial cluster, with an estimated demand of only 0.004m^3/s.

The demand calculated although useful must also be critically reviewed. Determining water demand based on the area of the industrial area is based on the standard guidelines set by the Viet Nam Ministry of Construction. However, the approach may provide results that are not reflective of the actual water demand conditions. In other words, the approach does not take into account the actual occupied area in the industrial zone and the type of industrial processes in each zones. For example, not all industrial areas are fully occupied by industrial firms, industrial areas may still have vacant lots. In addition, some industrial processes may require more water than others under a similar operating area.

A quick comparison between the Chu Lai Industrial Area and the Dien Nam- Dien Ngoc Industrial Area could prove the limitation of the approach. The Chu Lai industrial area is highly active with the majority of its allotted area occupied by factories and firms while the Dien Nam- Dien Ngoc industrial area is less so. The Dien Nam- Dien Ngoc industrial area occupies a larger area on plan, yet not the entire industrial area is occupied. Thus, to use the Ministry of Construction's guideline properly, only a proportion of the industrial area should be used instead. Given the limited information, this, however, was not possible.

Table 5-5: Industrial water demand and corresponding node in MIKE BASIN

	Node	Name of Industrial Area	Location	Demand m^3/s
Quang Nam	WSP_TB04	Dong Que Son	Huong An commune, Que Son District, Quang Nam	0.134
	WSP_TB04	Go Hoang Industrial cluster	Nhat Tay and Nhi Tay ward, Binh Lam Commune, Hiep Duc District, Quang Nam	0.004
	WSP_TK02	Chu Lai	Tam Thien commune, Nui Thanh District, Quang Nam	0.159
	WSP_TK01	Tam Thang	Tam Thang commune, Tam Ky City, Quang Nam	0.191
	WSP_TB05	Dien Nam-Dien Ngoc	Dien Nam and Dien Ngoc commune, Dien Ban District, Quang Nam	0.248
	WSP_TB05	Que Phu Industrial Cluster	Que Phu commune, Que Son District, Quang Nam	0.016
	WSP_TB05	Dong Yen Industrial Cluster	Duy Trinh commune, Duy Xuyen District, Quang Nam	0.008
	WSP_TK02	Tam Hiep	159B Tran Quy Cap street, Tam Ky City, Quang Nam	0.515
	WSP_TK02	Tam My Tay Industrial Cluster	My Tay commune, Nui Thanh District, Quang Nam	0.013
	WSP_TK01	Phu Xuan	Phu Ninh District, Quang Nam	0.223
	WSP_TK01	Thuan Yen	Tam Ky City, Quang Nam	0.080
	WSP_TK02	Bac Chu Lai	Lot 5, Road 1, Bac Chu Lai Industrial park, Tam Hiep commune, Nui Thanh District, Quang Nam	0.227
Da Nang	WSP_VG05	Hoa Khanh	Lien Chieu District, Da Nang	0.270
		Hoa Khanh extension	Lien Chieu District, Da Nang	0.208
		Lieu Chieu	Lien Chieu District, Da Nang	0.196
		Hoa Cam	Cam Le District, Da Nang	0.169
		Da Nang fishery	Son Tra District, Da Nang	0.049
		Da Nang	Son Tra District, Da Nang	0.032

In addition, the Chu Lai industrial area is highly active with heavy industries. This ranges from car manufacturing to thermal power plant. Thus, the water demand in the industrial area would be greater than for other light industrial processes. Without further information, the study was unable to account for this type of variation in water demand.

Domestic water demand for 16 township in the river basin is shown in Table 5-6. The highest demand is observed in Da Nang City where demand per capita and population is highest. Tam Ky City has the second highest domestic water demand. Tan An township has the least amount of water demanded at only 0.005m^3/s. Calculating domestic demand based on population is a common practice in civil engineering, hence, the results should be representative of the real domestic water demand.

Table 5-6: Domestic water demand in the study area (calculated based on Vietnam Ministry of Construction (2006))

Node in MIKE BASIN	Township	Water Demand m^3/s
WSP_VG01	Kham Duc	0.009
WSP_VG02	Thanh My	0.010
WSP_VG03	P'rao	0.006
WSP_VG04	Ai Nghia	0.024
WSP_VG05	Da Nang	2.298
WSP_TB01	Tra My	0.009
WSP_TB02	Tien Ky	0.010
WSP_TB03	Tan An	0.005
WSP_TB04	Ha Lam	0.023
WSP_TB04	Dong Phu	0.012
WSP_TB05	Vinh Dien	0.012
WSP_TB05	Nam Phuoc	0.032
WSP_TB05	Hoi An	0.117
WSP_TK01	Tam Ky	0.389
WSP_TK01	Phu Thinh	0.006
WSP_TK02	Nui Thanh	0.014

Total domestic and industrial water demand for the corresponding 12 demand nodes in the MIKE BASIN model are listed in Table 5-7. The total demand for the node is the sum of domestic and industrial demand components in each node. For example, WSP_VG05 includes domestic demand and industrial demand for the city of Da Nang. The highest demand node occurred in WSP_VG05. The node with the least demand is WSP_TB03 representing domestic water demand for the township of Tan An in Hiep Duc District. The township is relatively small with over 3000 inhabitants and have no industrial water demand.

Table 5-7: Domestic and industrial water demand (calculated based on Vietnam Ministry of Construction (2006))

Node	Domestic m³/s	Industrial m³/s	Sum m³/s
WSP_VG01	0.009	0.000	0.009
WSP_VG02	0.010	0.000	0.010
WSP_VG03	0.006	0.000	0.006
WSP_VG04	0.024	0.000	0.024
WSP_VG05	2.298	1.008	3.306
WSP_TB01	0.009	0.000	0.009
WSP_TB02	0.010	0.000	0.010
WSP_TB03	0.005	0.000	0.005
WSP_TB04	0.034	0.151	0.185
WSP_TB05	0.161	0.297	0.458
WSP_TK01	0.394	0.331	0.725
WSP_TK02	0.014	0.824	0.838

Agriculture water demand

Monthly agricultural demand for the 43 irrigation nodes under the baseline scenario in the MIKE BASIN model is shown in Table 5-8. Due to the crop cycle calendar, irrigation water is not normally required during the months of September and October (shown in *italics*). In particular, since no crop is grown in September and October, little if no irrigation is required during these months. In addition, September and October also marks the beginning of the rainy season, hence, soil moisture level is maintained at the sufficient level, reducing irrigation water demand. In other cases, during the cropping schedule of summer-spring and fall-winter crop, irrigation is required monthly for the irrigation nodes. For the majority of the nodes, the highest water demand occurred in April and May with the exception of irrigation node IRR_VG01 and IRR_VG02. This is a result of both the growing phase of rice as well as the climate conditions during the mid-summer drier months (highest water demand are underlined)

Table 5-8: Agricultural water demand under baseline condition (m³/s)

Node	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IRR_VG01	0.02	0.04	0.03	0.04	0.04	0.01	0.05	0.01	*0.00*	*0.00*	0.03	<u>0.07</u>
IRR_VG02	0.03	0.04	0.04	0.05	0.04	0.01	0.05	0.01	*0.00*	*0.00*	0.04	<u>0.07</u>
IRR_VG03	0.17	0.25	0.20	0.31	<u>0.96</u>	0.69	0.58	0.02	*0.00*	*0.00*	0.29	0.29

Node	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IRR_VG04	0.03	0.05	0.04	0.06	0.20	0.14	0.12	0.00	*0.00*	*0.00*	0.06	0.06
IRR_VG05	0.12	0.18	0.15	0.22	0.69	0.50	0.42	0.02	*0.00*	*0.00*	0.21	0.21
IRR_VG06	0.05	0.08	0.07	0.10	0.31	0.23	0.19	0.01	*0.00*	*0.00*	0.10	0.10
IRR_VG07	0.11	0.17	0.13	0.20	0.63	0.46	0.38	0.02	*0.00*	*0.00*	0.19	0.19
IRR_VG08	0.58	0.86	0.69	1.05	3.28	2.38	1.97	0.08	*0.00*	*0.00*	1.01	1.01
IRR_VG09	0.04	0.06	0.05	0.08	0.24	0.18	0.15	0.01	*0.00*	*0.00*	0.08	0.08
IRR_VG10	0.04	0.06	0.05	0.08	0.24	0.17	0.14	0.01	*0.00*	*0.00*	0.07	0.07
IRR_VG12	0.07	0.10	0.08	0.12	0.38	0.28	0.23	0.01	*0.00*	*0.00*	0.12	0.12
IRR_VG13	1.37	2.03	1.65	2.49	7.77	5.65	4.68	0.19	*0.00*	*0.00*	2.39	2.39
IRR_VG11	0.16	0.23	0.25	0.31	0.62	0.38	0.37	0.10	*0.00*	*0.00*	0.19	0.43
IRR_VG14	0.35	0.51	0.55	0.68	1.37	0.84	0.81	0.23	*0.00*	*0.00*	0.42	0.95
IRR_TB11	0.89	1.54	1.62	1.73	4.12	0.83	2.77	0.40	*0.00*	*0.00*	1.16	2.57
IRR_TB12	0.50	0.87	0.91	0.98	2.33	0.47	1.57	0.23	*0.00*	*0.00*	0.65	1.45
IRR_TB13	0.26	0.44	0.47	0.50	1.19	0.24	0.80	0.12	*0.00*	*0.00*	0.33	0.74
IRR_TB14	0.15	0.25	0.27	0.28	0.68	0.14	0.46	0.07	*0.00*	*0.00*	0.19	0.42
IRR_TB15	0.28	0.49	0.52	0.55	1.31	0.26	0.88	0.13	*0.00*	*0.00*	0.37	0.82
IRR_TB17	0.35	0.61	0.65	0.69	1.64	0.33	1.11	0.16	*0.00*	*0.00*	0.46	1.03
IRR_TB18	0.06	0.10	0.11	0.12	0.28	0.06	0.19	0.03	*0.00*	*0.00*	0.08	0.17
IRR_TB19	0.54	0.94	0.99	1.05	2.51	0.50	1.69	0.25	*0.00*	*0.00*	0.70	1.57
IRR_TB20	0.32	0.55	0.58	0.62	1.47	0.29	0.99	0.14	*0.00*	*0.00*	0.41	0.92
IRR_TB21	0.20	0.34	0.36	0.39	0.92	0.18	0.62	0.09	*0.00*	*0.00*	0.26	0.57
IRR_TB22	0.06	0.10	0.10	0.11	0.26	0.05	0.17	0.03	*0.00*	*0.00*	0.07	0.16
IRR_TB16	0.24	0.46	0.48	0.52	1.25	0.16	0.80	0.18	*0.00*	*0.00*	0.34	0.67
IRR_TB23	0.08	0.15	0.16	0.18	0.43	0.05	0.27	0.06	*0.00*	*0.00*	0.12	0.23
IRR_TB24	0.03	0.05	0.06	0.06	0.15	0.02	0.09	0.02	*0.00*	*0.00*	0.04	0.08
IRR_TB03	0.20	0.22	0.21	0.43	0.37	0.32	0.64	0.12	*0.00*	*0.00*	0.26	0.25
IRR_TB04	0.14	0.16	0.16	0.31	0.27	0.24	0.46	0.09	*0.00*	*0.00*	0.19	0.18
IRR_TB05	0.04	0.04	0.04	0.07	0.06	0.06	0.11	0.02	*0.00*	*0.00*	0.05	0.04
IRR_TB06	0.06	0.06	0.05	0.10	0.09	0.08	0.14	0.03	*0.00*	*0.00*	0.06	0.06
IRR_TB07	0.12	0.35	0.40	0.44	0.33	0.55	0.13	0.06	*0.00*	*0.00*	0.34	0.33
IRR_TB08	0.29	0.82	0.96	1.04	0.78	1.30	0.31	0.13	*0.00*	*0.00*	0.81	0.78
IRR_TB09	0.20	0.55	0.65	0.70	0.52	0.88	0.21	0.09	*0.00*	*0.00*	0.55	0.53
IRR_TB10	0.02	0.05	0.06	0.06	0.05	0.08	0.02	0.01	*0.00*	*0.00*	0.05	0.05
IRR_TB01	0.02	0.05	0.05	0.05	0.04	0.00	0.07	0.02	*0.00*	*0.00*	0.04	0.04
IRR_TB02	0.02	0.04	0.04	0.04	0.03	0.00	0.05	0.01	*0.00*	*0.00*	0.03	0.03
IRR_TK01	0.01	0.27	0.72	0.86	1.77	0.36	1.02	0.16	*0.00*	*0.00*	0.54	0.52
IRR_TK02	0.00	0.07	0.19	0.22	0.46	0.09	0.26	0.04	*0.00*	*0.00*	0.14	0.13
IRR_TK03	0.00	0.11	0.29	0.35	0.72	0.14	0.41	0.06	*0.00*	*0.00*	0.22	0.21

Node	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IRR_TK04	0.12	3.63	9.65	11.56	23.85	4.83	13.70	2.16	*0.00*	*0.00*	7.25	6.96
IRR_TK05	0.00	0.07	0.20	0.24	0.49	0.10	0.28	0.04	*0.00*	*0.00*	0.15	0.14

5.2.3 Reservoir model

There are 21 irrigation reservoir simulated within the MIKE BASIN model. It should be noted that only major reservoirs were fully represented. Other reservoirs are representative reservoirs, meaning they represent the sum of smaller reservoirs within the same branch of river. The approach is made to simplify the simulation and help reduces modelling time. However, such an approach also suffers limitation. In other words, the detail of the fluctuation of water in individual reservoirs are not simulated.

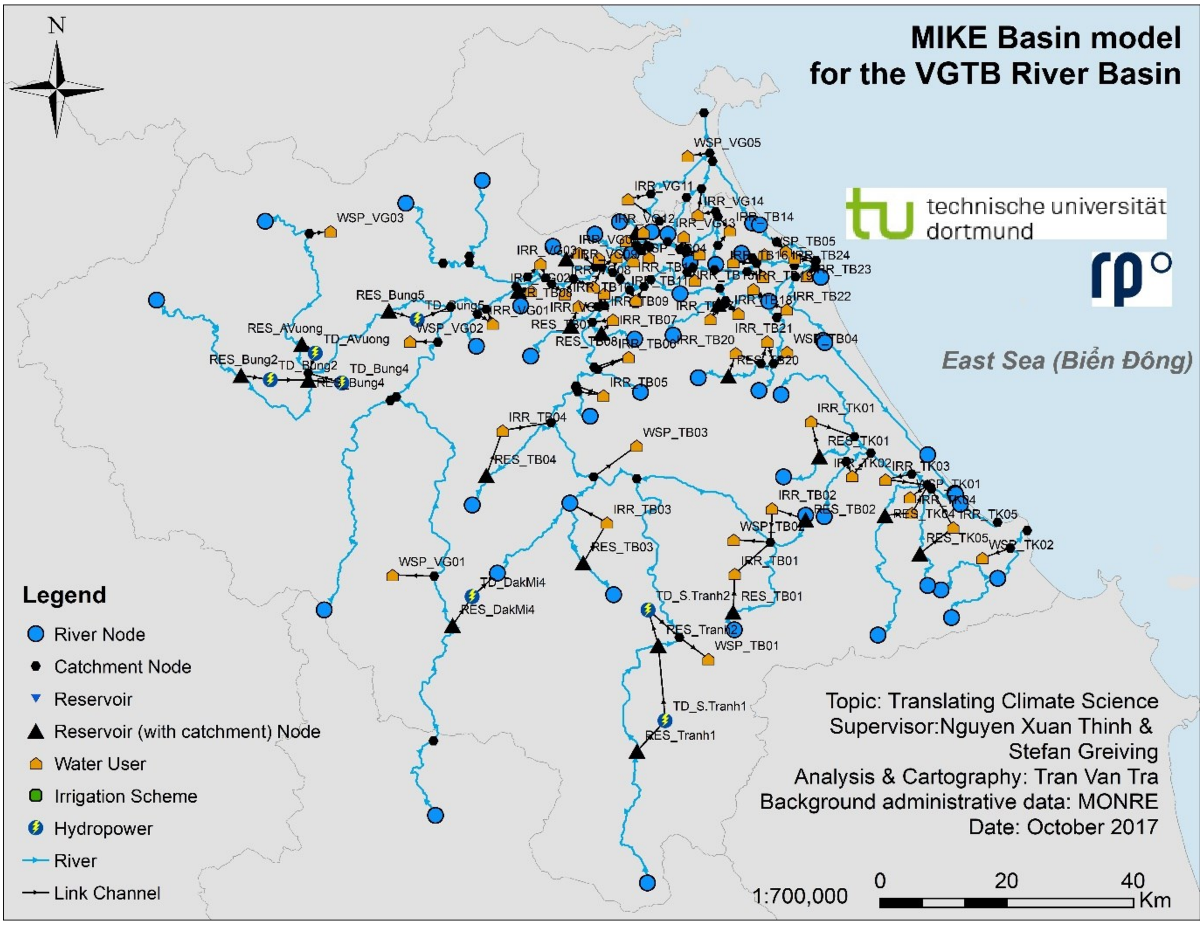

Figure 5-6: MIKE BASIN model fully developed

Major hydro-electricity production schemes upstream of the river were also included in the model. The inclusion does not aim at modelling electricity production in the river basin but to rather include the effects of the water released from the reservoirs from the reservoirs. This is because all major hydro-electricity schemes included releases its water used for power production several kilometers downstream where the powerhouse is located. The location of the powerhouse is to mostly take advantage of potential power. Therefore, there is a diversion of water from the reservoir upstream, bypassing the direct downstream river reach. This effect is accounted for in the study.

