Assessment of the Impacts of Climate Change on Water Allocation in the Upper Cau River Basin-Vietnam

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Abstract

Vietnam is likely to be one of the most significantly impacted nations in the world from climate change, due to its very long coastline, high dependence on agriculture, and relatively low levels of development in rural areas. Because of understanding the risk of climate change, the government of Vietnam ratified the United Nations Framework Convention on Climate Change, approved the program called National Target Program to Respond to Climate Change, and announced the Climate Change and Sea Level Rise Scenarios for Vietnam.

Assessment of impacts of climate change on water resources is an important step to implement The National Target Program to Respond to Climate Change. My research focus is on water allocation in the Upper Cau river basin in the Northern Part of Vietnam. The Upper Cau river basin includes the territories of two provinces Bac Can and Thai Nguyen of Vietnam. In these areas, water from the Cau River has a vital role for the socio -economic development in currently and in the future.

In my research, based on climate change scenarios from the Ministry of Natural Resources and Environment of Vietnam, and the Vietnam Institute of Meteorology, Hydrology and Environment, mathematical models were applied to estimate the impacts of climate change on water resources: CROPWAT for calculate crop water demand, NAM for calculate natural flow, and MIKE BASIN for calculate water allocation. The results from the above models are inputs for my analysis and assessment about the change of water supply for the water use sectors under impacts of climate change.

The average temperature and rainfall were both found to increasing in the 21st century under the climate change scenarios. As a result, the average annual water demand and annual natural flow showed an increasing tendency in whole basin. However, natural flow in dry season had decreasing trend, but the change was small. Combination of all these conditions leads to the increasing tendency of water shortage in four sub-areas of the basin.

Keywords: Climate change, water allocation, mathematical model, water demand, the Upper Cau River basin

Abbreviations

DHI	Danish Hydraulic Institute
FAO	Food and Agriculture Organization of the United Nations
HMDC	HydroMeteorological Data Center
IDW	Inverse distance weighting
IMHEN	Vietnam Institute of Meteorology, Hydrology and Environment
IPCC	Intergovernmental Panel on Climate Change
MAGICC/SCENGEN	Model for the Assessment of Greenhouse-gas Induced Climate Change /A Regional Climate SCENario GENerator
MOC	Ministry of Construction
MONRE	Ministry of Natural Resources and Environment
NAM	Nedbør-Afstrømnings-Model
NTP	National Target Program to Respond to Climate Change
NWRS	National Water Resources Strategy towards the year 2020
RMSE	Root mean square error
SA	Summer – Autumn season
TCVN	Standards, Metrology and Quality of Viet Nam
UNFCCC	United Nations Framework Convention on Climate Change
WS	Winter – Spring season

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Chapter 1 Introduction

1.1. Background

Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates, et al., 2008). Vietnam is likely to be one of the most significantly impacted nations in the world from climate change, due to its very long coastline, high dependence on agriculture, and relatively low levels of development in rural areas. The forecasted climate impacts to 2100 will likely be an increase in rainfall in wet seasons and decrease in dry of around 10 percent or more, increased intensity and frequency of storms and floods, and a likely sea level rise of at least 1 meter. Different regions in Vietnam are likely to have unique climate impacts, making a single national policy for adaptation difficult (McElwee, 2010).

Because of the potential risk of climate change impacts, the government of Vietnam ratified the United Nations Framework Convention on Climate Change (UNFCCC), approved the National Target Program to Respond to Climate Change (NTP) (2008), and announced the Climate Change and Sea Level Rise Scenarios for Viet Nam (2009 and 2012). Climate change scenarios in 2012 are the update of 2009 version in whole of Vietnam. However, in the study area and around, the differences of given data between the two version is not worth considering. Moreover, the climate change scenario for Vietnam version 2009 has daily data of temperature, rainfall and potential evaporation while the scenarios in 2012 only gives monthly data of those. Therefore, the climate change scenario for Vietnam version 2009 was chosen for the study. According to the scenarios, by the end of 21st century, Vietnam temperatures can raise 2.3^{o}C above the average of baseline period (1980 – 1999). The increase in temperature can be from 1.6^{o}C to 2.8^{o}C in different climate zones. Both annual rainfall and rainy season’s rainfall would increase, while dry season’s rainfall tends to decrease. Annual rainfall of Vietnam by the end of the 21st century can increase by 5% compared to that of the period 1980-1999. Therefore, assessment of impacts of climate change on water resources is very important to propose adaptation measures in the future.

