Assessment of climate change impacts on surface water resources in the Vu Gia-Thu Bon catchment

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Declaration

I, Pham Phuoc Toan, a Master Student of Sustainability in the School of Law, University of New England, certify that this thesis is my own work. The thesis, either in whole or part, has not already been or currently being submitted for degree at this or any other institution or university. I was assisted in this thesis by my supervisor, Dr Neil Dunstan (University of New England) and Dr Sarah Mika who improved my English. In addition, I have used some data from my colleagues and my friends to complete the thesis.

Abstract

Climate change and current hydropower development are expected to influence surface water resources in the Vu Gia-Thu Bon River catchment. By the end of the 21st century, temperature and rainfall are projected to increase by 2.6°C and 4.3%, respectively in the river basin. There are up to 44 hydropower projects planned for development in the catchment (total catchment area of 10.350km^2). Most noteworthy is the Dak Mi 4 hydropower plant, one of ten cascade hydropower plants (out of 44 projects), as it diverts water from the Vu Gia River into the Thu Bon River. Consequently, this plant is asked to return water from its reservoir to the Vu Gia River to satisfy downstream water demands in the Vu Gia River. However, the amount of water needed is disputed between either 8m^3/s or 25m^3/s.

My thesis examines the impacts of different climate change scenarios and hydropower development scenarios on surface water resources in the Vu Gia-Thu Bon river basin. Using Water Evaluation and Planning (WEAP), developed by the Stockholm Institute, I appraised eight variables including water availability, streamflow, catchment evapotranspiration (ET potential), catchment actual evapotranspiration (ET Actual), reservoir evaporation, runoff flow, hydropower generation and reservoir storage volume.

Acknowledgement

I would like to thank the Australian Government, who provided me with financial sponsorship for my Master’s degree through the Australian Scholarships for Development in Viet Nam. I hope to use this knowledge to contribute to the sustainable development process in my province.

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Chapter 1: Introduction

1.1 Introduction to water resources management

Recent decades have witnessed a crucial change in water resources management in many countries around the world. Many countries have shifted away from the traditional focus on water balance to a new concept of Integrated Water Resources Management (IWRM). As defined by the Global Water Partnership, IWRM is the process of developing and managing water resources including land, in a co-ordinated approach to enhance equitable economic and social well-being while securing the integrity of key ecosystems (Biswas 2008, Liu et al. 2013).

Viet Nam has reached two milestones in water resources management. Before 2006, the Government considered water resources as natural resources in general. The responsibility of water resources management was assigned to the Ministry of Industry and then the Ministry of Agriculture and Rural Development. The role of the two central agencies was the investigation of water resources and irrigation planning, respectively. In 2002, water resources management was transferred to the Ministry of Natural Resources and Environment. Institutionally, the outcomes of this period are the approval of the *Law on Water Resources in 1998* and the *Decree of 179/1999/ND-CP on Implementation of the Law on Water Resources 1998*. However, water resources were still traditionally managed.

The concept of IWRM has been employed since 2006 with the establishment of the *National Strategy on Water Resources to 2020*. The concept was consolidated by the approval of the *Decree 120/2006/ND-CP on River Basin Management* that adopted the principle of unified water resources management in river basins without administrative or upstream - downstream division. Additionally, the *Law on Water Resources in 2012* dictates that the management of water resources be based on river basins and water resources in combination with administrative boundaries. Therefore, water resources governance in Viet Nam has evolved from sectoral to multi-sectoral or IWRM approach over the last eight years.

However, IWRM is notoriously difficult to implement (Giordano and Shah 2014). In the Vu Gia-Thu Bon river basin in central Viet Nam, several factors are likely to impede IWRM. Some water-related projects have been implemented with funding from international organisations and the central or provincial governments. For example, the roadmap of Vu Gia-Thu Bon river basin for water-related investment was developed in 2011 by the Department of Natural Resources and Environment of Quang Nam province under the technical and financial support of the Asian Development Bank. The roadmap identifies some fast-track and high-impact projects for future investment in the IWRM approach (Department of Natural Resources and Environment 2011). The roadmap was derived from consultative workshops of stakeholders.

However, there are two key limitations in water resources governance in the Vu Gia-Thu Bon basin. Firstly, we lack an effective tool to manage the water system at the watershed scale. Such a tool would assist decision-making on water allocation, water protection and the prevention of and response to water-related disasters. Through scenario testing, this would require large datasets, including water availability, demand, supply and quality as well as information on the frequency, magnitude and context of historical water-related disasters. Secondly, current water resources management does not account for climate change despite predictions of severe impacts of climate change on water resources in many regions (IPCC 2007). The evidence for climate change in the watershed is showed in Section 3.2 of this thesis, specifically as it relates to rainfall and temperature.

The aim of my research is to resolve these limitations to water resources governance in the Vu Gia-Thu Bon river basin. I used the Water Evaluation and Planning model (WEAP), developed by the Stockholm Institute to test climate change impacts on surface water resources under four climate scenarios and two hydropower development scenarios in the Vu Gia-Thu Bon river basin. As a member of the staff of the Department of Natural Resources and Environment in Quang Nam province, I expect that the outcomes from my thesis will be expanded and applied on the ground.

1.2 Background information for the Vu Gia-Thu Bon river basin

The Vu Gia-Thu Bon river basin is located in the centre of Viet Nam (see Figure 1-1). This is one of the nine largest river basins of Viet Nam (larger than 10,000km^2) with an area of approximately 10,350km^2. Upstream reaches comprise a small part of Kon Tum province while downstream reaches comprise the majority of Quang Nam province and Da Nang city. The basin occupies 17 municipals and districts, including Dak Glei district (Kon Tum), North Tra My, South Tra My, Tien Phuoc, Phuoc Son, Dong Giang, Tay Giang, Nam Giang, Nong Son, Duy Xuyen, Dai Loc, Dien Ban and Thang Binh district (Quang Nam) and Da Nang municipal and Hoa Vang district (Da Nang city).

Figure 1-1 Vu Gia Thu Bon river basin location (reproduced from Department of Natural Resources and Environment of Quang Nam province 2011).

Crucial contributions to the economy of the catchment come from agriculture and forestry, industry (mining and manufacturing), and services. The last decade has witnessed rapid economic development in the basin with an increase in annual GDP of 11.6%, compared to 7.2% for the rest of the country (Ministry of Planning and Investment 2010). However, the economy in the basin started at a very low point. Population growth in conjunction with increasing water demands for economic development has increased pressure on water resources.

Recently, according to ICEM (2008), the Ministry of Industry and Trade (MOIT) and Provincial Government of Quang Nam have approved eight large (more than 30Mw), and 38 small (less than 10Mw) and medium (10 - 30Mw) hydropower plants, respectively. Approval from MOIT has been requested for another 11 projects. These plants were later revised in a pilot project named *Strategic Environment Assessment of the Quang Nam province Hydropower Plan for the Vu Gia-Thu Bon River Basin* and the number of hydropower projects were reduced to 43, including ten large, and 33 medium and small plants (Provincial People Committe of Quang Nam 2011). Numerous hydropower projects and climate change impacts are likely to increase the challenges of managing water resources in the basin in terms of water availability, quality, water demand and supply, as well as water-related disasters.

1.3 Natural characteristics of the Vu Gia-Thu Bon river basin

1.3.1 Climate conditions

Located in the centre of Viet Nam, the Vu Gia-Thu Bon catchment is characterised by a tropical monsoon climate (Malano et al. 1999). Average annual sunny hours range from less than 1,800 hours in mountainous areas to 2,260 hours in the plain areas such as Da Nang (Department of Water Resources Management 2010). Monthly hours of sunshine range from under 150 hours in winter to 200-255 hours in summer. December has the lowest average monthly hours of sunshine while July has the highest rate. Table 1-1 shows the monthly and annual average total sunshine hours in Da Nang, Tam Ky and Tra My stations.

Table 1-1 Monthly average sunshine hours in the catchment (Department of Water Resources Management 2010).

Station	**Monthly average sunshine (hours)**												**Annually**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Da Nang	141.5	140.7	187.7	208.3	243.9	239.2	255.0	218.9	177.2	146.9	121.4	103.3	2,200.6
Tam Ky	138.6	151.9	211.4	223.5	257.8	235.8	254.0	230.3	197.2	157.0	109.0	88.9	2,255.4
Tra My	114.8	136.9	190.6	196.2	213.5	193.2	209.4	197.5	156.5	121.4	76.0	64.2	1,874.0

Annual average temperature varies from 24-26^{0}C (Department of Water Resources Management 2010). There is a tendency for temperature to be higher in the coastal plains compared to mountainous regions. Air temperature varies seasonally. Monthly average temperature fluctuates from 25 to 30^{0}C, with the highest temperature in June or July (above 29^{0}C) and the lowest average temperature in January. Mean annual humidity is about 80 to 90%, high in winter and spring (September to April) but low in late summer and early autumn (May to August). The lowest humidity occurs in May, approximately 40%. Table 1-2 presents the monthly and annual average temperature and humidity in three stations, namely Da Nang, Tam Ky and Tra My.

Table 1-2 Average monthly and annual temperature and humidity in the Vu Gia-Thu Bon river basin (Department of Water Resources Management 2010).

Station	Monthly average temperature (^0C)												Annually
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Da Nang	21.4	22.3	24.1	26.4	28.3	29.3	29.3	28.9	27.5	25.9	24.1	22.1	25.8
Tam Ky	21.4	22.6	24.4	26.7	28.1	28.8	28.9	28.6	27.2	25.5	23.8	21.7	22.6
Tra My	20.6	22.0	24.1	26.1	26.8	26.9	26.9	26.9	25.7	24.2	22.4	20.6	24.4
	Monthly average humidity (%)												
Da Nang	84	84	83	83	79	76	75	77	82	84	85	84	81
Tam Ky	87	87	84	82	79	77	76	77	83	86	88	88	83
Tra My	89	87	84	82	84	84	84	84	88	90	93	92	87

Mean wind speed varies from 0.8 m/s (in Tra My station) to 1.8 m/s (in Tam Ky station). Two main wind seasons dominate the catchment, namely the southwest monsoon with a frequency of 20 to 30% hot and dry air from May to July, and the northeast monsoon carrying cold air prevails from November to February (Department of Water Resources Management 2010). Maximum wind speed may reach 15-25m/s in winter, 20 - 35m/s in summer or even 40 m/sand caused by storms. Table 1-3 exhibits the monthly and annual average wind speed in Da Nang, Tam Ky and Tra My stations.

Table 1-3 Monthly average wind speed in the Vu Gia-Thu Bon watershed (Department of Water Resources Management 2010).

Station	Monthly average wind speed (m/s)												Annually
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Da Nang	1.5	1.8	1.9	1.7	1.6	1.2	1.3	1.2	1.4	1.7	2.1	1.6	1.6
Tam Ky	1.5	1.5	1.7	1.8	1.9	1.9	1.8	1.8	1.8	1.9	2.4	1.8	1.8
Tra My	0.8	1.0	1.0	0.9	0.8	0.8	0.7	0.7	0.7	0.8	0.7	0.6	0.8

Potential evaporation varies from approximately 1,000mm/year in high mountainous areas to 1,500mm/year in the coastal region (Department of Water Resources Management 2010). Monthly potential evaporation is about 120-130mm in the mountains and 150-160mm in the lowland plains in summer and autumn (March to October, highest in May). Potential evaporation in winter and spring is appropriately 50-100 mm, with the lowest rate in December of 50-70mm. The average monthly and annual evaporation in the river basin are presented in Table 1-4.

Table 1-4 Monthly average evaporation in Da Nang, Tam Ky and Tra My station (Department of Water Resources Management 2010).

Station	**Monthly average evaporation (mm)**												**Annually**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Da Nang	80.7	86.7	121.0	134.9	155.5	152.3	158.6	151.5	126.8	107.9	91.0	73.0	1,439.8
Tam Ky	77.0	86.8	126.1	140.1	160.5	155.8	163.5	157.5	134.0	106.4	82.6	71.4	1,461.6
Tra My	62.0	74.4	107.6	119.0	128.0	119.7	124.0	121.7	102.5	83.4	59.0	51.3	1,152.5

Annual average rainfall is approximately 2,612mm (Department of Water Resources Management 2010). Rainfall in September through to December accounts for 70-75% of the annual total. Precipitation tends to increase from the north to the south and from low to high regions. For example, annual precipitation in Tra My, Nong Son, and Thanh My stations (north to south direction) decreases from 4,066 mm to 2,895 mm and 2,239 mm, respectively; in low to high elevations. Da Nang and Giao Thuy stations have annual average rainfall of 2,236mm and 2,452mm correspondingly, with 2,895mm for Nong Son. Average monthly and annual precipitation for Da Nang, Tam Ky and Tra My stations are shown in Table 1-5.

Table 1-5 Monthly average precipitations in the Vu Gia-Thu Bon watershed (Department of Water Resources Management 2010).

Station	Monthly average precipitation (mm)												Annually
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Da Nang	76.2	24.6	19.3	28.9	84.2	90.9	89.9	110.9	320.0	641.2	413.5	189.2	2,088.7
Tam Ky	115.4	46.3	41.2	50.2	97.3	100.2	72.4	89.3	344.5	691.1	616.3	364.7	2,629.0
Tra My	119.1	61.6	58.5	93.4	271.5	233.3	175.8	185.2	405.8	944.7	977.3	440.8	3,967.0

1.3.2 Topography

The catchment originates from the Ngoc Linh Mountain (Kon Tum province) with an elevation of 2,598m, belonging to the Greater Annamites (Loan et al., 2010). Most of the catchment occupies Quang Nam province and Da Nang city in downstream reaches. Elevation gradually decreases from the west to the east (Figure 1-2), but the topography of the catchment is complicated and comprises several district regions.

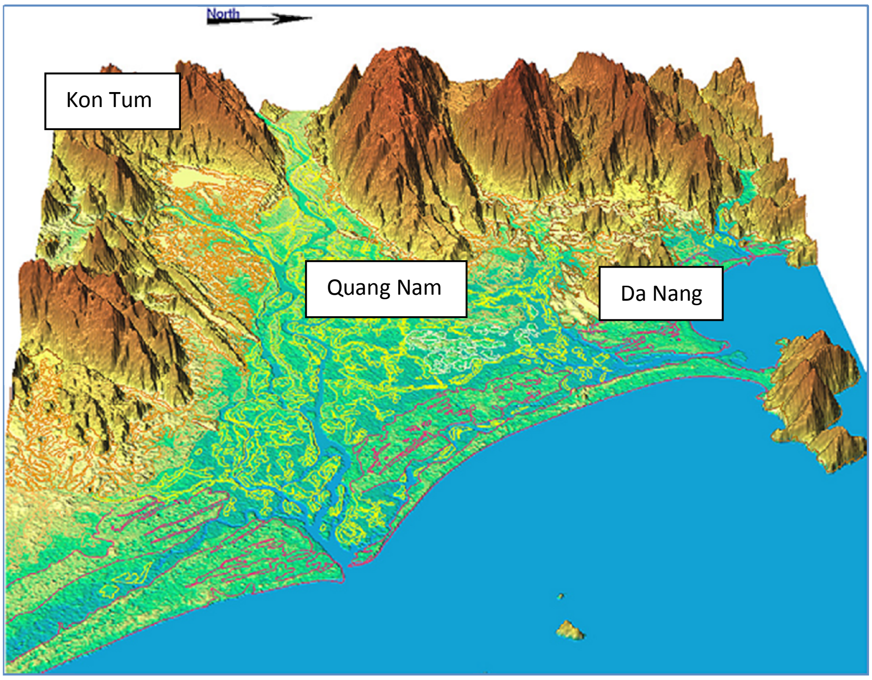

Figure 1-2 Vu Gia-Thu Bon river basin topography (reproduced from Loan and Umitsu 2011).

The four distinct topographic types comprise mountainous areas, hill-slopes, the lowland plain and the coastal zone. The mountainous area dominates the river basin. The Greater Annamites range from 500m to 2,000m above the sea level (for example Glelang 1,865m, Mang 1,708m, Tion 2,032m, and Lum Heo 2,045m). The boundary of the catchment is the Hai Van range (approximately 1,700m above the sea level) in the north and the Greater Annamites in the west and south. The hill-slopes region extends from the eastern side of the Greater Annamites. Hill-slope elevations gradually decrease from the west to the east. The small lowland plain consists of a narrow zone in the east of watershed that stretches north-south. Finally, the coastal zone comprises sand dunes (6 - 8m in height) and sand strips. The sand strips may extend to a hundred kilometres along the coast in the east.

1.3.3 Soil cover and land cover

Soil structure in the basin is also complex. Soil is locally formed and red-yellow soil, grey soil and humus accounts for approximately 81 - 85% of the basin area. The catchment also contains metamorphic schist with rich silica, and magmatic acid rock with rich quartz in the eastern side of the Greater Annamites. The mechanical components of soil range from mild to moderate in scale. The capacity to storage moisture is limited (LUCCi 2010).

Land cover in the catchment is also diverse (LUCCi 2010). Most of the eastern coastline is intensively cultivated with urban areas comprising 8.2% (LUCCi 2010). The western and southern parts of the basin are dominated by dense forest (22.7% of the watershed area). Song Thanh and Ngoc Linh Nature Reserves are located in the centre of the catchment. Forest lands are decreasing from the west to the east of the catchment as they are replaced by agricultural land (Figure 1-3).

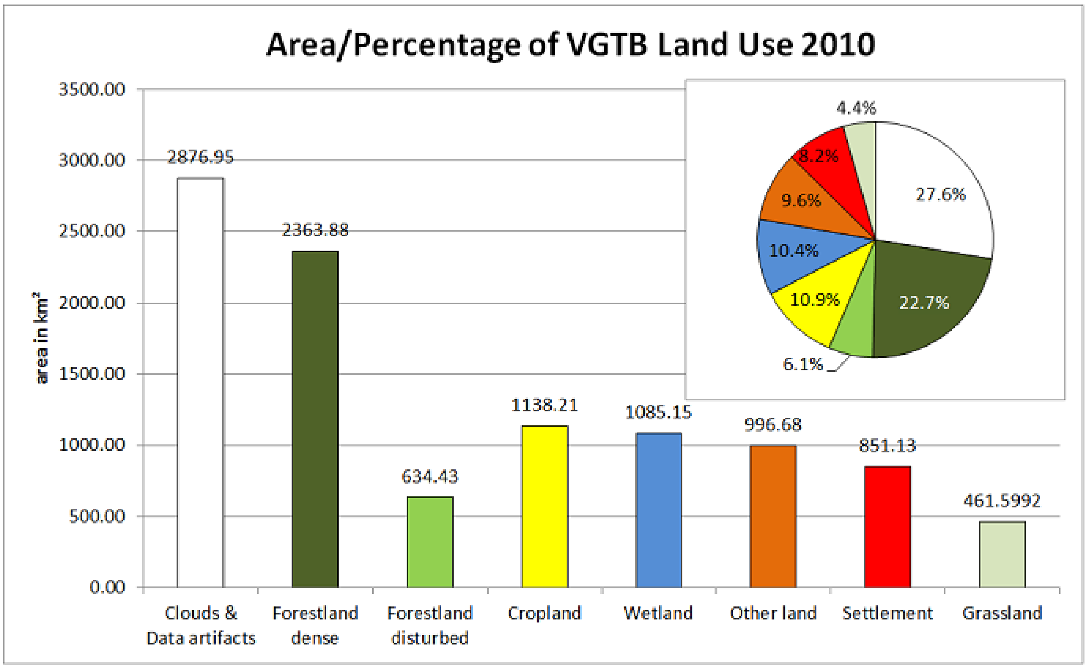

Figure 1-3 Land use by area (km^2) and percentage (inset pie chart) in the Vu Gia-Thu Bon catchment (reproduced from LUCCi 2010).

1.3.4 River network

Because of the topography of the catchment, rivers are short with high gradients, narrow valleys and steep riverbanks. In general, the river system consists of two main rivers - the Vu Gia and Thu Bon (Figure 1-4). These rivers comprise many tributaries. The Vu Gia River in the north of the basin is approximately 204km long and comprises Dak Mi (or Cai River), Song Bung, A Vuong, Con and Vu Gia rivers. Upstream reaches run southwest-northeast while mid reaches run west-east before returning southwest-northeast in estuarine reaches.

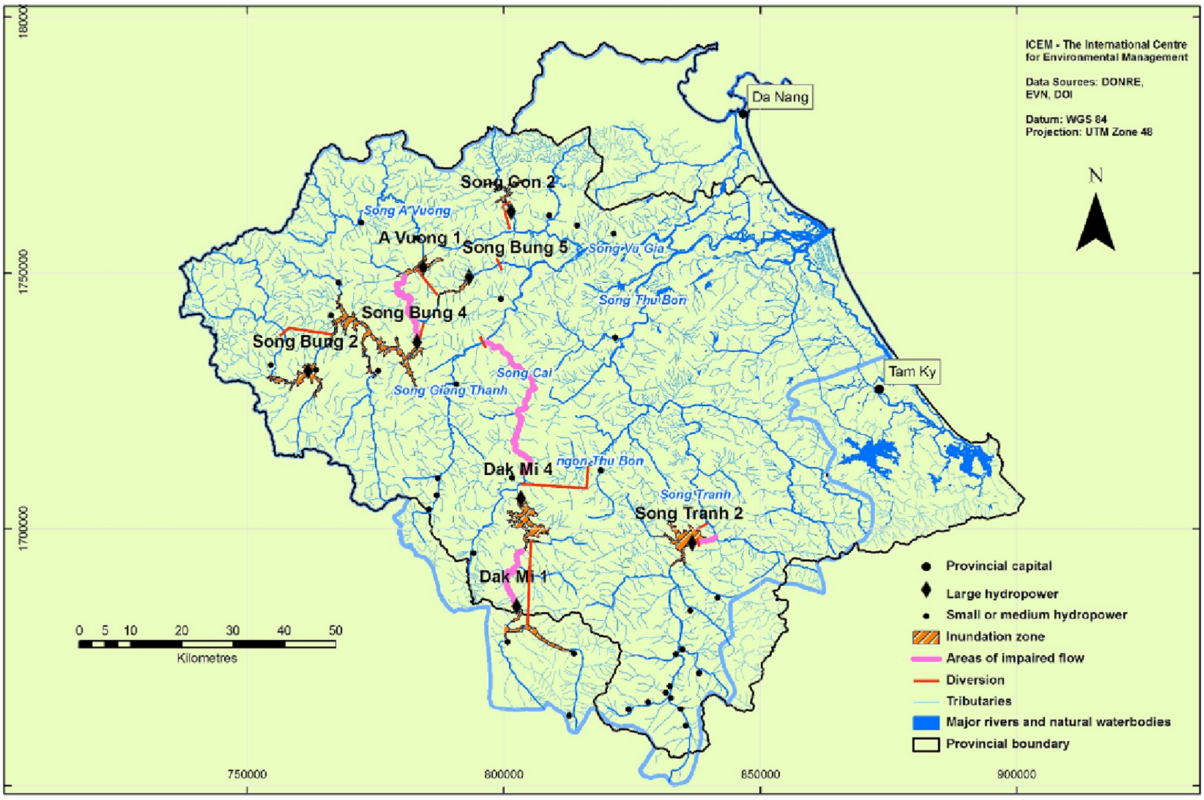

Figure 1-4 River network and hydropower development in the Vu Gia-Thu Bon catchment (reproduced from ICEM 2008).

Meanwhile, Tranh, Khang and Truong Rivers flow into the upper Thu Bon River. Ba Ren, Thanh Quyt, La Tho and Co Ca Rivers flow into the lower Thu Bon River. The Thu Bon River flows north-south before changing to a southwest-northeast direction and then west-east where it enters the Thu Bon alluvial plain and finally flows into the East Sea. The Vu Gia and Thu Bon Rivers enter the sea at Han (Da Nang) and Dai (Hoi An) estuaries, respectively. Naturally, two main river systems interact in Quang Hue River (Dai Loc district in the mid-catchment) and Vinh Dien River (Dien Ban district in the lower catchment). Additionally, water is diverted from the upper Vu Gia River to the Thu Bon River for the development of the Dak Mi 4 hydropower station.

1.4 Hydro-meteorological stations network

The network of hydro-meteorological stations is generally sparse. The data collected from these stations were recorded during the early twentieth century but were interrupted by the war. After the war (1975), observations were measured and stored systematically. Therefore, the post-war hydro-meteorological data are reliable for forecasting and predicting in hydrological models. The hydro-meteorological network is summarised in Table 1-6 and Figure 1-5. In this table, Q, H, ρ, X, T, U, Z and V represent discharge, water level, alluvium, rainfall, temperature, moisture content, evaporation and wind speed, respectively.

Table 1-6 The hydro-meteorological network in the Vu Gia-Thu Bon river basin (Department of Water Resources Management 2010).

No	Name	Location		River	Catchment (km^2)	Observed factors
		Latitude X	Longitude Y			
1	Thanh My	107.83	15.77	Vu Gia	1,850	Q, H, ρ, X
2	Nong Son	108.03	15.70	Thu Bon	3,150	Q, H, ρ, X
3	Da Nang	108.18	16.03			X, T, U, Z, V
4	Tra My	108.28	15.34			X, T, U, Z, V
5	Hoi An	108.33	15.88			X
6	Giao Thuy	108.14	15.84	Thu Bon		X, H
7	Cao Lau	108.27	15.86	Thu Bon		X, H
8	Tien Phuoc	108.30	15.47			X
9	Cam Le	108.20	16.01	Vu Gia		X, H
10	Ai Nghia	108.11	15.88	Vu Gia		X
11	Thang Binh	108.35	15.74			X
12	Hien	107.64	15.93			X
13	Que Son	108.10	15.70			X
14	Kham Duc	107.83	15.45			X
15	Phuoc Son					X
16	Hoi Khach	107.91	15.82			X
17	Tam Ky	108.46	15.57			X
18	Hiep Duc	108.10	15.58			X

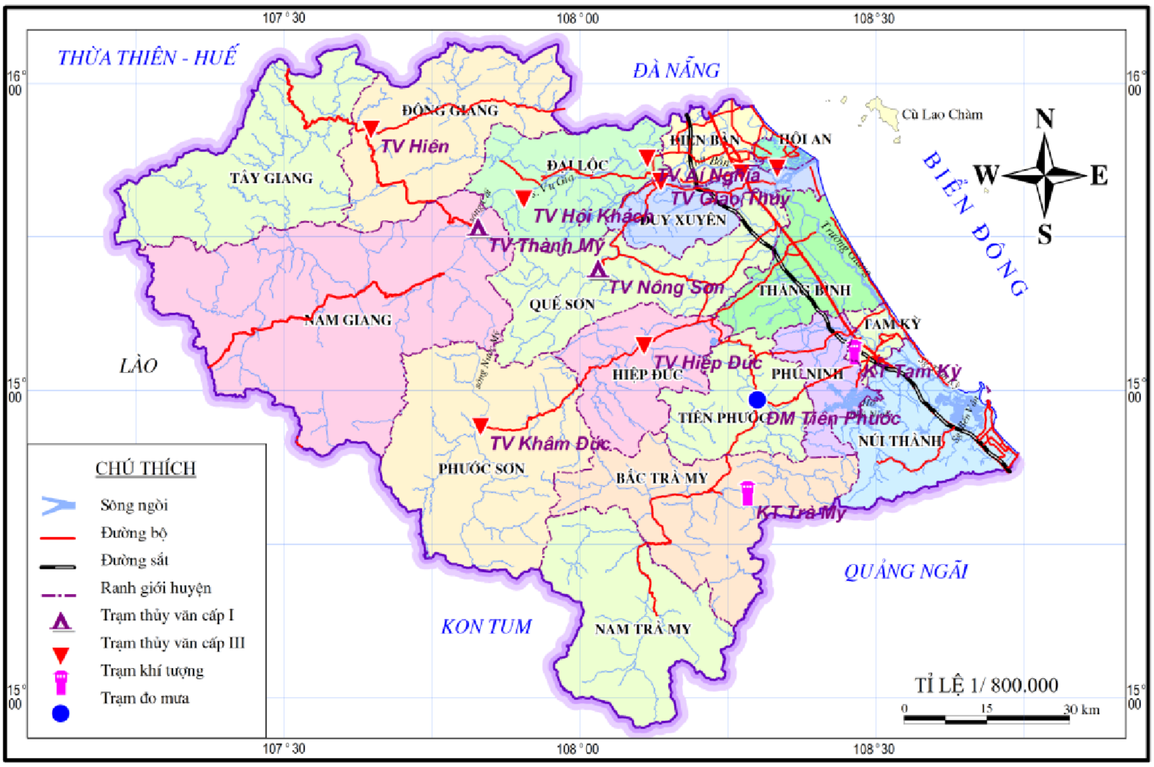

Figure 1-5 Map for Hydro-meteorological stations in Quang Nam province (reproduced from The Quang Nam Centre for Hydrometeorological Forecasting 2006).

1.5 Objectives and methodology

1.5.1 Objectives

I intend to assess the impacts of climate change scenarios on water resources (focusing on surface water resources) with the combination of socio-economic development scenarios in the Vu Gia-Thu Bon river basin in Viet Nam. My research provides an effective information system on water resources in the catchment to enhance the practice of integrated water resources management. It also develops a water management tool using WEAP model for water resources management in the Vu Gia-Thu Bon basin.

1.5.2 Methodology

This thesis combines a number of methods. Descriptions are given below:

Data gathering

Data for the thesis were gathered from many sources in many forms. Digital maps and government reports were collected during the time I worked for the Quang Nam provincial Department of Natural and Resources. I also used reports, digital maps and hydro-meteorological data from the Federal Ministry of Education and Research of Germany from their project examining land use and climate change interactions in Central Vietnam. The hydro-meteorological data I collected here comprises temperature (3 stations), precipitation (18 stations) and streamflow (2 stations).

Data processing

Data processing was the most essential step. This step was necessary to reject inappropriate data due to missing values and to convert digital maps from .jpeg (picture) or .tab (Mapinfo files) into ArcView (by ESRI - Environmental Systems Research Institute) shape files (.shp files) for input to the WEAP model to create climate scenarios. Processing the data revealed that precipitation records from 13 observation stations were suitable for modelling. Some data from these stations could not be used due to missing values from 1980-1999. Raster maps were converted into vector form. Vector maps were converted from the Universal Transverse Mercator coordinate system (.tab files) to longitudes and latitudes for input to WEAP.