The fully developed MIKE BASIN model with corresponding demand nodes, reservoir nodes with tributary runoff is shown in Figure 5-6. There are 43 irrigation water demand nodes, 12 domestic and industrial water demand nodes, and 21 water reservoirs included in the model. The majority of water users are highly concentrated downstream in the plain land where there is a higher density of both domestic, agriculture, and industrial users. Water user upstream constitutes mostly of domestic water supply of townships in the hilly areas.

5.3 Climate Risks Discoveries

5.3.1 Baseline results without upstream reservoir

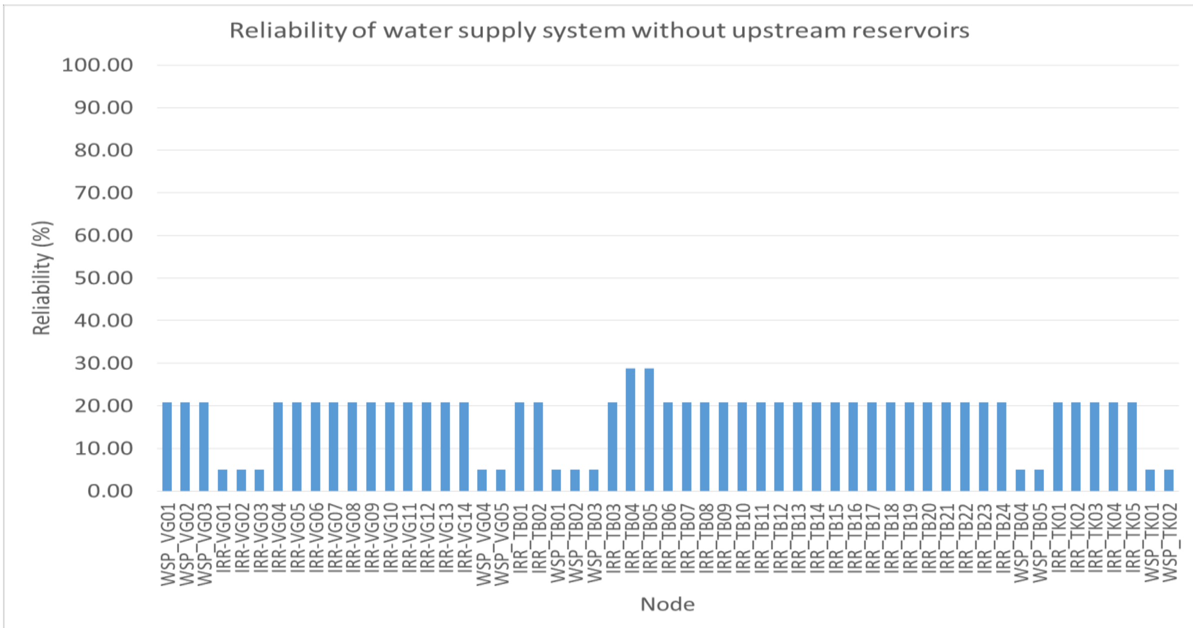

Figure 5-7: Water supply reliability without upstream reservoirs (baseline period: 1986-2005)

The first simulation for the baseline period without 8 upstream hydropower reservoir showed a poor overall performance of the system with low water supply reliability. Of the 7 irrigation zones delineated earlier, 5 irrigation zones have water shortages with reliability values well under 30%. In other words, only a third of the period simulated sufficient water was provided to the demand nodes. In more detail, all 43 water demand nodes faced water shortages with reliability well below the 92% threshold level, indicating problematic conditions requiring action. Most importantly, industrial and domestic demand nodes also faced water shortage problems. This is shown in Figure 5-7.

The result would be representative of the situation in the basin area prior to 2005 when the 7 upstream reservoirs have not been fully operational.

5.3.2 Baseline results with upstream reservoir

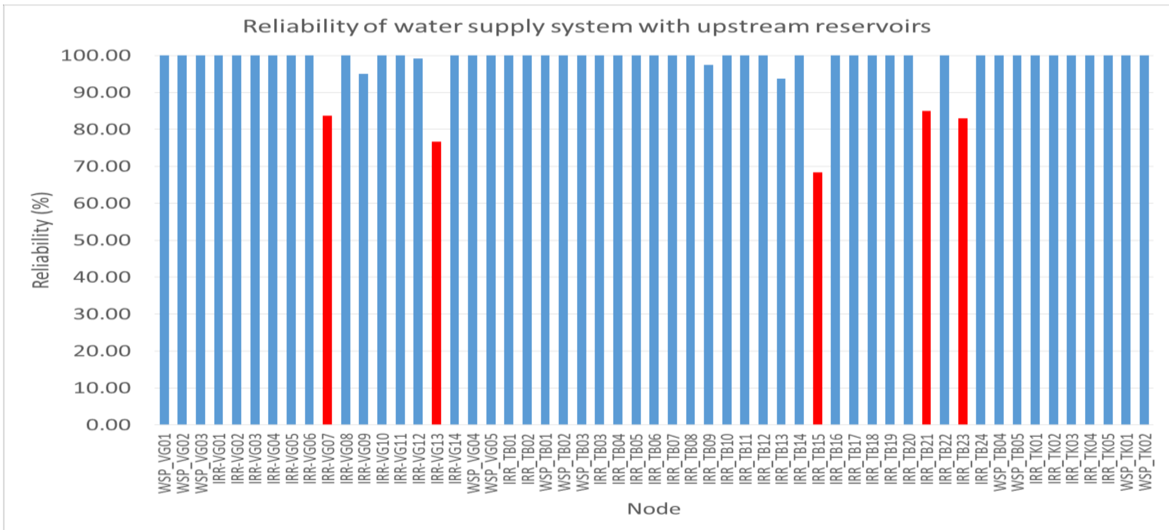

Figure 5-8: Water supply reliability with upstream reservoirs (baseline period: 1986-2005)

A baseline simulation in the MIKE BASIN model for the period of 1st January 1986 to 31st December 2005 with 8 hydropower reservoirs upstream, as expected, yielded different results. In relation to water reliability, for the most part of the river basin, reliability of the domestic and industrial demand nodes is at 100% (Figure 5-8). Water shortage only occurred at agricultural irrigation nodes. Within the 7 irrigation zones established earlier, only 5 irrigation node faced water shortage problems. This includes IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23 (highlighted in red).

Hence, it can be drawn that the 8 reservoirs upstream had a major impact on the supply of water in the river basin. From water shortages with reliability as low as 5%, water supply in the river basin is more reliable with the introduction of upstream reservoirs.

When the results are provided to local stakeholders and experts, it has been largely confirmed that although upstream reservoirs are highly controversial, their effect in securing water supply is clear. Local stakeholders and experts have often referred to the case of Phu Ninh reservoir in the South Eastern part of the river basin. Prior to its construction in 1986, the entire area now serviced by Phu Ninh reservoir is mainly sandy soil with little potential for agriculture or other economic activities. However, with the fully operational Phu Ninh reservoir after 1986, the entire area has been transformed into highly productive agriculture and green area.

The main controversy about the ability of upstream reservoir to secure water supply downstream is the tradeoff between water supply and electricity production. In certain instances, electricity production has normally been prioritized for industrial processes downstream over the use of water for agricultural production. This created a conflict of use from water. In the case studied here, little has been explored between the relationship of water use for agriculture and hydropower generation. The upstream reservoir were set to prioritize water usage, hence, a major component in optimizing hydropower production is not explored. For this reason, should electricity production been further included, different results could have been obtained and the overall effect of the upstream reservoirs may vary. Such a study would further require inputs from local stakeholders and can vary in time on the priority of electricity and water supply. There have been a large amount of studies on optimizing electricity and water supply in the literature.

5.3.3 Climate vulnerability space

A total of 73 MIKE Basin model runs were performed with varied precipitation and temperature values. Of the 43 irrigation demand nodes in the 7 irrigation zones, only 9 nodes have a reliability level of less than 92% in the range of precipitation and temperature simulation. This includes nodes IRR_VG07, IRR_VG09, IRR_VG12, IRR_VG13, IRR_TB09, IRR_TB13, IRR_TB15, IRR_TB21, and IRR_TB23.

Irrigation node IRR_VG07 which has a service area of 387 ha faces water shortage in all temperature and precipitation change scenarios evaluated. Even with an increase of annual precipitation up to 20% and no changes in temperature, reliability of the irrigation node falls below the threshold of 92%. The highest possible level of reliability in the range of temperature and precipitation evaluated for the irrigation node is at 90%, meaning only 90% of the time will the irrigated area receive enough water, the remaining 10% of the time the area is under water stress. The lowest reliability level possible in the same range of temperature and precipitation change is at 74%, meaning only 74% of the time will the area have enough water. The irrigation node is hence in trouble regardless of precipitation and temperature change (refer to Figure 5-9).

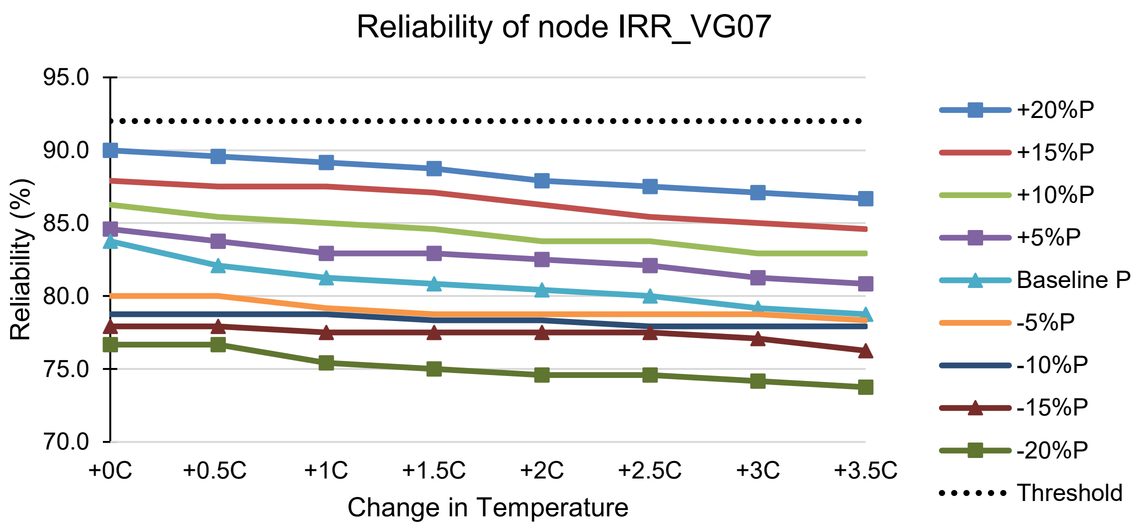

Figure 5-9: Reliability of node IRR_VG07

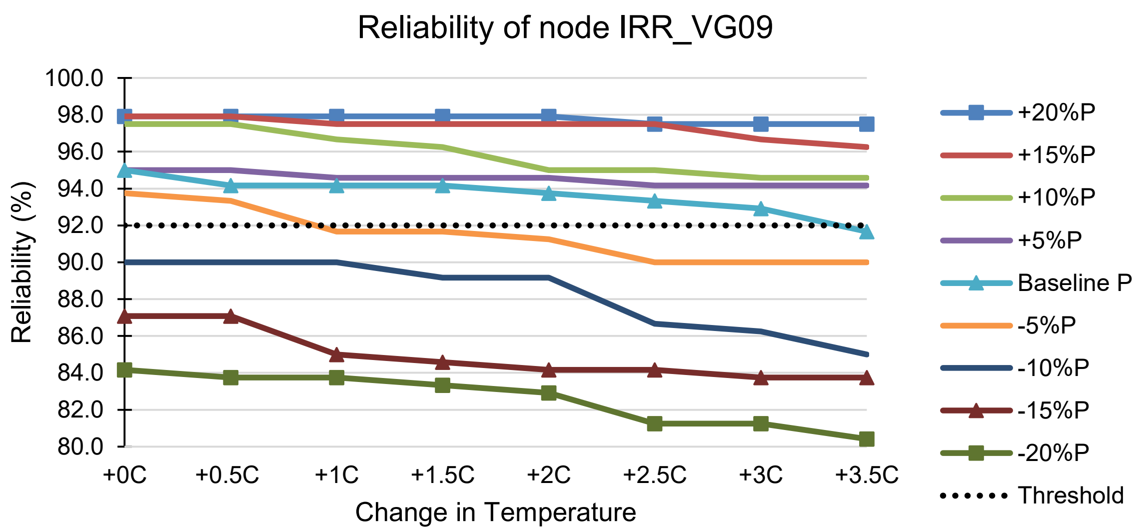

Figure 5-10: Reliability of node IRR_VG09

Irrigation node IRR_VG09 which provides irrigation water for some 15.0 km^2 of crops only faces water shortage problems when precipitation in the study area reduce by a minimum of 5%. If there are no changes in precipitation (baseline P), reliability problem only occurs at the irrigation node when temperature increases more than 3.5^{0}C. Overall, reliability of irrigation node IRR_VG09 is more sensitive to changes in precipitation than changes in temperature. The highest level of reliability of the irrigation node is 98% when there is an increase of precipitation of over 15%. The lowest level of reliability of the irrigation node is only at a mere 81% when precipitation decreases 20% and temperature increases 3.5^{0}C (the most extreme changes explored). The relationship between reliability and changes in temperature and precipitation for irrigation node IRR_VG09 is shown in Figure 5-10.

In the case of irrigation node IRR_VG12 which service 23.5 km^2 of crop, only a decrease in precipitation of 20% will trigger significant water shortages. Slightly milder water shortage occurs at the irrigation node when precipitation reduces 15% while temperature increases more than 1^{0}C as compared to the baseline period. At a 20% increase in precipitation and up to an increase of 1^{0}C, reliability of the irrigation node is at 100%, meaning 100% of the time the irrigation area could meet its water demand. The lowest reliability of the irrigated node is 87% corresponding to a precipitation decrease of 20% and an increase in temperature of 3.5^{0}C. Overall, irrigation node IRR_VG12 is less vulnerable to climate change as compared to irrigation nodes IRR_VG09 and IRR_VG07. Reliability plotted against changes in temperature and precipitation for irrigation node IRR_VG12 is shown in Figure 5-11.

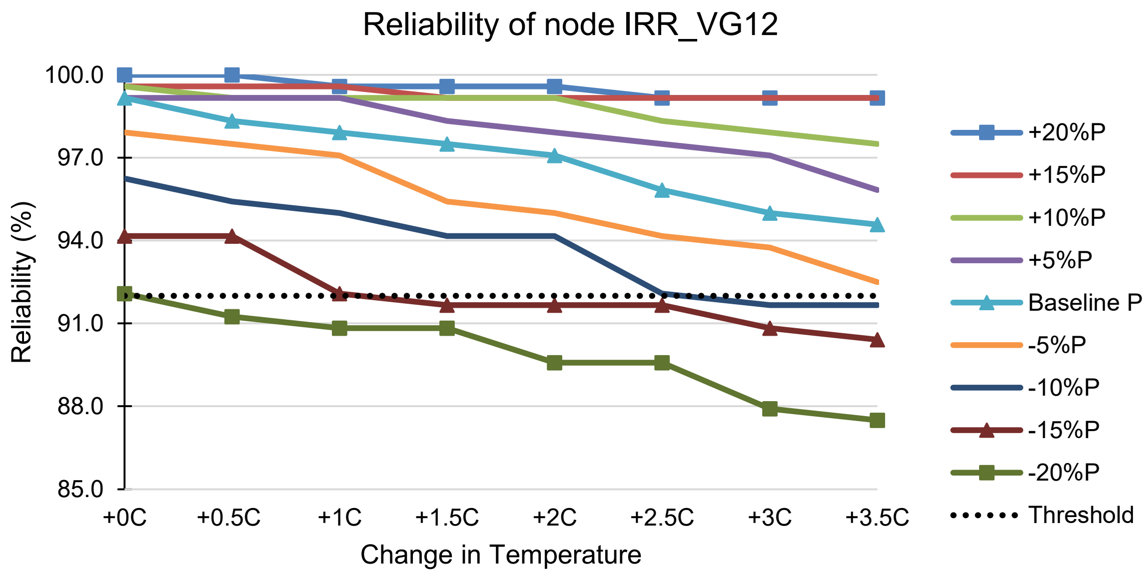

Figure 5-11: Reliability of node IRR_VG12

Reliability of irrigation node IRR_VG13 with 47.66 km^2 of crop is significantly low in all range of temperature and precipitation change evaluated. Even at the baseline scenario where no climate change is accounted for, the reliability of the irrigation node is only at approximately 76%. The highest possible reliability of the irrigation node is at 80% with a 20% increase in precipitation and no changes in temperature. However, this is highly unlikely in the face of climate change where temperature is expected to increase too. The lowest possible reliability in the evaluated range of precipitation and temperature is at 70% corresponding to a 20% decrease in precipitation and an increase of 3.5^0C. Part of the reason could be due to the large crop area that the irrigation node services, meaning more water is required overall. In addition, the irrigation node is located downstream of the VGTB River Basin, implying that available water would have otherwise reached the irrigation scheme have already been used up by upper stream irrigation nodes. Changes in precipitation and temperature with reliability value of irrigation node IRR_TB09 is shown in Figure 5-12.