The Cau River basin which is an important river in the Thai Binh river system is one of the large river basins in the North of Vietnam (Figure 1-1). It is located partly or entirely across six provinces in Northern Part of Vietnam (Bac Can, Thai Nguyen, Bac Ninh, Bac

Giang, Vinh Phuc and the capital Hanoi). Total catchment is 6,030 km^2 in area. The Upper Cau River basin with the total area of 308,142 km^2 is located in Bac Can and Thai Nguyen province. The river system is the important source of water supply for domestic uses, social-economic development, and other demands in the basin (IMHEN, 2006). Therefore, the Upper Cau River basin was chosen as the study site of the research.

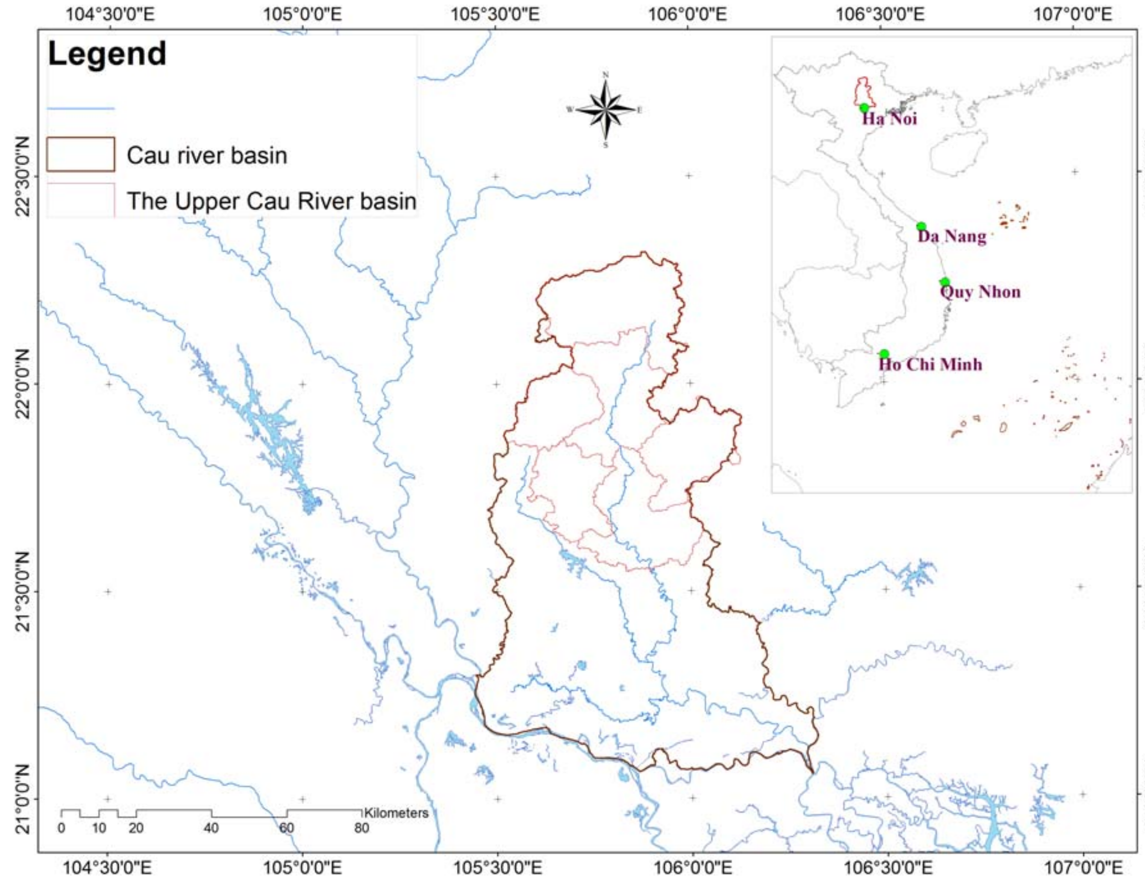


Figure 1-1 The Upper Cau river basin in Hong-Thai Binh River system

1.2. Literature review

The United Nations Framework Convention on Climate Change (UNFCC, 1992) defines climate change as, “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”.