Creating scenarios for WEAP

In order to generate climate scenarios, I used data from 13 stations for precipitation and 3 stations for temperature. The baseline period was 1980 to 1999. Three climate change scenarios were tested (1) increased temperature and unchanged rainfall, (2) unchanged temperature and increased rainfall, and (3) increased temperature and increased rainfall.

To identify climate conditions in terms of temperature and precipitation for the baseline period, I separated stations into two regional groups, namely lowland plain (alluvial plan and coastal zones) and upland (mountain and hill-slope regions). The weighted mean method was used to calculate monthly average temperature and precipitation for the catchment (Shaw 1994). This method multiplies temperature and precipitation in each gauge by the area covered by this gauge, and then divides the sum of all values by the total area of the catchment. Finally, climate change scenarios used the baseline climate data and predicted alteration in climate parameters in the Medium Climate change scenario developed by the Ministry of Natural Resources and Environment (Ministry of Natural Resources and Environment 2009, 2012).

WEAP outputs

This stage consists of three main steps, namely creating objects, entering data and running the WEAP scenarios. Objects such as catchments, rivers, reservoirs, diversions, hydro-meteorological stations and demand sites had to be created consistent with WEAP definitions. For instance, some tributaries that were diverted to other rivers are considered as diversions in WEAP.

In order to ensure the identified water allocation in WEAP, water demand priority for demand sites must be established in the system. Demand priority is applied to satisfy demand sites in appropriate orders, normally from 1 to 99. If there are multiple objects with the same priority, WEAP will allocate water to an equal level as percentage of demand.

Catchments are simulated in this study by the Soil Moisture Method, which is the most complicated of the four methods of Irrigation Demand Only, the Rainfall Runoff, the Soil Moisture Method and MABIA Method (Stockholm Environment Institute 2011). Using the Soil Moisture Method, catchments are represented by two soil layers. In catchments, changes in land use and soil type impact the processes of surface runoff, sub-surface runoff, evapotranspiration, and deep percolation for a watershed unit. The Soil Moisture Method is illustrated in Figure 1-6.

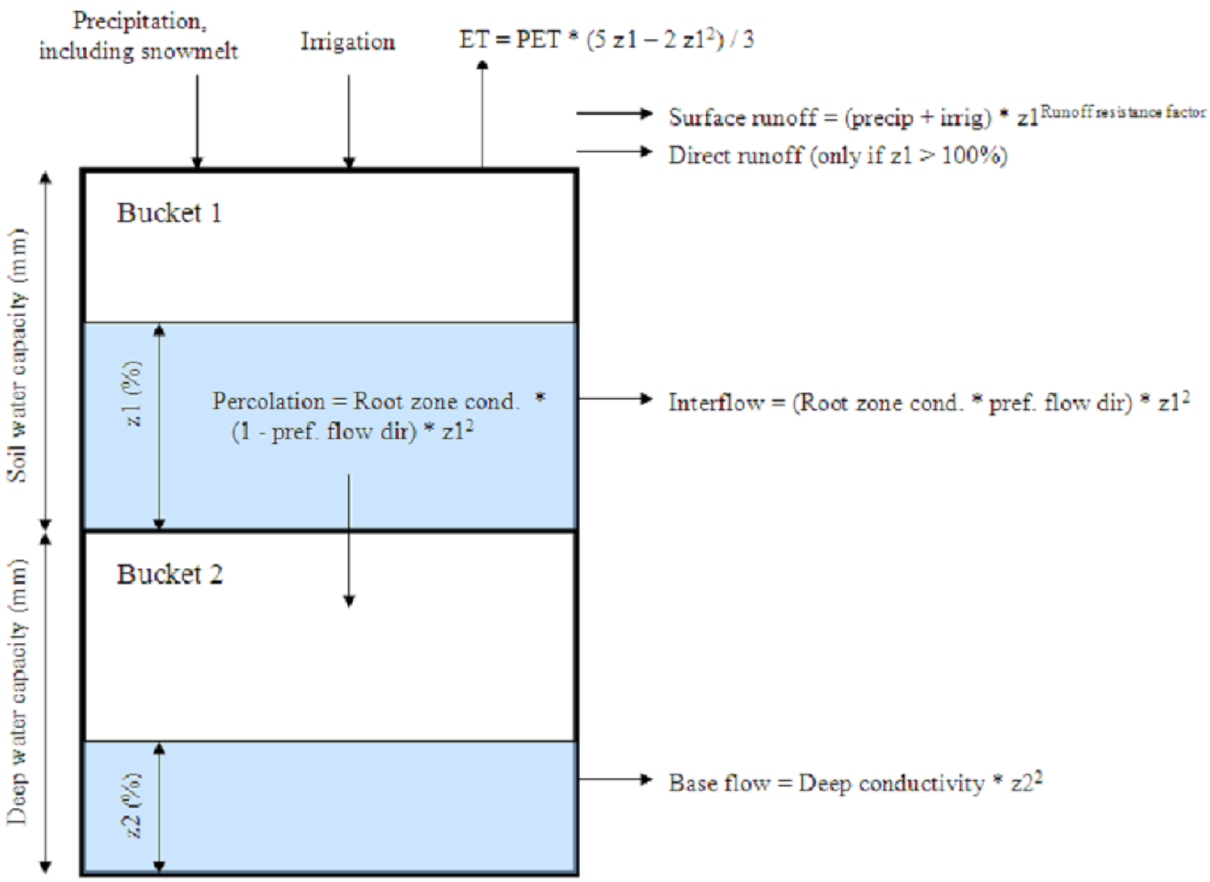

Figure 1-6 Conceptual Model of the Soil Moisture Method (reproduced from Stockholm Environment Institute 2011).

Different land uses and soil types in the watershed are represented by *N* fractional areas. The water balance for each fraction is computed as *j* of *N*. Climate conditions are supposed uniform for all areas. The water balance is calculated as the equation of:

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j}-2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - (1-f_j)k_{s,j} z_{1,j}^2 \quad \text{Equation (1)}$$

In this equation, $z_{1,j}$ = [1,0] is the relative storage known as a fraction of the total effective storage of the root zone. Land cover fraction j is presented as Rd_j while P_e as the effective precipitation. The

Penman-Monteith reference crop potential evapotranspiration is described as *PET*, whereas $k_{c,j}$ is the crop/plant coefficient for each fractional land cover. The third term represents surface runoff, where RRF_j is the Runoff Resistance Factor of the land cover. Higher values of RRF_j lead to less surface runoff. The fourth and fifth terms are the interflow and deep percolation terms, respectively, where the parameter $k_{s,j}$ is an estimate of the root zone saturated conductivity (mm/time) and f_j is a partitioning coefficient related to soil, land cover type, and topography that fractionally partitions water both horizontally and vertically.

1.6 Layout of the rest of the thesis

This thesis comprises five chapters. The first Chapter has provided a brief overview of water management and general catchment description of the Vu Gia-Thu Bon river basin. The second Chapter reviews climate change and its links to socio-economic development. Here, I summarise global climate change scenarios developed by the Intergovernmental Panel on Climate Change as well as specific climate change scenarios for Viet Nam (Ministry of Natural Resources and Environment 2009, 2012). I then review the predicted impacts of climate change on water resources in general and specifically for the Vu Gia-Thu Bon River basin as well as the use of WEAP for modelling climate change impacts.

Chapter 3 focuses on the key principles for modelling in WEAP as well as data requirements for spatial, precipitation, temperature and streamflow data. Master plans in the Central Region of Viet Nam, Quang Nam province and Da Nang city were used to divide water users into four groups, namely agriculture, hydropower, domestic and industrial use. I then present modelled climate change scenarios for the basin and some related scenarios relating to hydropower, irrigation and domestic water use.

Climate change impacts on water resources in the watershed are predicted in Chapter 4 for each of the three scenarios testing combinations of stable or increasing temperature and precipitation. Finally, Chapter 5 compares these modelled scenarios and their limitations. I conclude by suggesting questions for future research and implementation.

Chapter 2: Literature review

2.1 Climate change issues

According to the Intergovernmental Panel on Climate change (IPCC, 2007), climate change refers to a change in the average long-term conditions of the climate owing to natural alteration or human activity. Climate change research and debate have intensified over the last few decades. Climate change research includes geological data including marine and lake deposits, ice boreholes, cave deposits, and tree rings (Maslin 2004). Climate change supporters accept that increases in atmospheric concentrations of human-induced greenhouse gases are the main causes of climate change. Therefore, they suppose that reductions in greenhouse gas emissions and increasing carbon absorption are necessary to reduce further climate change in the future. However, other scientists strongly disagree with this interpretation and argue that natural factors are the key drivers of climate change rather than carbon dioxide emissions from human activity.

Here, I review the evidence that supports anthropogenic climate change. The evidence includes links between population growth, industrialization and the increase in carbon dioxide concentrations, the relationship between carbon dioxide levels and climate change, and finally, the increase in extreme climate disasters caused by climate change.

Firstly, global population growth and industrialization likely correlate with the increase in atmospheric carbon dioxide levels (Han and Chatterjee 1997). Economic productivity grows to meet the demands of increasing population size and this increases energy consumption or energy intensity (Bongaarts 1992). Energy intensity is characterised by carbon intensity which is the level of energy-related carbon emissions per unit GDP (Levine and Aden 2008). Figure 2-1 illustrates the factors that affect total carbon emission rates. As a population grows, the increasing industrialization shifts the economy from predominantly rural and agricultural activities to manufacturing industries, and these increase energy demand (Han and Chatterjee 1997). Thus, GDP is strongly correlated with carbon dioxide emissions (Roberts et al., 2003). In a study of nine developing countries from 1972 to 1990, the dominant driving force for increases in carbon dioxide emissions was the growth of GDP (Han and Chatterjee 1997). These countries released up to 28 million tons of carbon dioxide emission between 1980 and 1990 due to industrialization (Han and Chatterjee 1997).

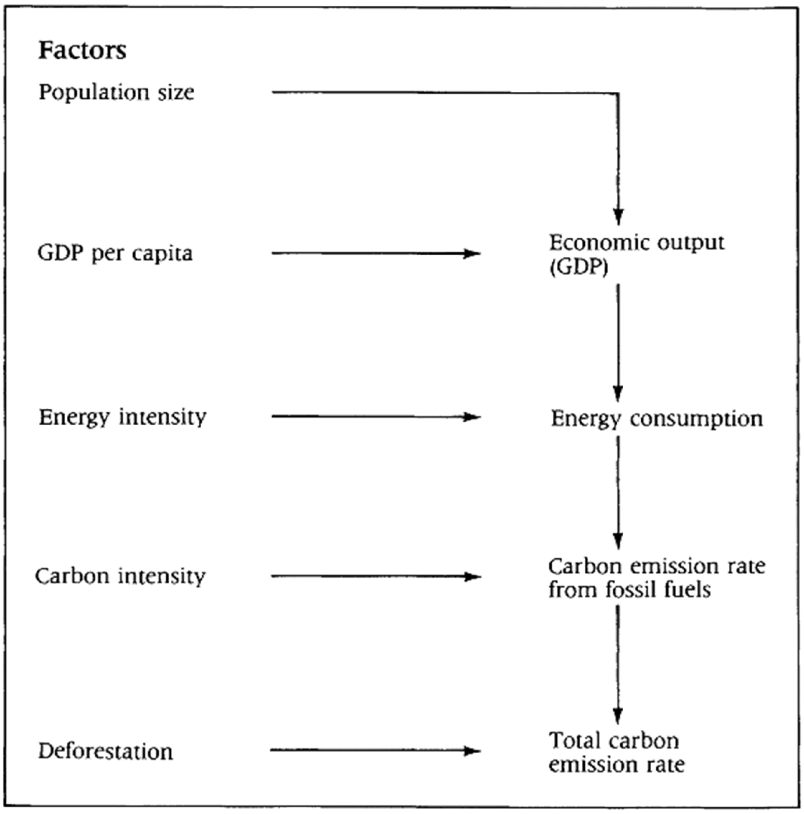

Figure 2-1 Interactions among population size, economic activity and carbon emissions (reproduced from Bongaarts 1992).

Thus, there is strong evidence that population growth and industrialization increase atmospheric carbon dioxide concentrations. Several examples demonstrate this correlation between increasing carbon dioxide concentrations and population growth. The world carbon emissions grew by fifty five precent owing to the increasing energy intensity of GDP and the carbon intensity of energy between 2000 and 2006 (Levine and Aden 2008). The global population is expected to increase from 3.6 to 9.0 billion in developing nations and from 1.2 to 1.5 billion in developed nations between 1985 and 2100 (Bongaarts 1992, see Figure 2-2). Meanwhile, the mean global GDP per capita is projected to increase from $3,000 to $36,000, with the annual growth rate expected to rise three percent in developing nations and two percent in developed countries between 1985 and 2100 (Bongaarts 1992). Furthermore, global carbon dioxide emissions are predicted to increase from 6 to 26.1 Billion tonnes per year; an average of 2.15 to 14.15 Billion tonnes per year for developing countries and 3.85 to 11.95 Billion tonnes per year for developed countries (Bongaarts 1992, see Table 2-1).

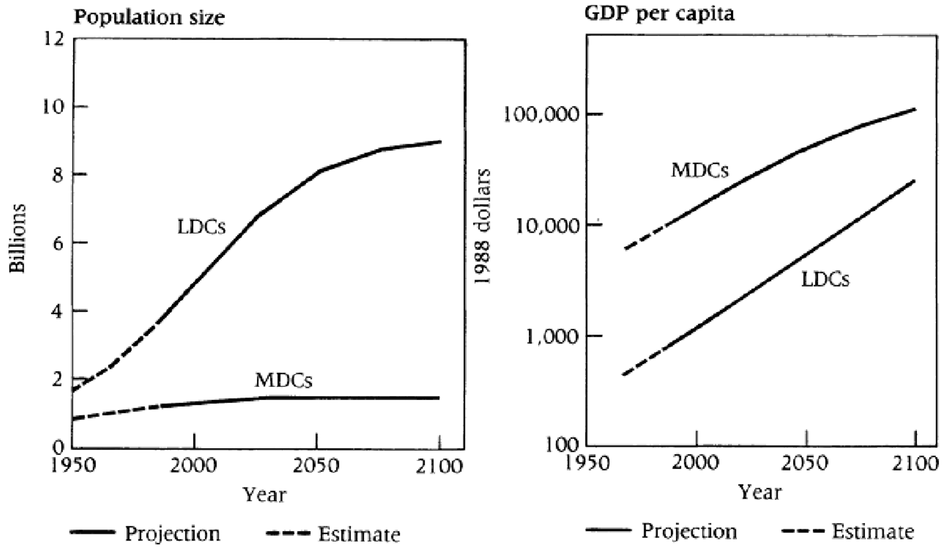

Figure 2-2 Predicted population size and GDP per capita for less developed countries (LDCs) and more developed countries (MDCs) for 1950-2100 (reproduced from Bongaarts 1992).

Table 2-1 Estimations for 1985 and projections for 2025 and 2100 of population size, carbon dioxide emission per capita and carbon dioxide emission rates in developing and developed countries Reproduced from (reproduced from Bongaarts 1992).

	Developing world	**Developed world**	**World total**
Population size (billions)			
1985	3.64	1.23	4.87
2025	6.76	1.43	8.19
2100	8.95	1.47	10.42
CO_2 emission per capita			
1985	0.59	3.13	1.23
2025	1.01	3.88	1.51
2100	1.58	8.13	2.50
Total carbon dioxide emission			
(Pgr of C/year)			
1985	2.15	3.85	6.0

	Developing world	Developed world	World total
2025	6.85	5.55	12.4
2100	14.15	11.95	26.1

Other data also support the trend of increasing carbon dioxide (CO_2) concentrations with industrial development. For instance, from 1850 to 2006, fossil fuel combustion and cement production released an approximate cumulative total of 330 Ptc (10^9 metric tons of carbon) to the atmosphere and world average atmospheric carbon concentrations grew from 280 ppm (parts per million) at the beginning of the industrial revolution to 381 ppm in 2006 (Canadell et al. 2007). Observed atmospheric carbon concentrations in Mauna Loa, Hawaii and the South Pole over four decades are correlated with industrial CO_2 emissions (Keeling et al. 1995, see Figure 2-3). Likewise, slowing increases in CO_2 concentration between 1989 and 1993 are partly explained by the decline in industrial CO_2 emissions after 1979 (Keeling et al. 1995).

Carbon dioxide concentrations in the atmosphere contribute to global warming. Thermal radiation emitted by the earth's surface and lower atmosphere wavelengths from 7 to 14 micrometres. Because carbon dioxide absorbs heat in this range, increased atmospheric CO_2 results in more trapped heat at the surface and lower atmosphere (Hansen et al. 1981). As CO_2 is the most common greenhouse gas comprising 55% of atmospheric greenhouse gases, (Han and Chatterjee 1997), fossil fuel combustion, with its CO_2 emission, is the main cause of global warming (Davis and Caldeira 2010).

The earth's temperature is estimated to have increased from 0.5 to 1.5^0C due to the rise in total emissions of greenhouse gases in the period from 1880 to 1989 (Han and Chatterjee 1997). The Intergovernmental Panel on Climate Change (2007) estimates global temperature increased by 0.57 ^{0}C from 1850 to 1899 and by 0.95 ^{0}C between 2001 and 2005 (see Figure 2-4). The strong relationship between increase in CO_2 emissions and global average temperatures are predicted in Figure 2-5. This scenario tests peaks in CO_2 emission of 450, 550, 650, 750, 850 and 1,200 ppmv. While CO_2 emissions drop to zero after peaks peaking in this scenario, world average temperatures are predicted to increase and remain stable (Solomon et al. 2009).

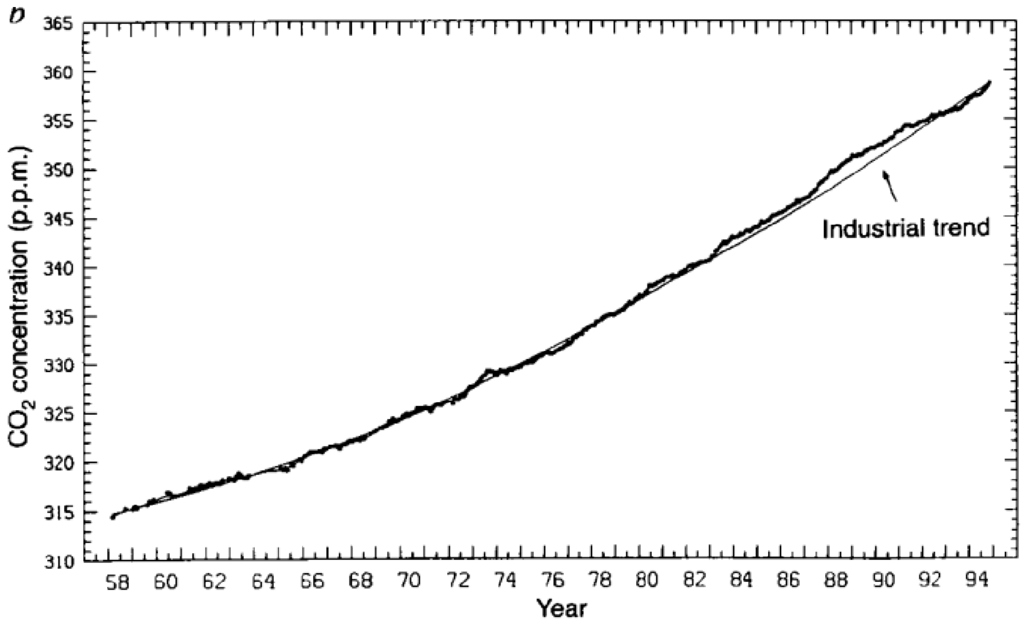

Figure 2-3 The average of carbon concentrations (smooth curve) and the cumulative industrial emissions of carbon dioxide (solid line) from fossil fuels combustion and cement production from 1958 to 1994 (reproduced from Keeling et al. 1995).

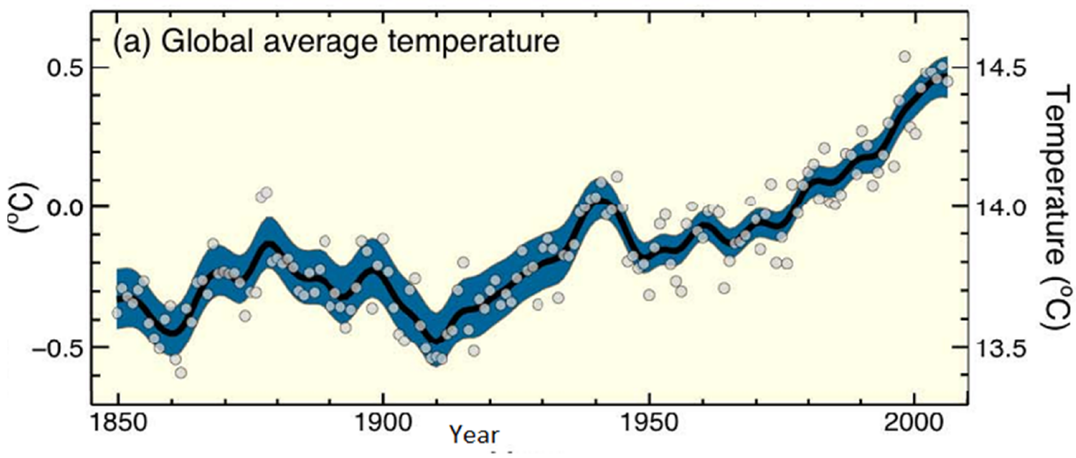

Figure 2-4 Increases in the observed global average temperature between 1850 and 2005 (reproduced from IPCC 2007).

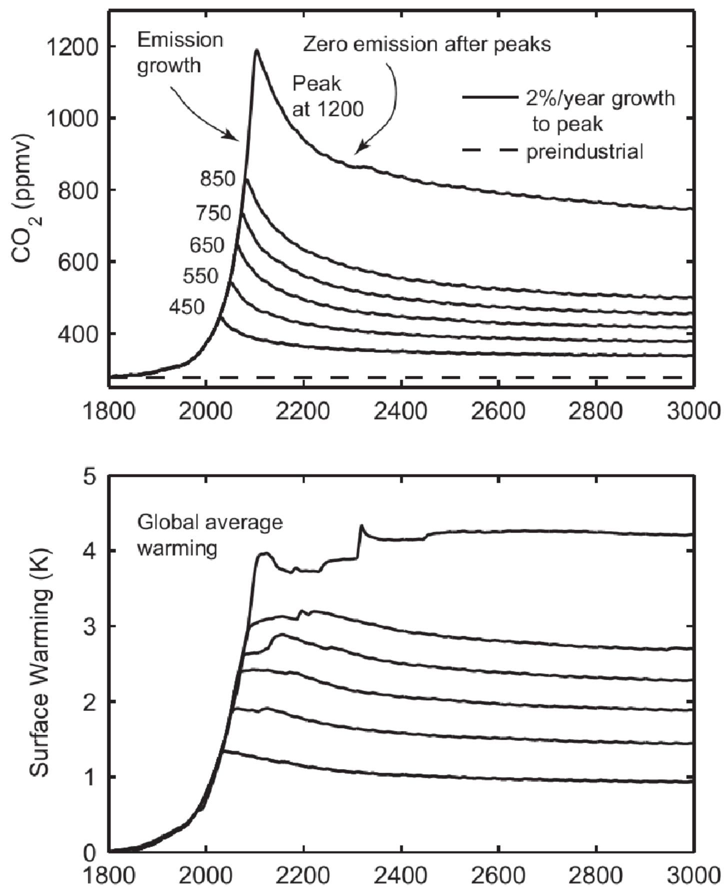

Figure 2-5 Carbon emissions scenarios and average global temperatures variations, where K is Kelvins (reproduced from Solomon et al. 2009).

Finally, the increases in extreme climate events may be a consequence of global warming. Extreme climate events refer to extreme daily rainfall amounts, extreme daily temperatures, large areas experiencing unusually warm monthly temperatures and storm events such as hurricanes (Meehl et al. 2000b). Extreme events are determined statistically from the point of view of the mean and variance, and the mean and variance distribution (Meehl et al. 2000a). From global observed data since the start of the twentieth century, global precipitation has increased and global mean temperatures have increased approximately 0.6 ^{0}C, the latter associated with a stronger warming in daily minimum temperatures than maximums (Easterling et al. 2000).

Between 1948 and 1993, the number of frost days became fewer in many regions of the world (Table 2-2). In the North Pacific region, tropical storm activity declined prior to the mid-1970s, but has since increased (Easterling et al. 2000). Global catastrophic floods between 1990 and 2000 were 10 times larger on average than for the period between 1950 and 1985 (Desonie 2007).

Table 2-2 Global extreme temperature events (reproduced from Easterling et al. 2000).

Country	Frost days	Warm minimum temperatures	Warm maximum temperatures	Cold waves	Heat waves
Australia	**Fewer**		**Up**		
China	**Fewer**	**Up**	**Down**	**Fewer**	
Central Europe	**Fewer**				
Nothern Europe	**Fewer**				
New Zealand	**Fewer**		**Up**		
United States	**Fewer**	**Up**	**No trend**	**No trend**	**No trend**

2.2 World-wide climate change scenarios

Climate change scenarios refer to simplified and plausible representations of the future climate, as a result of internally-consistent descriptions of the interaction of climatic factors, constructed for the purpose of analysing potential impacts of climate change (IPCC 2001). Concentrations of anthropogenic greenhouse gas (GHG) emissions in the atmosphere primarily determine current and future climatic conditions. Thus, development of climate scenarios are based on global socio-economic development scenarios (Ministry of Natural Resources and Environment (MoNRE) 2009).

Emission scenarios are categorised into four emission scenario families (A1, A2, B1 and B2), comprising 40 scenarios, that are based on a number of demographic, economic and technological processes that drive GHG emissions (IPCC 2007, MoNRE, 2009). These scenario families are illustrated in Figure 2-6 and summarised as follows (MoNRE, 2009):

- **A1 family** assumes that global economics rapidly grows. The world population may peak at 9 million in the mid-century and reduce thereafter. New and more efficient technologies are speedily introduced. The A1 family is separated into three groups in terms of technological change such as A1FI (fossil intensive or high emission), A1T (non-fossil energy resources or medium emission) and A1B (a balance across all sources or low emission).
- **A2 family** assumes a very heterogeneous world with continuously increasing population growth until the end of century. However, the world is expected to have slow economic development, and slow and fragmented technological change.

- **B1 family** assumes rapid global economic growth and the same global population as in A1 family. Economic structures rapidly change toward a service and information economy with the introduction of clean and resource-efficient technologies that reduce material intensity.
- **B2 family** assumes continuously increasing global population and intermediate economic growth. Solutions to economic, social, and environmental sustainability are localised but occur less rapidly and through more diverse technological change than in A1 and B1 families.

These emission scenarios are ranked from low to high, namely B1, A1T (low emission), B2, A1B (medium emission) and A2, A1FI (high emission). The suitability of these scenarios for climate change prediction depends on practical requirements and computing (MoNRE, 2009). Figure 2-7 illustrates anthropogenic emissions of carbon dioxide, methane, nitrous oxide and sulphur dioxide for six emission scenarios under different driving forces such as population growth, economic development, technological transfer, energy consumption and land use changes.

Figure 2-6 Conceptual diagram of four GHG emission scenario families (reproduced from MoNRE, 2009).

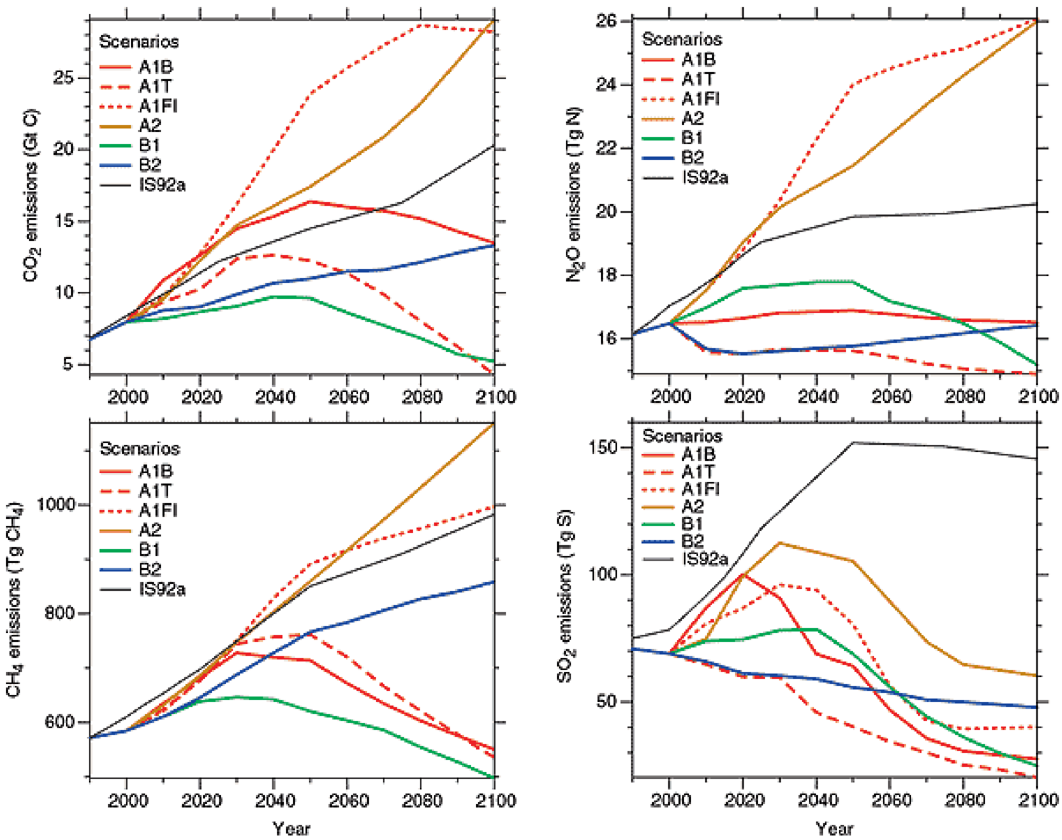

Figure 2-7 Predicted greenhouse gas emissions using the four emission family scenarios (reproduced from IPCC 2001).