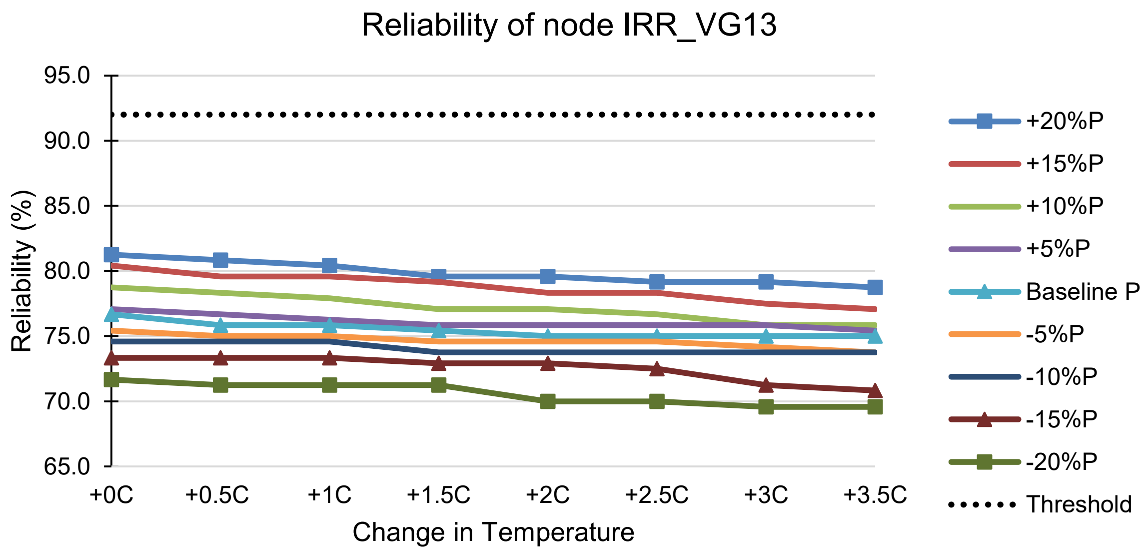

Figure 5-12: Reliability of node IRR_VG13

Irrigation node IRR_TB09 with 10.90 km^2 of crop only faces significant water shortage problems when precipitation decreases over 10%. With a 5% decrease in precipitation, reliability of the irrigation node is roughly at the threshold value of 92% and only when temperature increase over 2^0C will the irrigated area face water shortages. In the precipitation increase scenario, irrigation node IRR_TB09 will face little water challenges regardless of the changes in the temperature. Even at baseline precipitation value with an increase of 3.5^0C, reliability of the irrigation node would only be as low as the acceptable threshold value. Hence, irrigation node IRR_TB09 is also more sensitive to changes in precipitation than changes in temperature. Reliability of irrigation node IRR_TB09 against changes in temperature and precipitation is plotted in Figure 5-13.

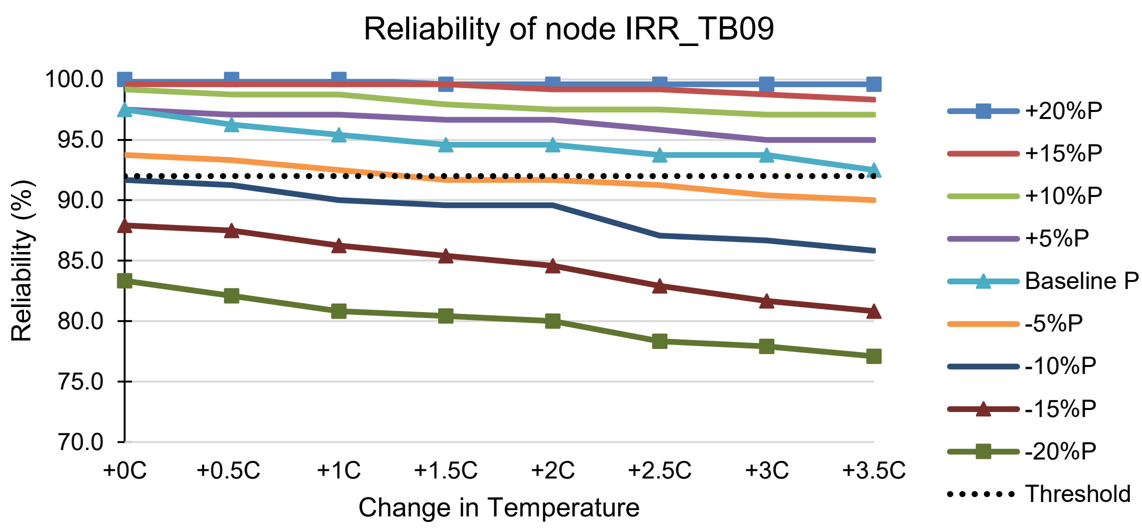

Figure 5-13: Reliability of node IRR_TB09

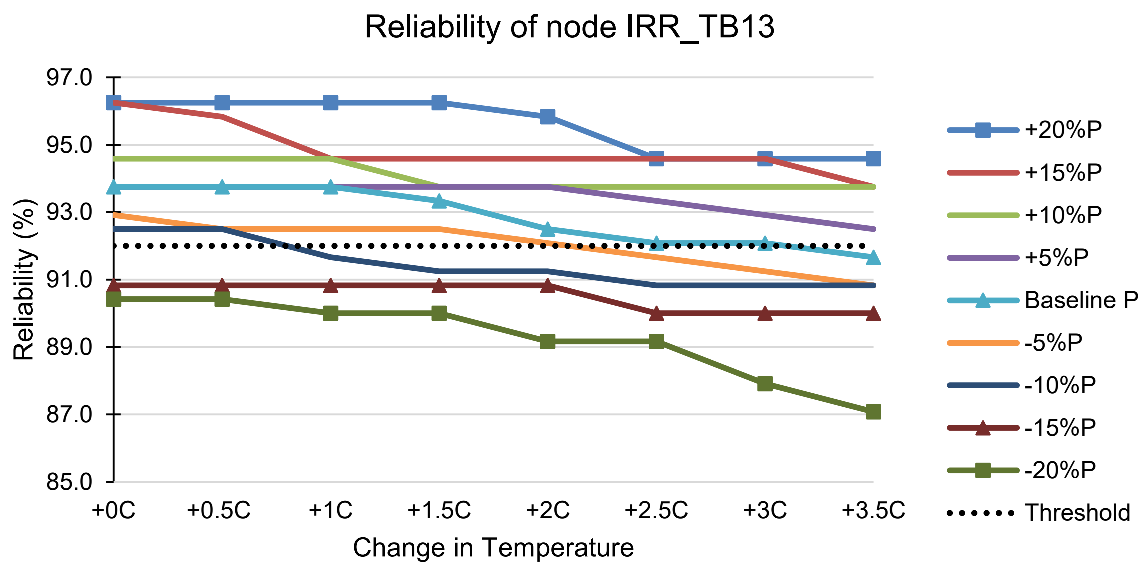

Figure 5-14: Reliability of node IRR_TB13

Irrigation node IRR_TB13 servicing 66.6 km^2 of crop faces water shortages under a different number of combination of precipitation and temperature change scenarios. With a decrease in precipitation of 5%, water shortages occur when temperature increase more than 2.5^{0}C. With a decrease in precipitation of 10%, water shortages occur when temperature increase more than 1^{0}C. Decreasing precipitation of more than 15% would lead to water shortages regardless to changes in temperature. At a 20% decrease of precipitation and an increase of 3.5^{0}C, the lowest possible reliability level occurred at 87%, i.e. 87% of the time water supply would be sufficient while the remaining 13% water shortage occurs. Reliability values according to changes in precipitation and temperature for irrigation node IRR_TB13 is shown in Figure 5-14.

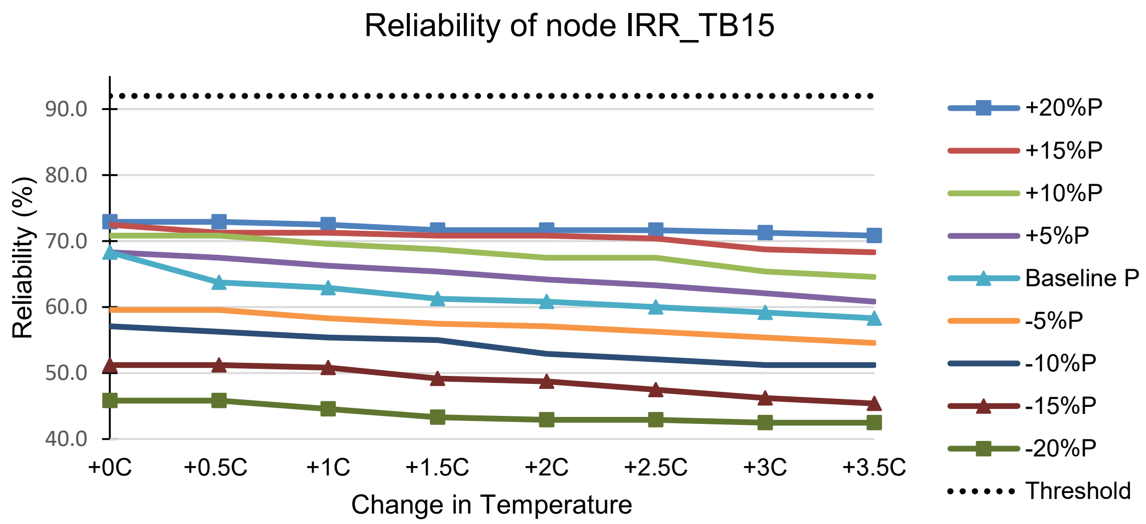

Figure 5-15: Reliability of node IRR_TB15

Reliability of irrigation node IRR_TB15 plotted against changes in precipitation and temperature is shown in Figure 5-15. For irrigation node IRR_TB15, water shortages occur regardless to changes in precipitation and temperature within the evaluated range of precipitation and temperature. Under the baseline scenario, with no changes in precipitation and temperature, reliability of the irrigation node is only at 69%. The highest possible reliability level occurs when there is a 20% increase in precipitation and no change in temperature. On the other hand, the lowest reliability level occurs at a 20% precipitation decrease and an increase of 3.5^{0}C. The case of irrigation node IRR_TB15 is similar to IRR_VG13.

Similarly, irrigation node IRR_TB21 will be facing water shortages problems regardless of changes in temperature and precipitation. Under a baseline scenario, reliability of the irrigation node is set at approximately 85%. Under climate change, reliability is further expected to decrease even further. Even when precipitation increase up to 20%, reliability of the irrigation system is only at 86%, lower than the threshold. With an increase in temperature of 3.5^{0}C and a decrease in precipitation of 20%, reliability could be as low as 71%, indicating significant water shortages.

Simulated reliability of irrigation node IRR_TB21 from MIKE BASIN versus changes in precipitation and temperature changes is shown in Figure 5-16.

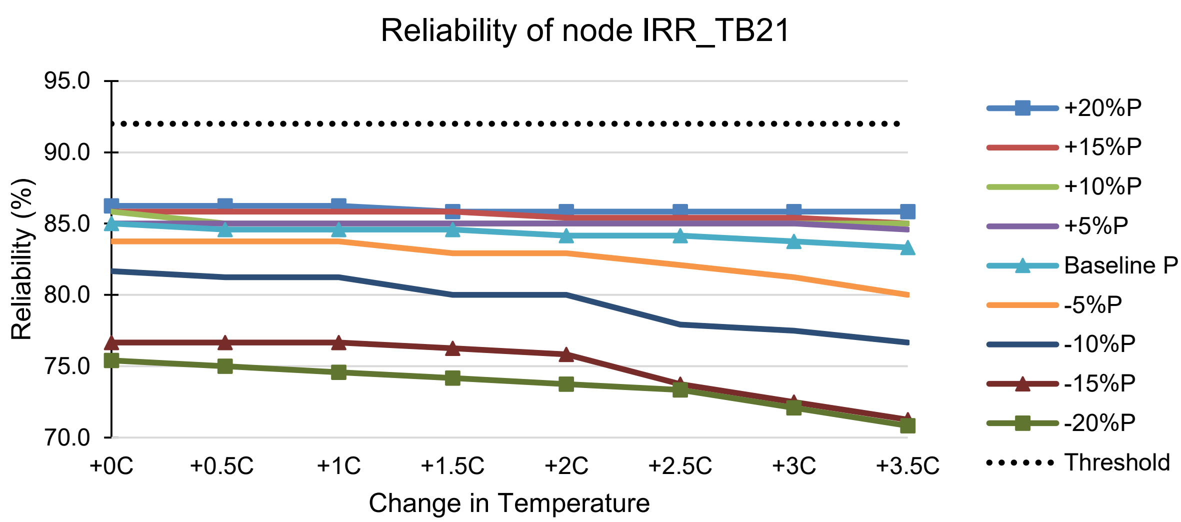

Figure 5-16: Reliability of node IRR_TB21

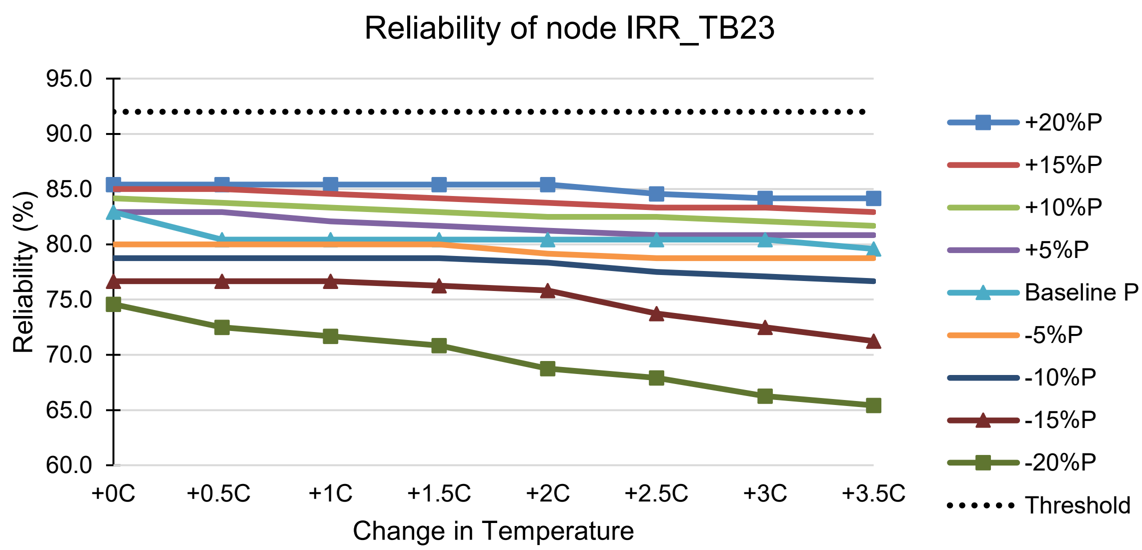

Figure 5-17: Reliability of node IRR_VG23

Lastly, 2.33 km^2 of crop in node IRR_TB23 is also likely to be facing water shortage problems. The highest possible reliability level of the irrigation node is 80% with a 20% increase in precipitation with no increase in temperature. With a 20% decrease in precipitation and 3.5^{0}C increase in temperature, the reliability level is only at 65%, showing severe water shortage (refer to Figure 5-17).

Overall, from the 9 irrigation nodes, there are 87.77 km^2 of crop land in the VGTB River Basin that are under threat of water shortages due to precipitation and temperature changes. It is useful to view the area at risk in the context of jurisdiction of the districts within the study area. In particular, the area is within the administrative boundary of 4 district within Quang Nam Province. The area at risk in each district is shown in Table 5-9. All four districts are located at the downstream end of the VGTB river system, in the plain lands.

Table 5-9: Agricultural area at risks of water shortage

Dai Loc	Dien Ban	Que Son	Duy Xuyen	Total
18.62 km^2	61.67 km^2	5.15 km^2	2.33 km^2	87.77 km^2

5.4 Tailoring Climate Information to Assist Decision Making

Once the vulnerable space of the water system has been established, possible future climate space have to be mapped. This section discusses the results of climate futures using output from GCMs. Key cases are further analyzed.

5.4.1 GCMs consensus

The GCM model outputs are summarized in Table 5-10, Table 5-11, and Table 5-12. The number in each cell represents the number of model output predictions within the same range of temperature and precipitation change. Note that output from all scenarios including RCP 2.6, RCP4.5, RCP6.0, and RCP8.5 are included. The higher the number in each individual cell shows a higher level of agreement between GCMs. On the contrary, the lower the number in each individual cell indicates a lower agreement of the range of temperature and precipitation changes between GCMs. In addition, the more clustered the higher numbered cells indicates a higher the precision of GCM outputs. In other words, GCM outputs converges on a smaller range of temperature and precipitation change value. On the other hand, the more spread in the range of the higher numbered cells, the higher the spread in predictions of GCMs, hence, implies higher uncertainty.