In many researches, climate change is considered as one of the greatest challenges of humankind in the 21st century. In the country report, the Asian Development Bank ranked Vietnam in the group of countries with high vulnerable risk due to climate change and sea level rise (ADB, 1994). In 2007, Vietnam was listed as one of the five worst affected countries by climate change by World Bank. According to Ministry of Natural Resources and Environment (MONRE) in the National Target Program to Respond to Climate Change in 2008, the annual average temperature during the last 50 years (1958 - 2007) in Vietnam increased by 0.5^oC to 0.7^oC. The annual average temperature for the last four decades (1961 to 2000) was higher than that of the three previous decades (1931 to 1960). Annual average temperatures for the period from 1991 to 2000 in Ha Noi, Da Nang and Ho Chi Minh City (Figure 1-1) were all higher than the average for the period from1931 to 1940 by 0.8^oC; 0.4^oC and 0.6^oC respectively (MONRE, 2008). At all locations, the change of annual average rainfalls for the last 9 decades (1911 - 2000) have not clear tendency and not consistent with each other. On average for the whole country, the rainfall over the past 50 years (1958 - 2007) decreased by about 2%.

Freshwater is essential for every living form on earth, and it is also the necessary for almost human activities. There is a complicated system of climate, freshwater, biophysical and socio-economic where every factor affects to others, so a change in one factors cause to change of another factor. Climate change resulting from the influence of human beings on nature puts “a major pressure to nations that are already confronting the issue of sustainable freshwater use”. About the freshwater, if we have too much water, or too little water, and/or water polluted, that can lead to problems. Climate change may make worse these problems. The issues related to fresh water plays an important role among the key regional and sectorial vulnerabilities. Therefore, “the relationship between climate change and freshwater resources is one of primary concern and interest” (Bates et al., 2008).

Assessing the impact of climate change is a crucial factor to propose any mitigation policies or adaptation. To select appropriate targets and decide action, policymakers need to compare the cost of action and inaction, and comparison of the costs of mitigation policies and the benefit of acting (Jamet and Morlot, 2009). In Vietnam, there are many studies on impacts of climate change on various fields such as: disaster (flood or drought), salty intrusion and agriculture. However, there are just a few researches mentioning about impacts of climate on water allocation based on the climate change scenarios of Vietnam. Those researches are focused on large scale, such as Hong-Thai Binh river basin (Thai, 2010) (Figure 1-1), or city scale such as Quy Nhon city (Van and Thai, 2011) (Figure 1-1). In order to propose adaptation measure to each province as NTP of Vietnam, it is necessary to assess the impacts of climate change on province scale. That is the reason why this study was conducted.

1.3. Objectives of the study

This study provides information on the tendency change of river flow and water allocation in the Upper Cau River basin under the impacts of climate change. In the study, based on the data sources about climate change scenarios from the Ministry of Natural Resources and Environment of Vietnam, and the Vietnam Institute of Meteorology, Hydrology and Environment, mathematical models will be applied to estimate the impacts of climate change on water resources. These models include CROPWAT developed by Food and Agriculture Organization (FAO) for calculating crop water demand, Nedbor-Afstromings Model (NAM) developed by Danish Hydraulic Institute (DHI) for calculating natural flow, and MIKE BASIN (DHI) for determining water allocation. There are three climate change scenarios for Vietnam were chosen and downscaling by MONRE and IMHEN, listed as A2 for high emission scenario, B2 for medium emission scenario, and B1 for low emission scenario (Figure 1-2).

To archive the objectives, the study was implemented step by step as shown in Figure 1-3.