2.2.1 Climate change scenarios in the IPCC Third Assessment Report (AR3)

According to the *Third Assessment Report* of IPCC (2001), the projected global average surface temperature increases by 1.4 to 5.8°C in between 1990 and 2100. The range of predicted average temperature increase encompasses all emission scenarios. Overall, although greenhouse gas emissions decrease after 2050, average projected temperatures for the six scenarios significantly increase until the end of the 21st century (see Figure 2-8). Similarly, average precipitation is generally predicted to increase during the 21st century (IPCC, 2001). However, precipitation predictions are more variable at the regional scale with both increasing and decreasing trends predicted for different regions. Precipitation is predicted to increase in both summer and winter over high latitude regions for A2 and B2 emissions scenarios while winter precipitation is predicted to increase over the northern mid-latitudes, Antarctica and tropical Africa (see Figure 2-8). Precipitation in eastern and southern Asia is projected to increase in summer whereas winter rainfall is predicted to decrease in Australia, Central America, and southern Africa (see Figure 2-9, IPCC 2001).

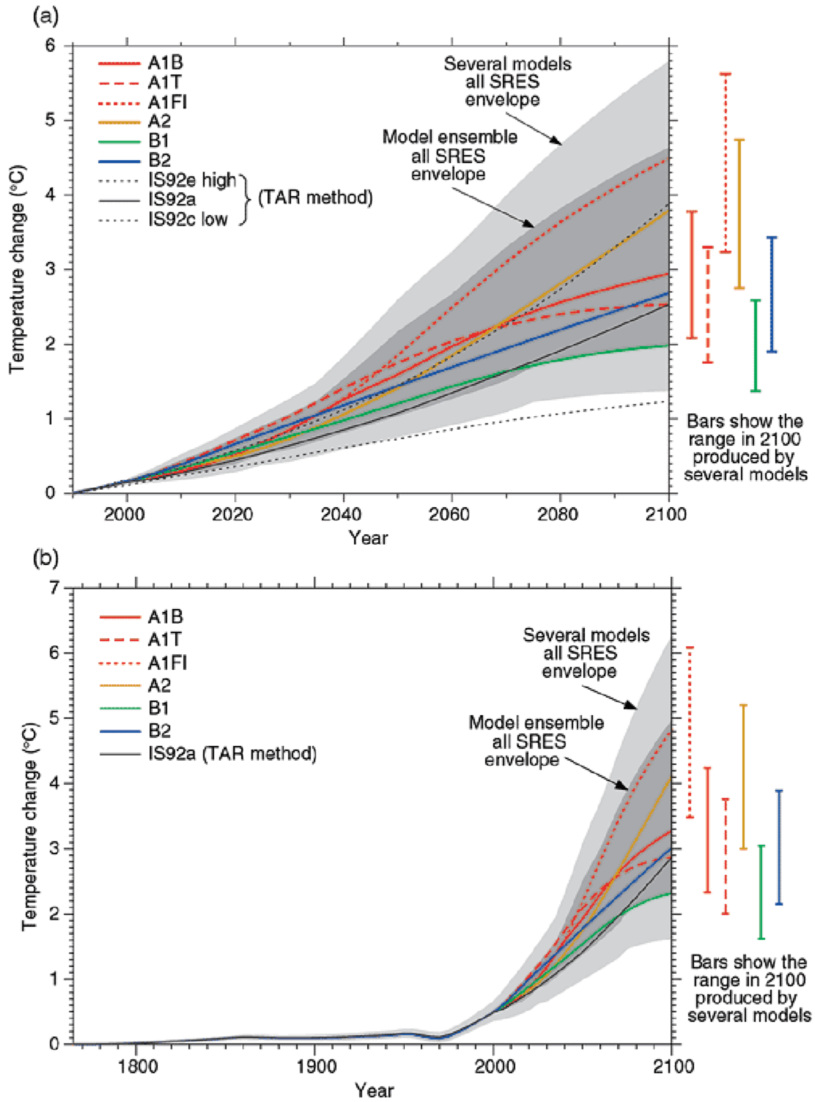

Figure 2-8 Average predicted global temperatures for the emission scenarios for **(a)** 2000 to 2100, and **(b)** within the context of 1800 - 2100 (reproduced from IPCC 2001).

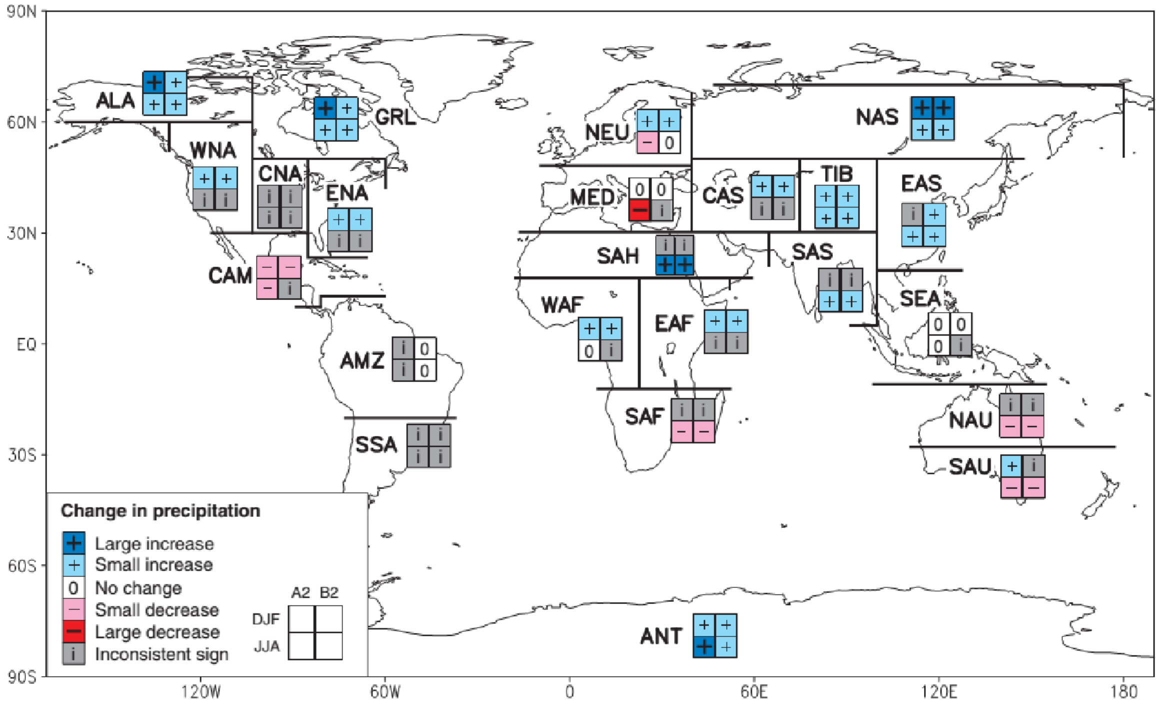

Figure 2-9 Predicted changes in regional precipitation (reproduced from IPCC 2001).

2.2.2 Climate change scenarios in the IPCC Fourth Assessment Report (AR4)

In 2007, IPCC released the *Fourth Assessment Report*. This report predicts future climate conditions until the end of the century. Surface warming of the Earth is projected to increase approximately 0.2°C per decade for the next two decades for a range of greenhouse gas emissions scenarios (IPCC 2007). This increase is predicted to then decline to approximately 0.1 °C per decade after the first 20 years given concentrations of greenhouse gases emission remain at year 2000 levels. Global average surface air warming for six emissions scenarios is shown in Table 2-3. Thus, global temperature increases depend on specific emission scenarios (see Figure 2-10). Improved estimations and reduced uncertainty of projected global temperatures for these different emissions scenarios are expected as advances occur in climate change modelling (IPCC 2007).

Table 2-3 Projected global average surface warming at the end of the 21st century for six climate scenario families (reproduced from IPCC 2007).

Emission scenarios (Constant year 2000 concentrations)	**Temperature change (°C at 2090-2099 relative to 1980-1999)**	
	Best estimate	**Likely range**
B1 scenario	1.8	1.1-2.9
A1T scenario	2.4	1.4-3.8
B2 scenario	2.4	1.4-3.8
A1B scenario	2.8	1.7-4.4
A2 scenario	3.4	2.0-5.4
A1FI scenario	4.0	2.4-6.4

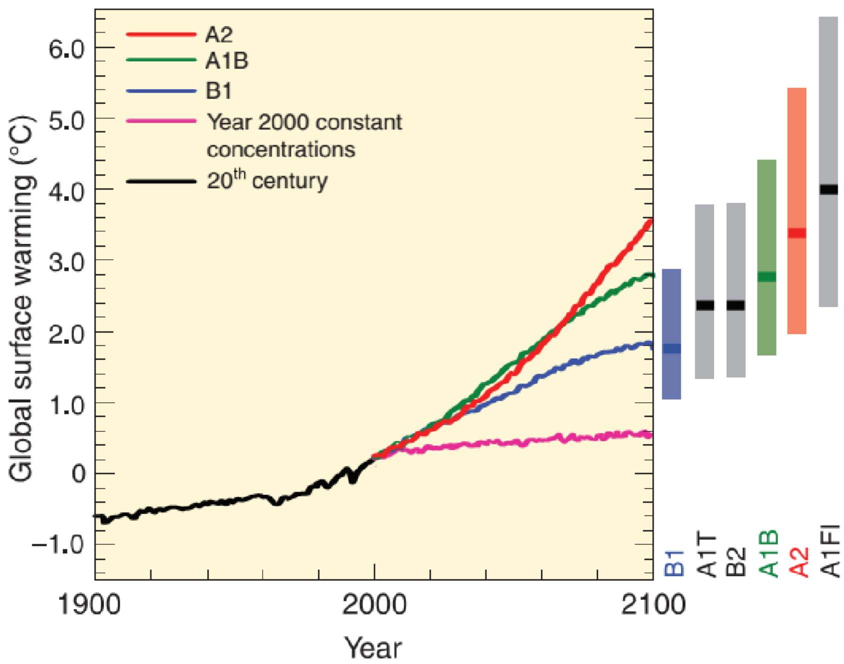

Figure 2-10 Predicted global surface temperatures in AR4 (reproduced from IPCC 2007).

The *Fourth Assessment Report* (IPCC 2007) also predicts mean precipitation and precipitation extremes. Generally, in warmer climate conditions, precipitation is predicted to increase in high latitudes, tropical regions and over the tropical Pacific but decreases in subtropical areas (see Figure 2-11, IPCC 2007). The projected intensity of precipitation events increases in tropical and high latitude areas experiencing increases in mean precipitation as well as areas where mean precipitation decreases. However, longer dry periods between rainfall events are also predicted (IPCC 2007).

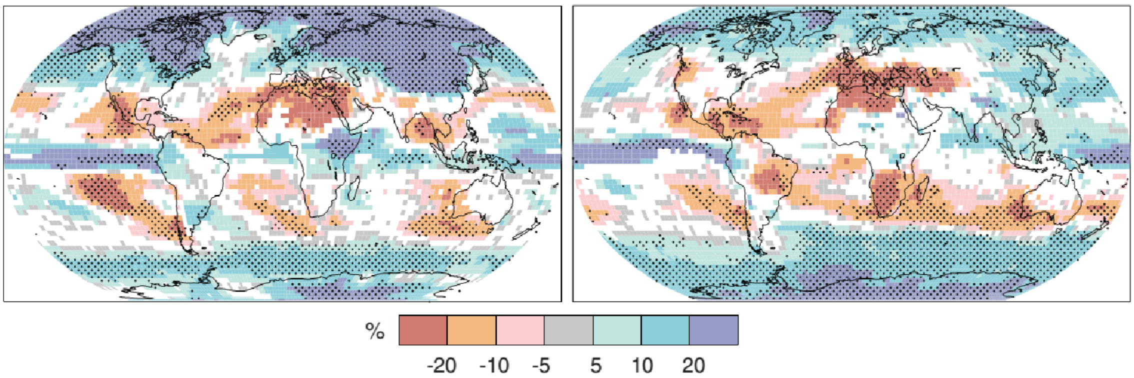

Figure 2-11 Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999 for the AIB scenario through December to February (left) and June to August (right, reproduced from IPCC 2007).

2.3 Climate change scenarios in Viet Nam

Climate change scenarios have been developed with the purpose of providing the basic information on future climate trends and sea-level rise in Viet Nam (Ministry of Natural Resources and Environment (MoNRE) 2009). These scenarios inform mainstream climate change issues at ministerial and local levels. In recent years, the Government of Viet Nam has developed many climate scenarios such as climate scenario 1994, 1998, 2007 and 2009 (Quy 2011) and lastly 2012. I will review climate change and sea-level rise scenarios for Viet Nam in 2009 and 2012.

2.3.1 Climate change scenarios for Viet Nam in 2009

The climate change scenarios for Viet Nam in 2009 developed and published by the Ministry of Natural Resources and Environment used B1 (low emission scenario), B2 (medium emission scenario) and A2 (high emission scenario) developed by IPCC (MoNRE 2009). Seven climate zones in Viet Nam, namely Northwest, Northeast, North Delta, North Central, South Central, Central Highlands and South used to develop climate change scenarios for temperature and precipitation (MoNRE 2009). The baseline period of 1980 and 1999 was used, similar to the IPCC *Fourth Assessment Report* in 2007. The temperature and precipitation projections are summarised below.

2.3.1.1 Temperature

a. Low emission scenario B1

Annual average temperatures in the North climate zone are projected to increase by 1.6^{0}C to 1.9^{0}C by the end of 21st century, compared to the period of 1980 and 1999 (MoNRE 2009). Temperatures in the South climate zone are expected to increase less than those on the North climate zone at approximately 1.1^{0}C to 1.4^{0}C (MoNRE 2009, Table 2-4).

b. Medium emission scenario B2

Compared to average temperatures of the period of 1980 and 1999, by the end of 21st century, annual average temperatures in the North Central zone are expected to increase at the highest rate of approximately 2.8^{0}C, followed by the Northwest, the Northeast and the North Delta climate zones at 2.6^{0}C, 2.5^{0}C and 2.4^{0}C, respectively (MoNRE 2009). The Central Highland zone is predicted to have about the lowest increase at approximately 1.6^{0}C (see Table 2-5).

Table 2-4 Predicted increases in annual average temperature (^{0}C) for climate zones in Viet Nam for the low emission scenario (B1, reproduced from MoNRE 2009).

Climate zones	Decades in the 21st century								
	2020	2030	2040	2050	2060	2070	2080	2090	2100
Northwest	0.5	0.7	1.0	1.2	1.4	1.6	1.6	1.7	1.7
Northeast	0.5	0.7	1.0	1.2	1.4	1.5	1.6	1.7	1.7
North Delta	0.5	0.7	0.9	1.2	1.4	1.5	1.5	1.6	1.6
North Central	0.6	0.8	1.1	1.4	1.6	1.7	1.8	1.9	1.9
South Central	0.4	0.6	0.7	0.9	1.0	1.2	1.2	1.2	1.2
Central Highlands	0.3	0.5	0.6	0.8	0.9	1.0	1.0	1.1	1.1
South	0.4	0.6	0.8	1.0	1.1	1.3	1.3	1.4	1.4

Table 2-5 Predicted increases in annual average temperature (^{0}C) for climate zones in Viet Nam for the medium emission scenario (B2, reproduced from MoNRE 2009).

Climate zones	**Decades in the 21st century**								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Northwest	0.5	0.7	1.0	1.3	1.6	1.9	2.1	2.4	2.6
Northeast	0.5	0.7	1.0	1.2	1.6	1.9	2.1	2.3	2.5
North Delta	0.5	0.7	0.9	1.2	1.5	1.8	2.0	2.2	2.4
North Central	0.5	0.8	1.1	1.5	1.8	2.1	2.4	2.6	2.8
South Central	0.4	0.5	0.7	0.9	1.2	1.4	1.6	1.8	1.9
Central Highlands	0.3	0.5	0.6	0.8	1.0	1.2	1.4	1.5	1.6
South	0.4	0.6	0.8	1.0	1.3	1.6	1.8	1.9	2.0

c. High emission scenario A2

Predicted increases in temperatures in Northern climate region zones are projected to range from 3.1^{0}C to 3.6^{0}C relative to the comparable period of 1980 and 1999. Predicted increases in annual average temperatures for the South, the South Central and the Central Highland zones are 2.6^{0}C, 2.4^{0}C and 2.1^{0}C, respectively (MoNRE 2009, Table 2-6).

Table 2-6 Predicted increases in annual average temperature (^{0}C) for climate zones in Viet Nam for the high emission scenario (A2, reproduced from MoNRE 2009).

Climate zones	**Decades in the 21st century**								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Northwest	0.5	0.8	1.0	1.3	1.7	2.0	2.4	2.8	3.3
Northeast	0.5	0.7	1.0	1.3	1.6	1.9	2.3	2.7	3.2
North Delta	0.5	0.7	1.0	1.3	1.6	1.9	2.3	2.6	3.1
North Central	0.6	0.9	1.2	1.5	1.8	2.2	2.6	3.1	3.6
South Central	0.4	0.5	0.8	1.0	1.2	1.5	1.8	2.1	2.4
Central Highlands	0.3	0.5	0.7	0.8	1.0	1.3	1.5	1.8	2.1
South	0.4	0.6	0.8	1.0	1.3	1.6	1.9	2.3	2.6

2.3.1.2 Rainfall

Changes in rainfall are also projected for the seven climate zones of Viet Nam for the low, medium and high emission scenarios. Overall, precipitation is expected to decrease in most climate regions during the dry season. In contrast, precipitation during the wet season and total annual rainfall are projected to increase across all climate zones (MoNRE 2009).

a. Low emission scenario (B1)

Annual precipitation is predicted to increase about 5% for the North Central, North Delta, Northeast and Northwest climate zones, and between - 2% for the South, Central Highlands and South Central climate zones by the end of this century, compared to the period of 1980 and 1999 (MoNRE 2009). In March and May, rainfall is projected to decrease about 3 – 6% in the North and up to 7 - 10 % in the middle of dry season in the South climate zone (MoNRE 2009, Table 2-7).

Table 2-7 Predicted annual precipitation changes (%) for the climate zones in Viet Nam compared to 1980 - 1999 for the low emission scenario (B1, reproduced from MoNRE 2009).

Climate zones	**Decades in the 21st century**								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Northwest	1.4	2.1	3.0	3.6	4.1	4.4	4.6	4.8	4.8
Northeast	1.4	2.1	3.0	3.6	4.1	4.5	4.7	4.8	4.8
North Delta	1.6	2.3	3.2	3.9	4.5	4.8	5.1	5.2	5.2
North Central	1.5	2.2	3.1	3.8	4.3	4.7	4.9	5.0	5.0
South Central	0.7	1.0	1.3	1.6	1.8	2.0	2.1	2.2	2.2
Central Highlands	0.3	0.4	0.5	0.7	0.7	0.9	0.9	1.0	1.0
South	0.3	0.4	0.6	0.7	0.8	0.9	1.0	1.0	1.0

b. Medium emission scenario (B2)

By the end of this century, precipitation is expected to increase across climate zones, relative to the baseline period (1980 - 1999, MoNRE, 2009). The greatest increase (7 - 8 %) is expected in the Northwest, Northeast, North Delta and North Central zones and about 2 - 3 % increase predicted across the remainder climate zones (MoNRE, 2009, Table 2-8).

c. High emission scenario (A2)

By the end of the 21st century, annual precipitation is projected to increase from 9.7 - 10.1% across all northern climate zones (MoNRE 2009). Annual precipitation increases of 4.1% and 2% are predicted for the South Central zone, and the Central Highlands, respectively (see Table 2-9).

Table 2-8 Predicted annual precipitation changes (%) for the climate zones in Viet Nam compared to period of 1980 and 1999 for Medium emission scenario (B1, reproduced from MoNRE 2009).

Climate zones	**Decades in the 21st century**								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Northwest	1.4	2.1	3.0	3.8	4.6	5.4	6.1	6.7	7.4
Northeast	1.4	2.1	3.0	3.8	4.7	5.4	6.1	6.8	7.3
North Delta	1.6	2.3	3.2	4.1	5.0	5.9	6.6	7.3	7.9
North Central	1.5	2.2	3.1	4.0	4.9	5.7	6.4	7.1	7.7
South Central	0.7	1.0	1.3	1.7	2.1	2.4	2.7	3.0	3.2
Central Highlands	0.3	0.4	0.5	0.7	0.9	1.0	1.2	1.3	1.4
South	0.3	0.4	0.6	0.8	1.0	1.1	1.2	1.4	1.5

Table 2-9 Annual predicted precipitation changes (%) for the climate zones in Viet Nam compared to period of 1980 and 1999 for the High emission scenario (A2, reproduced from MoNRE 2009).

Climate zones	**Decades in the 21st century**								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Northwest	1.6	2.1	2.8	3.7	4.5	5.6	6.8	8.0	9.3
Northeast	1.7	2.2	2.8	2.8	4.6	5.7	6.8	8.0	9.3
North Delta	1.6	2.3	3.0	3.8	5.0	6.1	7.4	8.7	10.1
North Central	1.8	2.3	3.0	3.7	4.8	5.9	7.1	8.4	9.7
South Central	0.7	1.0	1.2	1.7	2.1	2.5	3.0	3.6	4.1
Central Highlands	0.3	0.4	0.5	0.7	0.9	1.1	1.3	1.5	1.8
South	0.3	0.4	0.6	0.7	1.0	1.2	1.4	1.6	1.9

2.3.2 Climate change scenarios for Viet Nam 2012

2.3.2.1 Temperature

a. Low emission scenario (B1)

Annual average temperature are predicted to increase between 1.6^{0}C to 2.2^{0}C in most climate zones by the end of the 21th century (MoNRE 2012). Temperatures increases are predicted to be greater in the Northern regions than the Southern regions (see Figure 2-12).

b. Medium emission scenario (B2)

Annual average temperatures are expected to increase between 2^{0}C to 3^{0}C across most climate zones in Viet Nam. Larger increases are projected in the region from Ha Tinh to Quang Tri province (the North Central climate zone), comparing to other places (see Figure 2-12). Table 2-10 shows changes in annual average temperature in the Vu Gia-Thu Bon river basin comprising Da Nang city and Quang Nam province (the South Central climate zone) for medium emission scenario, relative to the baseline period.

c. High emission scenario (A2)

Under the high emission scenario (A2), annual average temperatures are predicted to increase approximately 2.5^{0}C to 3.7^{0}C over most of Viet Nam by the end of the 21st century (MoNRE 2012). The smallest increases (1.6 – 2.5^{0}C) are predicted for parts of the Central Highlands and Northwest climate zones (MoNRE 2012, see Figure 2-12).

Table 2-10 Predicted increases in annual average temperature (0C) for Da Nang and Quang Nam, relative to the baseline period 1980 - 1999, for the medium emission scenario (B2, reproduced from MoNRE 2012).

No	**Province**	**Decades in the 21st century**								
		2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
1	Da Nang	0.5	0.7	1.0	1.3	1.6	1.8	2.1	2.3	2.5
2	Quang Nam	0.5	0.8	1.1	1.4	1.7	2.0	2.3	2.5	2.7

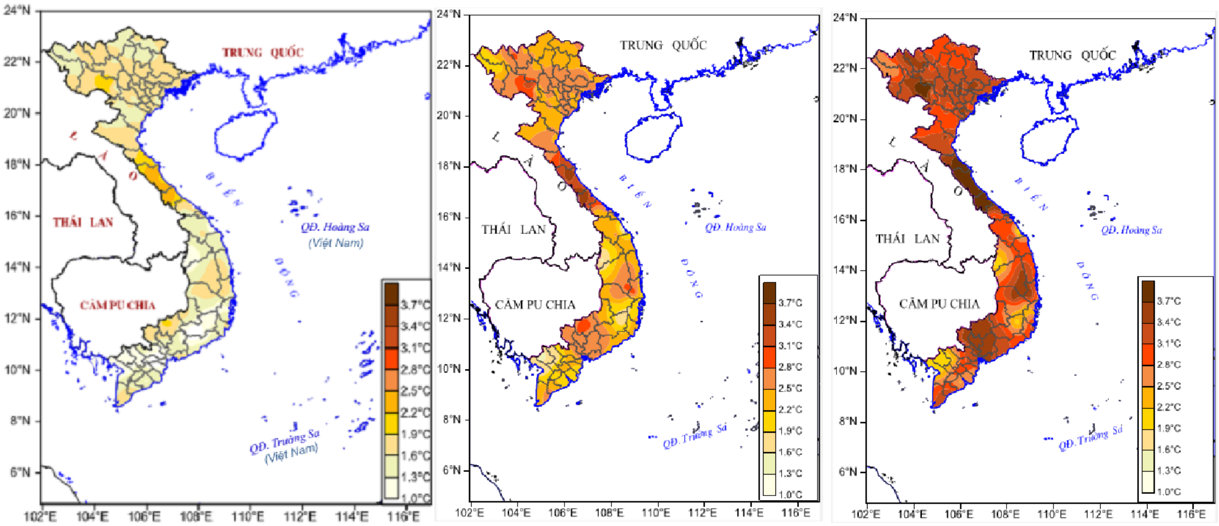

Figure 2-12 Predicted increases in annual average temperature (^oC) for low (B1), medium (B2) and high emission scenarios (A2, from left to right) by the end of 21st century, compared to the period of 1980 and 1999 (reproduced from MoNRE 2012).

2.3.2.2 Rainfall

a. Low emission scenario (B1)

Under the low emission scenario (B1), precipitation is predicted to increase by 5% by 2050 and 7% by the end of the century (2100, MoNRE 2012). The smallest increase of 2% is predicted to occur in the Central Highlands (MoNRE 2012, see Figure 2-13).

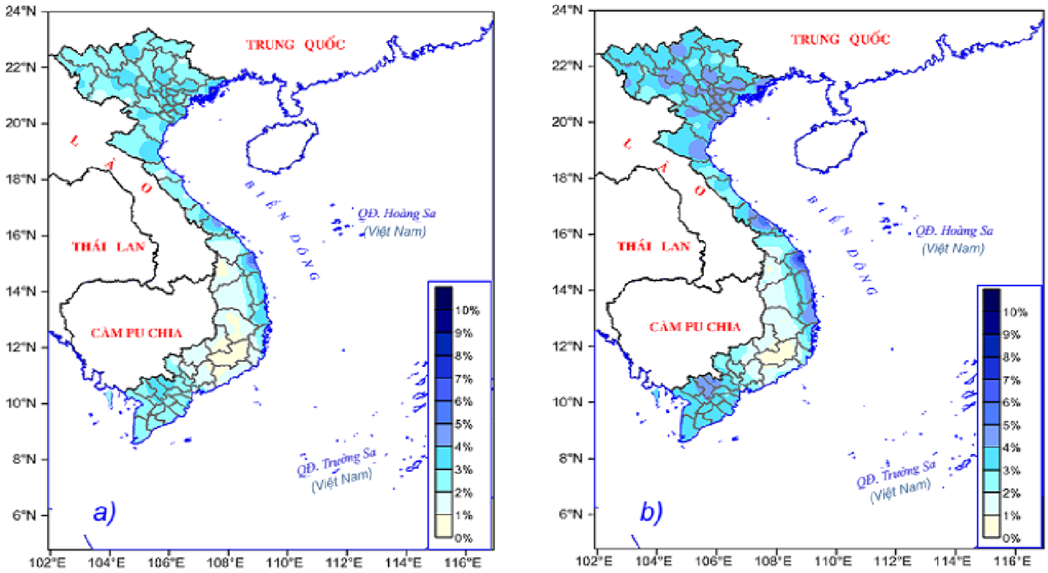

Figure 2-13 Predicted increases in precipitation by (a) the middle (2050) and (b) 2100 for the low emission scenario (B1, reproduced from MoNRE 2012).

b. Medium emission scenario (B2)

Under the medium emission scenario (B2), precipitation is projected to increase from 1 – 4% by 2050 and from 2 – 7% by the end of century (2100, MoNRE 2012). As with the low emission scenario, the smallest increase is predicted to occur in the Central Highlands, approximately 1% by 2005 and from less than 1% to 3% by the middle and end of the century (2100, MoNRE 2012, see Figure 2-14). Table 2-11 presents decadal increases in precipitation for the Vu Gia-Thu Bon river basin for the 21st century.

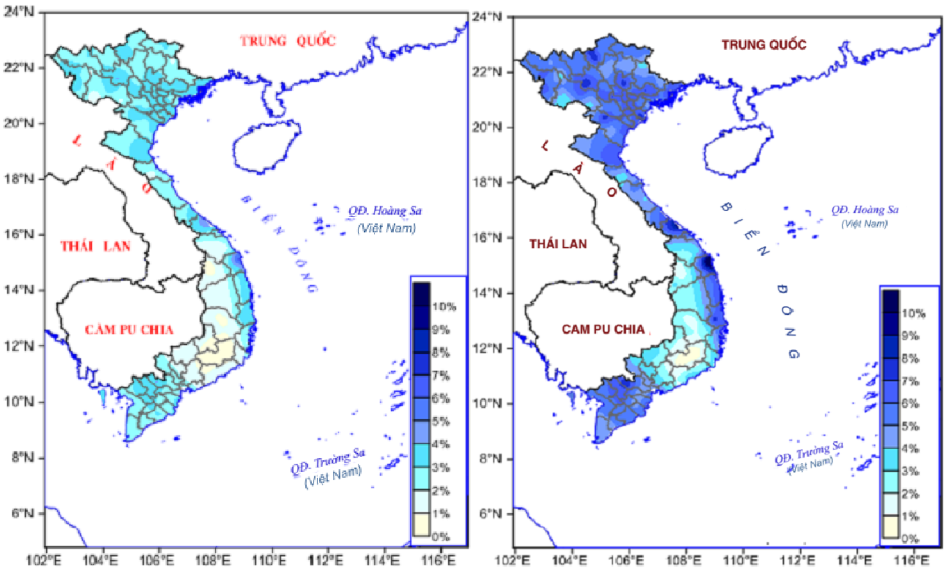

Figure 2-14 Predicted increases in precipitation by (a) 2050 and (b) 2100 relative to the baseline period under the medium emission scenario (B2, reproduced from MoNRE 2012).

Table 2-11 Predicted increases in precipitation (%) for Da Nang City and Quang Nam Province, relative to the baseline period 1980 – 1999, under the medium emission scenario (B2, reproduced from MoNRE 2012).