For the time period between 2016 and 2035, the majority of models under all different scenarios predict that future climate condition will be warmer (Table 5-10). In particular, it is predicted that there will be an increase between 0.5^0C to 1.5^0C (41 out of 55 model outputs, equivalent to 75%). A reasonable amount of GCM outputs predicts the increase in temperature will not likely be higher than 0.5^0C (11 out of 55 outputs). While only 3 model output predicted that temperature increase would be greater than 1.5^{0}C.

Table 5-10: Climate future for time period 2016-2035 (all scenarios)

		Annual Surface temperature (^{o}C)			
		Slightly warmer < +0.5	Warmer +0.5 to +1.5	Hotter +1.5 to +3.0	Much Hotter >+3.0
Annual Rainfall (%)	Much wetter > +15	0	0	0	0
	Wetter +5.0 to +15.0	2	6	1	0
	Little Change -5.0 to +5.0	9	25	0	1
	Drier -15.0 to -5.0	0	10	1	0
	Much Drier <-15.0	0	0	0	0

The majority of models predicted precipitation variation to be mostly unchanged, varying around the ± 5% of baseline annual precipitation (35 model outputs). However, there is also a reasonable amount of outputs predicting either wetter (9 outputs) or drier (11 outputs) precipitation conditions. No output represent either an increase or decrease of precipitation beyond the ±15% of baseline precipitation.

In the second time period of 2046 to 2065, a higher spread of prediction value is observed for both temperature and precipitation variation (refer to Table 5-11). Temperature is expected to increase between 0.5^{0}C to 3^{0}C by the majority of GCM scenarios (51 out of 55, equivalent to 93%). While precipitation is predicted to vary along the entire ±15% range of the baseline precipitation.

Unlike the previous period, temperature increase prediction has a tendency to be greater in the 2046-2065 period. Maximum consensus of GCM outputs is at a warmer temperature scenario (29 models). Only 1 model output predicted temperature would increase less than 0.5^{0}C as compared to 11 model outputs in the previous period. There is also reasonable justification for a hotter temperature with 22 model outputs predicting temperature to increase within this range. 3 model outputs predict temperature to increase more than 3^{0}C for the time period.

The variation in precipitation change prediction between models in this time period is also higher compared to the previous. Unlike the previous period of 2016-2035, there are models predicting precipitation to vary beyond the ±15% of annual baseline rainfall. In particular, 3 model outputs predict precipitation to increase more than 15%, while 1 model output predict precipitation to decrease more than 15%.

Table 5-11: Climate future for time period 2046-2065 (all scenarios)

		Annual Surface temperature (^oC)			
		Slightly warmer < +0.5	Warmer +0.5 to +1.5	Hotter +1.5 to +3.0	Much Hotter >+3.0
Annual Rainfall (%)	Much wetter > +15	0	1	1	1
	Wetter +5.0 to +15.0	0	9	6	0
	Little Change -5.0 to +5.0	1	11	9	1
	Drier -15.0 to -5.0	0	7	6	1
	Much Drier <-15.0	0	1	0	0

The spread of the prediction for both temperature and precipitation for the time period 2080-2099 is higher than the first period (2016-2035), yet less than the previous period (2046-2066). The majority of models predict changes at the upper right corner of the matrix (Table 5-12).

Table 5-12: Climate future for time period 2080-2099 (all scenarios)

		Annual Surface temperature (^oC)			
		Slightly warmer < +0.5	Warmer +0.5 to +1.5	Hotter +1.5 to +3.0	Much Hotter >+3.0
Annual Rainfall (%)	Much wetter > +15	0	0	6	2
	Wetter +5.0 to +15.0	0	11	6	4
	Little Change -5.0 to +5.0	1	6	8	6
	Drier -15.0 to -5.0	0	0	4	1
	Much Drier <-15.0	0	0	0	0

For the time period of 2080-2099, temperature is predicted to increase between 1.5^{0}C and 3^{0}C when viewed under the maximum number of model output agreement. In particular, 24 model outputs predict such temperature change. However, a reasonable amount of model outputs (17 outputs) predicts a more conservative temperature increase that is similar to the previous period of only between 0.5^0C and 1.5^0C. 1 model predicts an increase of no more than 0.5^0C in temperature within the time period while 13 other model outputs predict temperature to increase well beyond 3^0C.

There is a higher tendency of model output to predict an increase in precipitation trend for the time period 2085-2099. There are 29 model outputs with increasing precipitation as compared to only 5 predicting drier conditions. 15 model outputs predict little change in precipitation.

Overall, analyzing future precipitation and temperature predictions from GCMs showed a higher spread of model agreement in the long run. In the short-term period between 2016 and 2035, there exist an absolute highest number of model agreement with 25 model predicting the same range of precipitation and temperature change. Later time periods do not show such a high level of agreement. Rather, there exist a spread of the prediction of GCMs over different precipitation and temperature conditions. This further implicates the difficulties in using climate science to drive adaptation measures and reiterate the uncertainties of previous effort attempting to downscale one or a few GCM.

5.4.2 Key cases

Three key cases of maximum consensus, best-case scenario, and worst-case scenario are further evaluated. The maximum consensus scenario represents the maximum number of models predicting the same range of precipitation and temperature variation. Best-case scenario represent the least change in both temperature and precipitation. Lastly, worst-case scenario represents the most change in temperature and precipitation (increase in temperature and decrease in precipitation).

Maximum consensus case

Under a maximum consensus case, where the highest number of model outputs predict a similar change in precipitation and temperature, 5 irrigation nodes would be under water shortage conditions throughout the time period analyzed. In particular, irrigation node IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23 would face water shortage problems leading to a total of 66.36 km^2 of crops vulnerable (Table 5-13).

Table 5-13: Maximum consensus case of GCM outputs

Case	**2016-2035** Warmer, little change	**2045-2066** Warmer, little change	**2085-2099** Warmer, wetter
Nodes affected	IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23	IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23	IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23
Area affected	66.36 km^2	66.36 km^2	66.36 km^2
Water deficit	13.7- 16.9 million m^3	13.7- 16.9 million m^3	11.8- 15.6 million m^3

Furthermore, under the maximum consensus scenario, the amount of water demand deficit varies between the periods. For the first two period of 2016-2035 and 2045-2066, total water demand deficit is between 13.7 million m^3 and 16.9 million m^3. Given that GCMs predict a wetter future by the end of the century, only between 11.8 and 15.6 million m^3 of water is short in the last time period.

Best case scenario

Under a best-case scenario, for 3 time periods 2016-2035, 2045-2066, and 2085-2099, 66.36 km^2 of crop from 5 irrigation nodes would face water shortages (Table 5-14). The effect of this climate change scenario is mostly similar to the maximum consensus case.

Under a best-case scenario, water deficit for all three periods are similar. In particular, it would require between 13.3 and 15.9 million m^3 of water to meet the water deficit for agricultural purposes.

Table 5-14: Best-case scenario of GCM outputs

Case	**2016-2035** Slightly warmer, little change	**2045-2066** Slightly warmer, little change	**2085-2099** Slightly warmer, little change
Nodes	IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23	IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23	IRR_VG07, IRR_VG13, IRR_TB15, IRR_TB21, and IRR_TB23
Area affected	66.36 km^2	66.36 km^2	66.36 km^2
Water deficit	13.3- 15.9 million m^3	13.3- 15.9 million m^3	13.3- 15.9 million m^3

Worst case scenario

Under a worst-case scenario, it is predicted that the entire 9 irrigation nodes would face water shortage problems. Consequently, the entire 87.77 km^2 of crop under risks will face water shortages (refer to Table 5-15).

Water deficit under the worst-case scenario is also higher than water deficit of the other two scenarios. For the first period of 2016- 2035, an addition of between 15.5 and 20.4 million m^3 would be required to meet irrigation demand. For the second period between 2045 and 2066, an addition of 14.7 to 20.2 million m^3 of water is needed. For the last period, between 15.5 and 20.9 million m^3 is needed.

Table 5-15: Worst-case scenario of GCM outputs

	2016-2035	**2045-2066**	**2085-2099**
Case	Hotter, drier	Warmer, much drier	Much hotter, drier
Nodes	IRR_VG07, IRR_VG09, IRR_VG12, IRR_VG13, IRR_VG09, IRR_TB13, IRR_TB15, IRR_TB21, IRR_TB23	IRR_VG07, IRR_VG09, IRR_VG12, IRR_VG13, IRR_VG09, IRR_TB13, IRR_TB15, IRR_TB21, IRR_TB23	IRR_VG07, IRR_VG09, IRR_VG12, IRR_VG13, IRR_VG09, IRR_TB13, IRR_TB15, IRR_TB21, IRR_TB23
Area affected	87.77 km^2	87.77 km^2	87.77 km^2
Water deficit	15.5- 20.4 million m^3	14.7- 20.2 million m^3	15.5- 20.9 million m^3

Water demand deficit shown in three cases are results obtained from the 73 simulation using the MIKE BASIN model. An interesting aspect of the deficit is that water shortages only occurred within the summer- fall crop calendar, especially between the months of April and July. The main reason is due to the higher irrigation water demand during drier months where less precipitation is received.

Upon analyzing the three key cases, it becomes apparent that the minimum adaptation effort would include the consideration of only 66.36 km^2 of crops in 5 irrigation nodes. This is suggested by both the maximum consensus of GCM outputs and the best-case scenario. The total affected area is equivalent to roughly 67% of the vulnerable area. The irrigated area would include those within Dai Loc, Dien Ban, Que Son, and Duy Xuyen districts.

Under a worst-case scenario, all 9 irrigation nodes would require adaptation measures. This amounts to 87.77 km^2 of crops. Similarly, the irrigated areas are also within the four districts of Dai Loc, Dien Ban, Que Son, and Duy Xuyen districts. A maximum of 20.9 million m^3 would be required in order to curve water deficit. Adapting to the worst-case scenario would represent a more conservative approach in climate change adaptation.

5.5 Current Status and Effects of Land Use Policies

The following section discusses the results obtained from analyzing the effects of land use policies using satellite images.

5.5.1 Classification results

Land cover classification for the years 2011 and 2016 using a maximum likelihood algorithm supervised classification scheme results are as shown in Figure 5-18 and Figure 5-19 respectively. The corresponding accuracy assessment are as shown in Table 5-16.

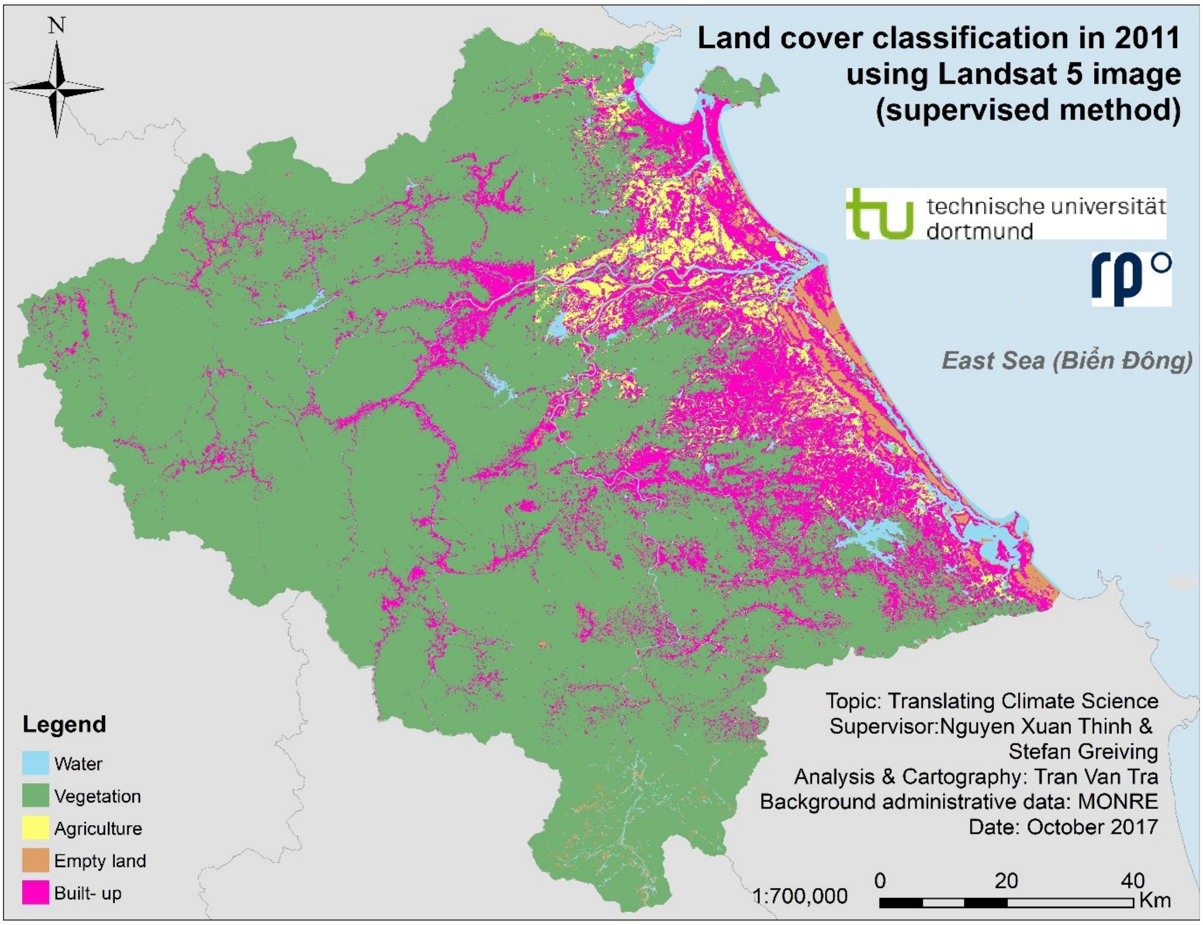

Figure 5-18: VGTB land cover in 2011 using supervised classification

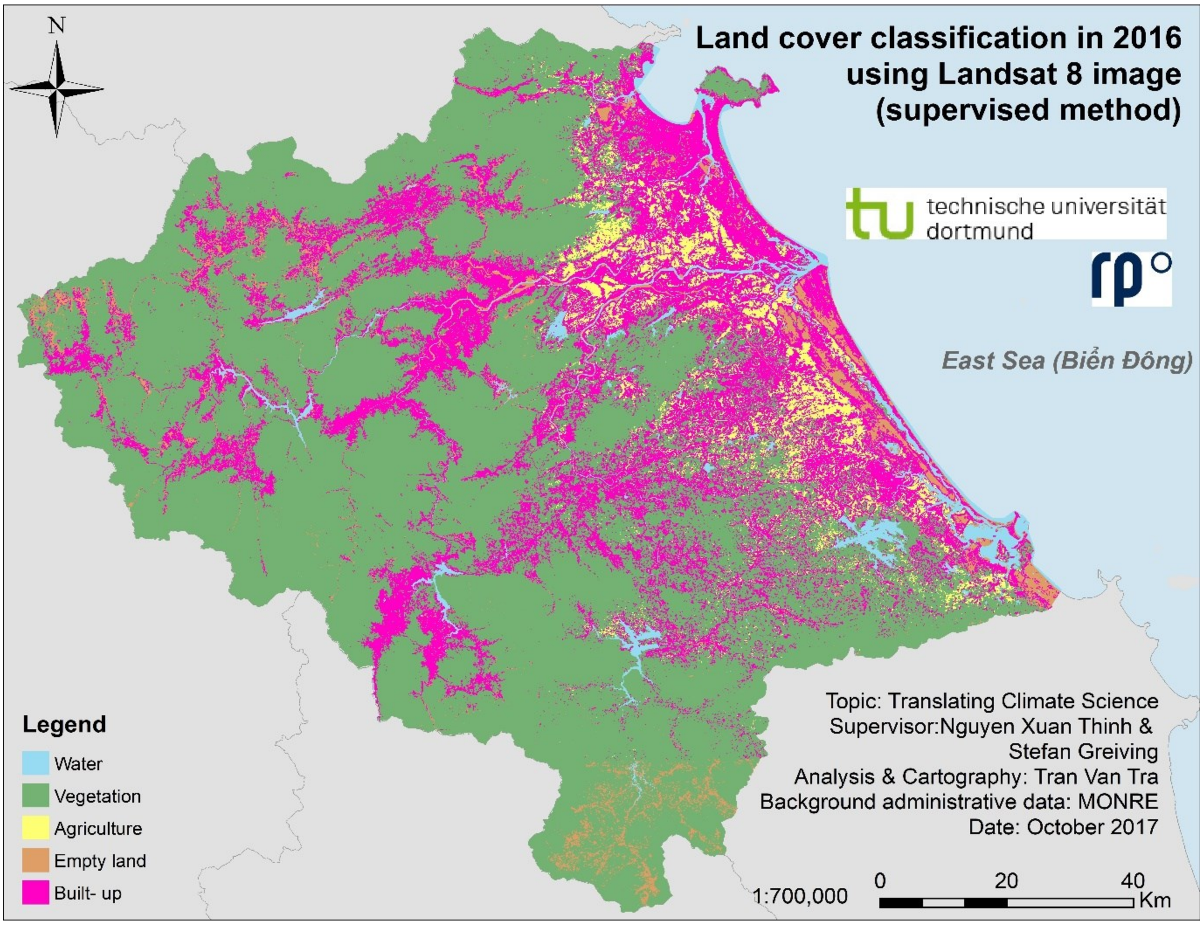

Figure 5-19: VGTB land cover in 2016 using supervised classification

For the 2011 classification scheme, a supervised classification method yielded results with an overall accuracy of 58% and a Kappa coefficient of 0.46. A supervised classification scheme for 2016 provided an overall accuracy of 65% and a Kappa coefficient of 0.54. Both accuracy assessment measures are low and thus, the results were not used for further analysis.