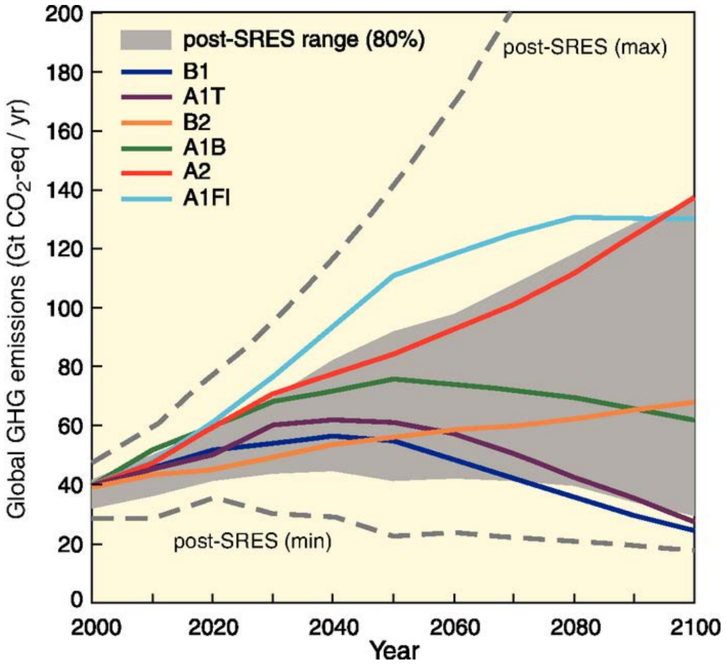


Figure 1-2 Simulated carbon dioxide emissions from 2000 to 2100 by Emission Scenario (IPCC 2007)