No	Province	Decades in the 21st century								
		2020	2030	2040	2050	2060	2070	2080	2090	2100
1	Da Nang	1.0	1.4	2.0	2.6	3.2	3.7	4.2	4.6	5.0
2	Quang Nam	0.7	1.0	1.5	1.9	2.3	2.7	3.0	3.3	3.6

c. High emission scenario (A1)

Under the high emission scenario (A1), precipitation is projected to increase from 1 - 4% by 2050 and 2 - 10% by 2100 for most climate regions (Figure 2-15). The smallest increases are predicted to occur in the Central Highlands: less than 2% by the middle of the century and 1 - 4% by the end of the century (MoNRE 2012).

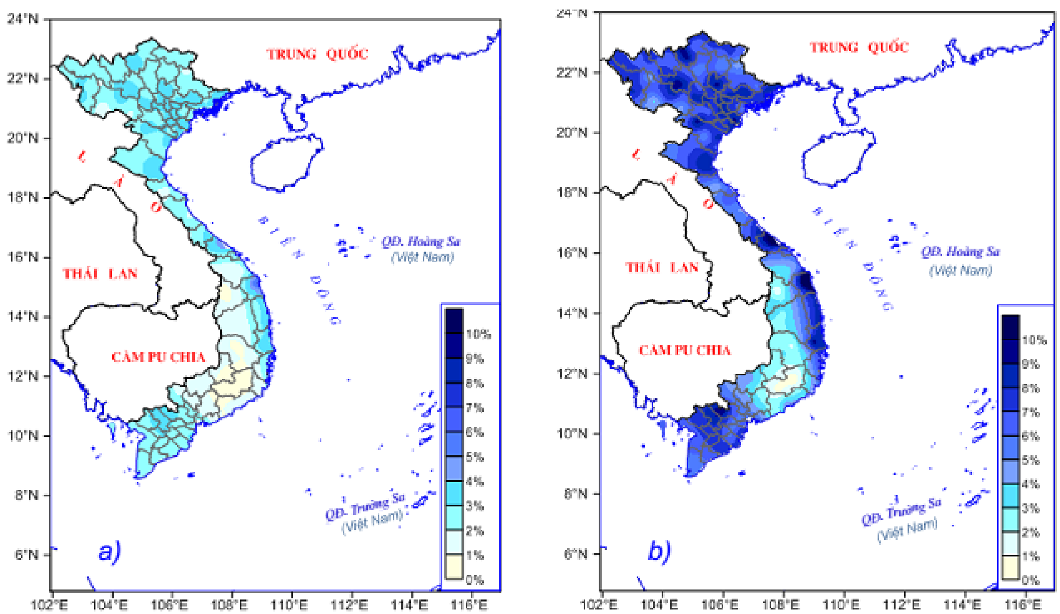

Figure 2-15 Predicted increases in precipitation in Viet Nam by (a) 2050 and (b) 2100, relative to baseline of 1980 – 1999 under the high emission scenario (A1, reproduced from MoNRE, 2012).

2.4 Climate change impacts on water resources

Globally, water resources are currently under pressure from population growth, urbanisation, and economic and land use change. Climate change is projected to increase these stresses on water resources (IPCC 2007). Increases in average temperature lead to increases in evaporation of water in land and water surfaces (Gleick et al. 1997). Thus, intensifying increases in global temperature will alter the hydrological cycle (Cornea et al. 2011). The *IPCC Third and Fourth Assessment Reports* suggest changes in climate conditions, such as temperature and precipitation are like to affect runoff, streamflow, water availability, the frequency and severity of floods and droughts, water quality, and the demand for water (2001, 2007). These hydrological impacts vary regionally and among climate scenarios (Hagemann et al. 2013). Next, I review the impacts of climate change on surface water resources (focusing on temperature and rainfall factors) based on these two IPCC reports.

By the end of the 21st century, climate change is predicted to increase mean runoff by 10 – 40% in high latitude regions and in some wet tropical areas, such as East and Southeast Asia, North America and Eurasia (Nohara et al. 2006). However, over some dry regions at mid-latitudes and dry tropics, including the Mediterranean, Southern Africa and Western USA/Northern Mexico, mean runoff is projected to decrease by 10 – 30% due to increases in evaporation and decreases in rainfall (Nohara et al. 2006).

Overall, annual average streamflow is predicted to increase in high latitudes and Southeast Asia, and decrease in Central Asia, southern Africa, Mediterranean and Australia (IPCC 2001). Trends in decreasing water availability are similar, with predictions of greater than 10% decreases in streamflow in Central, Eastern and Southern Europe, the catchments of the Euphrates/Tigris Rivers in the Middle East, Zhu Jiang River in southern China, the Mississippi River in North America, Okavango and Limpopo Rivers in southern Africa, and the River Murray in Southeast Australia (Hagemann et al. 2013). In many areas, peak streamflow is also predicted to shift from spring to winter because increasing temperatures change snowfall patterns (Hagemann et al. 2013).

Additionally, in many regions as the frequency of heavy rainfall events increases, the frequency and severity of hydrological extremes such as floods and droughts are also predicted to increase significantly. By 2080, increased flood hazards are predicted to impact up to 20% of the global population (Kleinen and Petschel-Held 2007).

Water quality as well as quantity is predicted to decline (Gleick et al. 1997). Higher temperatures likely affect the physical, chemical and biological properties of water resources (IPCC 2007). Lower water levels in streams and lakes in conjunction with more intense rainfall will likely lead to increases in suspended solid loads (IPCC 2007). This will reduce aquatic primary productivity, affecting invertebrate, amphibian and fish populations, as well as increase the costs of treating potable water.

Higher suspended solid loads are commonly linked with higher nutrient and pollutant loads that can lead to eutrophication and contamination of water bodies, respectively (Boulton et al. 2014).

As well as declines in water quantity and quality, and increasing variability in precipitation, climate change is also predicted to affect demand for water use (Frederick and Major 1997, Gleick et al. 1997, IPCC 2007). However, these impacts vary across regions and sectors. Increasing water demand is predicted to occur in many developing countries (Vörösmarty et al. 2000). Water-rich areas are likely to have adequate quantities of water, but the issues will be in providing adequate clean water (Vörösmarty et al. 2000). Conversely, in arid and semiarid regions where water scarcity is already problematic, demand for water will intensify (Vörösmarty et al. 2000). The greatest increases in water demand are likely to arise from agriculture, due to increasing evapotranspiration, rather than industrial or urban uses (IPCC 2007).

2.5 WEAP-related studies on climate change impacts

The Water Evaluation and Planning System (WEAP), developed by the Stockholm Environment Institute, is an integrated practical tool to balance water resources in the context of water systems (supply, demand, quality etc.) and ecosystem preservation, as well as policy orientation. Since its establishment in 1988, it has been used as the basis of many studies (Stockholm Environment Institute 2013). Generally, most studies relating to climate change impacts on water resources combine outcomes of climate change scenarios (i.e. temperature and rainfall) from Global Circulation Models (GCM) by downscaling methods (Nam et al. 2013b) and WEAP. These studies cover a range of climate change impacts on alterations to water quality and quantity across groundwater and surface water resources. Next, I discuss downscaling methods (Gonzalo et al. 2012) used to derive climate factors (i.e. temperature and precipitation), module calibration and previous climate change modelling studies relating to water supply and demand (Haidera et al. 2011, Rochdane et al. 2012), streamflow (Donley et al. 2012, Woodbury et al. 2012), water quantity and quality (Slaughter et al. 2011), and water availability (Strzepek et al. 1999).

General Circulation Models or Global Climate Models (GCMs) are mathematical models simulating the climate system of the Earth (Gonzalo et al. 2012). Such models compute mathematical relationships between various land, ocean and atmosphere processes (Nam et al. 2012). However, coarse spatial resolution for calculations are based on grid divisions of the Earth's surface, from tens or hundreds of kilometres, or 2 - 5 degrees (Nam et al. 2012). Therefore, statistical downscaling techniques are employed to assess climate change impacts at fine spatial scales (Rochdane et al. 2012). Generally, these techniques establish mathematical relationships between the observed and modelled climate values. Regional features are then statistically modelled from large-scale climate patterns, and applied to the outputs of GCM models to predict different regional climate change scenarios (Gonzalo et al. 2012).

Rochdane and colleagues (2012) predict impacts of climate variation on water supply and water demand in the Rheraya catchment in Morocco. They analysed different scenarios of socio-economic development until 2100 and used two emission scenarios (A2 and B2) to project future temperatures and precipitation by statistical downscaling. The projections suggest increases in mean temperatures of 1ºC, 3ºC and 4ºC during the periods of 2011–2040, 2041–2070 and 2071–2099, respectively, compared to a baseline period of 1961–2000. Meanwhile, precipitation decreases are predicted to be from 5–10% (2011–2040), 10–40% (2041–2070), and 40–60% (2071-2099). Empirical field surveys at the village level and expert consultations in 2008, 2009 and 2010 indicate significant increases in unmet water demand over the coming decades (Rochdane et al. 2012).

Similarly, Haidera and colleagues (2011) predict impacts of climate change on water resources in three basins (Sana's, Sadah and Aden City) in Yemen until 2025. This project used a range of approaches to collect data, construct scenarios for WEAP including incorporating groundwater aquifers as supply sites, as well as for adaptation strategies. Haidera and colleagues (2011) found that no single adaptation strategy will successfully mitigate climate change impacts; but rather, a combination of different approaches will be required as a sustainable alternative for water resource management under climate change conditions.

Two recent regional models of impacts on streamflow have been published for Joint Front Range, Colorado, America (Woodbury et al. 2012), and the central Columbia River basin (Donley et al. 2012). The study for Joint Front Range, Colorado, employed two hydrologic models to simulate streamflow, namely WEAP, and Sacramento by the National Weather Service River Forecast System. These models were calibrated by comparing the sensitivity of each model under climate change and normal conditions. However, this study used average monthly parameters for climate condition instead of average annual parameters.

The study of the central Columbia River basin analysed the sensitivity of late summer flows needed for listed salmonoids under climate variations (Donley et al. 2012). The work employed single or combinations of various scenarios, such as climate change, possible changes to existing water management policy and water quantity changes due to irrigation. However, the input data for this model were not recent, with most of the water withdrawals before 2009. Neither study considered water quality.

Slaughter and colleagues (2011) developed climate change adaptation measures and a decision-support system for selected South African water boards. They report the modelling of hydrology, water use, water availability and water quality for current conditions in comparison with combined development scenarios and climate change scenarios. Climate data were derived from the outcome of downscaling from nine GCMs applying the A2 emission scenario. WEAP and the Pitman model - the latter model represents the main hydrological processes at the basin scale (Bharati and Gamage 2011) - were employed to predict changes for current conditions and the near future (2046-2065). The result from the modelling of tributary hydrology indicates that WEAP (using the FAO (Food and Agriculture Organisation) rainfall-runoff model provided a better simulation when modelling tributary hydrology than the Pitman model (Slaughter et al. 2011).

Strzepek and colleagues (1999) integrated models of water supply and water demand with irrigation management and crop growth for agricultural and water resource planning under climate change scenarios. They demonstrated the usefulness of their model with a case study for the U.S. corn belt where they modelled current conditions and scenarios for future conditions in climate, population, gross domestic product and agricultural production. This involved three general steps. First, climate factors for the decades 2010s, 2020s and 2050s were calculated from data provided by the Goddard Institute for Space Studies, the Geophysical Fluid Dynamics Laboratory and the Max Planck Institute (Strzepek et al. 1999).

In the second stage, the WATBAL model which simulates streamflow by using the observed streamflow data, rainfall and potential evapotranspiration to assess climate change impacts on river basin runoff (Matondo and Msibi 2006) was used to estimate water supply, while crop water demand was projected by dynamic process crop growth models (CERES-Maize to predict the yield of grain crop (Lizaso et al. 2003) and SOYGRO to predict the soybean yield (Egli and Bruening 1992)) and the irrigation management model CROPWAT to estimate water requirement for crop irrigation (Al-Najar 2011). Strzepek and colleagues (1999) tested a number of scenarios relating to population, technology, and development, as well as assumptions regarding institutional arrangements. In the final step, outputs of the previous stages were inputted to the WEAP model to examine potential water demand alternatives.

2.6 Climate change-related impacts in the Vu Gia-Thu Bon river basin

This section details studies on climate change impacts in the Vu Gia-Thu Bon river basin till 2013. At the moment, there are two current projects and two previous studies relating to impacts of climate change on streamflow and flood and drought trends within Vu Gia-Thu Bon river basin.

The first project is being conducted in Quang Nam and Ben Tre provinces under the National Target Program to Respond to Climate Change in the period 2009-2015, supported by the Government of Demark (Embasy of Denmark in Vietnam 2013). The objective of this project is to enhance capacity to respond to climate change through sustainable development. From 2009 to 2012, I worked for this project in Quang Nam province as a staff member of the Department of Natural Resources and

Environment. The second project currently conducted in the basin is the Land Use and Climate Change interactions in Central Vietnam (LUCCi 2013), under the sponsorship of the Federal Ministry of Education and Research of Germany. I used data, reports and other outputs from this latter project in this research.

Projections for future streamflow in the Thu Bon river basin were conducted by Nam et al. (2012). This study used rainfall data obtained from seven gauges that measured daily rainfall within or nearby the catchment. The streamflow gauge at Nong Son is the outlet of the catchment and was used to assess runoff variation and simulation. These hydro-meteorological stations have recorded data since 1981. The baseline period for Nam projections is from 1980 to 2000. Changes in short-term and long-term monthly streamflow (2040-2069 and 2070-2099, respectively) were calculated for the scenario A1B. Modelling suggested future streamflow will decline during dry seasons, but the duration of high streamflow will increase during rainy seasons (Nam et al. 2012). Importantly, the high streamflow period is predicted to shift to October-January from its present timing in September-December (Nam et al. 2012).

The impacts of climate change on hydrological disasters (floods and droughts) in Quang Nam, Viet Nam by 2020 were assessed by Quy (2011) using a range of methods including investigation and field work, statistical analyses, modelling and critical review of previous work. This study predicts that flooding area will increase from 4.76% in 2020 to 14.4% in 2100, compared to a baseline peak flood in 2007 (583.73 km^2). The length of the dry season is also projected to increase by 10 - 15 days compared to the period 1980-1999, while the risk of drought is likely to intensify in midland and coastal plain areas (Quy, 2011).

Chapter 3: Results – using the WEAP model to predict water availability under several climate change scenarios

3.1 WEAP description

In recent decades, the integrated water resource management approach has increasingly replaced conventional simulation models to sustainably manage limited water resources. The Water Evaluation and Planning System (WEAP) developed by the Stockholm Environment Institute, is an integrated practical tool to balance water resources in the context of water systems (supply, demand and quality), ecosystem preservation and policy orientation. The role of WEAP is to provide a straightforward, comprehensive and easy-to-use tool to support planners, so that:

(i) As a database, the system allows users to maintain historical water demand and supply information for short-term and long-term analysis.

(ii) As a forecasting tool, this system provides the ability to simulate water flow, demand supply and storage and generation, treatment and discharge of water pollution.

(iii) As a policy analysis tool, a full range of scenarios or development and management alternatives would be evaluated by WEAP. WEAP is also able to prioritize multiple and competing users, thereby effectively allocating water resources.

WEAP may be applied to a wide range of uses and geographical scales, from agriculture to urban and from single sub-basins to complex catchments. A nodal structure is used to simulate water supplies and demands (Strzepek et al. 1999). Moreover, WEAP enables analysis of a broad range of “what if?” scenarios (Hammouri 2009). In general, the use of WEAP includes several stages:

(i) Set up analysis: identify the spatial and temporal framework, components of the system and configuration of the problem.

(ii) Set up Current Accounts: provide baseline data for present water demand, pollution loads, supplies and resources for WEAP.

(iii) Scenario construction: alternative sets of future assumptions are based on policies, costs, technological development and other factors affecting demand, pollution, supply and hydrology. These scenarios are called Reference Scenarios and are used to answer a wide range of "what if?" questions.

(iv) Finally, the evaluation step tests the results of previous scenarios respecting water sufficiency, benefits and costs, sensitivity to uncertainty in key variables and compatibility with environmental targets.

Components in the water system are represented by River, Diversion, Reservoir, Demand Site, Groundwater, Catchment, Runoff/infiltration, Transmission Link, Wastewater Treatment Plant, Return Flow, Run-of-River Hydro, Flow Requirement and Streamflow Gauge (Figure 3-1). A River is described by a number of reaches. A Diversion withdraws water from a river and then diverts this flow to the other river. The diversion is considered as a river with the diverted flow as its headflow. The flow into the first reach of a river is defined as headflow.

A reservoir is considered as a demand site in WEAP so that the reservoir will not be drained unless to satisfy downstream demands. A Demand Site may be identified as a number of water users or actual physical infrastructures in a region (but located out-of the river) such as well fields, withdrawal facilities, pumping stations and wastewater treatment plants. Depending on the level of data available, the Demand Site could be aggregated into Demand Sites or divided into individual Demand Sites. A Transmission Link directly connects a Demand Site and a River (surface water), an aquifer (groundwater), or other supplies. This could include reused wastewater outflow from wastewater treatment plants and demand sites to be delivered to other demand sites. A reservoir in WEAP is divided into different functional zones, including Flood Control Zone, Conservation Zone, Buffer Zone and Inactive Zone (Figure 3-2).

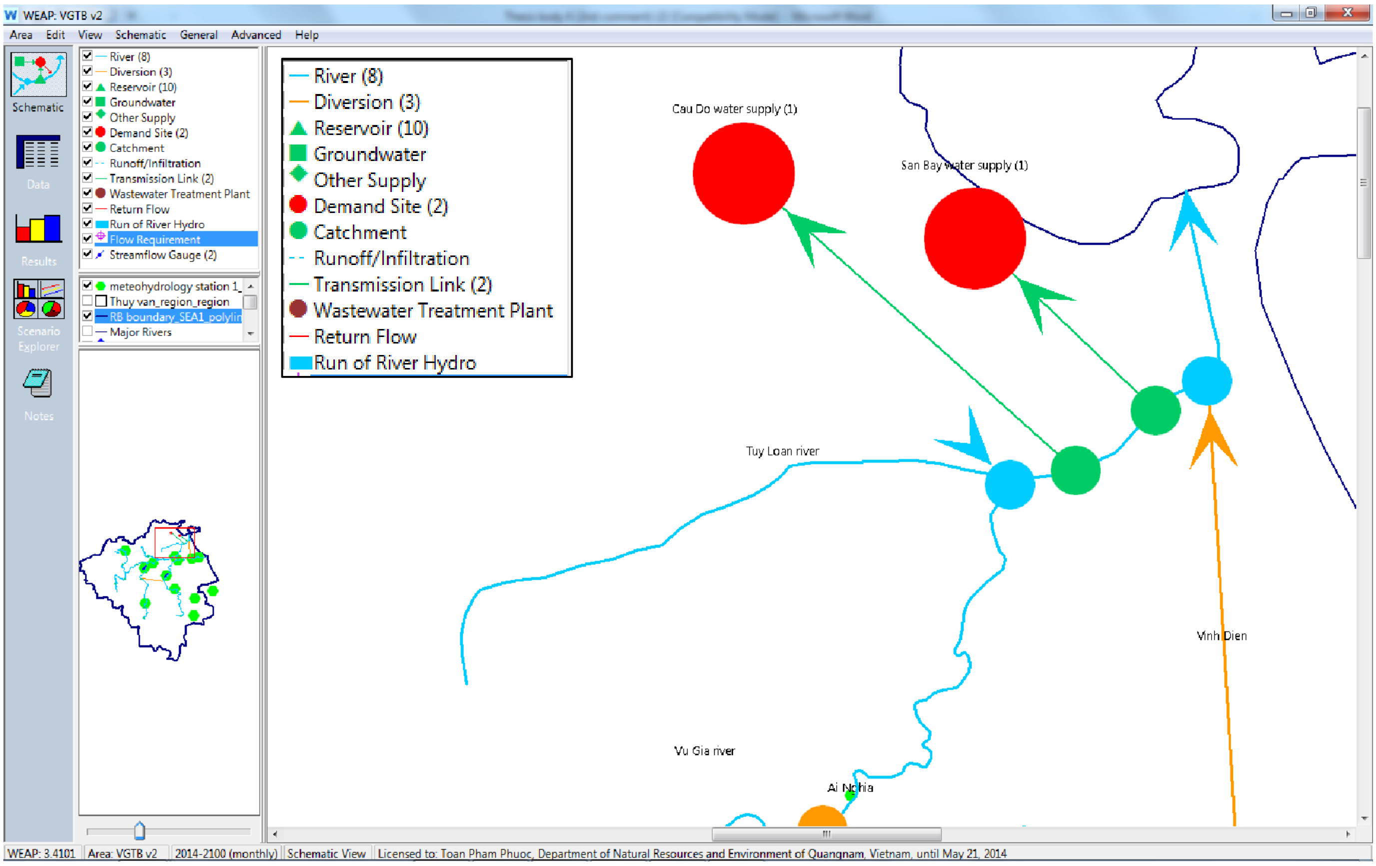

Figure 3-1 The WEAP graphical user interface.

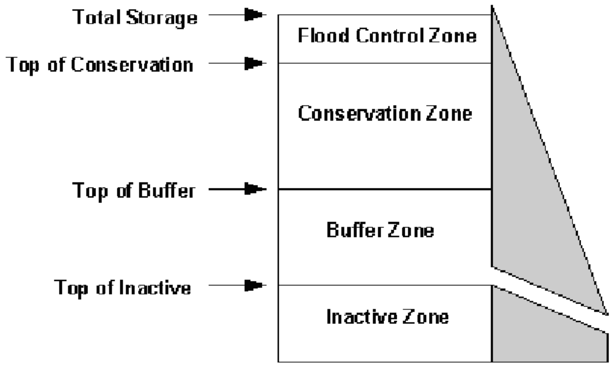

Figure 3-2 Reservoir structure in WEAP (reproduced from Stockholm Environment Institute 2011).

A Catchment is an area defined by the WEAP user, where specific processes occur such as runoff, evapotranspiration, precipitation, and irrigation on non-agricultural and agricultural land. Runoff/infiltration Links pass runoff and infiltration flow from river basins to groundwater nodes, rivers and reservoirs. An aquifer is defined by the Groundwater term. The aquifer may be hydraulically linked to catchments, rivers and reservoirs or man-made transmission links to demand sites and wastewater treatment plants. A Return Flow represents a percentage of the outflow from a demand site or the amount of water that is not consumed by the demand site. This amount of water may be directed to other demand sites, surface or groundwater nodes and wastewater treatment plants. Wastewater treatment plants also have Return Flow to demand sites, local supply sources and river nodes.

It is important to understand how WEAP simulates water quantity for each node and link. The foundation of WEAP is the mass balance equation. WEAP assumes that monthly total inflows equal total monthly outflows and net of any change in storage (in case of aquifers and reservoirs) from every node and link in the water system. The equation is described as below:

$$\sum_{\text{Inflow}} = \sum_{\text{Outflow}} + \text{AdditionToStorage}$$

$$\text{Or: } \sum_{\text{Inflow}} - \sum_{\text{Outflow}} - \text{AdditionToStorage} = 0 \qquad \text{Equation (2)}$$

The AdditionToStorage is a positive or negative value for an increase or decrease in storage, respectively. The allocation to demand sites depends on supply preferences and demand priorities. WEAP allocates water to demand sites with Priority 1 before satisfying that of Priority 2 and so on. If there are many demand sites with the same priority and limited water, WEAP strives to satisfy their demands with the same percentage of water.

The concentration of water quality variables are simulated by several methods, including simple mixing (mass balance), first-order decay, biochemical oxygen demand and dissolved oxygen, or by linking to QUAL2K software. In the simplest assumption, the concentration of surface water in a river is modelled by the mass balance equation.

$$c = \frac{Q_w C_w + Q_r C_r}{Q_w + Q_r}$$

c is the new concentration (mg/L)

Q_w is the flow of wastewater discharged (m^3/time)

C_w is the concentration of pollutant in the wastewater (mg/L)

Q_r is the flow of receiving water (m^3/time)

C_r is the concentration of pollutant in the receiving water (mg/L)

Equation (3)

The ability to link to other programs is one advantage of WEAP. For example, a MODFLOW-2000 model may be linked to a WEAP model. The MODFLOW-2000 model is a three-dimensional finite-difference platform for groundwater with steady and non-steady flow. A range of aquifer layers can be incorporated in MODFLOW-2000 such as confined, unconfined or a combination of both. Alternatively, a MODPATH model may be linked to a WEAP model. The MODPATH model is also a finite-difference groundwater flow model developed to calculate flow paths by the use of output of steady-state or transient groundwater flow from MODFLOW. QUAL2K models can also be linked to a WEAP model.QUAL2K models are one-dimensional, steady state and instream water quality models for laterally and vertically well-mixed channels. The concentrations of water variables that can be modelled include ammonia, organic and inorganic phosphorous, nitrate, algae, sediment, pathogens and pH.

However, WEAP models have some limitations in simulating water systems. First, WEAP models do not model water quality in reservoirs and groundwater. The water constituents in reservoirs and aquifers are modelled in MODFLOW-2000, MODPATH and QUAL2K and then linked to the WEAP model. Therefore, WEAP users must also learn how to model in these programs. Secondly, spatial data, particularly river topography and shape, are not considered in WEAP models. Instead, WEAP assumes that all rivers are located on a flat surface. This assumption may lead to inaccuracy in computing instream flows. Thirdly, WEAP does not accept most coordinate systems to properly place spatial data on the WEAP- incorporated global map.

3.2 Data requirements

Modelling real systems requires a large amount of data. Therefore, gathering data is one of the most important steps. Generally, the more detailed the data, the better the model outputs. In general, the

WEAP user is expected to provide spatial data, supply demand data for all sectors, priorities and preferences for supply, transmission link data, hydrology, groundwater, reservoirs, other supply sources, surface water quality and wastewater treatment facilities. My analysis incorporates spatial data, climate data (precipitation and temperature), streamflow data, demand data (water users) and master plans. These data are clarified below.

3.2.1 Spatial data

I collected spatial data to create the Schematic View in the WEAP graphical user interface. The Schematic View is an easy-to-use drag-and-drop graphical interface for describing and visualizing the physical features of demand and supply sites in the water system. Spatial data includes maps, schematics and figures of river networks, reservoirs, urban and agricultural sites, hydro-meteorological stations and sub-basins in the catchment. Data can be in raster or vector format, but raster data are digitised to vector data for input to the WEAP model.

3.2.2 Precipitation data

As previously described in Section 1.4, there are 18 rainfall stations within the catchment. However, I used data from only 12 stations due to missing data in some years or months at six of the stations. The 12 stations I used have long historical datasets: more than 30 years' observation for most of the stations. Therefore, I used 30-years of precipitation data to represent the whole catchment.

In this section, I concentrate on the Tra My, Da Nang and Hoi An stations to analyse general climate condition for the basin. Data for the other stations are given in Table 3-1 (monthly and annual average precipitation). The Tra My station represents upstream precipitation, while the stations of Da Nang and Hoi An represent downstream reaches of the Vu Gia and Thu Bon Rivers, respectively. The available daily rainfall data for each of the Tra My, Da Nang and Hoi An stations extends from 01/02/1977 to 31/12/2012, 01/01/1970 to 31/12/2012 and 01/01/1976 to 31/12/2012, respectively.

Annual rainfall for Tra My (1977-2012), Da Nang (1970-2012) and Hoi An (1976-2012) stations are given in Figures 3-3, 3-4 and 3-5, respectively. Overall, precipitation increased at all stations during the observed periods. Of these, precipitation increased most at Da Nang station. Monthly average rainfall for three stations indicates two seasons per year, namely the dry season from January to August, and the rainy season from September to December (see Figure 3-6). Rainfall rapidly increases in May at the upstream station (Tra My), triggering the so called May-rain flood or periodic minimum flood. Precipitation peaks in October and November at the upstream station. Similar rainfall patterns occur at the downstream stations (Da Nang and Hoi An) with the dry season from February to April and the largest floods in October.

Annual average rainfall since 2000 increased relative to the baseline period (1980 – 1999) at all stations except for Hoi An. Average rainfall between 2000 – 2012 increased by approximately 200mm at Tra My station and 250mm at Da Nang station. Conversely, precipitation decreased by about 139mm at Hoi An station. This can be explained by the anomalies in 1999 with the high recorded rainfall of approximately 4,260mm and low recorded rainfall of less than 1,500mm in 2003, 2003 and 2012. If the data in 1999 is excluded from the baseline period, annual average precipitation at Hoi An station reduces by approximately 35mm. The most likely reason for this is that rainfall levels at this station have been falling in the declining phase of climate cycle.

Table 3-1 Monthly and annually average precipitation (mm) for Tra My, Da Nang and Hoi An stations.