Table 5-16: Accuracy assessment of land cover classification using supervised classification

Accuracy measurement	2011 scene	2016 scene
Overall Accuracy (%)	58	65
Kappa coefficient	0.46	0.54

The low accuracy of the supervised classification scheme could be attributed to the quality of the training samples and the nature of the reflectance of the image. A poor training sample would result in poor classification results. The selection of training sample is highly subjective, it requires the judgement on how many types of sub-land cover samples would be needed for a class of land cover. The highly heterogeneous nature of the land cover in the east and the highly homogeneous land cover in the west further complicated the choice of training samples. In addition, there is little control over how selecting different training sample would affect the final classification result. Producer’s and user’s accuracy for the supervised classification scheme is as shown in Table 5-17.

Table 5-17: Producer's and User's accuracy (supervised classification)

Class	2011		2016	
	Producer's	User's	Producer's	User's
Water	76.0	92.7	88.0	97.8
Vegetation	35.9	70.0	28.4	86.4
Agriculture	42.1	88.9	65.7	100.0
Empty land	66.7	38.1	64.3	50.0
Built-up	86.7	37.9	86.0	42.6

Land cover classification using an index approach results for the years 2011 and 2016 are as shown in Figure 5-20 and Figure 5-21. Accuracy assessment and the kappa coefficient value is shown in Table 5-18.

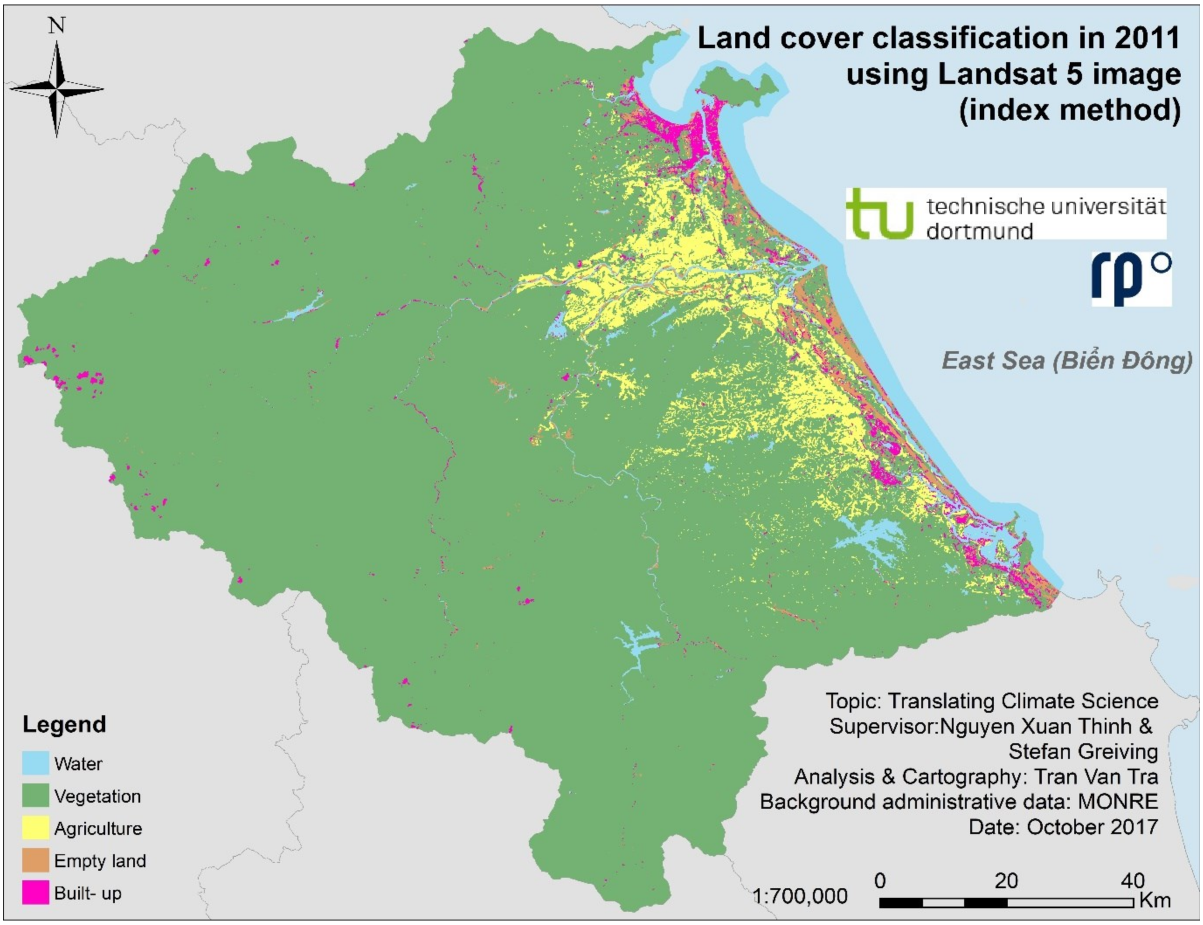

Figure 5-20: VGTB land cover in 2011 using index-based approach

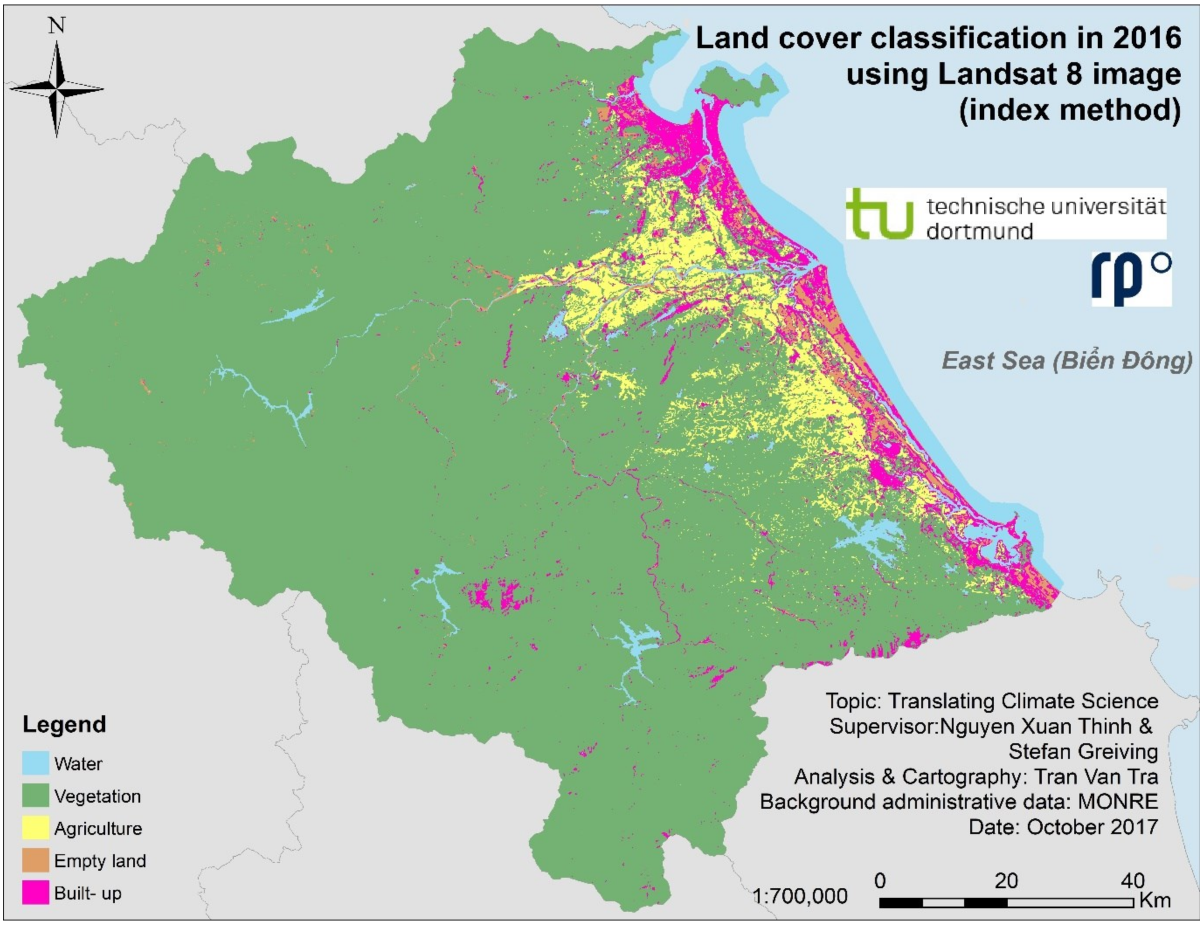

Figure 5-21: VGTB land cover in 2016 using index based approach

Table 5-18: Accuracy assessment of land cover classification using index based approach

Accuracy measurement	2011 scene	2016 scene
Overall Accuracy (%)	82	85
Kappa coefficient	0.77	0.81

The index-based classification scheme in both 2011 and 2016 are relatively successful. The overall accuracy and Kappa coefficient of the classification scheme in 2016 is 85% and 0.81 respectively. Overall accuracy and kappa coefficient for 2011 is lower, being 82% and 0.77 respectively. The level of accuracy and Kappa coefficient obtained from the study is still within the range accepted by other studies (Hanh *et al.*, 2015; Li and Thinh, 2013; Tilahun and Teferie, 2015), therefore, the results are accepted for further analysis.

The user's and producer's accuracy for the index land cover classification are shown in Table 5-19. Producer's accuracy represent how well reference points are classified. User's accuracy on the other hand represent the probability that a pixel classified into a given category actually represents that category on the ground. Overall, water and built-up classes in the 2011 classification scheme do not agree well with the ground reference points. The user's accuracy for vegetation and empty land in 2011 indicated that other land cover classes have been misclassified into these classes. The 2016 land cover classification scheme is more successful. However, built-up area in the 2016 classification scheme is more likely of being misclassified from other type of land cover.

Table 5-19: Producer's and User's accuracy of land cover classification (index method)

Class	2011		2016	
	Producer's	User's	Producer's	User's
Water	74.5	100.0	86.3	100.0
Vegetation	91.0	76.3	80.6	84.4
Agriculture	86.8	100.0	91.4	97.0
Empty land	83.3	62.5	78.6	84.6
Built-up	71.1	72.7	87.7	71.4

A general case for all four classified image is the dominant of vegetation cover. The types of cover are highly diverse and different, ranging from forest to grassland and in some cases, may also include unused land (empty-land). During the field trip, it has been determined that even empty-land of sand in the area exhibit vegetation growth (see Figure 5-22). As such, the reflectance of the satellite image have shown a highly green area (also mostly due to the coarse resolution) and the NDVI measure indicated these areas are covered by vegetation. This classification as a whole, is not false.

Figure 5-22: Example of empty-land covered with vegetation

A second relative measure of the success of the land cover classification scheme is the comparison with the land use inventory by the Vietnam Ministry of Natural Resources and Environment (Table 5-20). However, only 4 land cover classes were compared. This is due to the limited information of the land use inventory data on surface water area.

Overall, it could be said that the land cover classification results and the land use inventory agrees well with each other in the order of magnitude. However, there are also notable differences that are worth discussing. Without losing much accuracy and for the purpose of the discussion, an under-prediction of the land cover classification scheme indicates a lesser area of a particular land cover class when compared to the land use inventory data. Likewise, an over-prediction of the land cover classification scheme indicates a greater area of a land cover class in comparison to the land use inventory.

Table 5-20: Comparing land cover results with land use data from MONRE (units: km^2)

		Vegetation	Agriculture	Empty Land	Built-up
2011	Classification results	10344.09	635.26	180.91	200.58
	Land use (MONRE)	10316.29	607.84	156.05	280.60
	Difference	27.80	27.42	24.87	-80.03
	Difference (%)	0.27%	4.32%	13.74%	39.90%
2016	Classification results	10036.95	581.39	181.92	543.03
	Land use (MONRE)	9983.24	566.63	169.61	623.94
	Difference	53.71	14.76	12.31	-80.91
	Difference (%)	0.54%	2.54%	6.77%	14.90%

For the classification scheme of 2011, there is a large magnitude of mismatch of built-up land between the land cover classification scheme and the land use inventory data. The land cover classification scheme estimated that there are approximately 80km^2 less of built-up area in 2011 as compared to the land use data. The under-prediction is compensated by the over-prediction of vegetation, agriculture, and empty land.

A similar over-prediction and under-prediction is observed between the land cover classification scheme and the land use inventory in 2016. In other words, the land cover classification scheme consistently under-predicts the total area of built-up land while over predicts the total area of vegetation, agriculture, and empty land. Therefore, the suggestion of the mismatch mentioned aforementioned could be accepted.

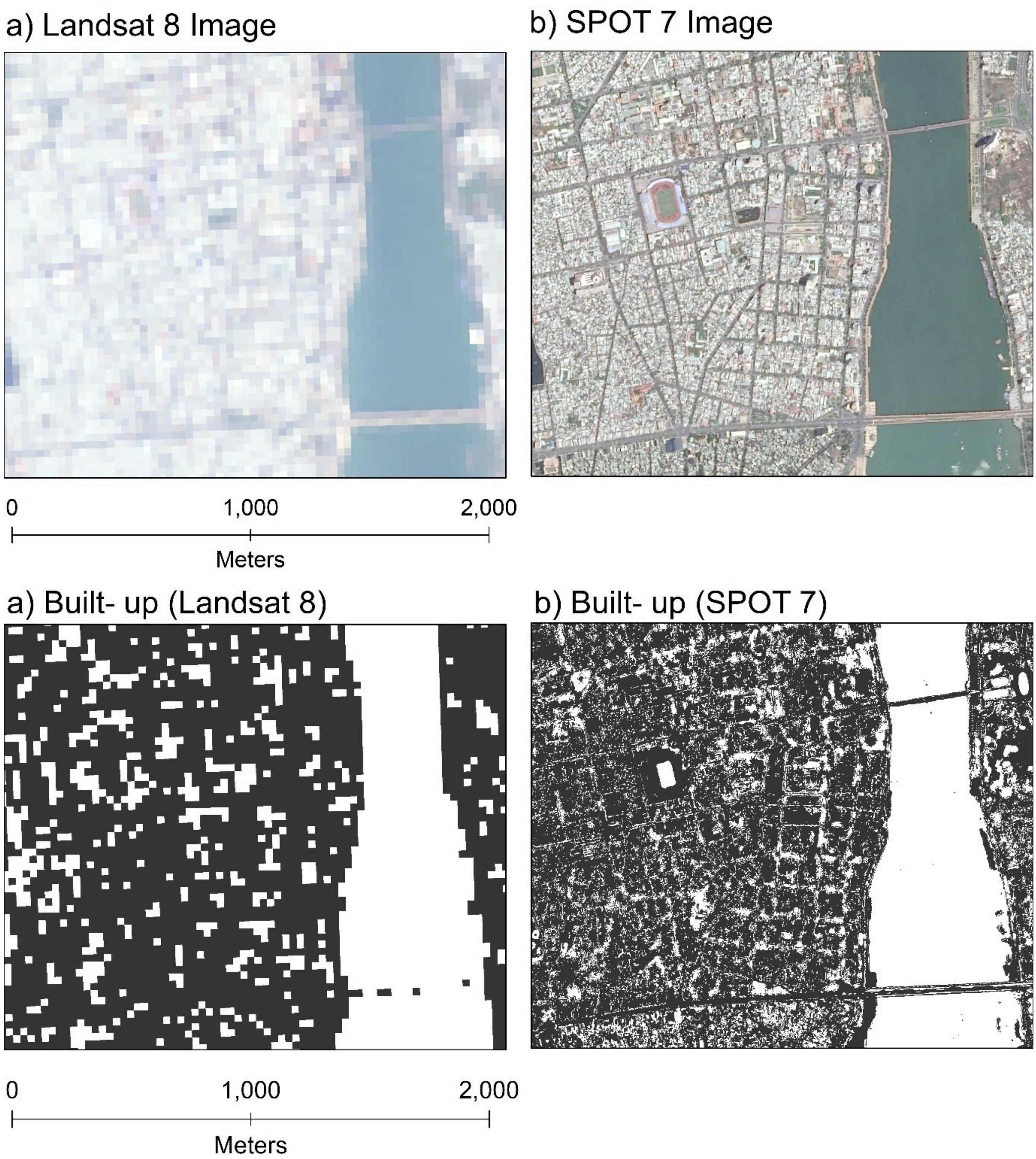

Figure 5-23: Comparison of Landsat 8 and SPOT 7 Images

The reason leading to an overall lower than expected accuracy of the land cover classification is explained through comparing the results obtained from the land cover classification using Landsat 8 image and SPOT 7 image. The built-up area within the Central Business District of Da Nang City, along the banks of the Han River classified using SPOT 7 image and using Landsat 8 image are compared in Figure 5-23. The selected area has been highly developed and there is little change between 2015 (the date of the SPOT 7 acquired date) and 2016 (the date of the Landsat 8 acquired date). Therefore, comparison of the two is meaningful.