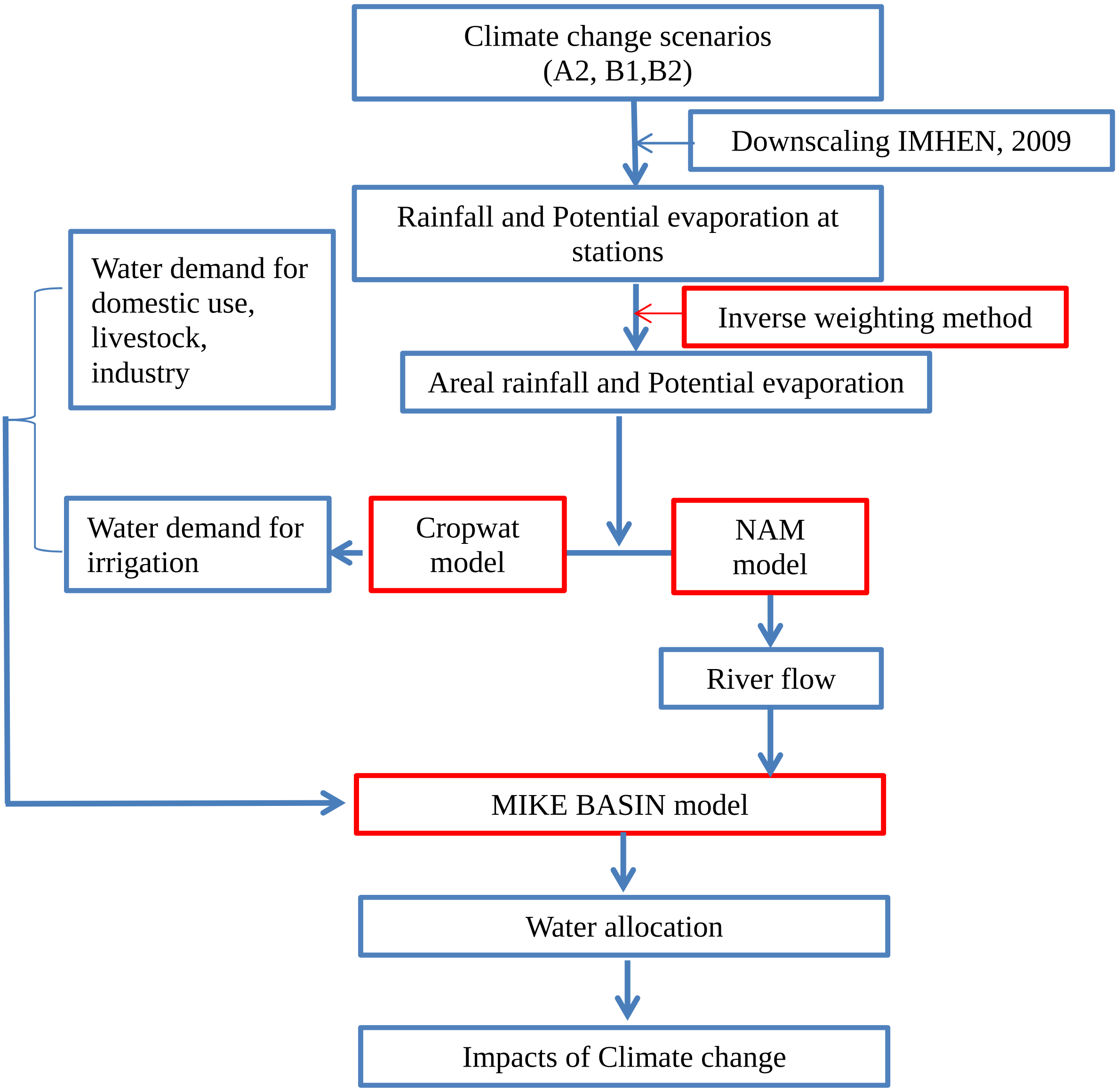


Figure 1-3 Implementation steps in the study

Chapter 2 Methodology

2.1. Overview of study site

2.1.1. Geography and topography

The Cau River basin belongs to the Thai Binh River Basin System. It can be divided into 6 sub basins, namely Upper Cau River, Upper Cong River, Lower Nui Coc River, Ca Lo River, Thac Huong River and Bac Duong River (Figure 2-1). The study area is located in the Northern part of Cau River basin with the total area of 308,142 ha.

The Upper Cau River Basin has a diverse and complex topography including mountainous terrain and midland (Figure 2-2). In general, the basin topography is lower from the Northwest to the Southeast. The mountain areas with elevation of more than 1,000 m are distributed in the north and northwest of the basin. Low mountains and hill lands are distributed in almost north and east of the basin. The south and southwest of the basin is the low hill land.