Station	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Tra My	156.1	67.5	68.9	101.7	274.4	209.9	168.7	220.9	416.6	951.6	984.4	461.7	4,082
Da Nang	72.5	23.7	22.8	37.2	88.2	92.2	94.1	144.8	346.3	656.0	450.0	199.1	2,227
Hoi An	80.0	30.5	23.6	40.1	80.9	79.8	64.4	126.8	343.0	598.0	468.8	229.1	2,165

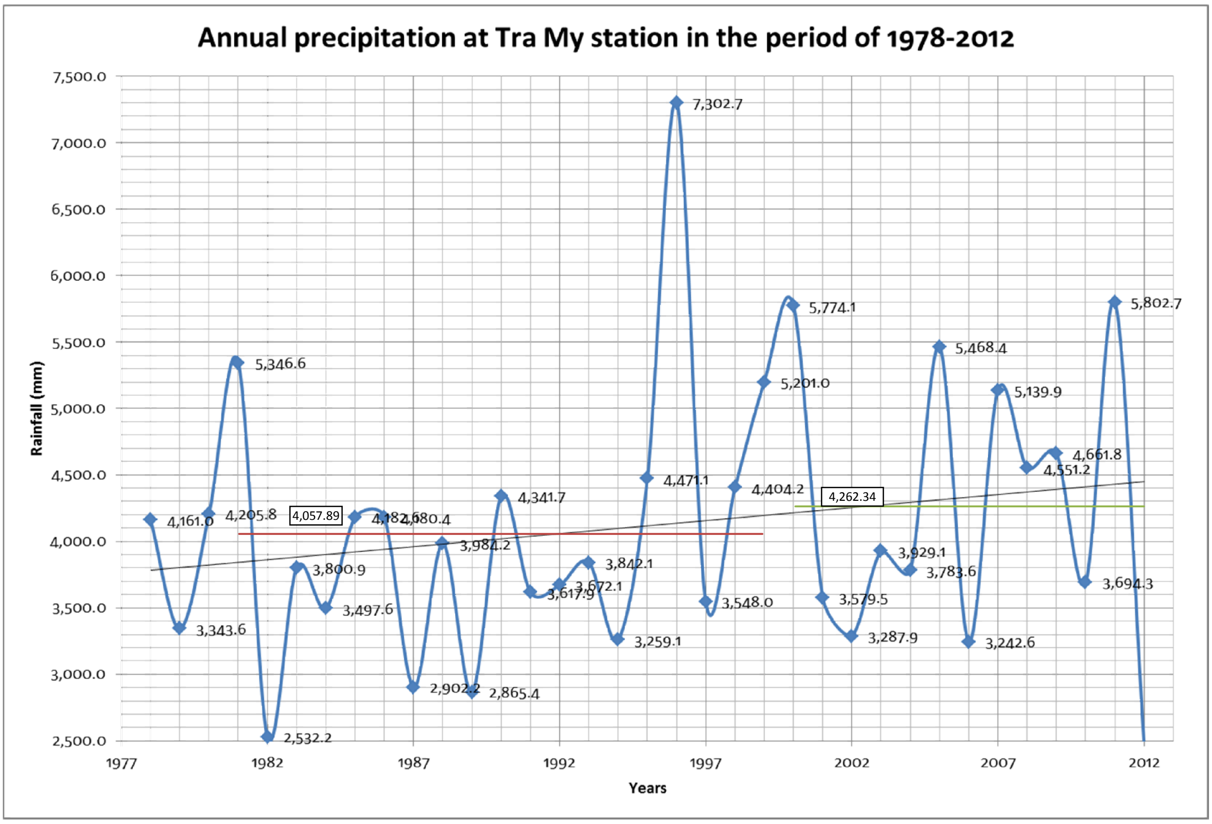

Figure 3-3 Annual rainfall at Tra My station, the red line and green line represent average rainfall in the baseline period and the period of 2000 and 2012, respectively.

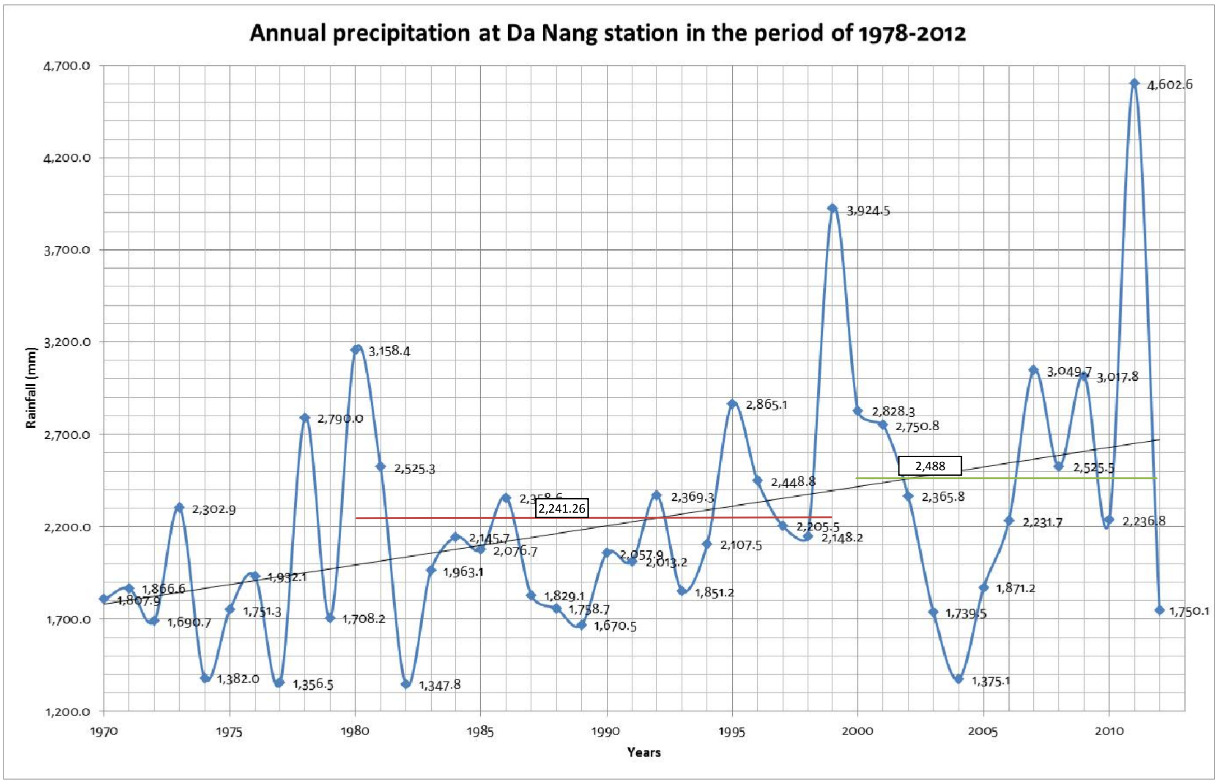

Figure 3-4 Annual rainfall at Da Nang station, the red line and green line represent average rainfall in the baseline period and the period of 2000 and 2012, respectively.

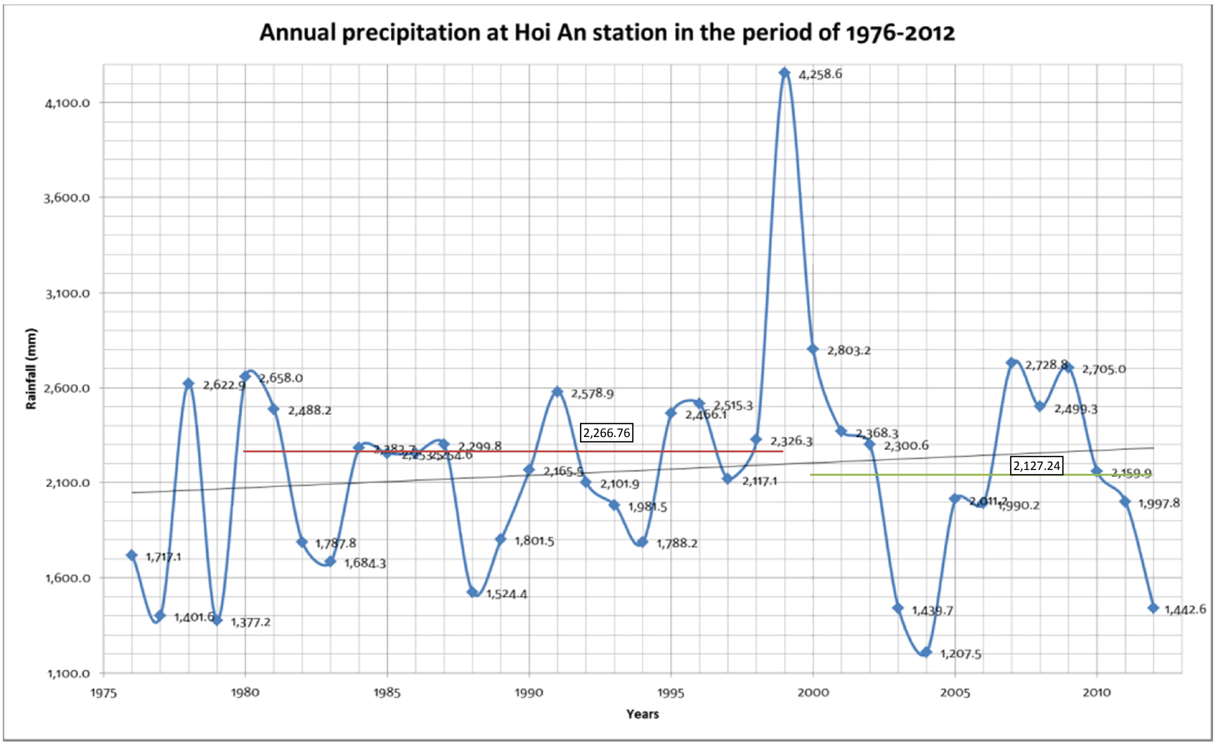

Figure 3-5 Annual rainfall at Hoi An station, the red line and green line represent average rainfall in the baseline period and the period of 2000 and 2012, respectively.

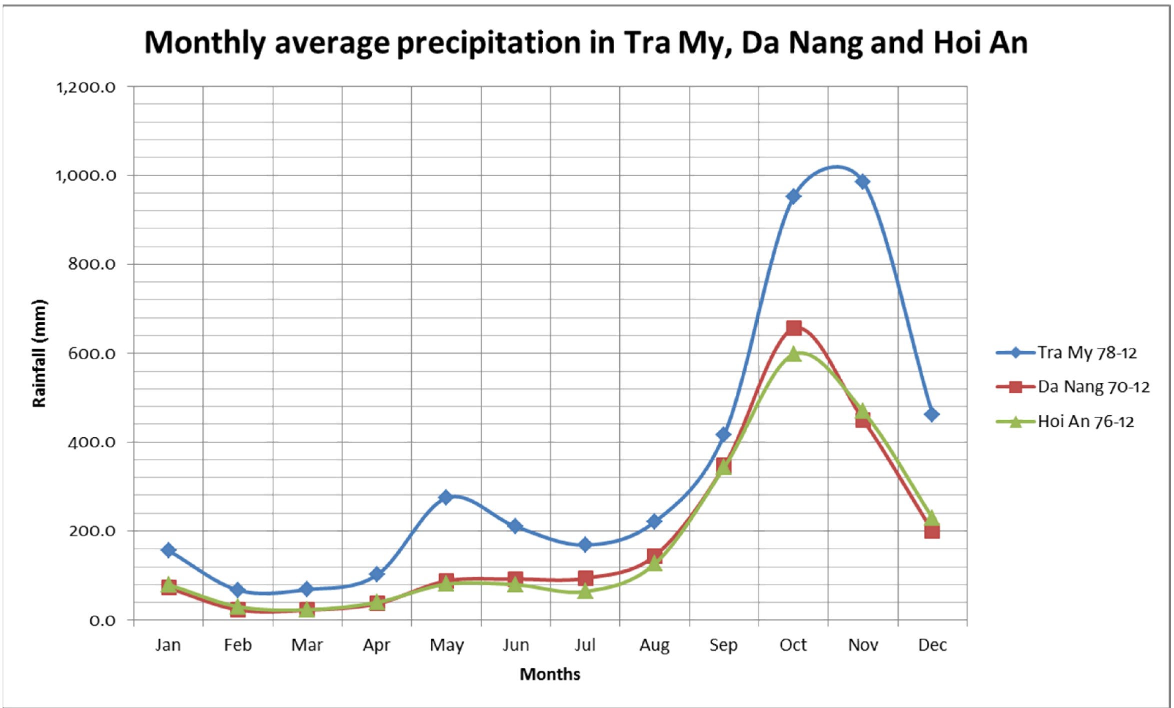

Figure 3-6 Monthly average rainfall at Tra My, Da Nang and Hoi An stations.

3.2.3 Temperature data

There are two temperature stations in the catchment. The Tra My and Da Nang stations have recorded temperature in the catchment for more than 30 years. The Tam Ky station located in the north-east of the basin also monitors temperature for the region. As with rainfall, the Tra My station records daily temperature for upstream reaches whereas the Da Nang and Tam Ky stations record daily temperature in downstream reaches. Tra My station has recorded temperature from 01/01/1978 to 31/12/2012. Da Nang and Tam Ky stations have recorded temperature from 01/01/1976 to 31/12/2012 and 01/01/1979 to 31/12/2011, respectively.

Average annual temperatures increased at all three stations through the observed periods (see Figure 3-7). Temperatures at the downstream stations increased more rapidly than at the upstream station. Compared to the baseline period, annual upstream temperature increased by 0.14^{0}C from 24.46^{0}C to 24.6^{0}C (Tra My station), by 0.26^{o}C, from 25.70^{0}C to 25.96^{0}C (Da Nang station) and by 0.23^{0}C, from 25.57^{0}C to 25.80^{0}C (Tam Ky station). Annual average temperatures are 24.50^{0}C for Tra My station (upstream reaches), and 25.77^{0}C (Da Nang station) and 25.65^{0}C (Tam Ky station) for downstream reaches, respectively.

Monthly average air temperature is high from the end of March to October. Monthly average temperatures peak in June and July in both upstream and downstream reaches of the catchment, about 27^{0}C and greater than 29^{0}C, correspondingly, (see Figure 3-8). However, the temperature speedily decreases in November to February.

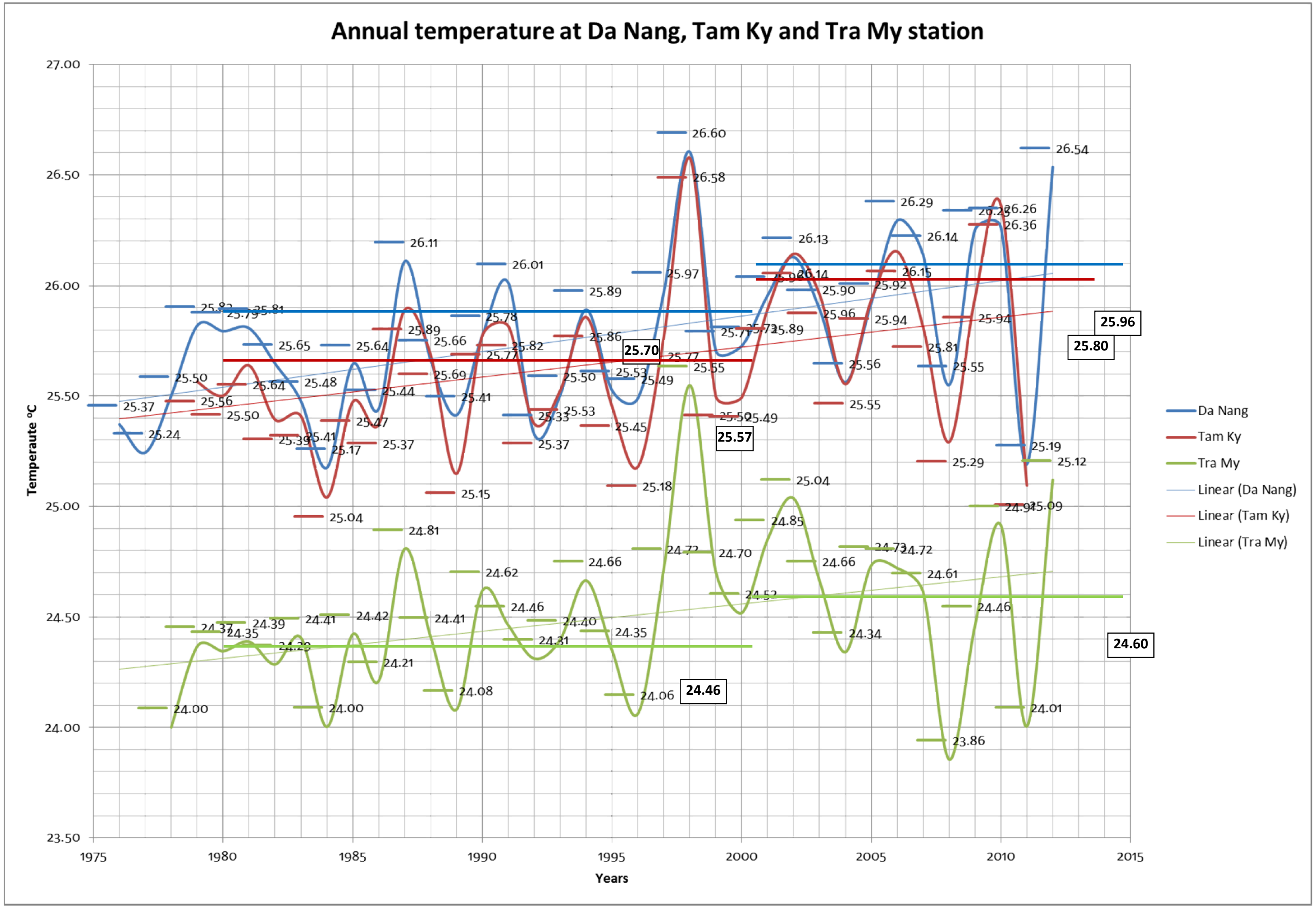

Figure 3-7 Annual average temperature at Da Nang, Tam Ky and Tra Mi stations.

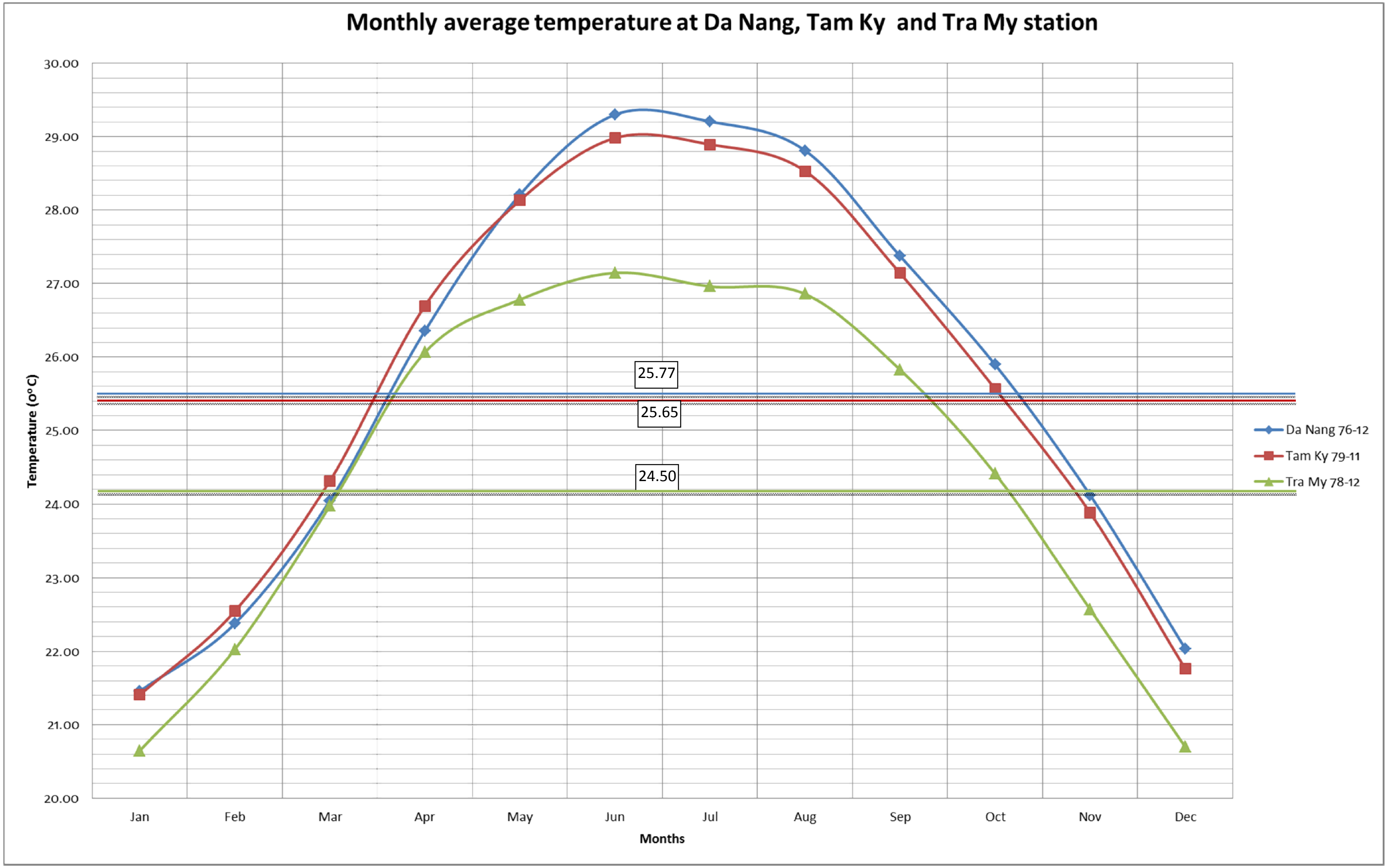

Figure 3-8 Monthly average temperatures at Da Nang, Tam Ky and Tra My stations.

3.2.4 Evaporation data

As with temperature, evaporation data is taken from Da Nang, Tam Ky and Tra My stations from 01/01/1976 to 31/12/2011, 01/01/1979 to 31/12/2012 and 01/01/1978 to 31/12/2011, respectively. Annual average evaporation decreased over these periods at all stations, but most abruptly at Tra My station than the two plan stations. Conversely, annual average evaporation decreased considerably over the period 1983 to 1999, with larger decreases recorded by the plain stations than the Tra My station (see Figure 3-9).

Monthly average evaporation increases rapidly from March to July at all stations (see Figure 3-10). Monthly average evaporation peaks from March to late August, consistent with temperature trends (see Figure 3-8). Evaporation decreases from July to December for all stations as temperature decreases and rainfall increases. Thus, when the monthly rainfall level rises consecutively with the decrease in temperature, evaporation decreases in the river basin.

My thesis used evaporation data from 1980 to 1999 for the baseline period. The monthly average data for the baseline period is displayed in Table 3-2.

Table 3-2 Monthly average evaporation for the basin.

Station	Monthly average evaporation for the baseline period (mm/month)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Da Nang	65.44	61.47	75.98	81.18	95.67	107.83	117.60	108.77	80.15	66.71	61.04	59.67
Tam Ky	55.46	55.95	88.07	101.26	122.71	141.91	153.68	141.23	88.24	66.43	55.53	50.06
Tra My	40.14	47.05	69.39	80.07	74.90	71.25	70.20	70.48	49.15	37.77	29.00	26.78
Average	45.21	49.96	72.55	82.86	83.47	84.65	86.56	84.11	57.91	44.97	36.32	33.80

Figure 3-9 Evaporation trends observed in Da Nang, Tam Ky and Tra My stations.

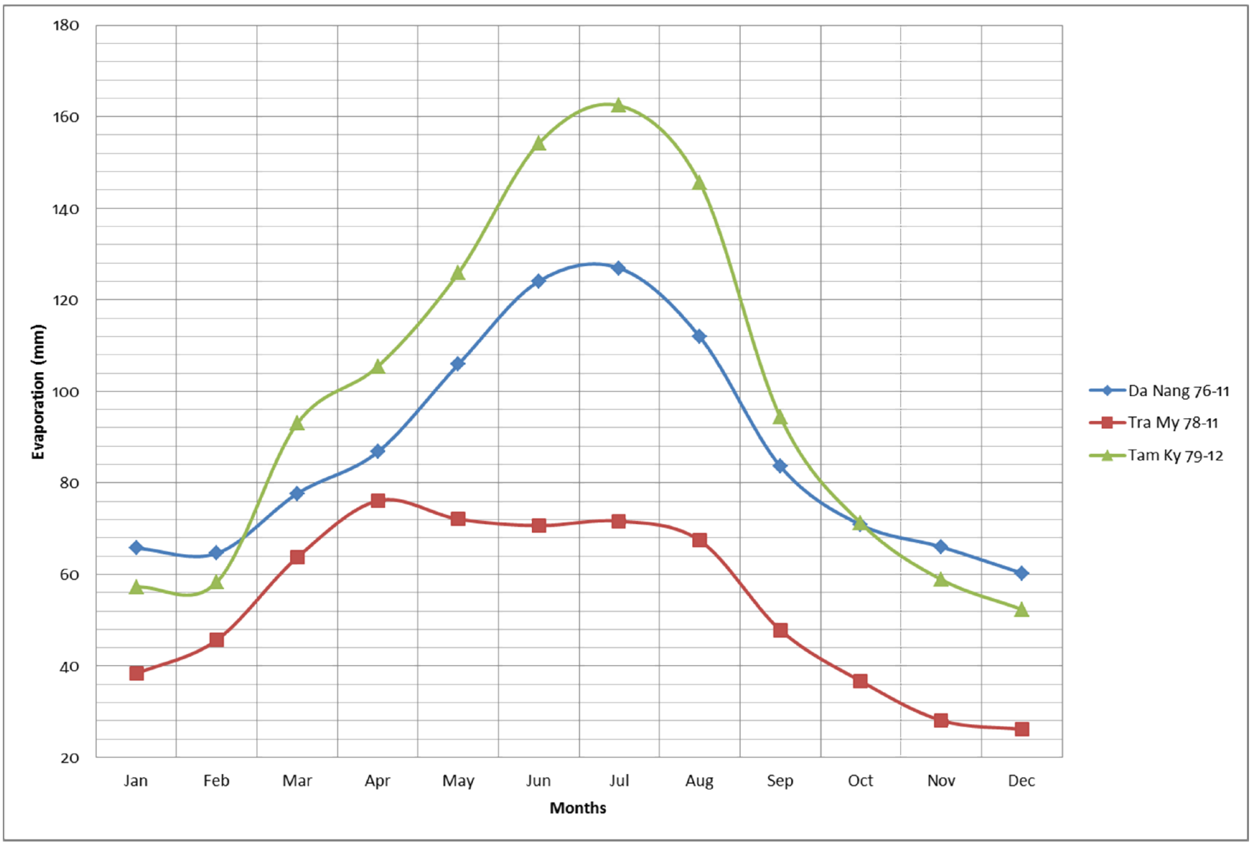

Figure 3-10 Monthly average evaporation in Da Nang, Tra My and Tam Ky stations.

3.2.5 Streamflow data

Streamflow was recorded by Thanh My and Nong Son stations for more than 20 years. The Thanh My station is located in Vu Gia subbasin with a catchment area of 1,850km^2. The Nong Son station represents the Thu Bon subbasin with a catchment area of 3,150km^2. Streamflow records for the Thanh My and Nong Son stations were collected for the period 01/01/1976 to 31/12/2011.

Similar to precipitation and temperature, annual recorded data for streamflow reveals increases at the Thanh My and Nong Son stations (see Figure 3-11 and 3-12). Increases are likely greater for the Nong Son station than the Thanh My station. In comparison to the baseline period, annual average discharges for the Thanh My and Nong Son stations increase by approximately 24cbm/s and 41cbm/s during the period 2000 - 2011, respectively.

Monthly average discharge is similar between these stations (see Figure 3-13). There are two periods of streamflow recorded at the Thanh My and Nong Son stations: the dry period occurs February to August while the flood period occurs September to January, with a rapid increase in streamflow, particularly in November. Streamflow data at both stations implies that streamflow is least in April and July, with approximately 40cbm/s for the Thanh My station and 80cbm/s for the Nong Son station. In contrast, the discharge at the two stations peaks in November, at 400cbm/s at Thanh My station and twice that at Nong Son station.

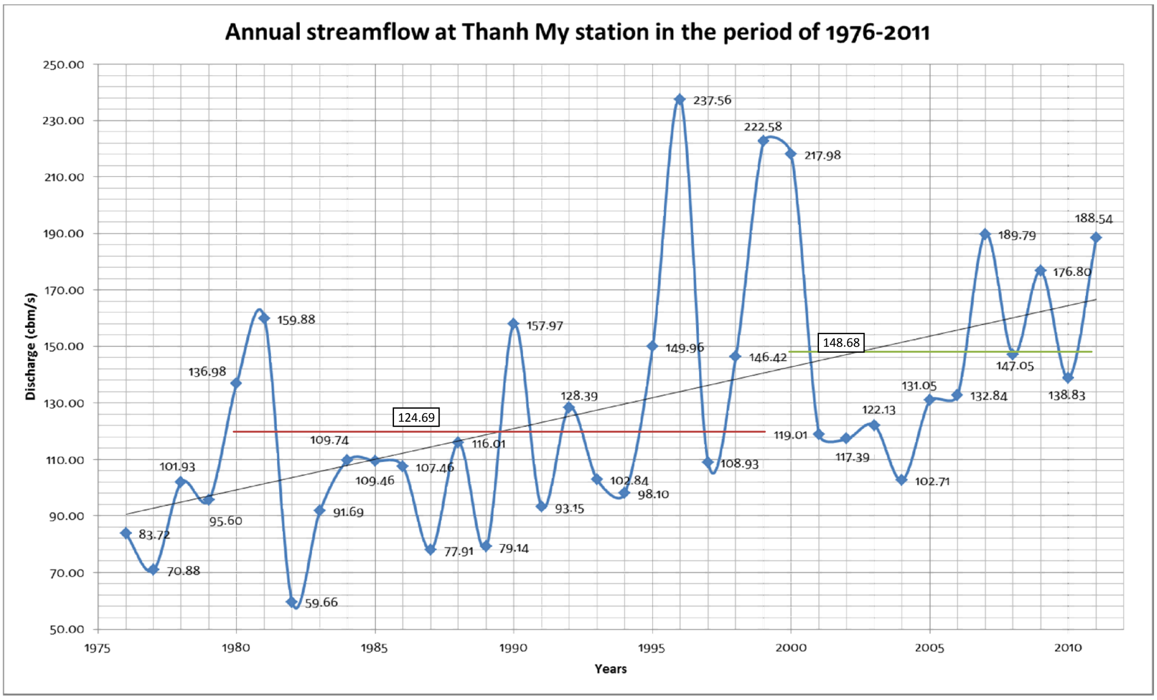

Figure 3-11 Annual streamflow at Thanh My station for the period of 1976 and 2011.