Given a higher resolution, the SPOT image classification using the SPOT 7 image was able to better distinguish the built-up area in a highly heterogeneous land cover area in the CBD of Da Nang. The Landsat image, given a lower resolution, did not perform as well. Built-up area classified using the Landsat 8 image hence does not necessary provide the actual ground conditions that would have otherwise been determined using the SPOT 7 image. A similar case could also be observed through using different land cover classes. The coarse resolution of the Landsat 8 image thus creates a major source of uncertainty and error in the classification of land cover in the study. An overall low accuracy of the classification scheme is thus explained.

5.5.2 Land cover change results

Land cover change detection was then performed. The land cover change matrix is as shown in Table 5-21. The rows shows the composition of changes that a particular type of land cover in 2011 under went. The columns shows the total area in which a particular land cover in 2011 was converted into. For example, 580.13 km^2 of water in 2011 remained to be water body in 2016. However, 2.32 km^2 of water in 2011 was converted into vegetation.

Table 5-21: Land cover change matrix between 2011 and 2016 (units: km^2)

		2016 land cover					
		Water	Vegetation	Agriculture	Empty land	Built-up	Change
2011 land cover	Water	580.13	2.32	0.45	4.05	23.42	17.53
	Vegetation	35.45	9,936.38	14.12	52.42	305.72	-307.13
	Agriculture	1.91	53.81	566.37	3.06	10.11	-53.86
	Empty land	4.79	14.51	0.45	105.73	55.42	1.01
	Built-up	5.63	29.93	0.00	16.65	148.36	342.45

An interesting result should be noted between the conversion of agriculture and vegetation. Between 2011 and 2016, 53.81 km^2 agricultural land was converted into vegetation area in 2016. However, in the other direction, 14.12 km^2 of vegetation in 2011 was converted into agricultural land in 2016. This could suggest an error in the classification scheme where a smaller amount of paddy rice area were not fully detected from the multi-temporal NDVI analysis leading to agricultural area being falsely classified as vegetation.

Conversion of built-up area into other types of land cover should also be viewed cautiously as this conversion mechanism is not normally expected. The conversion of built-up area into water could be attributed to the increase of new artificial lakes in the city of Da Nang, the seasonal fluctuation of water in streams (flooding), and error in classification. Water surface could have very similar reflectance value with built-up, hence, water surface in 2011 were incorrectly classified as built-up and correctly identified in 2016, leading to the changes of built-up area into water surface. On the other hand, the conversion of built-up area in 2011 into vegetation in 2016 is a direct result of cloud coverage west of the river basin in the 2011 image. Since clouds also have a similar reflectance to built-up area, it was falsely classified as built-up in 2011.

In the time period from 2011 to 2016, an increase of 342.45 km^2 built-up area could be observed. When comparing to the overall planning goal until 2020 from the land use master plan of Quang Nam Province and Da Nang City, the area has reached 117% of its target, meaning more built-up land have been created than planned (Table 5-22).

Planned paddy rice area conversion between 2011 and 2016 is also smaller than actual changes in the same period. Within the same period, 53.86 km^2 of rice cultivation land have been converted while only 46.60 km^2 has been planned. In other words, 16% more of the total paddy rice land have been converted as compared to the master plan (Table 5-22).

Table 5-22: Land planning changes in Quang Nam and Da Nang until 2020

	Planned (2011-2020) (km^2)	Status (2011-2016) (km^2)	Goal reached (%)
Agriculture (rice)	-46.60	-53.86	116
Urban area	+292.57	+342.45	117

A quick analysis of the land price in Da Nang City for the period 2011-2015 showed some further interesting results. Within the period from 2011 to 2015, land price in Da Nang City increased significantly. For the time period under consideration, land prices in Da Nang City increased as much as 35% with an average price increase approximately 18% (Da Nang People's Committee, 2014, 2011).

Given that there is only a fixed amount of available land supply, the increase in land prices hence indicates significant increase in land demanded. Assuming that there is little to no land price speculation, it could be stated that during the period under consideration, there is clearly a significant increase in built-up area demand. This could include increase housing development as a result of population increase, increase industrialization and commercialization, increase in tourism, etc.

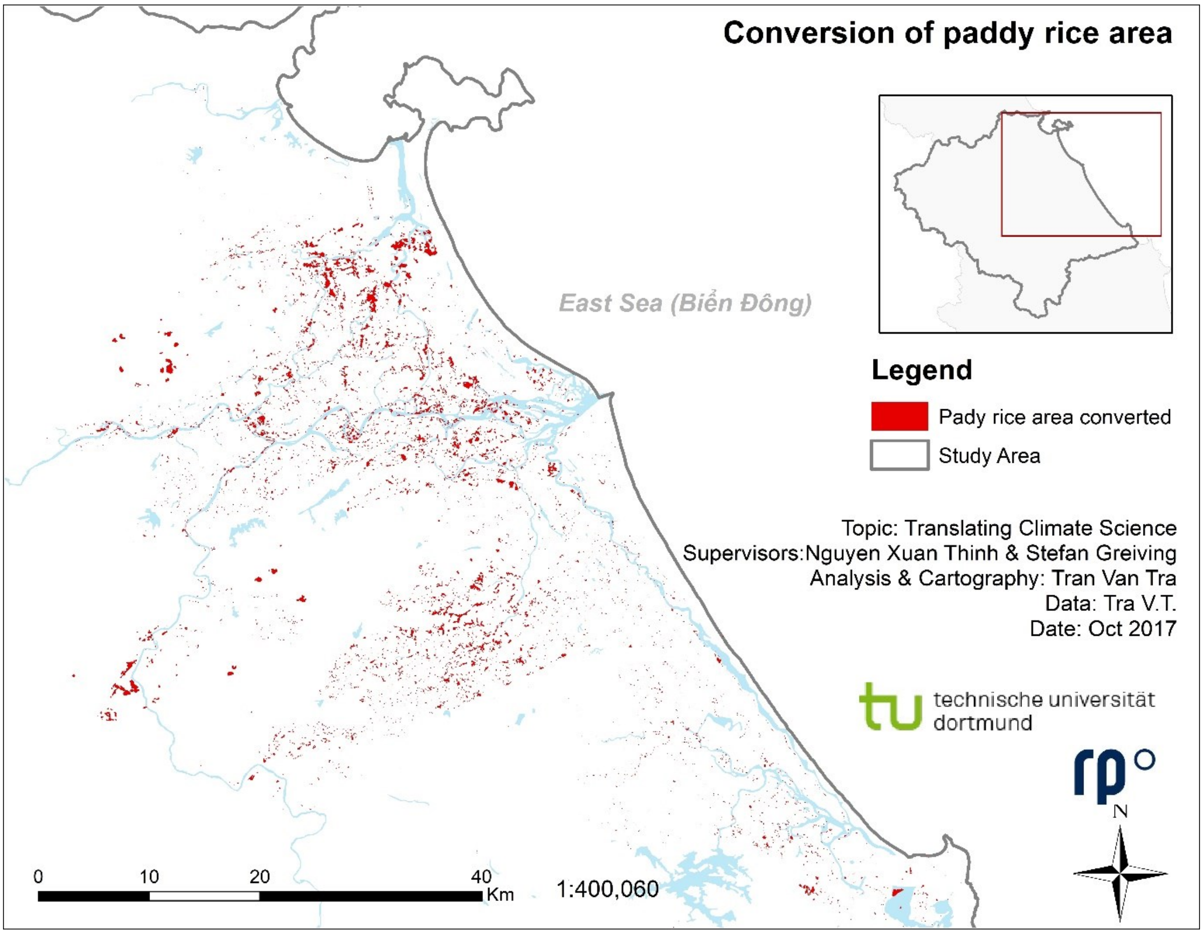

Figure 5-24: Paddy rice area converted in between 2011 and 2016

Mapping the paddy rice area conversion between 2011 and 2016 suggests that the removal of paddy rice area are fragmented. In other words, there appears to be no systematic and large-scale paddy rice area reduction, but rather smaller scale (refer to Figure 5-24). Therefore, one could state that most conversion took place at the farmer's household level.

A closer inspection into the conversion of paddy rice land, however, showed some interesting results. Of the 68.89 km^2 of rice cultivation area converted, roughly 25% were converted into built-up areas. A small proportion of the conversion of paddy rice land is into water. The remaining majority of paddy rice land conversion was into vegetation, and empty land (Table 5-23).

Table 5-23: Conversion of agricultural land

Converted into Built-up	Converted into Water	Converted into Vegetation	Converted into Empty land	Total conversion
10.10 km^2	19.12 km^2	53.81 km^2	30.60 km^2	68.89 km^2

Paddy rice land conversion into built-up area is mostly due to development. Due to the increase in built-up area land price discussed earlier, there is an incentive for more development to take place at the cost of converting low value agricultural land into higher value real estate and for industrial processes. The conversion mechanism, however, by Vietnam law 2013 (Land law in 2013) (National Assembly of Vietnam, 2013), is heavily regulated and is performed on a case-by-case review basis. For this reason, the fragmented conversion of paddy rice land could be explained.

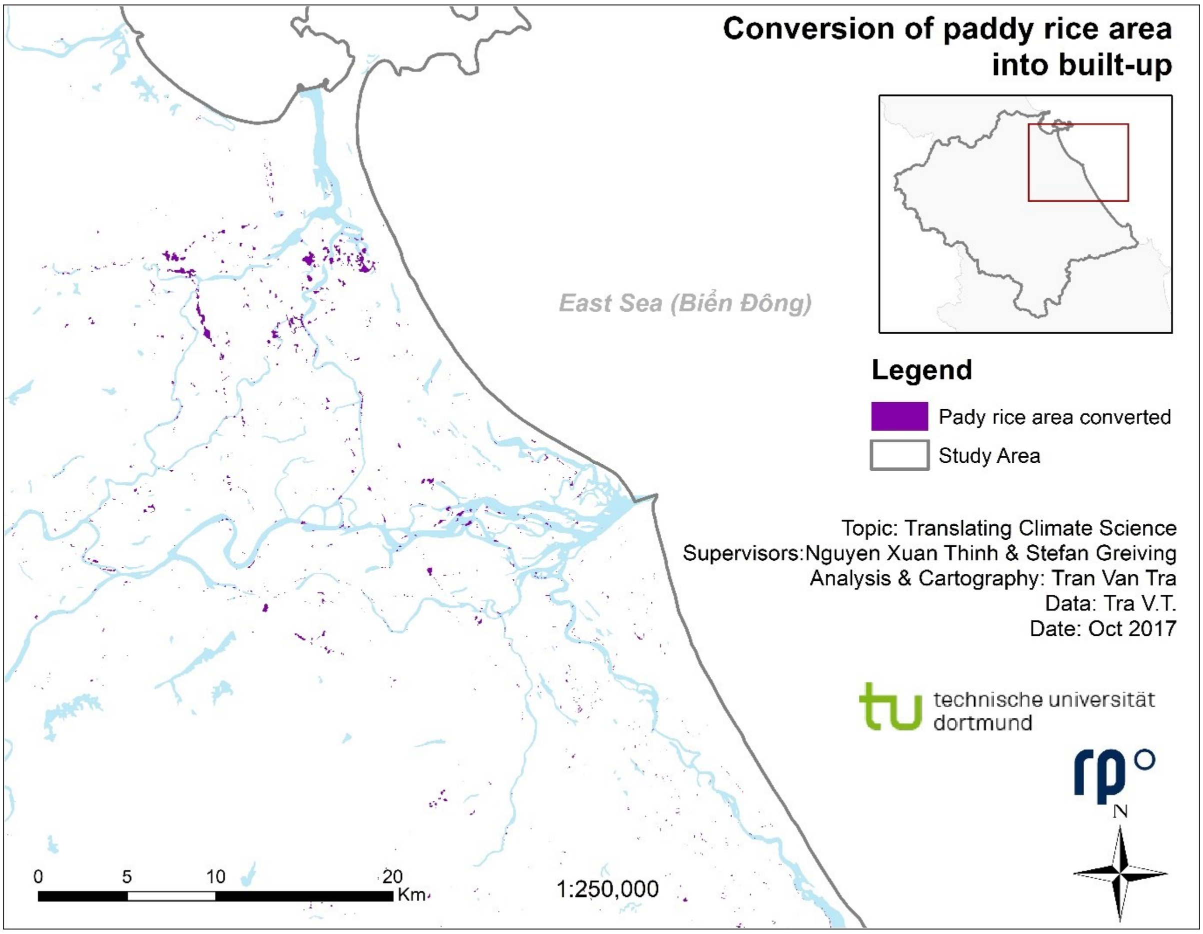

Figure 5-25: Conversion of agricultural area into built-up area

Additionally, mapping the conversion of paddy rice into built-up areas showed that the conversion took place within the Da Nang City as well as along the Da Nang- Hoi An- Tam Ky route (Figure 5-25). Given that there has been extensive development project such as the construction of the Da Nang- Hoi An- Tam Ky connecting road, it could be said that urbanization had some effect on the conversion of paddy rice area along this line.

Land cover change is justified through further analyzing socioeconomic data within the same period. In particular, 4 socioeconomic indicators are evaluated including average monthly income (million Viet Nam Dong), average population (inhabitants), gross output of economic sector (million Viet Nam Dong- VND), and gross domestic product share by economic sector (%). Data are taken from Statistical Yearbook of Quang Nam in 2011 and 2015 (Quang Nam Statistical Office, 2012, 2016). The selection of 2015 as the end period instead of 2016 is due to the nature of the statistical yearbook and land cover classification scheme. Land cover classification was performed for early 2016 while socioeconomic data in 2015 were compiled in early 2016, hence, the overlapping time period provides a better comparison basis.

Within the period of 2011-2015, average monthly income increased in both rural and urban areas in Quang Nam Province (Table 5-24). The rate of change in income is significant in both areas with income in urban area nearly doubled and income in rural area increased 1.5 times. However, increase in average monthly income of in the urban area is slightly higher than in rural area both in absolute terms (Viet Nam Dong) and relative terms (percentage). The higher income increase in urban area could provide incentives for rural population to migrate to urban areas for improved earnings.

Table 5-24: Average monthly income per capita in Quang Nam Province

	2011 million VND	**2015** million VND	**Change**
Urban	1.413	2.585	82.9%
Rural	1.179	1.862	57.9%

In fact, the migration pattern from rural to urban area could also be identified using the population data for Quang Nam Province (Table 5-25). In particular, population in urban area increased significantly by 30.7% for the time period. However, population in the rural area decreased by 3.3%. The increase in population in the urban area could be attributed to two mechanisms: increase natural birth rate and immigration.

Table 5-25: Population (inhabitants) and birth rate in the VGTB River Basin

	Population			**Birth rate**		
	2011	2015	Change	2011	2015	Change
Urban	273,072	356,845	30.7%	9.56%	9.92%	0.36%
Rural	1,161,928	1,123,945	- 3.3%	10.80%	10.79%	0.01%

Natural birth rate for urban and rural areas are shown in Table 5-25. As can be seen, natural population increase in urban area recorded a positive increase while natural population increase in rural area is stagnant. The increase in immigration could be determined by deducting the total increase in population to the increase in natural birth rate. Hence, the majority of increase in population in urban area in Quang Nam was from immigration. A small portion of the immigrant could thus be attributed to the flow of people from the rural area to urban area for better job and/or living standards. Thus, higher demand for housing in the urban area created a need for increase built-up area.

In addition, the built-up area in the river basin consist of industrial and commercial area in addition to urban housing. Thus, the increase in built-up area could also be driven by the increase in demand for industrial and commercial space in the urban areas. This could be justified through analyzing the economic output and economic share of industrial sector versus agricultural sector in Quang Nam. The underlying assumption is that built-up area increase as a result of increase in industrial activities and decrease in agricultural activities within the urban area of the river basin.

Within the same period 2011-2015, gross product in both agriculture and industry sector in Quang Nam Province increased significantly (Table 5-26). More particularly, gross product more than doubled in both sectors with a slightly higher increase in industry. The measure of gross output is in Vietnam Nam Dong.

Table 5-26: Gross output and contribution of agriculture and industry in the VGTB River Basin

	Gross output			**Contribution**		
	2011 Million VND	**2015** Million VND	**Change** %	**2011** %	**2015** %	**Change** %
Agriculture	7,829,380	17,614,624	125.0	20.7	16.4	- 4.3
Industry	28,845,598	75,044,064	160.2	40.5	43.2	2.6

However, the share of gross product in agriculture in the total economy of Quang Nam dropped slightly for the same period while share of industry increase (Table 5-26).