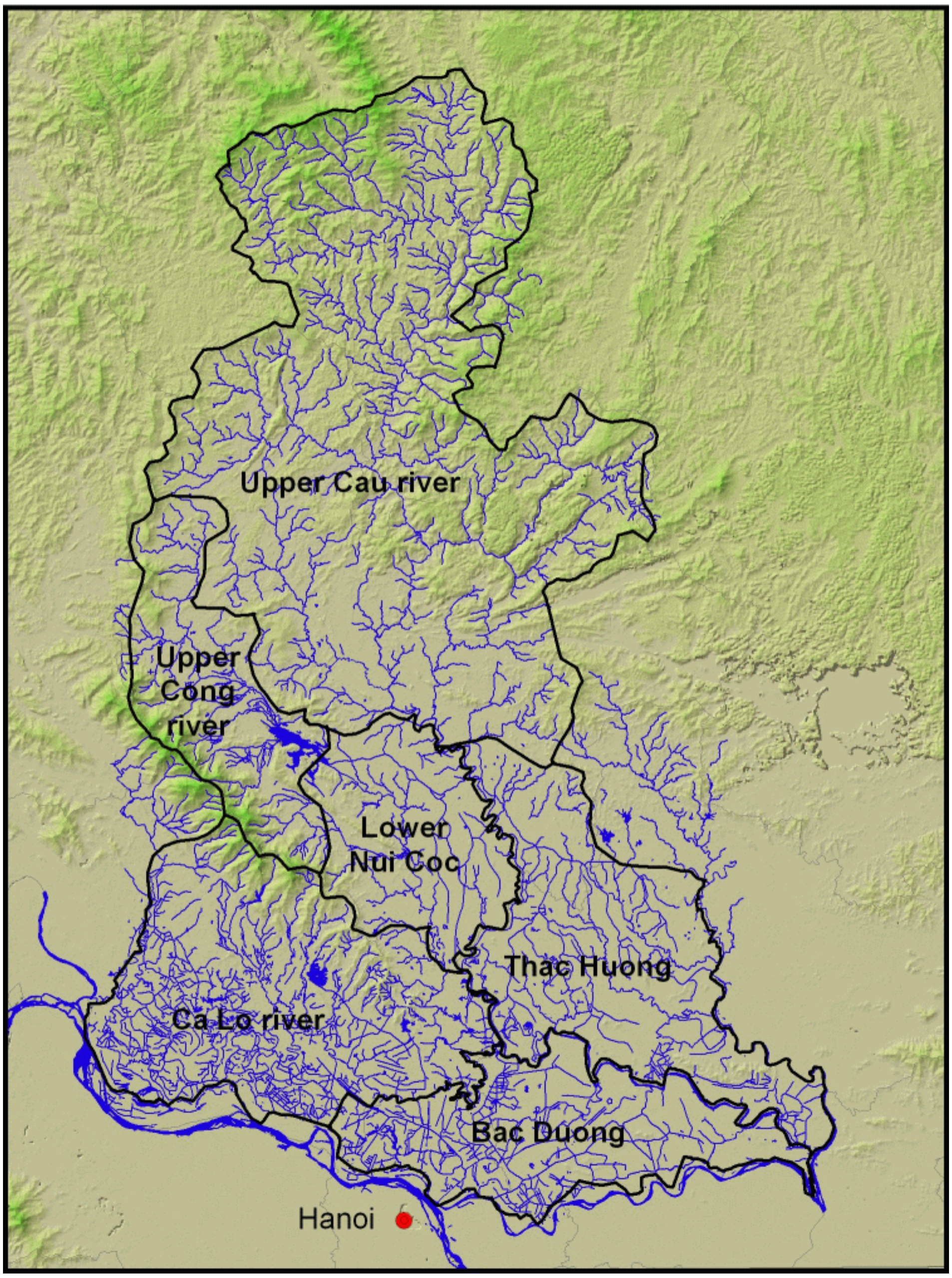


Figure 2-1 Overview of the Cau sub-basin and river network (Institute for Water Resources Planning Hanoi, 2005)