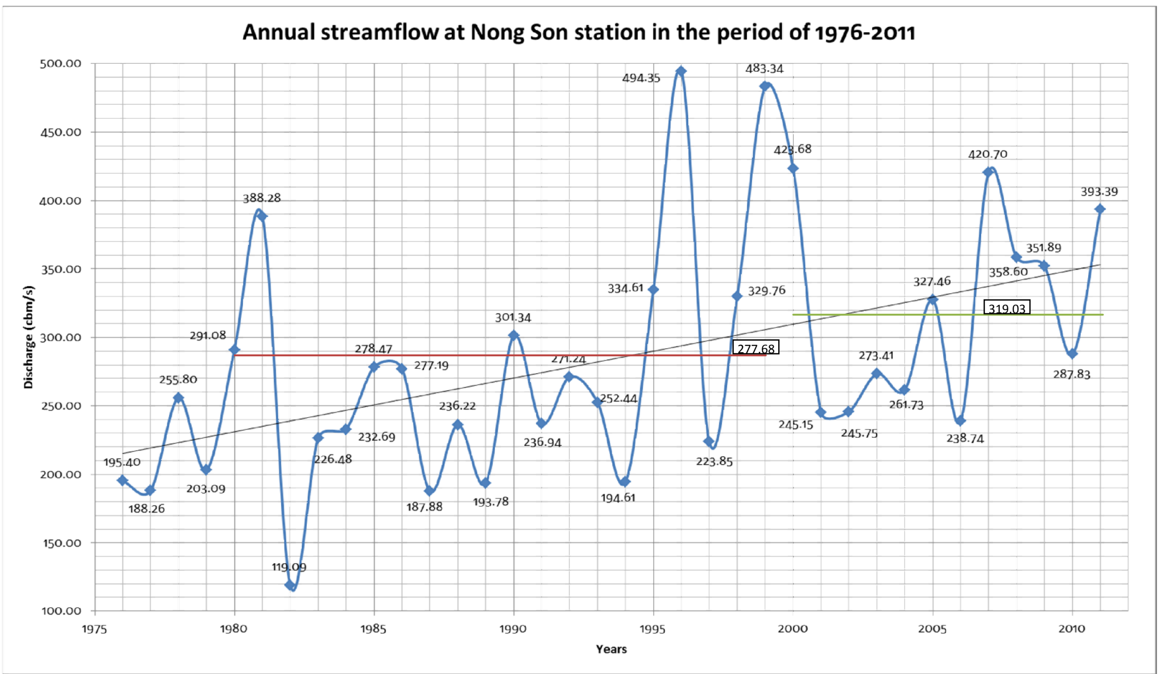

Figure 3-12 Annual streamflow at Nong Son station for the period of 1976 and 2011.

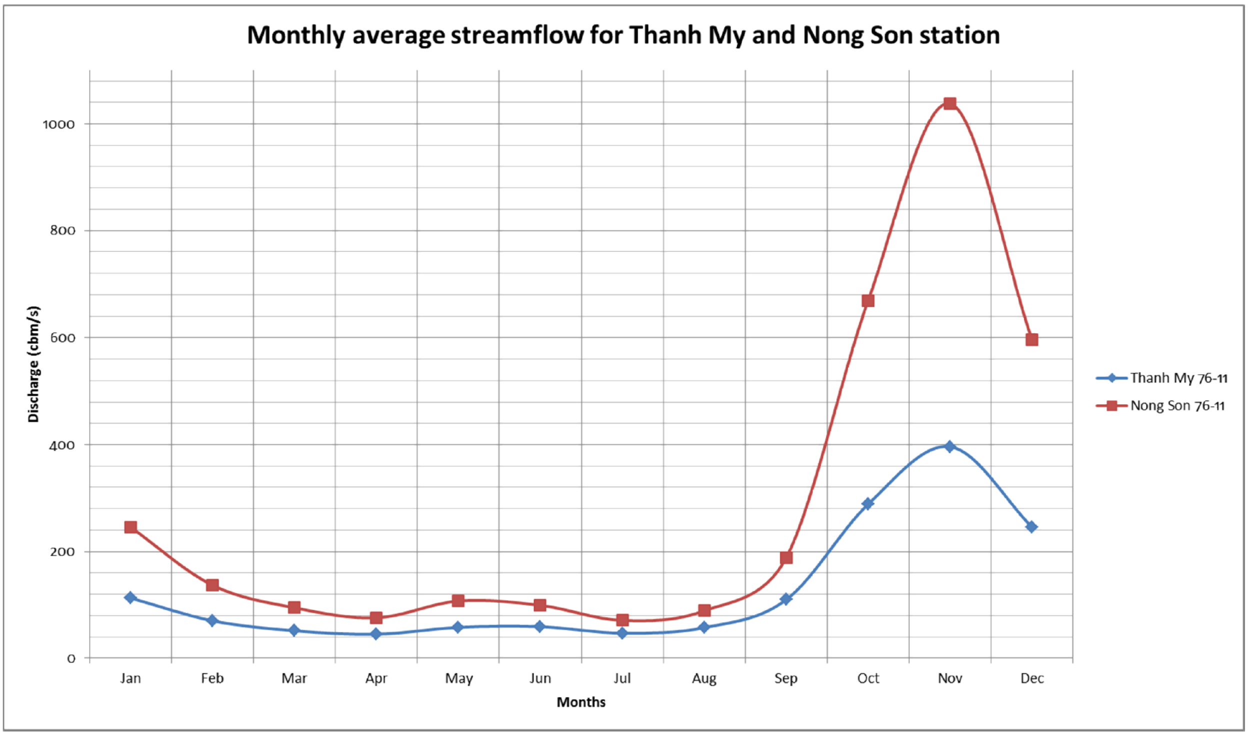

Figure 3-13 Monthly average streamflow for Thanh My and Nong Son stations.

3.2.6 Master plans

In this thesis, I gathered as many master plans as possible. These plans include socio-economic development, agriculture and rural development, construction and land use. These are listed below.

Hydropower development plan: Hydropower development plans by The Ministry of Industry and Trade and by the Quang Nam Provincial People Committee.

Socio-economic development plans: the Decision of 1114/QD-TTg dated 09 June 2013 on general socio-economic development in the North Centre and Central Coastal Zone to 2020, the Decision of 1866/QD-TTg dated 08 October 2010 on approving the master plan on Da Nang city's socio-economic development through 2020, that of Quang Nam province till 2015 at the Decision of 148/2005/QD-TTg dated 17 June 2005, and the Resolution of 85/NQ-HDND dated 04 July 2013 on the supplementation of socio-economic development plan until 2020, vision 2025.

Agriculture and Rural development plan: economic-agricultural and rural development plan of Da Nang city to 2020.

Constructional plan: the supplementation of general construction plan of Da Nang city to 2030.

Land use plan: Land use master plan of Quang Nam province until 2020 and planning for the period of 2011 and 2015.

3.2.7 Water users

Based on the above master plans, I divided water users into four groups, namely agricultural, hydropower, domestic and industrial. Environmental water use of ecosystems was not considered as water demands for ecosystems are too complicated to identify. Identification of the water requirements of ecosystems requires additional data, and financial and temporal resources beyond the scope of this thesis.

Generally, surface water use is concentrated into the three groups of agriculture, hydropower and domestic. Irrigation occurs in some locations of both Quang Nam and Da Nang, while all reservoirs for hydropower are mostly built in Quang Nam. Domestic water use for Da Nang is extracted from downstream reaches of the Vu Gia River with two stations at Cau Do and San Bay. Quang Nam exploits groundwater for most domestic water supplies. The industrial sector mainly occurs in downstream reaches of the basin. Groundwater is the primary water source for this sector. However, current groundwater use for domestic and industry supply is unsustainable.

Agriculture is the biggest water user in the catchment. According to the Department of Water Resources Management (2013), there are 78 reservoirs, 358 weirs and 147 pumping stations. This infrastructure supplies large areas of rice and crops. However, actual irrigation areas are lower than the designed capacity. Water is provided in two seasons, that is Winter-Spring (20th September to 10th April) and Summer-Autumn (10th May to 31st August). Water demand for Winter-Spring is approximately 7.500-7.800 m^3/ha and 9.700-10.500 m^3/ha for Summer-Autumn (Department of Water Resources Management 2013).

3.3 Climate scenarios for the Vu Gia-Thu Bon river basin

Climate change scenarios are the basis of my thesis. Future climate scenarios are built by combining monthly average observed climate parameters (rainfall and temperature) and medium climate scenarios (B2) developed by MoNRE (2012). Four future climate scenarios are assumed, namely (i) unchanged climate, (ii) increased temperature and unchanged rainfall, (iii) unchanged temperature and increased rainfall and (iv) increased temperature and rainfall. The baseline period for estimation was 1980 to 1999. Monthly average rainfall and temperature data are presented below.

3.3.1 Non-climate change scenario

This scenario is derived from monthly observed average temperatures and precipitation in the baseline period. Data for temperature is obtained from three stations while 12 stations provide rainfall data. Stations for temperature include two in the plains area (Da Nang and Tam Ky) and one in the mountainous area (Tra My). There are five and nine precipitation stations located in the plains and mountainous areas, respectively. Stations used for the plains region include Cam Le, Cau Lau, Da Nang, Hoi An and Tam Ky. Stations representing the mountainous regions include Ai Nghia, Giao Thuy, Kham Duc, Nong Son, Son Tan, Thanh My and Tra My. Table 3-3 shows the projected monthly average temperature and rainfall for the non-climate change scenario for the basin.

Table 3-3 Predicted monthly average temperatures and rainfall in the non-climate change scenario.

Climate parameters	Monthly											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (^{0}C)	20.76	22.08	24.08	26.13	27.09	27.57	27.41	27.33	26.14	24.80	22.89	20.77
Rainfall (mm)	63.85	33.77	28.33	62.61	170.12	148.59	108.97	126.98	331.55	719.30	616.91	254.35

3.3.2 Increased temperature and same rainfall scenario

This scenario assumes changes in temperature and constant precipitation compared with the baseline period. Temperature variations are presented in Table 3-4. In order to identify projected monthly temperatures in the future, I illustrated the increase in temperatures over ten-year periods using a linear function. The derived function is $y = 0.0289x - 57.91$ with $R^2 = 0.9845$ (where R^2 is the coefficient of determination, y is the increased value of temperature for the particular months, and x is the year of interest. Thus, future average monthly temperatures are calculated as the sum of average temperature of the corresponding month of the baseline year plus the projected future increase. As a result, the projected future temperatures may differ slightly from that projected in the medium climate change scenario (B2) by MONRE (2012).

Table 3-4 Projected average monthly temperature and rainfall in the increased temperature and same rainfall scenario.

Climate parameters	Decades in the 21st century								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Temperature (^{0}C)	25.25	25.50	25.85	26.10	26.40	26.65	26.95	27.15	27.35
Rainfall (mm)	222.11	222.11	222.11	222.11	222.11	222.11	222.11	222.11	222.11

3.3.3 Same temperature and increased rainfall scenario

Compared with the baseline period, temperature is projected to remain stable while precipitation increases slightly. At the end of the 21st century, rainfall is expected to rise 4.3% compared with the baseline period (see Table 3-5). Similar to temperature, increases in monthly future rainfall are calculated using the linear function of $y = 0.1058x - 212.21$ with $R^2 = 0.9831$. Therefore, projected future rainfall values also differ marginally from the B2 scenario previously calculated by MoNRE (2012).

Table 3-5 Projected average monthly temperature and rainfall in the same temperature and increased rainfall scenario.

Climate parameters	Decades in the 21st century								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Temperature (^{0}C)	24.75	24.75	24.75	24.75	24.75	24.75	24.75	24.75	24.75
Rainfall (mm)	224.00	224.78	226.00	227.11	228.22	229.22	230.11	230.88	231.66

3.3.4 Increased temperature and precipitation scenario

Both temperature and rainfall are predicted to increase. Temperature is projected to rise by up to 2.6^{0}C while precipitation is expected increase 4.3% at the end of this century. Projected climate variations in temperature and precipitation in the Vu Gia-Thu Bon catchment are given in Table 3-6. The monthly average future values of temperature and rainfall are incorporated by the two preceding climate change scenarios.

Table 3-6 Projected monthly average temperature and rainfall in the increased temperature and precipitation scenario.

Climate parameters	Decades in the 21st century								
	2020	2030	2040	2050	2060	2070	2080	2090	2100
Temperature (^{0}C)	25.25	25.50	25.80	26.10	26.40	26.65	26.95	27.15	27.35
Rainfall (mm)	224.00	224.78	226.00	227.11	228.22	229.22	230.11	230.88	231.66

3.4 Hydropower development scenario

According to the Hydropower Development Plan for the Vu Gia-Thu Bon river basin, there are 44 potential plants with a total capacity of 1,584.6Mw. These comprise 10 cascade hydropower plants or large hydropower plants that are located in the catchment. Other medium and small scale plants are situated in tributaries. Currently, there are 13 constructed plants with a total capacity of 766.7Mw, comprising five large scale plants (A Vuong, Song Con 2, Song Tranh 2, Dak Mi 4 and Song Bung 6), and eight medium and small scale reservoirs (Khe Dien, Dai Dong, Song Cung, Za Hung, Tra Linh, An Điem 2, Ta Vi, and Dak Mi 4C).

Nine projects are under construction with a total capacity 654Mw, including five large scale plants (Song Bung 2, Song Bung 4, Song Bung 5, Dak Mi 2, and Dak Mi 3), and four medium and small scale projects (Song Bung 4A, Tr'Hy, Song Tranh 3, and Song Tranh 4). With the exception of Dak Mi 2 and Dak Mi 3, these hydropower plants are expected to commence operations in 2015. Nineteen other medium and small scale projects are currently being assessed for feasibility, comprising Dak Pring, Cha Val, Dak Di 1, Dak Di 2, A Vuong 3, Song Bung 3A, Nuoc Bieu, Nuoc Che, Dak Di 4, Song Bung 3, Dak Sa, A Vuong 4, Nuoc Buou, Tra Linh 2, Nuoc Xa, Dak Pring 2, Tam Phuc, and Ag Rong. They are expected to contribute to a total of 158.46Mw and commence operation by 2020.

This section considers the 10 cascade projects, which are annual regulated reservoirs. These hydropower plants are predicted to crucially affect flow regimes of the main rivers in the catchment. All the proposed large scale hydropower plants (A Vuong, Song Con 2, Song Tranh 2, Dak Mi 4, Song Bung 6, Song Bung 2, Song Bung 4, Song Bung 5, Dak Mi 2, and Dak Mi 3) are expected to be operational by 2015. Table 3-7 provides the basic parameters of these projects.

Table 3-7 Characteristics of the ten large hydropower projects in the Vu Gia-Thu Bon basin.

Name	Total volume (M. m^3)	Inactive volume (M. m^3)	Maximum turbine discharge (m^3/s)	Basin area at dam (km^2)	Average annual flow (m^3/s)
A Vuong	343.55	77.07	78.4	682	39.8
Song Con 2	30	4.28	9.7	248	15
Song Tranh 2	733.4	212.3	185	1,100	106
Dak Mi 4	313	154.29	128	1,125	71
Song Bung 6	3.29	3.29	239.8	2,386	119
Song Bung 2	94.3	20.4	35	334	22
Song Bung 4	510.8	276.81	159	1,477	86
Song Bung 5	20.14	17.7	219	2380	130
Dak Mi 2	Data invalid				
Dak Mi 3	Data invalid				

3.5 Agricultural water use scenario

Agriculture is well developed in the catchment. There are 78 reservoirs, 358 weirs and 147 pumping stations in the entire basin. The 78 reservoirs cover an area of 289km^2 and irrigate approximately 4,882ha of rice and crops. Annual agricultural water demand is around 54,673,988m^3. Weirs cover 2,730ha of irrigated land in the watershed but are outside the scope of this study. Pumping stations play a fundamental role. They provide 14,815ha of cultivated land (13,555ha of rice and 1,259ha of crops) and use a total of 154,319.548m^3 water per year.

To simplify calculations, I divided all pumping stations into 27 groups. These are named from 1 to 27 in WEAP. These pumping stations are all operating and are therefore active in the Current Account (2014) in WEAP. Table A-1 (Appendix) describes the groups of pumps.

3.6 Domestic water use scenario

Domestic water demand is expected to increase rapidly in downstream reaches due to population growth in Da Nang and the increase in water use criteria. The population was 926,000 in 2010. The population is predicted to reach approximately 1,082,000 in 2015, and 2,200,000 in 2030 (Department of Construction of Danang City 2013). Water use per capita is assumed at 150 - 200l/day for the period of 2010 to 2020. This will increase up to 180 - 250l/day for the period 2020 - 2030. In 2030, the predicted total domestic water demand for Da Nang city is around 800,000m^3/day.

Currently, there are three domestic water supply plants to Da Nang city, including Cau Do 1 (50,000m^3/day), Cau Do 2 (120,000m^3/day) and San Bay (30,000m^3/day), with a total capacity of 180,000m^3/day. Water is extracted from the Vu Gia River. The capacity at Cau Do 1 will be increased to 170,000m^3/day by 2020, while the capacity of Cau Do 2 will increase to 240,000m^3/day by 2030. Table 3-8 summarises the domestic water use scenarios for the watershed.

Table 3-8 Current and predicted domestic water development scenarios for the Vu Gia-Thu Bon basin.

Plan	Capacity (m^3/day)		
	2014	2020	2030
Cau Do 1	50,000	170,000	170,000
Cau Do 2	120,000	120,000	240,000
San Bay	30,000	30,000	30,000

Chapter 4: Future trends

In this Chapter, I predict the impacts of climate change on water resources in Vu Gia-Thu Bon river basin in terms of:

1. Water Availability,
2. Streamflow of the Vu Gia and Thu Bon River,
3. Catchment Evapotranspiration (ET potential),
4. Catchment Actual Evapotranspiration (ET Actual),
5. Reservoir Evaporation,
6. Runoff Flow,
7. Hydropower Generation, and
8. Reservoir Storage Volume.

The future trends of climate impacts are projected by the combination of two story-lines of future climate scenarios and hydropower development scenarios. There are four climate change scenarios:

1. Unchanged climate,
2. Increased temperature and unchanged rainfall,
3. Unchanged temperature and increased rainfall, and
4. Both increased temperature and rainfall.

Hydropower development includes the non-hydropower and hydropower development described in Section 3.4 with two cases of water returned to the Dak Mi River from the Dak Mi 4 hydropower plant. When the Dak Mi 4 plant diverts water from the Dak Mi River (upstream of the Vu Gia River) to the Tranh river (upstream of the Thu Bon River), water deficit may occur in downstream reaches of the Vu Gia River. Therefore, Da Nang city requires the Dak Mi 4 plant to release the minimum discharge of $25m^3/s$. However, future average minimum discharge requirements are proposed of $8m^3/s$ (MoNRE 2014). I have considered both scenarios of water release into my modelling. Consequently, I have modelled 12 scenarios.

To satisfy all conditions for the Dak Mi 4 project, the plant is divided into five components (see Figure 4-1). They are a Dak Mi 4 online reservoir with the original physical features located in the Dak Mi River and a diversion to divert water from the Dak Mi 4 reservoir to the Song Tranh River. A run-of-river hydropower is placed on this diversion representing the operation of the Dak Mi 4 hydropower plant. Another diversion permanently releases water from the Dak Mi 4 reservoir to the Dak Mi River. The final component is a flow requirement on the latter diversion. The flow requirement ensures the minimum amount of water is returned to the Dak Mi River. Therefore, in the

WEAP model, I gave this the highest priority while other components were established at lower levels.

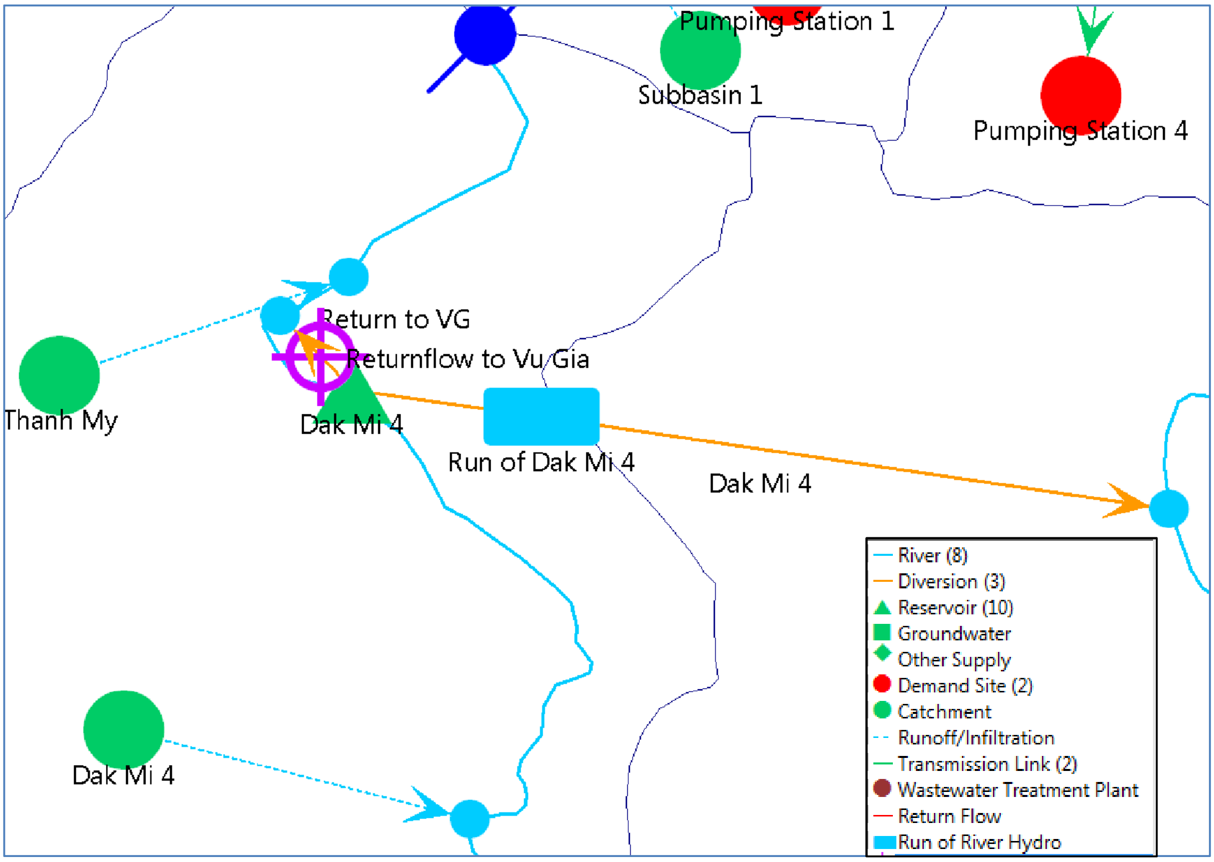

Figure 4-1 Schematic diagram of the Dak Mi hydropower components.

Before projecting all scenarios, it is important to state the model assumptions:

(1) Water demands are constant in all scenarios. There are two key forms of water use in the catchment, that is domestic and irrigation. In WEAP, these forms are illustrated as demand sites.

(2) Land conditions are homogenous for all patterns in the river basin and do not affect changes in water supply and demand in any scenario. Hence, I employed the Rainfall Runoff method (soil moisture model) to model demand sites and sub-catchments within the Vu Gia-Thu Bon river basin.

4.1 Water availability

In the catchment, increases in rainfall leads to increases in water availability, while the rise in temperature does not affect either of these. Increases in both temperature and rainfall also increase water availability at the same pattern as the unchanged temperature and increased rainfall scenario. Hydropower development in the basin significantly affects water availability.

In the absence of hydropower, there are a total of 25.5 Billion m^3 of water for the unchanged climate scenario, and the increased temperature and unchanged rainfall scenario. Increases in rainfall slightly increase water availability. This tendency also occurs in the same temperature and increased rainfall scenario, and the increased temperature and precipitation scenario (Table 4-1). By the end of the century, if precipitation increases as according to climate change scenarios, water availability is projected to increase by 4.47% compared to the unchanged climate scenario. Thus, climate change will likely increase water availability in the catchment (Table 4-1).

Table 4-1 Expected changes in water availability without hydropower development in the different climate scenarios.

Scenarios	Year - Billion m^3								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
None CC	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50
Increased T	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50
Increased R	25.67	25.79	25.91	26.03	26.15	26.28	26.40	26.52	26.64
Increased T and R	25.67	25.79	25.91	26.03	26.15	26.28	26.40	26.52	26.64

Similarly, water availability in the catchment increases marginally when rainfall increases. In addition, the development of hydropower considerably contributes to the amount of water available. However, the return of water from the Dak Mi 4 hydropower of either $8m^3/s$ or $25m^3/s$ does not significantly change water availability (Table 4-2).

Table 4-2 Projected changes in water availability with hydropower development in different climate scenarios.

Scenarios	Year - Billion m^3								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
None CC 25m^3	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55
None CC 8m^3	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55
Increase T 25m^3	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55
Increased T 8m^3	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55	29.55
Increased R 8m^3	29.72	29.84	29.96	30.08	30.20	30.32	30.45	30.57	30.69
Increased R 25m^3	29.72	29.84	29.96	30.08	30.20	30.32	30.45	30.57	30.69
Increased T and R 25m^3	29.72	29.84	29.96	30.08	30.20	30.32	30.45	30.57	30.69
Increased T and R 8m^3	29.72	29.84	29.96	30.08	30.20	30.32	30.45	30.57	30.69

Without changes to rainfall, the development of hydropower projects likely increases water availability by 15.88% in the catchment. Increasing precipitation in combination with hydropower development also contributes to growth in water availability compared with the unchanged climate with or without hydropower development scenarios, and the increase rainfall without hydropower scenario. However, the trend for each case is different.

Figure 4-2 depicts trends of water availability of different climate scenarios in combination with the hydropower development scenario. The amount of water available in the catchment steadily increases from the beginning to the end of the century in the scenario of increased rainfall with hydropower development, compared to the unchanged climate with hydropower and the unchanged climate without hydropower scenarios. Increases in water availability in the catchment are also greater for increased rainfall with hydropower development compared with increased rainfall without hydropower development. However, water availability slightly decreases by the end of the century compared to the beginning of the century.

Comparing the increased rainfall with hydropower development scenario with the unchanged climate without hydropower scenario suggests that water availability will increase 16.55% by 2020 and 20.35% by 2100. This is expected to alleviate water shortages in the catchment. Comparing the scenario of increased precipitation with hydropower with the unchanged climate but with hydropower development scenario suggests that increases in water availability are marginal, about 0.58% by 2020 and 3.86% by the end of century. Water availability is projected to grow by 15.78% by 2020, but only by 15.20% by 2100 in the scenario of increased rainfall with hydropower compared to the increased rainfall without hydropower scenario. There is strong evidence that the development of hydropower will increase water resources in the catchment.

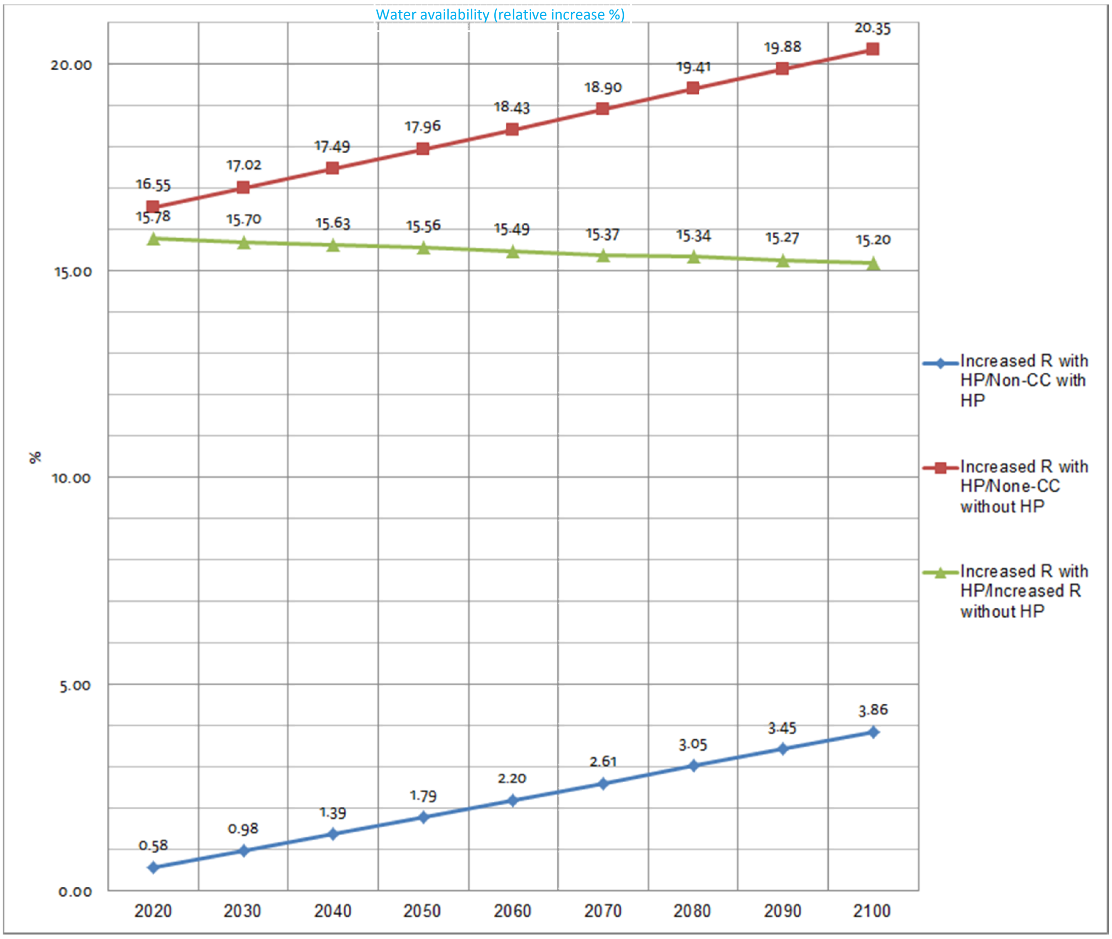

Figure 4-2 Relative increases in water availability for different climate and hydropower scenarios.

4.2 Streamflow

Here I examined streamflow in the Vu Gia River (represented by streamflow below the Tuy Loan River) and in the Thu Bon River (represented by streamflow below the Vinh Dien River) in terms of climate scenarios and hydropower scenarios. Monthly average streamflow of the no climate change scenario is compared with different climate scenarios and hydropower scenarios.

4.2.1 Annual average streamflow in the Vu Gia River

The no-hydropower scenario suggests changing streamflow in the Vu Gia River (below the Tuy Loan River) during the 21st century. Streamflow is projected to fluctuate between 213m^3/s and 213.3m^3/s in the unchanged climate scenario. Streamflow is projected to marginally decrease with temperature increases in the basin. The increase in precipitation causes a significant increase in streamflow. In the increased temperature and rainfall scenario, streamflow increases are slightly greater than those of the increased temperature scenario but lower than those of the increased rainfall scenario. By the end of century, streamflow is projected to increase by 7.1% for the increased rainfall scenario, and by only 2.3% for the increased temperature and precipitation scenario. In contrast, streamflow is predicted to decline by 4.5% compared to the unchanged climate scenario. Table 4-3 describes changes in streamflow without hydropower development below the Tuy Loan river node.