From Table 5-26 without being too presumptuous, one could conclude that there has been a shift within the economic structure of Quang Nam province between 2011 and 2015. As the economy rely more on industry and commerce, more land would be required for these activities. On the other hand, since the economy relies less on agriculture, land for agricultural activities could be reduced.

Through reviewing the socio-economic indicators, the conversion of agricultural area into built-up area is justified. The conversion mechanism is fueled by urbanization processes namely immigration from rural area to urban area for improved living standards, and the increased share of industry over agriculture production in the economy.

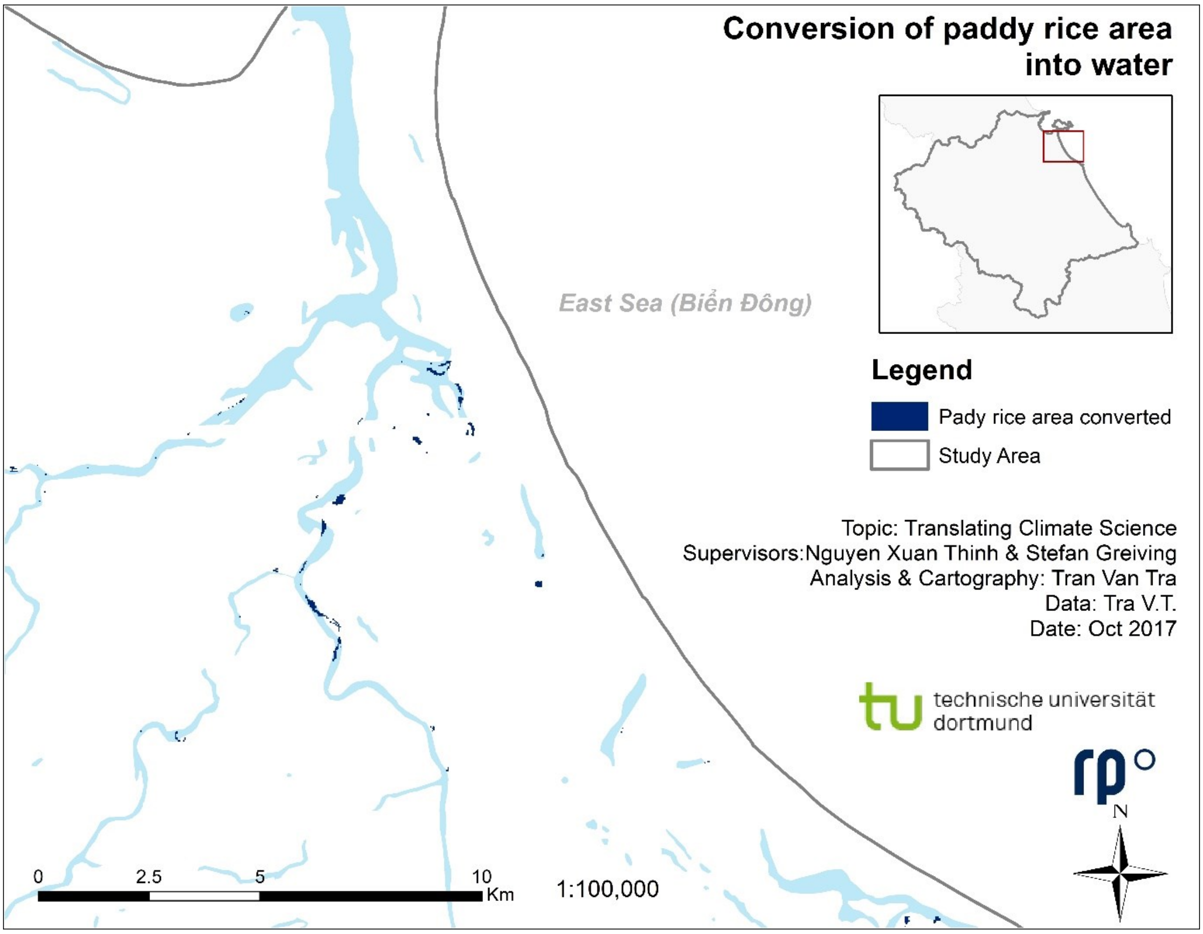

Figure 5-26: Conversion of agricultural land into water bodies

Given that the conversion of agricultural area into water bodies only occurs near river streams (example shown in Figure 5-26), the conversion of paddy rice land into water bodies can suggest two conversion mechanisms. *Firstly*, Paddy rice cultivation land close to river streams have been totally abandoned due to erosion. This suggests but only a small proportion of the conversion. The other conversion mechanism could be the conversion from cropland to aquaculture. The explanation is somewhat justifiable given the market value for aquaculture product is higher than the market value for crop, giving incentives to farmers to change their produce. In particular, shrimp prices are approximately 40 times higher than rice per kilograms (200,000 Vietnam Dong versus 5,000 Vietnam Dong) (Hanh *et al.*, 2015). In addition, there have been incentives by the Viet Nam Ministry of Agriculture and Rural Development to increase the country's agricultural export value. Thus, more cropland is being converted into fish or shrimp farms (aquaculture).

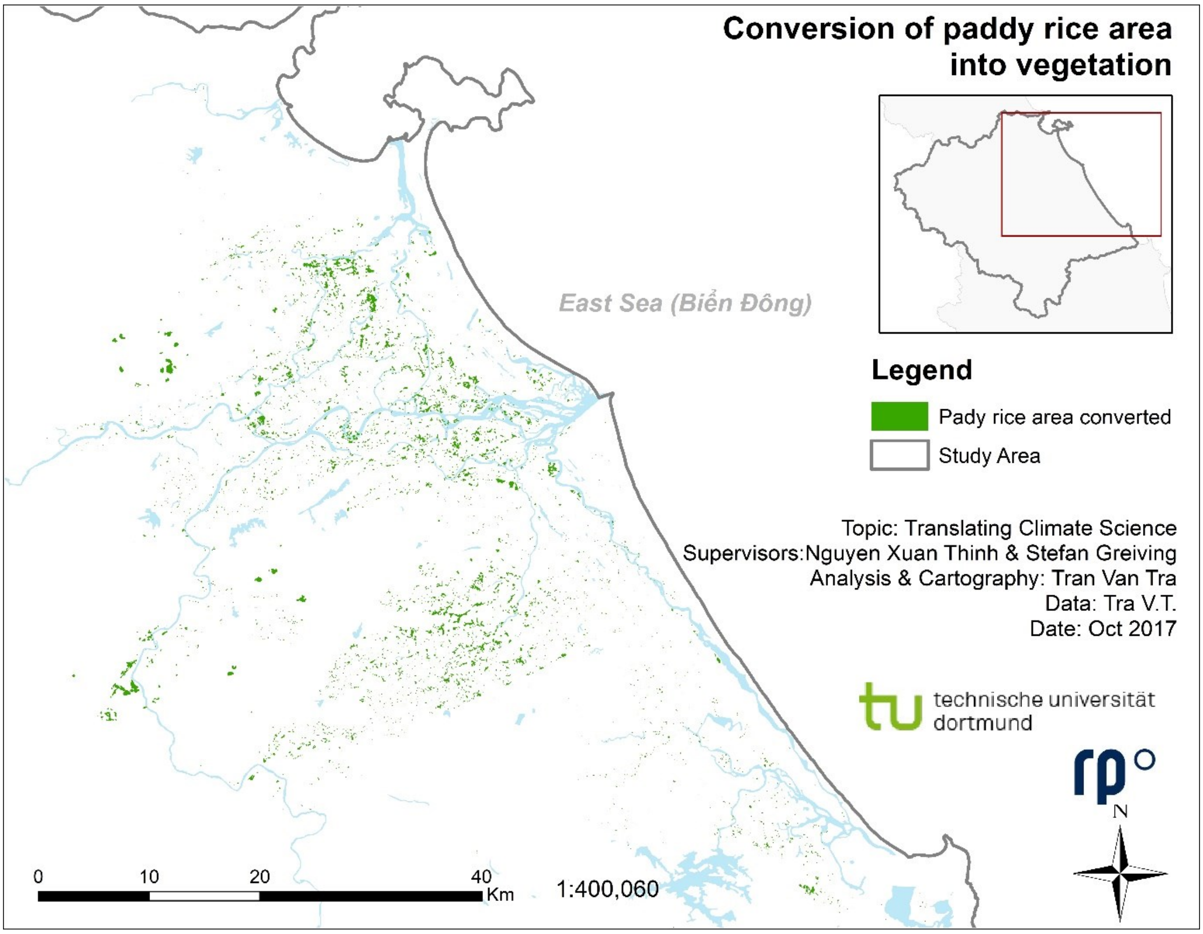

Figure 5-27: Conversion of agricultural area into vegetation

The bulk of paddy rice land conversion between 2011 and 2016 was into vegetation. Due to the setup of the classification scheme, little could be said about the type of vegetation that paddy rice cultivation land was converted into. One suggestion is that the type of crop cultivated changed from paddy to perennial crops. This is because using the classification method, these areas are green throughout the different months that was not expected by paddy rice cultivation. Hence, these areas would have been occupied by another type of vegetation other than paddy rice. The spatial distribution of the conversion of paddy rice into other types of vegetation is shown in Figure 5-27.

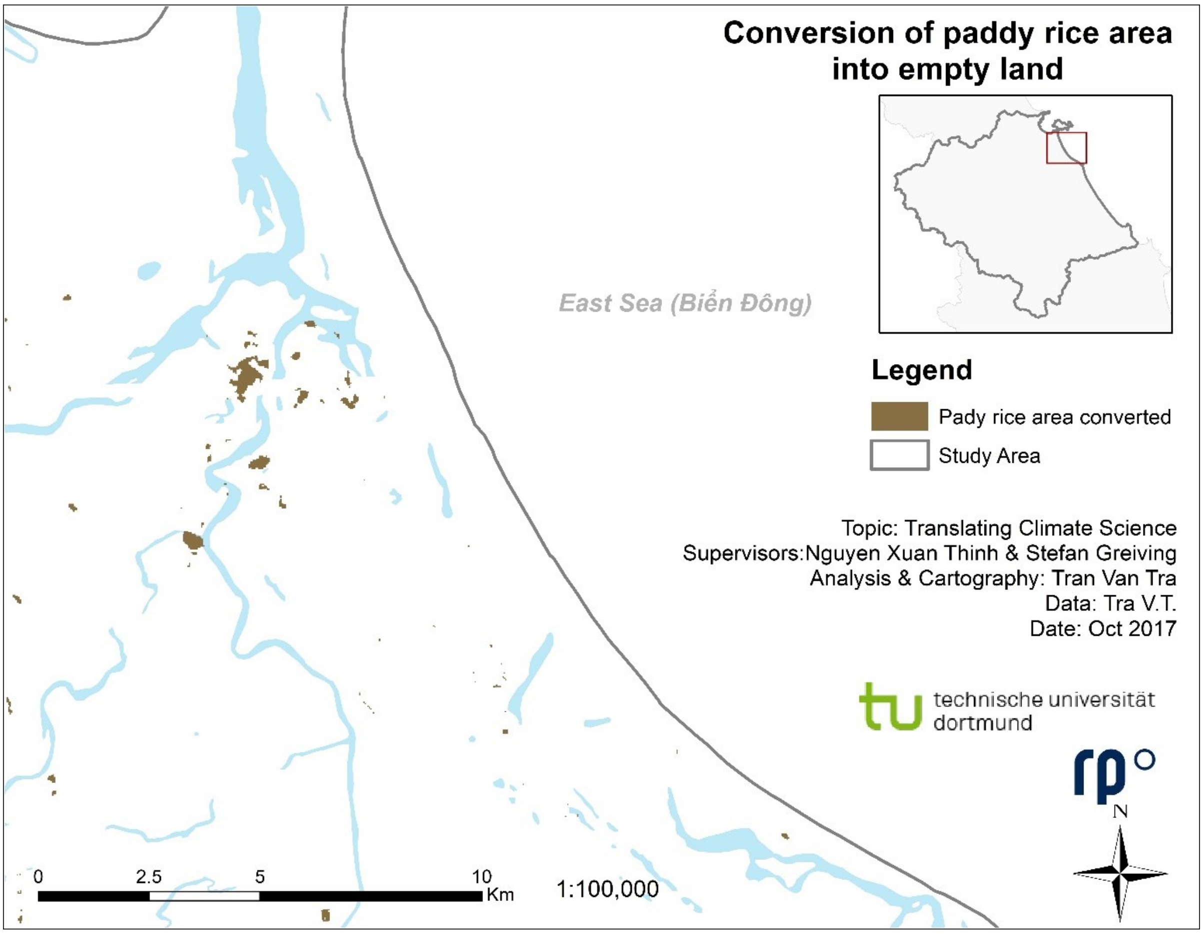

Figure 5-28: Conversion of agricultural area into empty land

The remaining of the agricultural land conversion was into empty land. All conversion took place within the city area of Da Nang. This suggest that previously cultivated area of paddy rice is now abandoned. Given the rapid urbanization pressure discussed earlier, these agricultural area would have now been converted into built-up area, however, they are still in the process of being developed at the time of the satellite image. An example of the spatial distribution of such conversion is as shown in Figure 5-28.

With the land cover change detection, a number of findings could be drawn on the issue of water usage in the river basin. *Firstly*, the conversion of paddy rice cropland into water could be presumed to be aquaculture conversion. Water usage in aquaculture constitute another major usage yet has not been explored in the study. Thus, water demand in the river basin could be higher than previously determined, imposing further challenges in the management of water resources under climate change. *Secondly*, there is a high urbanization process in the river basin. The increase in built-up area has met its initial target set in 2011 four years ahead of schedule. Increase in built-up area also implies an increase in water demand from domestic and industrial sources. *Thirdly*, conversion of rice to perennial crops could reduce agricultural water demand given rice is fairly water-intense. Little could be said about the relative reduction from this change.

5.6 Adaptation Policy Proposal

From the analysis of affected agricultural land area, there are two scenarios for adaptation. An optimistic scenario would require the adaptation for 5 irrigation nodes in the river basin, this amounts to roughly 66.36 km^2 of rice. On the other hand, a more conservative approach would be to consider all 9 irrigation nodes with up to 87.77 km^2 of rice. The optimistic approach is backed by the maximum consensus of GCM predictions and the best-case scenario. The conservative approach would be backed by the worst-case scenario provided from GCM output analysis.

An extreme option of total retreat of agriculture area affected could be considered. In effect, the agricultural area that has been determined to be facing water shortages in the future would be abandoned either completely or during the water shortage period (April to July). Under an optimistic scenario, 66.36 km^2 would be abandoned. While under a more conservative approach, all 87.77 km^2 of crop would need to be converted to other uses. The crop areas are within the boundary of four districts namely: Dai Loc, Dien Ban, Que Son, and Duy Xuyen. However, given the value of arable land, such an approach would be unjustified. In addition, with the more complex problem of the different water deficit scenarios, a more thorough analysis would provide beneficial for the study area.

A more compromise approach in dealing with affected agricultural area in the river basin needs to take into consideration of the possible water deficit in future climate conditions. As analyzed above, between 11 and 21 million m^3 of additional water is required between the months of April through to the end of July to meet water demand. Therefore, the adaptation option is limited to either conserve or reduce water usage to make up for the deficit, or to produce additional water to meet the demand. Conserve and reducing water usage is considered a soft-engineering approach while producing additional water would require hard-engineering measures.

The conservation and reduction of water usage in the river basin could be established through changes in agricultural practices. This includes changing of crop types, and changing of agricultural irrigation practices. Changing in crop types aims at choosing crops that are more adapted to climate change and use less water. Changing of irrigation practices involves using a smarter irrigation system that is more efficient.

As indicated in the land cover status change in the previous section, a majority of agricultural land conversion between 2011 and 2016 have been a conversion from paddy rice to other perennial crops. Given that paddy rice is a water intense crop, the conversion could prove to reduce water usage in the agricultural area in the river basin. The conversion of paddy rice to perennial is a non-reversible option in the short term. In particular, it may not be possible to revert back to planting rice once the land has been converted to perennial crops. This is due to the growth time of perennial crops and the additional establishment of irrigation scheme leading to a sunk cost.

Changes in agricultural irrigation practices could provide another line of adaptation. Current paddy rice irrigation techniques require the field to be flooded. However, paddy rice does not require water inundation for the entire growth period. It has been well established that not all rice growth phases require high soil moisture. There are four growth phases of paddy rice namely the germination phase, vegetative phase, reproductive phase, and ripening phase. Previous studies have shown that fields do not need to be flooded in all four phases. For the vegetation phase, field could be left out dry for 7 to 10 days. Similarly, during ripening phase, field could be left dry completely (Tuan and Dung, 2011). Through using a more efficient crop irrigation schedule, water conservation could be achieved leading to a reduced crop water demand especially during the dry season.