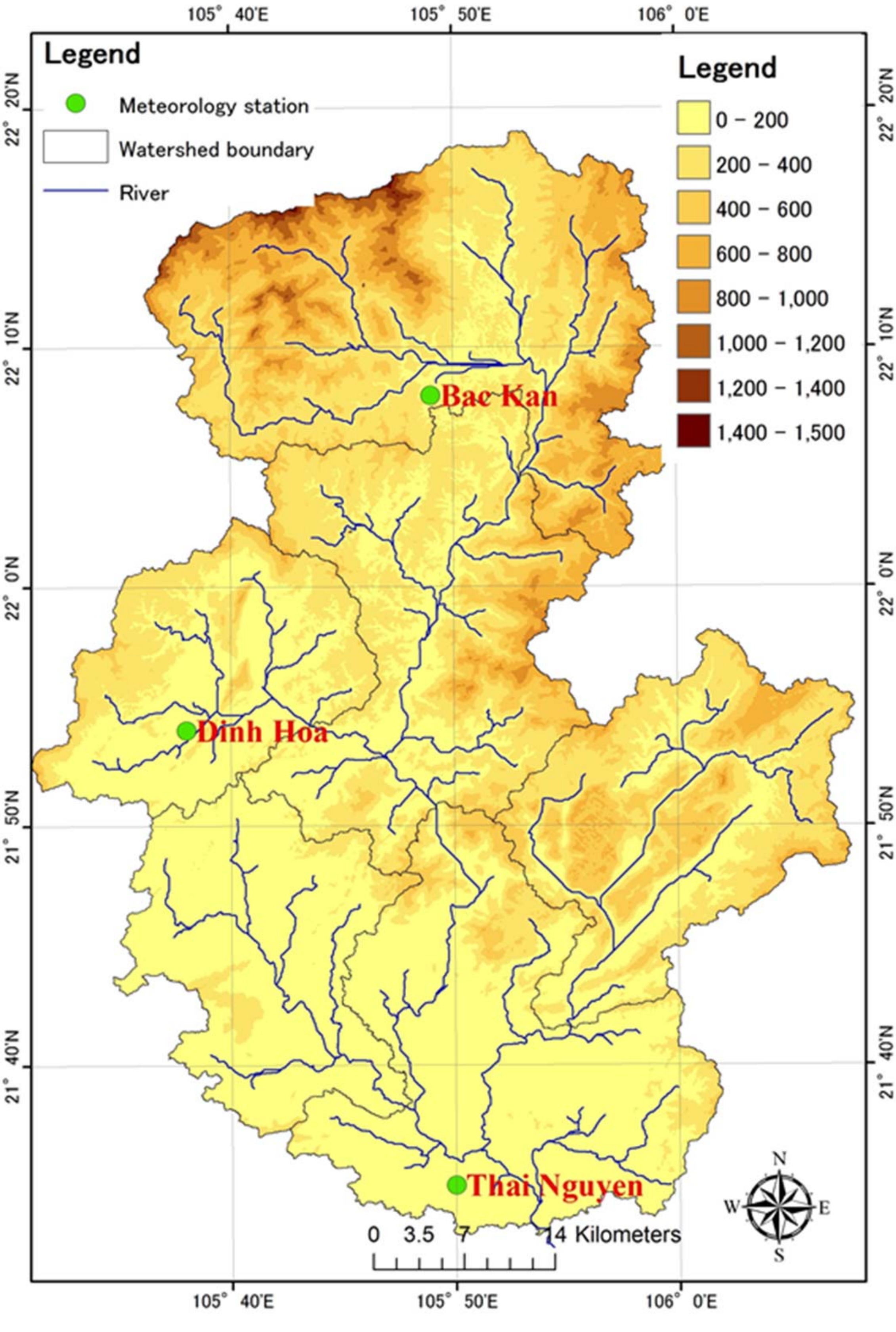


Figure 2-2 Topography map of the Upper Cau river basin (created from: ASTER GDEM)

2.1.2. Land cover

In the Upper Cau river basin, natural forest is covered by 21% of total basin land in the Northern and North-East part. Poor forest covers 51% of total land. Agriculture land and limestone mountain covers respectively 15% and 13% of total area (Figure 2-3).