With hydropower development, streamflow below the Tuy Loan River is slightly less than in the no-hydropower development scenario. Streamflow when the Dak Mi 4 hydropower returns 25m^3/s to the Dak Mi River is similar to hydropower releases of 8m^3/s (see Table 4-4).

Table 4-3 Projected streamflow below the Tuy Loan River without hydropower projects.

Scenarios	**Year – m^3/s**							
	2030	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
None CC	213.1	213.0	213.3	213.0	213.3	213.0	213.3	213.3
Increased T	210.5	209.3	208.6	207.3	206.7	205.3	204.7	203.7
Increased R	217.0	218.4	220.4	221.6	223.6	224.9	226.8	228.5
Increased T and R	214.3	214.7	215.6	215.8	216.7	216.9	217.8	218.3

Table 4-4 Projected streamflow below the Tuy Loan River for different climate scenarios with hydropower development.

Scenarios	Year – m^3/s							
	2030	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Non CC-HP $8m^3$	212.4	212.2	212.6	212.3	212.6	212.3	212.6	212.6
Non CC-HP 25 m^3	212.4	212.3	212.6	212.3	212.6	212.3	212.6	212.6
Increased T $8m^3$	209.8	208.6	207.9	206.6	205.9	204.6	204.0	203.0
Increased T 25 m^3	209.8	208.7	208.0	206.7	206.0	204.7	204.0	203.0
Increased R $8m^3$	216.2	217.7	219.6	220.9	222.8	224.1	226.1	227.7
Increased R 25 m^3	216.3	217.7	219.7	220.9	222.9	224.2	226.1	227.8
Increased T and R $8m^3$	213.5	213.9	214.8	215.1	215.9	216.2	217.0	217.6
Increased T and R 25 m^3	213.6	214.0	214.9	215.1	216.0	216.2	217.1	217.6

4.2.2 Monthly average streamflow in the Vu Gia River

Monthly average streamflow below the Tuy Loan River node is presented in Table 4-5. Overall, the operation of hydropower considerably improves streamflow in the dry season while decreasing streamflow in the rainy season (see Figure 4-3). Monthly average streamflow is projected to particularly increase from January to April. It is likely that hydropower development in the catchment may reduce flooding in the rainy season while increasing streamflow during the dry season.

By comparing the monthly average streamflow between pairs of climate scenarios (e.g. no climate change with water returned from the Dak Mi 4 hydropower of either $8m^3/s$ or $25m^3/s$), monthly average streamflow in the dry season increases when more water is returned to the Dak Mi River. Meanwhile, monthly average streamflow in the rainy season correspondingly decreases. In particular, monthly average streamflow is expected to decrease most in October. Therefore, the Dak Mi 4 hydropower plant plays an important role in increasing streamflow in dry seasons while contributing to flood control in rainy seasons in the Vu Gia River (see Figure 4-3). The period of lowest predicted streamflow is likely to shift from February – April to July – August.

Table 4-5 Expected monthly average streamflow below the Tuy Loan river node.

Scenarios	Monthly average streamflow below the Tuy Loan river node (m^3/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Non CC	85.7	44.1	28.1	40.2	73.2	66.7	45.4	47.5	168.7	696.4	888.3	365.7
Non CC 8m^3	131.7	99.5	61.1	40.2	69.0	65.7	44.5	46.6	168.0	579.4	841.4	396.3
Non CC 25 m^3	139.8	115.9	78.1	56.0	72.4	65.9	44.6	46.7	161.5	526.8	841.4	396.3
Increased T 8m^3	125.6	99.0	56.8	38.1	63.1	61.2	41.4	43.2	159.2	563.9	828.4	390.7
Increased T 25 m^3	134.1	115.6	73.8	52.6	67.2	61.3	41.5	43.3	154.0	510.0	828.4	390.7
Increased R 8m^3	144.2	103.4	70.4	43.9	77.2	72.2	49.7	51.9	180.1	598.3	858.7	406.6
Increased R 25 m^3	150.6	118.5	87.4	60.9	82.4	72.3	49.8	52.0	171.2	548.0	858.7	406.6
Increased T and R 8m^3	136.5	102.3	67.2	41.6	71.0	67.3	46.2	48.3	170.7	582.6	845.6	400.9
Increased T and R 25m^3	143.5	117.7	84.2	58.6	75.4	67.4	46.4	48.4	163.3	530.9	845.6	400.9

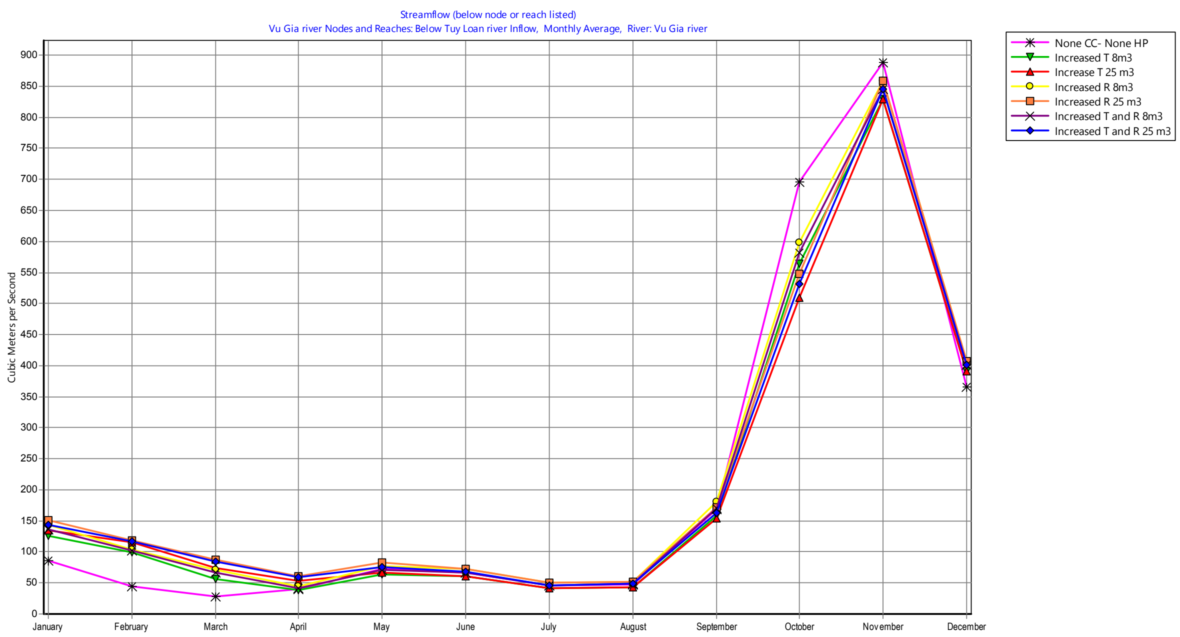

Figure 4-3 Monthly average streamflow in the Vu Gia River under different climate and hydropower development scenarios.

4.2.3 Annual average streamflow in the Thu Bon River

Similarly to the Vu Gia River, annual average streamflow in the Thu Bon River demonstrates the same pattern for all climate change scenarios without hydropower projects (see Table 4-6). The annual streamflow for the unchanged climate scenario fluctuates between 151.3 and 151.5m^3/s. In the increased temperature without change in rainfall scenario, streamflow decreases steadily. By the end of the century, streamflow is projected to decrease by roughly 5% compared to the unchanged climate scenario. In contrast, increase in precipitation without change in temperature results in considerably more streamflow. Under the increased temperature and precipitation scenario, streamflow marginally increases throughout the century by approximately 7.1%. Under the increased temperature and increased precipitation scenario, streamflow is projected to increase by 1.6% by the end of the century.

Table 4-6 Expected annual average streamflow of the Thu Bon River without hydropower.

Scenarios	**Year – m³/s**							
	2030	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
None CC	151.4	151.3	151.5	151.3	151.5	151.3	151.5	151.5
Increased T	149.3	148.3	147.7	146.7	146.1	145.1	144.5	143.7
Increased R	154.1	155.1	156.5	157.4	158.8	159.7	161.1	162.2
Increased T and R	152.0	152.1	152.6	152.6	153.1	153.2	153.6	153.9

Table 4-7 shows changes in annual streamflow of the Thu Bon River under different climate change scenarios with the operation of hydropower. No change in annual streamflow is predicted between the corresponding climate scenarios (e.g. the increased temperature scenario) in combination with different operation scenarios of hydropower. This indicates that the return of water from the Dak Mi 4 hydropower station with either 8m^3/s or 25m^3/s to the Dak Mi River does not significantly change annual average streamflow of the Thu Bon River under the same climate scenario. However, the presence of hydropower projects in the catchment significantly changes river streamflow in the Thu Bon River.

Without climate change, hydropower development increases annual streamflow in the Thu Bon River by 84.5% by 2100. When only temperature increases, streamflow increases by 79.3%, whereas under the increased rainfall without temperature change scenario, streamflow is projected to increase by 91.5% by 2100. Increases in both temperature and precipitation in the catchment are projected to increase streamflow by 86% by the end of the 21st century (Table 4-7).

Table 4-7 Expected annual average streamflow of the Thu Bon River with hydropower.

Scenarios	**Year – m^3/s**							
	2030	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Non CC- None HP	151.4	151.3	151.5	151.3	151.5	151.3	151.5	151.5
Non CC 8m^3	279.5	279.3	279.6	279.4	279.6	279.4	279.6	279.6
Non CC 25 m^3	279.5	279.3	279.6	279.4	279.6	279.4	279.6	279.6
Increased T 8m^3	277.3	276.4	275.8	274.7	274.2	273.1	272.5	271.7
Increase T 25 m^3	277.3	276.4	275.8	274.7	274.2	273.1	272.5	271.7
Increased R 8m^3	282.2	283.2	284.6	285.5	286.8	287.7	289.1	290.3
Increased R 25 m^3	282.2	283.2	284.6	285.5	286.8	287.7	289.1	290.3
Increased T and R 8m^3	280.0	280.1	280.7	280.7	281.2	281.2	281.7	281.9
Increased T and R 25 m^3	280.0	280.1	280.7	280.7	281.2	281.2	281.7	281.9

4.2.4 Monthly average streamflow in the Thu Bon River

Monthly average streamflow in the Thu Bon River without the development of hydropower is given in Figure 4-4. Streamflow is projected to increase slightly during the dry season, but decrease marginally during the rainy season under scenarios with increased precipitation. However, streamflow is expected to decrease slightly across all months overall.

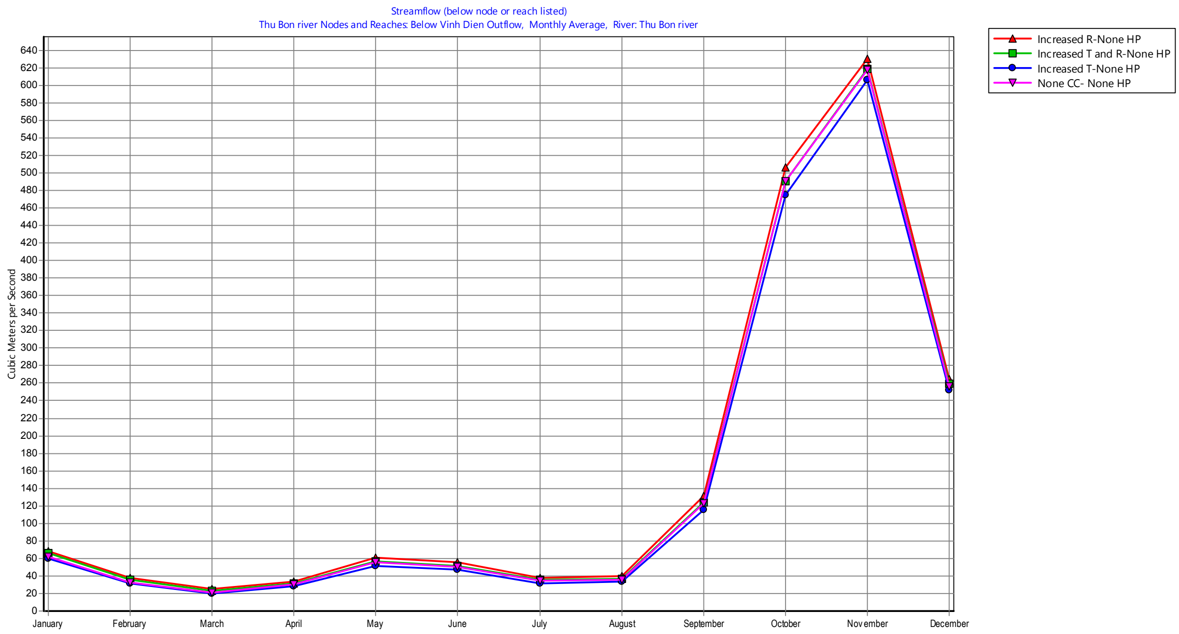

Figure 4-4 Projected monthly average streamflow in the Thu Bon River without hydropower.

Figure 4-5 shows the future monthly average streamflow of the Thu Bon River with the operation of hydropower projects. Streamflow is projected to increase across all months, except for October. Unchanged climate change scenarios in combination with either returning $8m^3/s$ or $25m^3/s$ from the Dak Mi 4 hydropower station show similar patterns in streamflow. The high streamflow period is likely to extend to March (September to March) from the present period of September to December. The duration of the high streamflow period in the Thu Bon River in my study is longer than that of Nam's work (2012). Consequently, the low streamflow period in my study is shorter, from April to August (Figure 4-5).

The monthly average streamflow from January to September in the climate change scenarios in combination with the hydropower development scenarios is expected to increase significantly (approximately two to 11 times) compared to the unchanged climate scenario without hydropower development. Specifically, the ratios for February, March and September are about 7, 11 and 2, respectively. It is clear that the operation of hydropower plants in the catchment contributes to water shortages in the Thu Bon River but also increases the risk of downstream flooding.

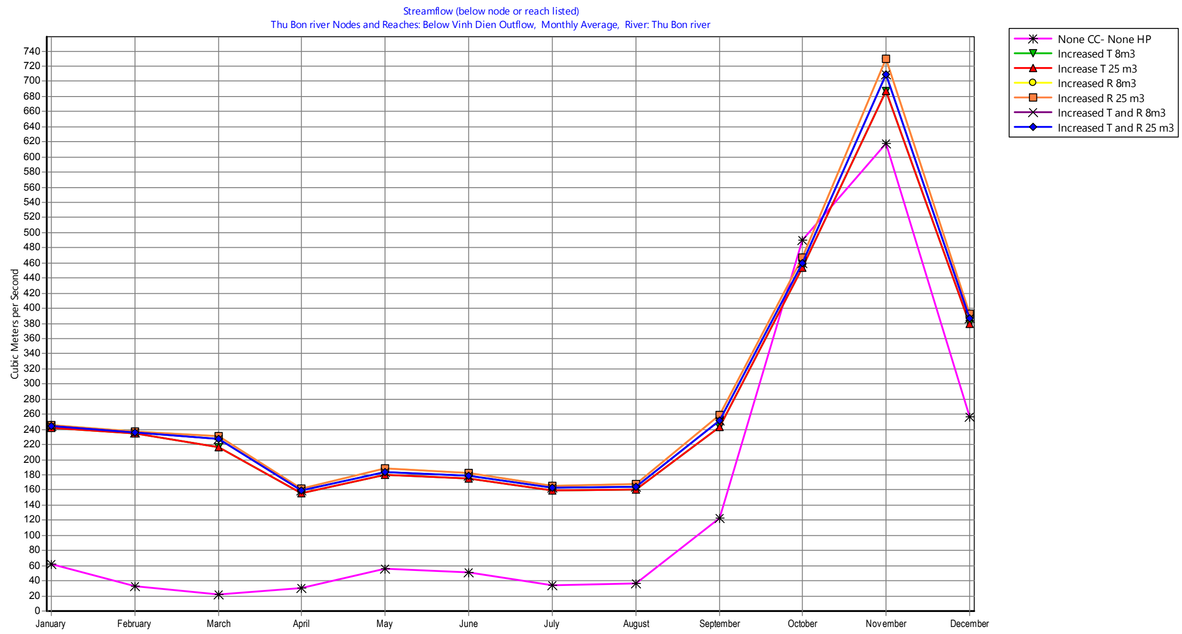

Figure 4-5 Projected monthly average streamflow in the Thu Bon River with hydropower scenarios.

4.3 Potential Catchment Evapotranspiration (ET potential)

Potential catchment evapotranspiration is correlated with temperature (see Table 4-8). The increase in rainfall is unlikely to affect annual Potential Catchment Evaporation and the presence of hydropower does not affect this factor. The Potential Catchment Evapotranspiration is projected to increase from 0.1 to 0.2 Billion m^3 in each decade. By the end of century, Potential Catchment Evapotranspiration is estimated to increase by 7.3% if temperatures rise by 2.6^0C.

Table 4-8 Projected Potential Catchment Evapotranspiration.

Scenarios	Year – Billion m^3								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Non CC	19.3	19.2	19.3	19.2	19.3	19.2	19.3	19.2	19.2
Increased T	19.5	19.6	19.8	19.9	20.1	20.2	20.4	20.5	20.6
Increased R	19.3	19.2	19.3	19.2	19.3	19.2	19.3	19.2	19.2
Increased T and R	19.5	19.6	19.8	19.9	20.1	20.2	20.4	20.5	20.6

4.4 Actual Catchment Evapotranspiration (ET Actual)

Increases in temperature and/or precipitation without hydropower development are projected to increase the annual actual catchment evapotranspiration (see Table 4-9). The latter is about 13.4 Billion m^3 annually for the unchanged climate scenario. Actual catchment evapotranspiration is projected to increase by 4.5% when only temperature is increased, and by 2.2% by 2100 under the increased rainfall scenario. Increases in both temperature and rainfall are projected to increase actual catchment evapotranspiration by around 6.7% by the end of the 21st century. I found that the operation of hydropower (and thus, hydropower development) does not contribute to changes in annual actual catchment evapotranspiration.

Figure 4-6 describes the monthly average actual catchment evapotranspiration for climate scenarios without hydropower operations. Similarly to annual actual catchment evapotranspiration, hydropower also does not affect the monthly actual catchment evapotranspiration. Overall, changes in the monthly actual catchment evapotranspiration are likely to be same for most scenarios, except for the increased precipitation and same temperature scenario. The monthly average actual evaporation for the catchment peaks in March and October. However, the latter peak is greater than the former. The monthly average actual catchment evaporation for the increased temperature with the unchanged rainfall scenario from October to March is higher than that of the increased precipitation without change in temperature. However, the opposite occurs from April to August.

Table 4-9 Projected Actual Annual Catchment Evapotranspiration.

Scenarios	Year – Billion m^3								
	2020	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
Non CC	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Increased T	13.5	13.6	13.6	13.7	13.8	13.8	13.9	13.9	14.0
Increased R	13.5	13.5	13.5	13.5	13.6	13.6	13.7	13.7	13.7
Increased T and R	13.6	13.6	13.8	13.8	14.0	14.0	14.1	14.2	14.3

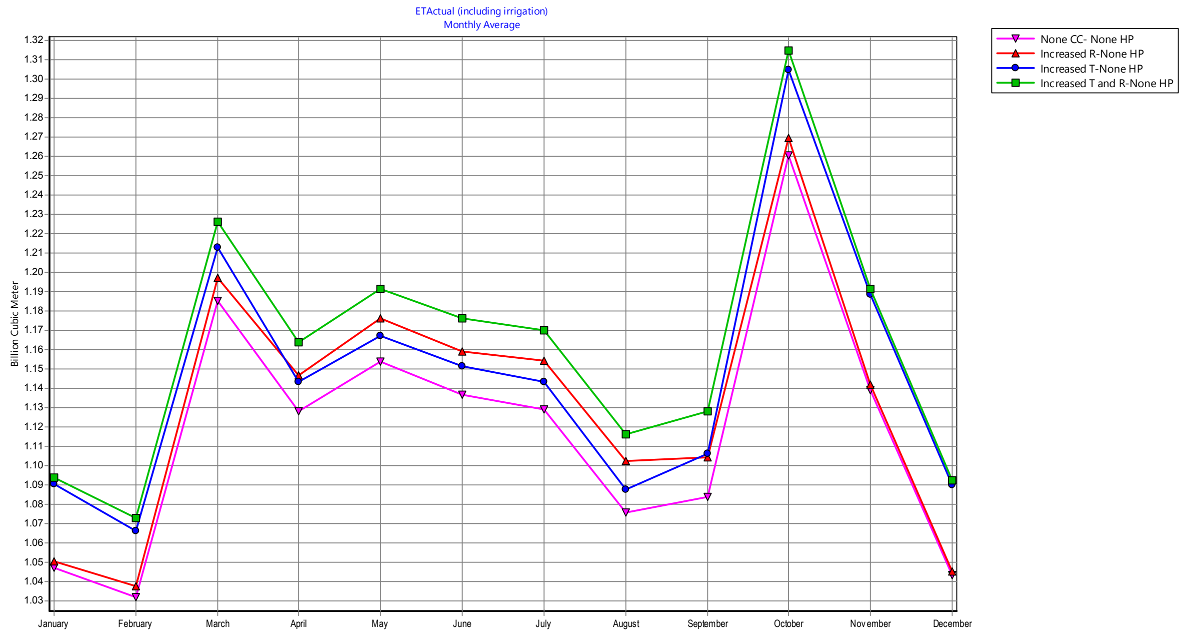

Figure 4-6 Projected monthly average actual catchment evaporation.

4.5 Reservoir evaporation

Annual reservoir evaporation for all climate scenarios with the return of $8m^3/s$ from the Dak Mi 4 hydropower plant to the Dak Mi River is higher than that of the return of $25m^3/s$ from the Dak Mi 4 hydropower plant (see Figure 4-7). Under the same climate conditions, the increase in water returning from the Dak Mi 4 plant increases reservoir evaporation by 5.2% to 5.7%. Increases in temperature decrease reservoir evaporation. In contrast, the increase in rainfall increases reservoir evaporation. The combination of increases in both temperature and rainfall also increases reservoir evaporation. However, the increase of reservoir evaporation in all climate scenarios is marginal, that is, less than 0.5%.

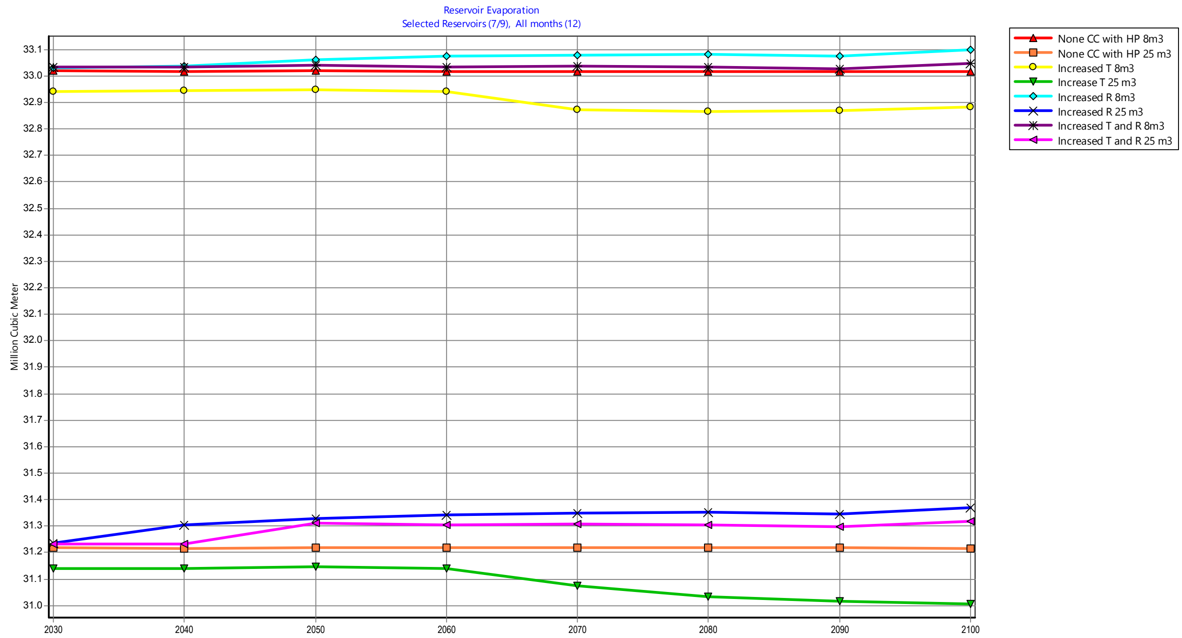

Figure 4-7 Expected annual reservoir evaporation for climate conditions in combination with hydropower development scenarios.

Under all climate conditions, monthly reservoir evaporation is projected to peak in March for the return of 25m^{3}s and 8m^3/s water from the Dak Mi 4 hydropower reservoir (see Figure 4-8). The monthly average reservoir evaporation for the higher return rate from the Dak Mi 4 hydropower station is expected to be smaller than the lower return rate over the period of March to October.

The total monthly average reservoir evaporation under all climate conditions follows the same pattern for the two cases of returning water from the Dak Mi 4 reservoir. Monthly average reservoir evaporation is about 2.7 Million m^3 in January and decreases slightly in February. In March, monthly average reservoir evaporation is projected to increase considerably to peak at approximately 3.3 and 3.35 Million m^3 for the return rates of 25m^3/s and 8m^3/s from the Dak Mi 4 hydropower plant, respectively. However, reservoir evaporation decreases afterward until June. In July, the monthly average reservoir evaporation is projected to have a second, lower peak. However, there are rapid declines in the monthly average reservoir evaporation during the period of August to October. Under both return rates, the monthly average reservoir evaporation in October decreases to 1.6 and 1.75 Million m^3, respectively. For the rest of year, this element is projected to be less than 2.1 Million m^3.

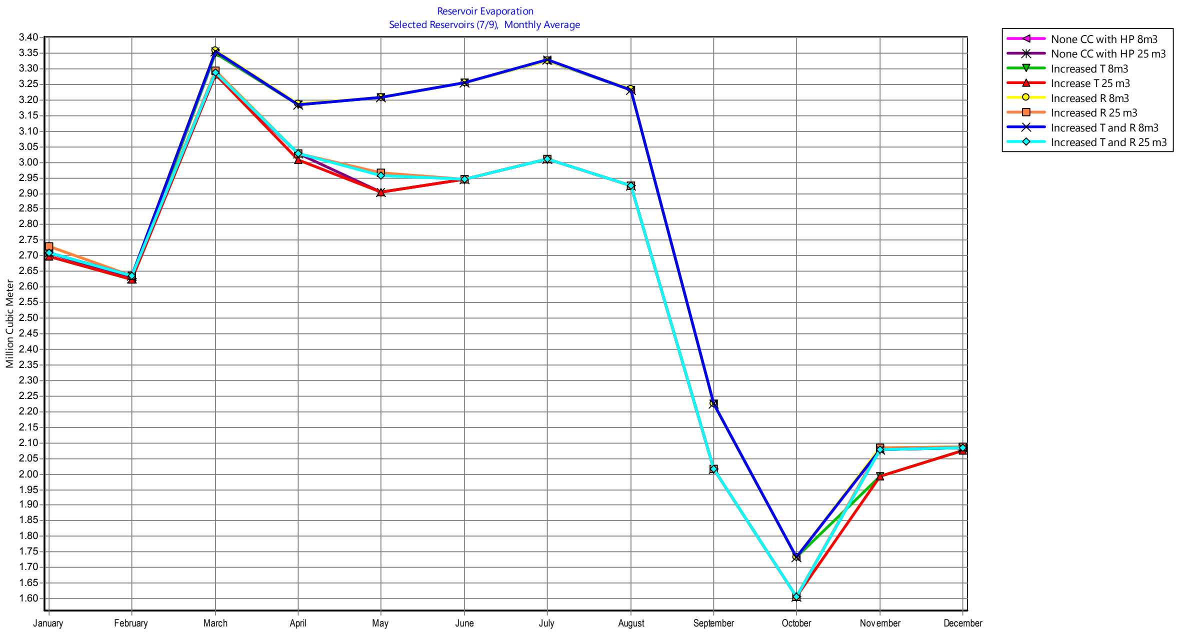

Figure 4-8 Changes in monthly average reservoir evaporation.

4.6 Runoff flow

Precipitation reaches the ground as snow, rain or in other forms and part of this precipitation returns to the atmosphere as evaporation and evapotranspiration (Frind 1969). The remainder is collected in the basin and eventually discharges at the basin outlet as runoff (Frind 1969). Aquifers extending beyond the boundaries of any particular drainage basin are recharged by precipitation in other catchments. The annual average runoff for all climate conditions without the development of hydropower follows the same pattern as the annual average streamflow component (see Figure 4-9). Operations of hydropower projects do not change annual average runoff in the watershed. In the unchanged climate scenario, the annual average runoff fluctuates from 12.8 Billion m^3 to 12.10 Billion m^3. Increases in temperature decrease annual average runoff while the latter is expected to increase significantly with increases in rainfall. The combination of increasing temperature and precipitation causes slight increases in the annual average runoff. By the end of the century, annual average runoff declines by 4.79% for the increased temperature scenario but increases by 6.94% for the increased precipitation scenario. However, the combination of increased temperature and rainfall increases annual average runoff by only 1.98%.