In theory, through reducing water demand in industrial processes and domestic uses, more water could be readily available for agriculture. However, there is a general policy geared towards further developing the industrial sector in the economy and increasing birth rate nation-wide. The resolution of the 5th plenary session of the Communist Party of Vietnam in 2017 has established the importance of industrialization. Hence, more priority will be given to the industrial sector, making any efforts to curtail water demand in industrial process contradicting the national policy. In addition, the currently revised Population Act by the Viet Nam National Assembly at its current form promotes the increase of birth rate and population increase. Hence, methods for population control to limit domestic water demand would be strictly against national policy line.

As such, only methods to improve water use efficiency and conservation in domestic and industrial demand is proposed. This includes applying the newest available water technology, providing standards and guidelines for the use of water in public spaces, and programs to increase population awareness on the importance of water conservation. Newer technologies could be applied in both domestic and industrial water users. For example, water efficient system could be used in combination with improving water delivery efficiency so that minimal water is lost in transport. The usage of water in public spaces including watering gardens, parks, and public fountains could be better manage to prevent excessive use. Land use policies could also further incorporate the design of public spaces using water in a way that promotes water saving and climate change adaptation (Schmidt-Thome and Greiving, 2013). Lastly, educational programs could be implemented to increase the general awareness of the population towards conserving water usage at home.

Aside from conservation and reduction in water use, additional water could potentially be produced in the river basin. This would include hard-engineering options such as the construction and upgrading of water supply facilities, as well as the introduction of new water producing technologies.

As previously analyzed, in order to meet the water deficit in the river basin, approximately 11 to 21 million m^3 of water would be required to meet water supply deficit during the dry season. Depending on the scenario, the amount of additional water can be different. Under a maximum consensus scenario, a conservative amount of water supply increase is 16.9 million m^3. Whereas under the worst-case scenario, the amount of additional water would be 20.9 million m^3. For this reason, additional water retention facilities could potentially be constructed to store water during the rainy season and release during the dry season.

Construction of water retention areas providing additional 11 to 21 million m^3 of water could be performed through the use of one single or multiple reservoirs. Given the problematic irrigation nodes are relative close, one single retention facility could be constructed to service these nodes. On the other hand, multiple irrigation reservoirs could be constructed to optimize irrigation for the problematic nodes. Further study would be required to determine the optimal option and detailed designs.

Additionally, measures to increase the production of water could be a substitute. As Schmidt-Thome and Greiving (2013) have analyzed for the coastal zone in Spain, new water producing technologies could also be adopted in the VGTB River Basin. This includes the construction of desalination plant, wastewater treatment plant and water reusing scheme. In this case, a minimum of 11 million m^3 would need to be produced during the months from April through to the end of July to meet water deficit. Another study to explore the size of a desalination plant and its electricity requirement as well as economic input would be required. It should be noted, however, that desalinated water would most probably serve domestic and industrial uses only given the high financial costs

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6 CONCLUSIONS

In the previous chapters, theoretical background with concepts and methods of climate change impact assessment have been described. Introduction to the VGTB River Basin and the selection justification for the study were provided. A detailed methodological framework was also used for the study area to better assess climate change impact for the VGTB River Basin. Adaptation measures to climate change in the VGTB River Basin have also been proposed. This final chapter refers back to the initially set up research objectives and determine whether they have been fully achieved. In addition, based on the results obtained, the limitation of the research and outlook are provided.

6.1 Fulfilling Research Objectives

The study has been successful in meeting the originally objectives. Through addressing the objectives, the study was able to provide answers to the research questions that were set out.

1. ***To develop a hydrological model to further understand the response of the river basin in different climate states***

The status of water shortage in the VGTB was assessed using the MIKE BASIN water balance model. The MIKE BASIN model utilizes results from the basin model, the MIKE NAM rainfall-runoff model, the CROPWAT irrigation water demand model, the domestic and industrial water demand calculation, and the reservoir model.

Simulation was performed using the MIKE BASIN model. This includes the baseline simulation of the 1986-2005 period to concur with IPCC's Fifth Assessment Report period. Two baseline run was performed including one with 8 major upstream reservoirs and one without to determine the effects of these reservoirs. The reliability measure of water user node in the model is then calculated. The result showed that major upstream reservoirs have a profound impact on reducing water shortage downstream (see section 5.3.1 and section 5.3.2)

2. ***To identify the range of possible changes in temperature and rainfall in the VGTB River Basin using GCMs and the response of the system to those changes***

The study utilizes 25 GCMs to obtain information on projected changes in rainfall and temperature in the VGTB River Basin. The choice of GCMs were based on their established use both globally and in Viet Nam. In addition, the choice of 25 GCMs were also influenced by the limitations in obtaining data and storing of the large data.

Results from 25 GCMs and their corresponding RCP scenarios were collectively analyzed for three time periods of 2016-2035 (short-term), 2046-2065 (medium-term), and 2080-2099 (long-term). This was achieved through grouping output of GCMs into projected ranges of change in rainfall and temperature. Three key cases of climate future was identified. This includes a maximum consensus scenario, a best-case scenario, and a worst-case scenario for all three time period (see section 5.4.1).

Rainfall in the VGTB River Basin is expected to remain slightly unchanged for the short-term and the long-term under the maximum consensus scenario. In particular, there is a high degree of convergence in model outputs predicting rainfall in the VGTB River Basin to fluctuate within the ±5% of baseline rainfall.

Rainfall in the long-term is expected to increase as compared to the baseline. This is evident in firstly, the number of models predicting increase in rainfall in the future and secondly, the maximum consensus of model predictions. Only a limited number of GCM outputs predict rainfall to decrease in the future.

Temperature in the VGTB River Basin is predicted to increase in the future. For all time period under consideration, a maximum consensus of GCM outputs confer to an increase of no more than 1.5 degrees Celsius. The increase in temperature under a worst-case scenario can be over 3.5^0C.

Due to climate change, the status of water shortage in the VGTB River Basin will also change. An increase in annual average temperature meant that there will be less water for cloud condensation to produce rainfall as well as there will be an increase in water demand due to evaporation and transpiration. Since rainfall projections can vary markedly between GCMs, there are projections of rainfall increase and rainfall decrease. Should rainfall decrease in the future, runoff is reduced, hence, further exacerbating dry conditions. However, should rainfall increase in the future, this might offset the increase in temperature by providing an increase of water availability.

As for the MIKE BASIN model developed for the VGTB River Basin, 9 irrigation nodes have been identified to be facing water shortages. This is equivalent to approximately 87.77 km^2 of rice distributed among four districts downstream of the VGTB River Basin. Depending on the scenarios evaluated, water shortage in the river basin could vary between 11 million m^3 and 21 million m^3 of water (refer to section 0).

3. ***To determine the potential effects of land use policy in the VGTB River Basin***

Land use policy has been evaluated in the study through the use of GIS and Remote Sensing technologies. Land cover maps for 2011 and 2016 were produced. Land cover map for 2011 represent land cover prior to the current land use master plan while land cover map for 2016 represent land cover after the current land use master plan (see section 5.5).

Land cover change detection between 2011 and 2016 showed an increase in built-up area and a decrease in paddy rice area. Built-up area in 2016 met its targeted plan four years ahead of schedule. This indicated a rapid urbanization process. Paddy rice area have also met its target in 2016. However, the conversion of paddy rice area has largely been conversion between different type of crops and to aquaculture. There have also been conversion from paddy rice into built-up area.

The increase in built-up area in the VGTB River Basin could indicate an increase in domestic and industrial water demand between 2011 and 2016. This is due to the increase in population and increase in standard of living. Urban dwellings have connection to water mains whereas rural inhabitants do not. In addition, the increase in built-up area could indicate an increase in industrial processes, thus, increase in industrial demand.

The decrease in paddy rice area is more complex. Conversion of agricultural area from mostly rice into perennial crops could reduce water demand from irrigation. Since rice has been traditionally flood-irrigated, water demand is intense. This is especially true during the dry season. The conversion of agricultural area into built- up area could also implicate a reduction in irrigation water demand since irrigation demand for paddy rice is higher than domestic water demand. The conversion of rice into aquaculture in the context of water usage, however, is inconclusive. This is due to a lack of detailed information.

4. ***To be able to utilize the best available information on climate change in the future to provide adaptation measures for policy makers***

The study has been able to identify key vulnerable climate space of the VGTB River Basin in the context of water shortage. This includes the maximum-consensus, best-case, and worst-case scenario. General recommendations for adaptation have been proposed. In that, several line of actions could be taken. This includes abandonment of affected agricultural area, adaptation using soft-engineering, and adaptation using hard-engineering (section 5.6).

The first line of action includes the total abandonment of agriculture area expected to face water shortages. This limits further actions required in the future since the problem would be solve when there is no problem in the first instance. However, given the arable value of land, such an approach is not optimum and would not be recommended unless under extremely dire situation.

Soft-engineering approaches provides a more robust adaptation strategy and is reversible. In particular, water conservation and reduction of water demand is proposed. This could be achieved through using crop variants that are more resistant to water shortages, changing irrigation practices, using more water-efficient technologies in irrigation. The conversion of paddy rice into less water demanding crop or agricultural production could also be undertaken. However, the approach is less reversible in the short-term.

Hard-engineering approaches to climate change adaptation in the VGTB River Basin seeks to address water shortages using engineering solution. This includes increasing water production in the river basin. This is achieved through constructing new water retention structures, reservoirs to store water during the rainy season and release water during the dry season. Between 11 million m^3 and 21 million m^3 of water retention is required. Additionally, the use of technology to desalinate sea water to fresh water for domestic use could also be considered. This is possible due to the vicinity of the river basin to the sea with a long coastal line. Other methods of water re-use could also be evaluated as plausible options.

6.2 Limitations of the Research

There also exist a number of limitations to the study. This includes the validity of assumptions to simplify water demand calculations, assumptions made when calculating runoff using the donor catchment method in the MIKE BASIN model, the lack of paralleled modelling, and the limitation of data.

Assumptions made in the earlier phase of water demand calculations are based on standards. This includes the calculation of industrial water demand using standard and guidelines by the Viet Nam Ministry of Construction, and the assumption that nearby catchments share the same physical properties. However, as evaluated above, the water demand calculated using industrial zone area may be invalid without considering the type of industry that is active. Likewise, the use of the donor catchment method to transfer model parameters and assume an average parameter value for Nong Son and Thanh My catchment is a common practice, yet the physical similarity between catchments may not hold true for the assumption to be performed.

No parallel modelling is performed in the study. In particular, the changes in policy and its effect on water resources management in the VGTB River Basin have not been determined. For example, with the option of constructing additional water retention facilities to meet the water supply deficit, the total effects of such reservoirs are not assessed. This is partly due to the detail of adaptation measures. In addition, variables within the research were mostly assumed to be static. That is, the effects of climate change and socio-economical changes on changes in physical properties of the river basin are not modelled. The lack of modelling of the feedback of variables within the complex system could impact the accuracy of the results.

In addition, no land change modelling is carried out. The study was limited to only current land use practice using the land use master plan for the river basin for the period 2011-2020 to extrapolate and gain information on land use changes and its effect on water usage in the river basin. This limits possible information that could be better used for policy options. Future studies could potentially incorporate Cellular Automata to simulate changes in land cover.

Although the study uses information and input from stakeholders and experts in the earlier phase, the involvement of stakeholders in the later stage of research is quite limited. Thus, no validation of the applicability of adaptation options proposed in the study were presented. This limitation is mostly due to limited time and resources.

The limitation of data including the unavailability of high resolution satellite images created a large source of uncertainty and error in the assessment of land cover. As described in section 5.5.1, given the coarse resolution of the Landsat images, land cover classification suffers from lower than expected accuracy. The use of higher resolution images such as the SPOT 7 image could potentially address this limitation.

6.3 Outlook

The study has demonstrated the usefulness of adopting a combined top-down and bottom-up approach in climate change impact assessment for VGTB River Basin. The results were able to better communicate the uncertainties related to climate change projections from GCMs to policy makers. In addition, adaptation recommendations were made to address water shortage problem in the river basin. However, there are still room for improvement in the future.

From the results obtained from the MIKE BASIN model, the analysis of GCMs, and the analysis of land use change, multiple adaptation measures were proposed. The adaptation measures provide policy makers in the river basin with a whole range of possible action path. Each action path would need to be further evaluated to determine the optimum solution. This was not performed in the study given the limited time, space, and effort. However, future study could choose the range of adaptation measures and weight them according to their respective effectiveness/value. This could provide an optimum adaptation solution.

Additionally, through addressing the limitations aforementioned in the previous section, future studies could more accurately reflect real conditions in the VGTB River Basin. This includes better estimate water demand, better implications of land use changes, and better information on the feedback of the different adaptation measures.

Finally, the results expected could be able to provide a framework for climate adaptation in other river systems in Viet Nam. Although there are certain differences between different river systems in Viet Nam such as rainy and dry season initiation period, the majority of river basins in Viet Nam faces the same challenges if not even more severe than the VGTB River Basin in the context of water shortage in a changing future climate. For this reason, being able to successfully provide a range of solutions for the VGTB River Basin in particular would then turned out to be useful for the adoption of the similar solutions in other river basins

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APPENDICES

Appendix A: List of CMIP5 models used

Modeling Center (or Group)	Institute ID	Model Name
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC)
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CESM CMCC-CM CMCC-CMS
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadGEM2-CC HadGEM2-ES
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR MPI-ESM-LR MPI-ESM-P
Meteorological Research Institute	MRI	MRI-CGCM3 MRI-ESM1
Norwegian Climate Centre	NCC	NorESM1-M

Appendix B: SWSI values for drought years

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1982	-1.2	-2.3	-3.3	-0.1	-2.9	1.9	0.6	-0.4	-0.5	-2.6	-2.7	-3.3
1983	-3.7	-3.5	-3.8	-3.7	-3.0	0.1	0.2	1.0	-0.4	0.8	1.9	-2.1
1984	-1.4	0.7	-2.1	-0.8	0.4	2.0	-0.2	-3.1	-3.9	1.4	1.1	1.4
1985	0.8	0.1	-1.7	0.7	-1.2	-1.4	-3.0	-3.5	0.0	-2.4	-1.4	-1.2
1988	-3.0	-2.0	-1.9	-1.8	-1.8	-1.1	-1.0	-0.4	-1.8	1.3	-1.0	-2.1
1993	-1.9	-1.5	-1.4	-1.5	-1.1	0.0	-1.5	-2.9	-3.6	0.0	-0.7	1.4
1998	-2.3	-2.6	-3.3	-2.3	-1.7	-0.7	-1.8	-3.7	0.4	-2.0	1.5	2.0
2001	1.5	0.6	1.0	1.8	1.9	-0.7	-1.4	0.6	-3.6	0.2	-2.9	1.7
2008	0.5	1.7	2.0	1.8	0.0	-0.6	-1.3	0.8	0.7	-0.8	0.2	-1.4
2009	0.8	1.0	0.6	0.7	1.5	1.2	2.1	-1.5	1.1	1.5	-0.7	-1.8

Appendix C: List of stakeholders and experts involved

No.	Organization/person	Role	Relevance in study area
1	Central Regional Center for Hydrology and Meteorology	Stakeholder	Hydrological- meteorology forecasting, drought warning for Quang Nam and Da Nang
2	Quang Nam Center for Hydrology and Meteorology	Stakeholder	Hydrological- meteorology forecasting, data collection, and drought warning for Quang Nam
3	Irrigation Company of Quang Nam	Stakeholder	Irrigation water supply for Quang Nam Province
4	Quang Nam Department of Agriculture and Rural Development	Stakeholder	Management of agriculture, irrigation, and disaster in Quang Nam
5	Da Nang Department of Agriculture and Rural Development	Stakeholder	Management of agriculture, irrigation, and disaster in Da Nang
6	Quang Nam Department of Natural Resources and Environment	Stakeholder	Management of natural resources (i.e. water, land use) in Quang Nam
7	Da Nang Department of Natural Resources and Environment	Stakeholder	Management of natural resources (i.e. water, land use) in Da Nang
8	Department of Water Resources Management	Stakeholder	National water resources management policies
9	Viet Nam Disaster Management Authority	Stakeholder	Management of disasters in Viet Nam (i.e. water shortages, droughts, etc.)
10	Viet Nam Institute of Meteorology, Hydrology and Climate Change	Expert	Leading research institute in Viet Nam on issues of meteorology, hydrology and climate change
11	Prof. Dr. Nguyen The Hung	Stakeholder, Expert	Local resident of Da Nang, experienced in climate change research in the area
12	Dr. Trinh Quoc Viet	Stakeholder, Expert	Local resident of Quang Nam, experienced in climate change research in VGTB
13	Mr. Duong Anh Diep	Stakeholder, Expert	Local resident of Da Nang, technical expert in the area
14	Mrs. Tran Thi Ha Van	Stakeholder, Expert	Local resident of Da Nang, familiar with research topic and area

EIDESSTATTLICHE VERSICHERUNG

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertationsschrift zum Thema

“Translating Climate Science into Policy Making in the Water Sector for the Vu Gia-Thu Bon River Basin”

selbstständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Quellen entnommen wurden, habe ich als solche gekennzeichnet. Des Weiteren erkläre ich an Eides statt, dass diese Arbeit weder in gleicher noch in ähnlicher Fassung einer akademischen Prüfung vorgelegt wurde.

Dortmund, 07.03.2018 Tran, Tra Van