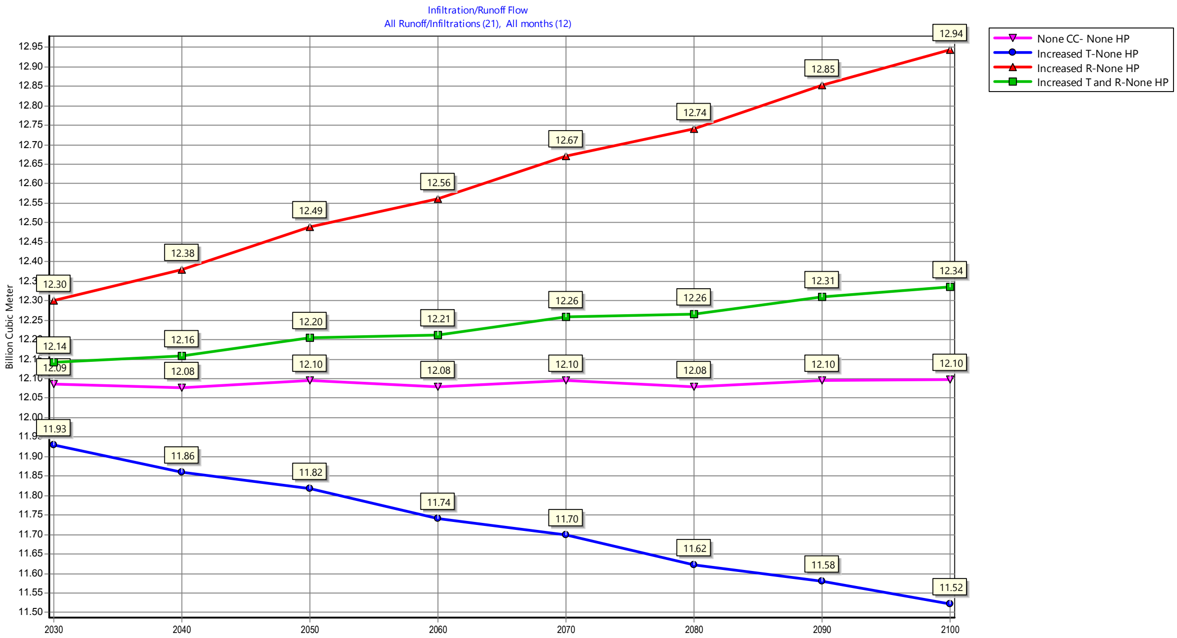

Figure 4-9 Projected annual average runoff in different climate scenarios.

4.7 Hydropower generation

Under unchanged climate conditions, annual hydropower generation from the eight hydropower projects in the catchment is independent of water returning from the Dak Mi 4 reservoir (see Figure 4-10). Total hydropower generation in the watershed follows the same pattern as runoff and streamflow. Without climate change, hydropower generated by the eight plants fluctuates from 2.65 to 2.66 Billion kWh. By the end of the 21st century, annual hydropower generation decreases by 3.76% due to increases in temperature and is projected to increase by 2.63% due to increases in rainfall. Increases in both temperature and precipitation are projected to increase hydropower generation by 1.13%.

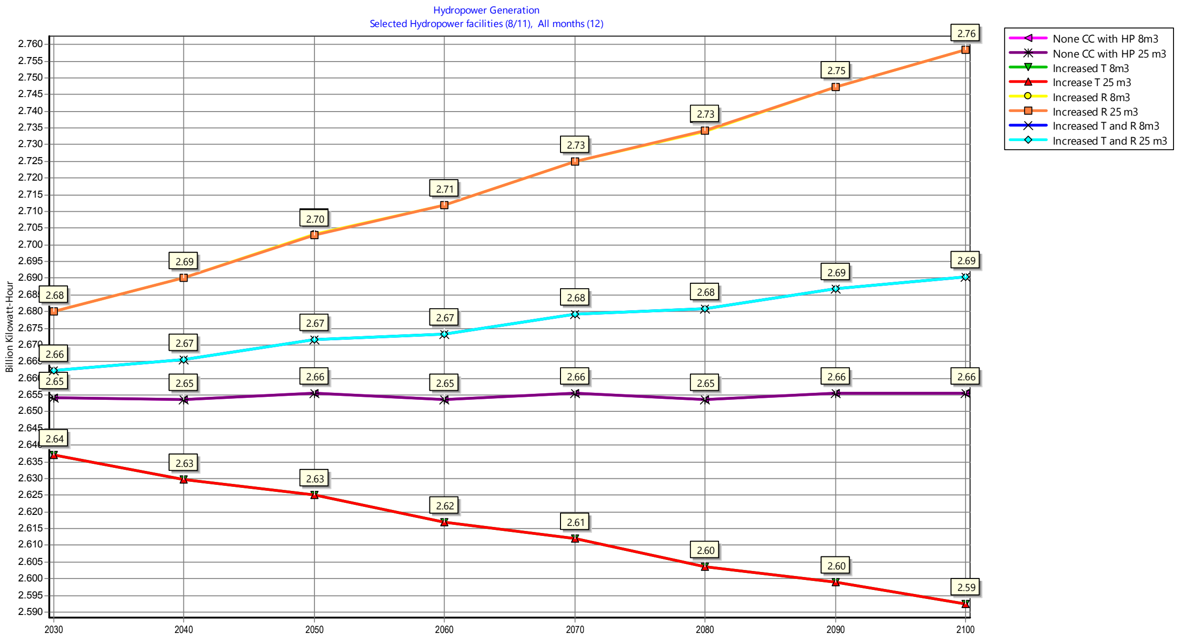

Figure 4-10 Future annual hydropower generation in the catchment

Similar to annual average hydropower generation, different water releasing scenarios from the Dak Mi 4 hydropower do not influence monthly average hydropower generated in the river basin. Figure 4-11 shows three phases of hydropower generation. The amount of hydropower generated is lowest in period from April to August. In May to July, hydropower generation increases significantly consistent with the increase in rainfall. Monthly hydropower generation peaks just below 470 Billion kWh during September to November. Afterward, hydropower generation declines steadily with decreasing precipitation. However, hydropower generation during January to March is likely to be high despite minimum rainfall occurring in this period.

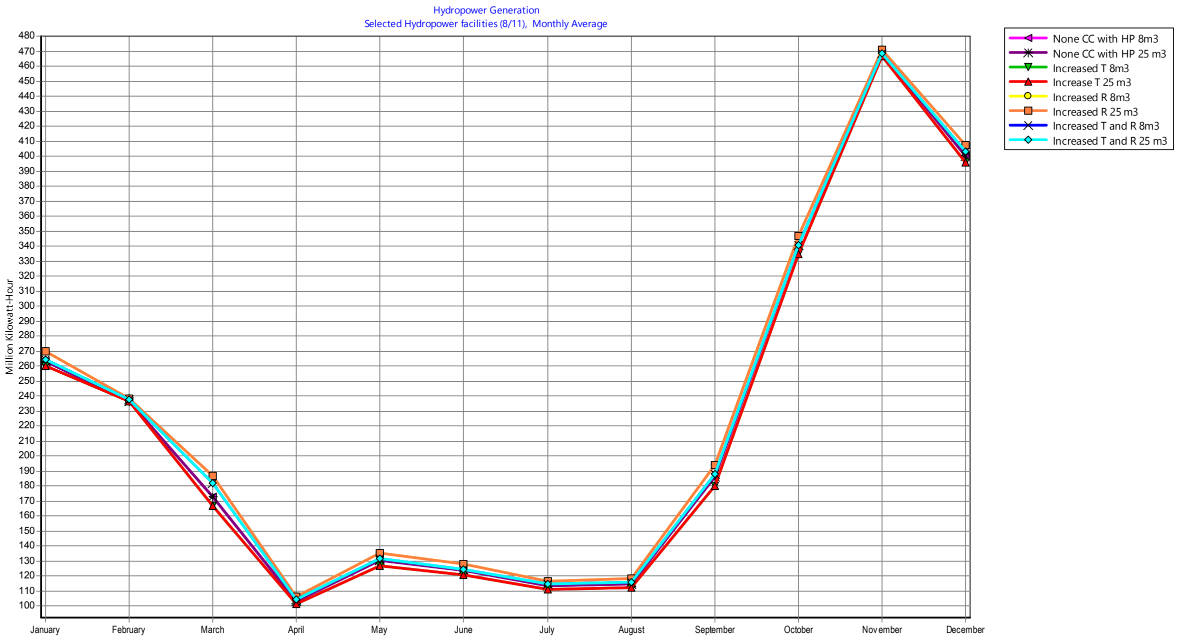

Figure 4-11 Expected monthly average hydropower generated in the catchment.

4.8 Reservoir storage volume

Total monthly average volumes for reservoirs (except for Dak Mi 2, Dak Mi 3 and Song Bung 6) reveal a higher trend in returning the lower rather than the higher amount of water from the Dak Mi 4 hydropower (see Figure 4-12). The volume of water in reservoirs is projected to be least in the period of March and September, at just under 0.95 Billion m^3. The volume of water increases sharply in October while peaking at slightly less than 1.9 Million m^3 in November. However, it declines considerably in the period December to February. From October to December, the monthly reservoir volume is expected to be similar to the unchanged climate scenario.

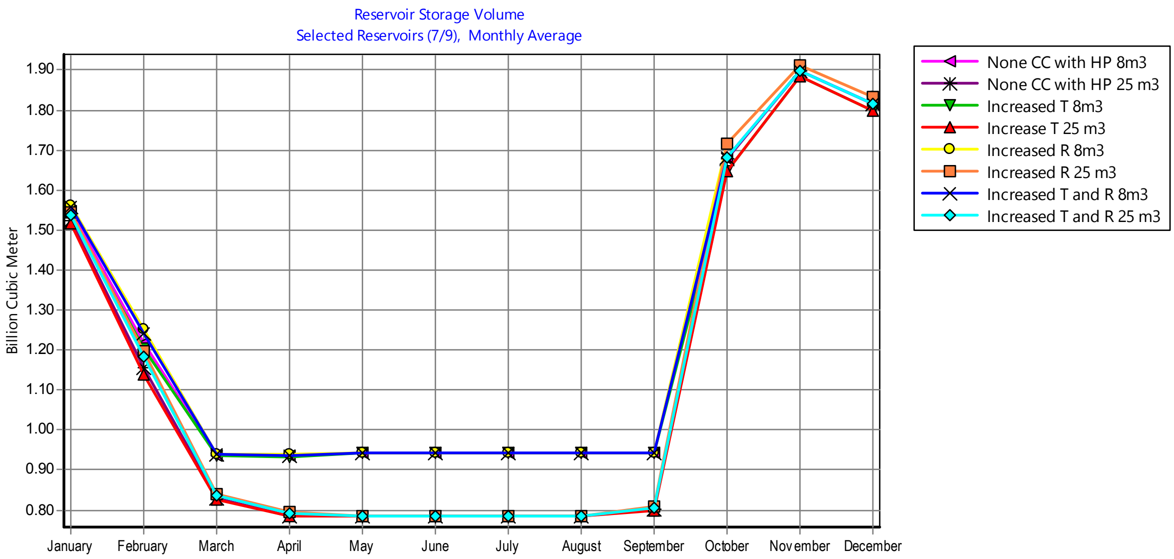

Figure 4-12 Expected monthly average reservoir volume in different climate and hdyropower development scenarios.

There is a large difference in the Dak Mi 4 reservoir storage volume between the two water returning scenarios. In general, the more water released from the reservoir, the less the water volume stored during the dry season from January to August and September during the rainy season. Climate change scenarios do not significantly influence changes in the water volume in hydropower reservoirs (Figure 4-13).

The 8m^3/s water returning scenario from the Dak Mi 4 reservoir maintains the greatest conservation volume (active storage) of 310.32 Million m^3, except for March and April that ranges from 303 to 306 Million m^3. This is the driest period when rainfall is least.

In the 25m^3/s water returning scenario from the Dak Mi 4 hydropower station, water storage in the hydropower system is predicted to be at 152.30 Million m^3 from April to August for the unchanged climate scenario and the increased temperature scenario, which is marginally greater than that of the top inactive volume of 152.29 Million m^3. For the increased rainfall scenario and the increased temperature and precipitation scenario, this pattern occurs later in the year, from May to August. The Dak Mi 4 reservoir volume also increases to approximately 170m^3 in September then peaks at the top of conservation from October to December. However, water storage in the reservoir system declines rapidly during the period of January to April.

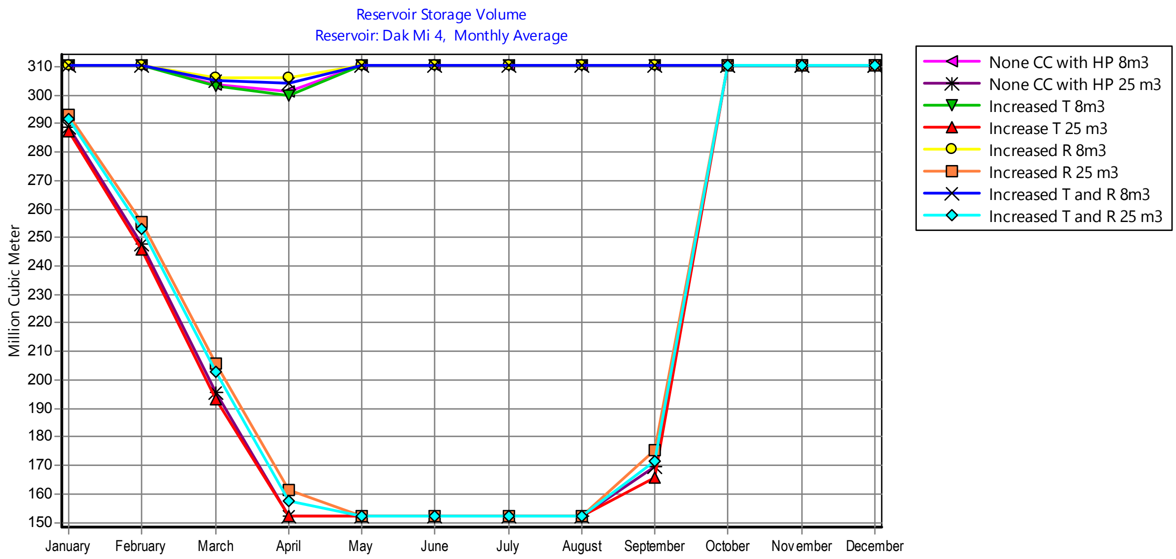

Figure 4-13 Projected monthly average volume of the Dak Mi 4 reservoir in different climate and hydropower scenarios.

Chapter 5: Conclusions and Recommendations

5.1 Summary

My study has evaluated the impacts of changes in climate conditions in combination with hydropower development on surface water resources in the Vu Gia-Thu Bon river basin - the Centre of Viet Nam - over the 21st century. I used the WEAP model, developed by the Stockholm Institute, to predict changes in water availability, streamflow of the Vu Gia and Thu Bon River, Catchment Evapotranspiration (ET potential), Catchment Actual Evapotranspiration (ET Actual), Reservoir evaporation, Runoff flow, Hydropower generation and Reservoir storage volume.

I tested four climate scenarios in this study. These are unchanged climate, increased temperature and unchanged rainfall, unchanged temperature and increased rainfall, and both increased temperature and rainfall. The baseline period or the unchanged climate scenario is considered as the average climate conditions in the period of 1980 to 1999. The annual average temperature and rainfall for the baseline period are approximately 24.75^{0}C and 222.11mm, respectively. By the end of the century, annual average temperature and rainfall are projected to increase by 2.6^{0}C and 4.3%, respectively. Changes in the monthly temperature were projected by the linear function y = 0.0289x -57.91, and monthly rainfall by y = 0.1058x - 212.21.

I considered two hydropower development scenarios involving the operation of the Dak Mi 4 hydropower plant returning water from the Dak Mi 4 hydropower reservoir to the original river (the Dak Mi River) at either 8m^3/s or 25m^3/s. The amount of water permanently diverted from the Dak Mi River to the Tranh River for hydropower generation is 128m^3/s.

My analyses (Chapter 4) revealed the following key conclusions:

- Evidence for climate change is apparently at the global scale as well as the catchment scale. The evidence at the global scale includes links between population growth, industrialization and the increase in carbon dioxide concentrations, the relationship between carbon dioxide levels and climate change, and finally, the increase in extreme climate disasters caused by climate change. The catchment-scale evidence demonstrates increases in observed temperature and precipitation after the baseline period (1980 to 1999).
- Surface water resources in the catchment are particularly sensitive to changing climate conditions. Temperature increases do not affect water availability, but result in decreases in streamflow, runoff flow, potential catchment evapotranspiration, actual catchment evapotranspiration, reservoir evaporation and hydropower generation in the Vu Gia and Thu Bon Rivers. Increases in rainfall increase surface water resources. Increases in both

temperature and rainfall also increase surface water resources. Overall, if climate conditions change as projected, surface water resources in the catchment will increase.

- The development of hydropower will significantly enhance surface water resources in the catchment. Monthly streamflow in the Vu Gia and Thu Bon Rivers are projected to increase considerably during the dry season. Particularly, there is a shift in minimum streamflow from February - April to April - August. Streamflow in the Vu Gia River is projected to decrease in the rainy season (October – November), and substantially increase in the Thu Bon River (November – December). This tendency is expected to increase the risk of downstream flooding in the lowland plain of the Thu Bon River.
- The amount of water returned back to the Dak Mi River from the Dak Mi 4 hydropower reservoir (either 8m^3/s or 25m^3/s) does not influence the total hydropower generated in the catchment. However, it does affect the volume of water storage in reservoirs during the dry season, especially from March to September. The volume of water stored the Dak Mi 4 reservoir is always above its top of inactive (dead water level in reservoir) even when the Dak Mi 4 reservoir returns 25m^3/s to the Dak Mi River.

5.2 Limitations of the study

This study has not taken all water users into account. There are only eight cascade hydropower plants out of 44 planned projects simulated in the study. The two remaining cascade plants (Dak Mi 2 and Dak Mi 3) are in the pre-feasibility study period so data for these is unavailable. The Dak Mi 2 and Dak Mi 3 hydropower plants will originate from the Dak Mi 1 which has a gross storage of 223 million m^3. Therefore, the operation of these proposed plants is expected to contribute to water availability and streamflow in the catchment. Additionally, although water use by the agricultural sector involves 78 reservoirs and 358 weirs, providing water for more than 7,600ha of rice and crops, the unavailability of data on this sector prevented its conclusion into the WEAP model presented here.

Interactions between surface water and other water resources were not modelled in this study. Groundwater and surface water interactions may be significant in downstream reaches of the Vu Gia and Thu Bon Rivers, particularly their delta areas. Crucially, saline infiltration from sea water (tidal and sea-level rise) in downstream estuary reaches of both rivers severely compromises the operations of domestic and agricultural pumping stations, particularly during the dry season (Nam et al. 2013a). Some groundwater aquifers in the middle river basin also discharge water to surface rivers or recharge from these rivers.

Socio-economic development scenarios regarding increasing water-use standards for human and agriculture due to climate change are ignored. Rather, future demands for water were assumed to be constant, except for the increase in hydropower by 2020 and domestic water use for the period of 2020 - 2030. Agricultural water demands over the total cultivated area (> 22,400ha) may increase in the future as a result of increasing temperature. Temperature rise leads to the increasing evaporation from land surfaces and transpiration of plants.

The streamflow of the Quang Hue, Bau Sau and Vinh Dien diversions were not modelled. Consequently, the WEAP model equally allocated water to all downstream reaches at the intersections. Therefore, modelled streamflow below these intersections in WEAP may be lower than observed streamflow in the dry season (the Vu Gia River) and higher than observed in the rainy season (the Thu Bon River).

I simulated river basins using the Rainfall Runoff Method or Soil Moisture Method. This method represents the catchment with two soil layers. The method simulates evapotranspiration in terms of irrigation and rainfall regarding non-agricultural and agricultural land, shallow and runoff interflow and changes in soil moisture. It allows users to project the characterization of land-use and/or soil type impacts. However, evapotranspiration data was not available in the catchment. Therefore, the thesis employed evaporation data as an alternative. Data relating to soil characteristics were not considered. Therefore, the model results are relative.

5.3 Further development

The above limitations need to be addressed in order to improve the model and its application. Importantly, the model needs to be calibrated. Firstly, all reservoirs and weirs in the catchment should be taken into account. This will affect streamflow predictions because of the large volume of water stored in reservoirs and the impediment of riverflow by weirs. Secondly, groundwater aquifers in upstream and downstream reaches will interact with streamflow, particularly during the dry season. Seawater intrusion affects water availability in downstream reaches. Therefore, the WEAP model would be significantly improved by linking it to a MODFLOW model of groundwater movement in the catchment. Furthermore, setting minimum flow requirements and observing salt levels in downstream reaches of the Vu Gia and Thu Bon Rivers may assist to identify unmet demand at pumping stations.

Thirdly, future socio-economic development is likely to change patterns of water use. Water demand will possibly increase due to higher living standards, climate change, the shift of water use from groundwater to surface water, and improvements in waste water treatment. Fourthly, identifying flow constraints in the Quang Hue, Bau Sau and Vinh Dien Rivers will improve the accuracy of modelled downstream river flows. However, these improvements are estimated to be costly and time-consuming. Fifthly, future studies should consult the Department of Agriculture and Rural

Development for characteristics of soil layers to model catchments by the Soil Moisture Method. Alternatively, that information can be obtained from the Land Use and Climate Change Interactions in Central Vietnam.

Finally, the WEAP model provides a parameter estimation tool (called PEST) to automatically compare WEAP outputs to historical data and modify related parameters of the model to improve model accuracy. In particular, PEST compares observed streamflow data with modelled streamflow results for the node located immediately upstream of the gauge.

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APPENDIX

Table A-1 Descriptions of pumping station groups in the Vu Gia-Thu Bon river basin.

Pumping Group	Name	Location (commune)	River	Irrigation area (ha)		
				Design	Operation	
					Rice	Crop
1	Dong Cay	Dai Son	Vu Gia	10	6.00	
	Dong Dun	Dai Son		22	14.00	
				32	**20.00**	
2	An Diem	Dai Hung	Con	110	e temp	
	Village 3	Dai Hung		70	51.26	7.05
	Truc Ha 2	Dai Hung		300	254.64	36.48
	Truc Ha 1	Dai Hung		200	136.48	10.85
	Truoc Ha 1	Dai Lanh				
				680	**496.45**	**54.38**
3	Village 8	Dai Lanh	Vu Gia	102	84.72	
	Song Con T9			20	12.20	
	Dong An			70	51.20	1.00
	Go Cam			100	82.20	
	Song Cai T9			130	119.40	
	Cay Da			60	40.80	
	Bau Tre			8	8.00	
	Tan Doi	Dai Son		30	26.71	
	Dong Mieu	Dai Hiep		50	50.00	
	Ha Tan	Dai Lanh		200	40.00	
	Dong Phuoc			50	30.00	
				820	**545.23**	**1.00**
4	Ha Thanh	Dai Dong	Vu Gia	100	79.62	8.54
	Vinh Phuoc			130	75.92	36.98
	Cau Phao			150	113.82	24.02
	Lam Phung 1			45	42.20	
	May Trang			150	128.50	3.00
	Bau Ga			51.1	31.58	3.15
	Village 2 Ngoc Kinh	Dai Hong		35	27.16	
	Lam Phung LX	Dai Quang		120	105.54	
				781.1	**604.34**	**75.69**
5	Ao Lang	Dai Quang	Vu Gia	15	10.00	
	Bau Lo			30	15.00	
	Phu Huong			68	58.30	
	Dong Lam			25	18.00	
	Hoa Thach			100	85.54	1.36
	My An			25	22.00	
	Song Binh			50	48.00	

Pumping Group	Name	Location (commune)	River	Irrigation area (ha)		
				Design	Operation	
					Rice	Crop
				313	**256.84**	**1.36**
6	Dai Phu	Dai Nghia	Vu Gia	160	70.00	
	Nghia Tan			62	40.00	2.51
	Phuoc Nghia 1	Ai Nghia Town		240	210.30	14.03
	Hoa Dong			100	85.48	8.16
	Khu 5			120	90.36	24.70
	Khu 7			40	35.22	4.50
	Ai Nghia			1,600	363.60	2.40
				2322	**894.96**	**56.30**
7	Bau Thach Bo	Dai Hiep	Vu Gia	120	120.00	
	Phu Dong			500	403.10	58.98
				620	**523.10**	**58.98**
8	Dong Phu	Dai Hiep	Yen (Vu Gia)	75		60.00
	Dong Mieu			50	50.00	
	Bau Vang			90	63.24	
	Thai Son	Dien Tien		754	187.76	59.92
	Thai Son 2			80	56.37	66.87
				1049	**357.37**	**186.79**
9	An Trach	Hoa Tien	Yen (Vu Gia)	450	450.00	
	Le Son			50	50.00	
	Cam Toa			100	100.00	
				600	**600.00**	**0.00**
10	Thach Ban	Hoa Phong	Yen (Vu Gia)	65	65.00	
	Thach Bo			30	30.00	
	Dong Lam	Hoa Phu		8	8.00	
				103	**103.00**	**0.00**
11	Hoa Khuong	Hoa Nhon	Tuy Loan	23	23.00	
	Thai Lai			23	23.00	
	Ninh An			45	45.00	
	Tuy Loan			180	180.00	
	Dong Tri	Hoa Khanh		15	15.00	
	An Tan			100	100.00	
				386	**386.00**	0.00
12	Ha Cung	Hoa Xuan	Bau Sau (Vu Gia)	100	100.00	
	Tung Lam			40	40.00	
				140	**140.00**	**0.00**
13	Cam Van	Dien Hong	Bau Sau (Vu Gia)	2,100	534.74	74.93
	Chau Son	Dien Tien		175	150.30	6.00
	To Bi			40	19.08	20.92
	Doi 9A	Dien Hong		20	32.00	3.00

Pumping Group	Name	Location (commune)	River	Irrigation area (ha)		
				Design	Operation	
					Rice	Crop
	Doi 9B			15	20.00	2.10
	Lac Thanh			160	130.00	7.00
	Ben Dinh			80	50.50	10.46
	Doi (Village 10)			6.5	7.00	6.70
	Doi (Village 11)			10	6.00	2.90
	Van Ly			40	19.60	
				2,647	**969.22**	**134.01**
14	Dong Quang	Dien Hoa	Bau Sau (Vu Gia)	2,140	692.79	33.34
	Dong Quang 2			70	59.10	9.72
				2,210	**751.89**	**43.06**
15	Bich Bac	Dien Hoa	Bau Sau (Vu Gia)	1,100	420.00	40.00
				1,100	**420.00**	**40.00**
16	La Tho	Dien Hoa	La Tho (Vu Gia)	160	184.94	6.31
	Con Toi			36		18.00
	Bau Nit			25	7.37	0.37
				221	**192.31**	**24.68**
17	Thuy Chu	Dien Thang	Thanh Quyt (Thu Bon)	30	20.26	
	Bo Mung			30	18.00	8.00
	Huong Bieu			15		5.00
	Thanh Quyt			275	154.07	3.22
	Tra Duc			70	66.50	0.50
				420	**258.83**	**16.72**
18	Ha Nong	Dien Phuoc	Co Ca (Thu Bon)	249	83.16	
	Hamlet 15			60	51.69	3.55
	Hamlet 1			20	9.74	
	Binh Tri Thuong			15	78.38	
	Binh Tri Ha			10	10.93	
	Hamlet 17			30	31.60	0.24
	Ha Dong			50	159.00	13.58
	Dong Thon			20	18.00	
	Mieu Than Hoang			60	25.02	0.79
	Tan Binh 3	Dien Trung		360	107.99	6.21
				874	**575.51**	**24.37**
19	Ngoc Tam	Dien An	La Tho (Thu Bon)	80	66.37	
	Ka Huan			30	6.86	4.10
	Dong ho			800	448.09	24.36
				910	**521.32**	**28.46**

Pumping Group	Name	Location (commune)	River	Irrigation area (ha)		
				Design	Operation	
					Rice	Crop
20	Vinh Cuong	Duy Tan	Thu Bon	30	21.60	3.15
	My Luoc	Duy Hoa		70	45.89	11.28
	Cu Ban	Duy Chau		250	24.59	4.44
				350	**92.08**	**18.87**
21	Tu Phu	Dien Quang	Thu Bon	300	225.70	
	Ky Lam			107	45.00	13.90
	Ky Lam	Dien Tho		60	28.12	1.29
	Thuy Bo			40	40.00	4.80
	Ben Hoc			200	103.10	5.40
	Thon Tay			60	45.00	16.00
				767	**486.92**	**41.39**
22	Chau Hiep	Nam Phuoc	Ba Ren (Thu Bon)	200	79.34	12.02
	My An			90	7.05	9.29
	2/9			55	25.10	6.10
	My Hat			33	32.24	4.95
	Deu Ga			8	8.25	0.95
	Ben Nhon			90	31.20	5.33
	Go Lua			30	21.41	13.69
	Thi Thuong			20	2.10	6.96
	Xuyen Dong			524	514.83	71.47
	Roc Chua	Dien Phong		160	121.86	7.59
	Bau Lo			30	18.59	2.13
	Ha Mat			30	20.37	
	Phuoc My	Duy Thanh		200	103.80	7.60
	An Lac			150	77.90	4.60
	Dong Lanh	Dien Trung		100	83.69	13.11
	Nam Ha			660	93.13	1.37
				2,380.20	**1,240.86**	**167.16**
23	Cau Chim	Duy Trung	Ba Ren (Thu Bon)	140	90.20	
	Minh Khanh			50	22.48	
	Ly Ly	Duy Thanh		140	81.88	3.67
	Thi Thai			174	150.14	24.34
	Van Buong	Duy Trinh		50	8.29	2.59
	Duong Mong	Que Xuan 1		288	165.40	31.60
	Cong Ba			60	164.00	13.00
	Mong Lanh			120	72.24	5.50
	Thanh Hoa			56	24.46	4.38
	Thuong Vinh	Que Xuan 2		120	137.00	9.00
	Village 4	Que Chau		13	13.00	
	Xuan Phu	Que Xuan 1		49	45.18	3.36
	Phu Sa			15	12.12	3.00

Pumping Group	Name	Location (commune)	River	Irrigation area (ha)		
				Design	Operation	
					Rice	Crop
	Cua Chua			10	8.90	0.96
				1,285	**995.29**	**101.40**
24	19/5	Duy Phuoc	Thu Bon	360	143.80	27.70
	Duy Vinh	Duy Vinh		50	54.37	17.29
				410	**198.17**	**44.99**
25	Triem Nam	Dien Phuong	Thu Bon	40	31.16	11.19
	Dien Binh	Dien Minh		150	61.86	69.37
	Lam Thai			150	104.89	
	Dien Phong	Dien Phong		180	145.00	
	Dien Phuong			100	80.00	
				620	**422.91**	**80.56**
26	Team 6	Vinh Dien	Vinh Dien	40	13.59	1.05
	Vinh Dien			1,015	718.41	25.51
	Cam Thanh	Cam Chau		50	58.84	8.94
	Ha Chau	Cam Ha		370	262.13	
	Xo	Dien Nam		60	54.86	
				1,535	**1,107.83**	**35.50**
27	Ha Ban	Dien Ngoc	Vinh Dien	50	36.50	
	Lau Dai			30	29.00	1.52
	Tu Cau			870	243.04	1.96
	Cam Sa	Dien Nam Bac		820	86.70	20.69
				1,770	**395.24**	**24.17**
	Total			**25,344.8**	**13,555.7**	**1,259.8**