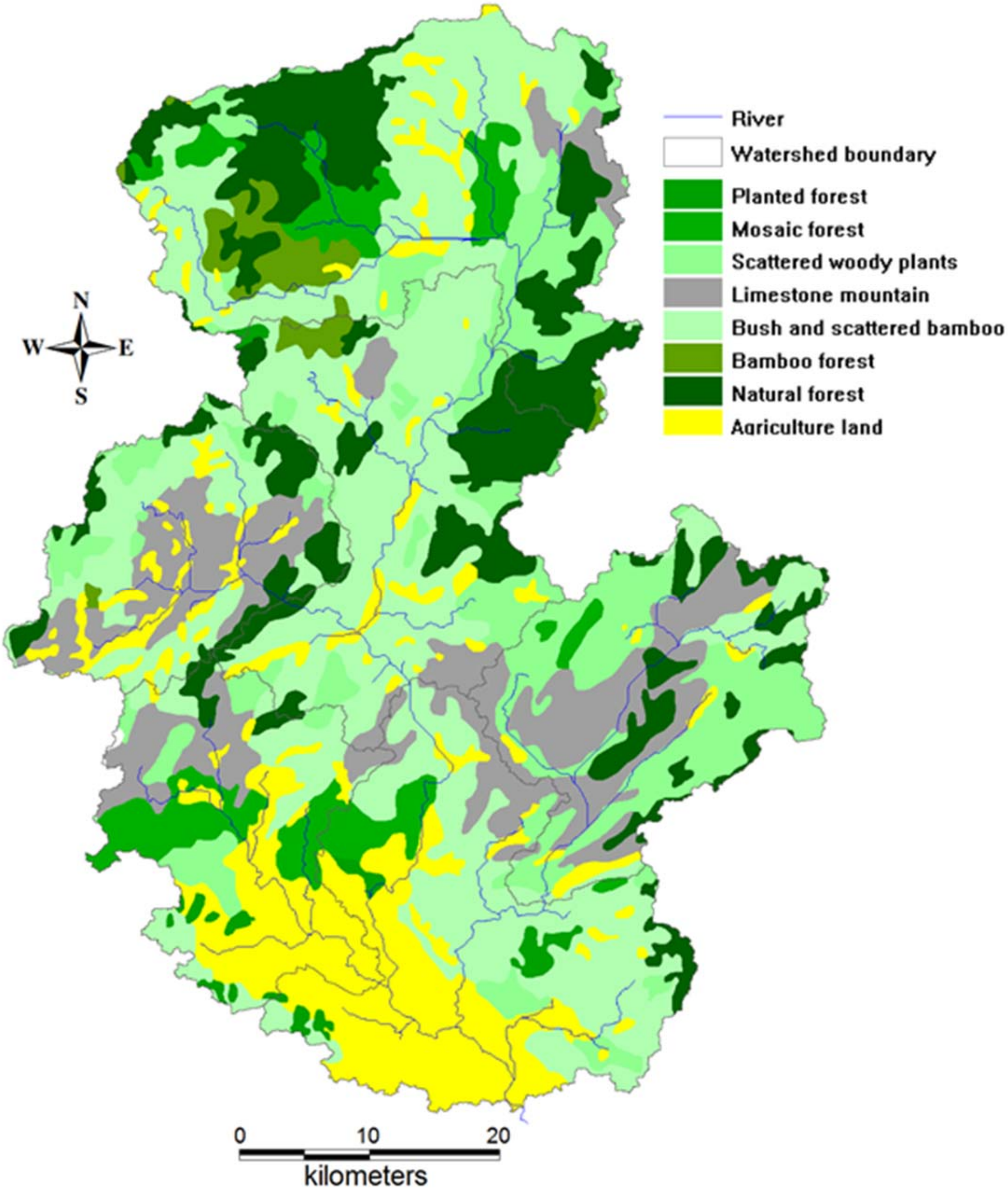


Figure 2-3 Land cover in the Upper Cau River basin

2.1.3. Water resources

2.1.3.1. Rainfall

The average annual rainfall varies from 1500mm to 2000mm. But the rainfall is distributed unevenly both in space and time. The rainy season, which provides more than 80 percent of total annual rainfall, usually starts in May and ends in September (Figure 2-4). The data is shown in Figure 2-4 was synthesized from daily rainfall data collected from HydroMeteorological Data Center (HMDC).

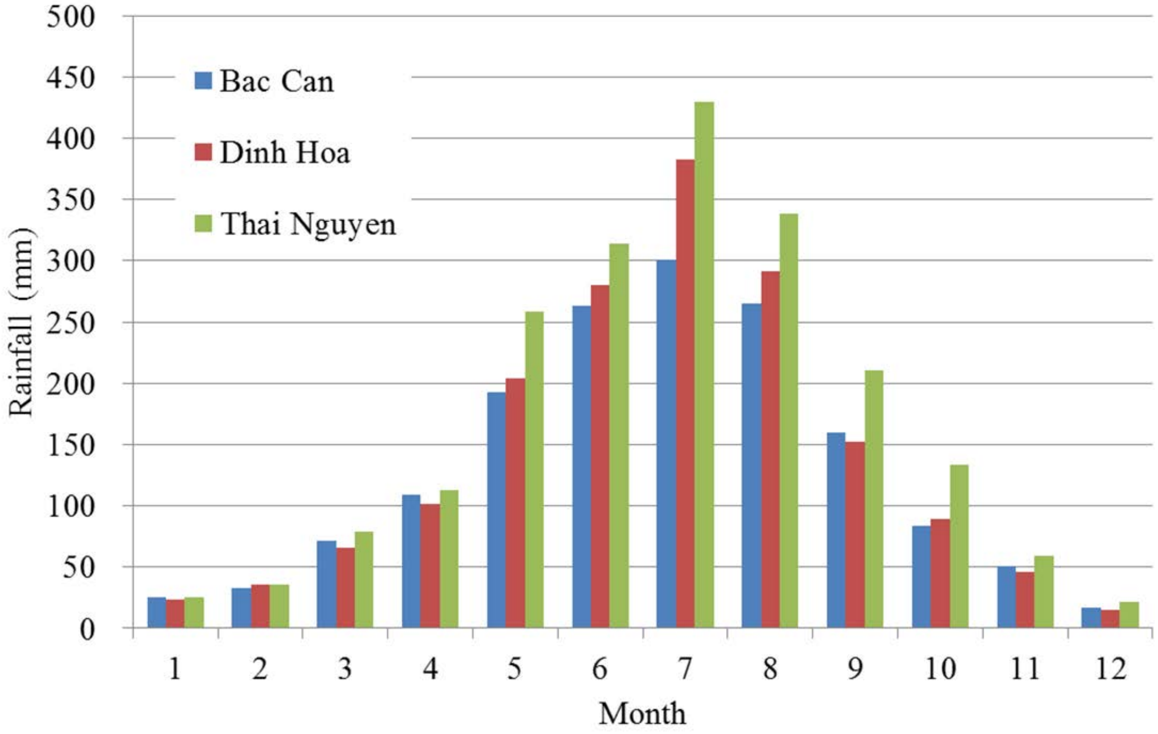


Figure 2-4 Rainfall distribution in years of the Upper Cau River basin (source: HMDC)

As for space, the rainfall distribution is affected by separation of the topography and change in mountain direction and, thus, in some areas, the rainfall may reaches up to 2,000 mm per year or more while in other places, the annual rainfall as little as 1,300-1,400 mm (Figure 2-5).

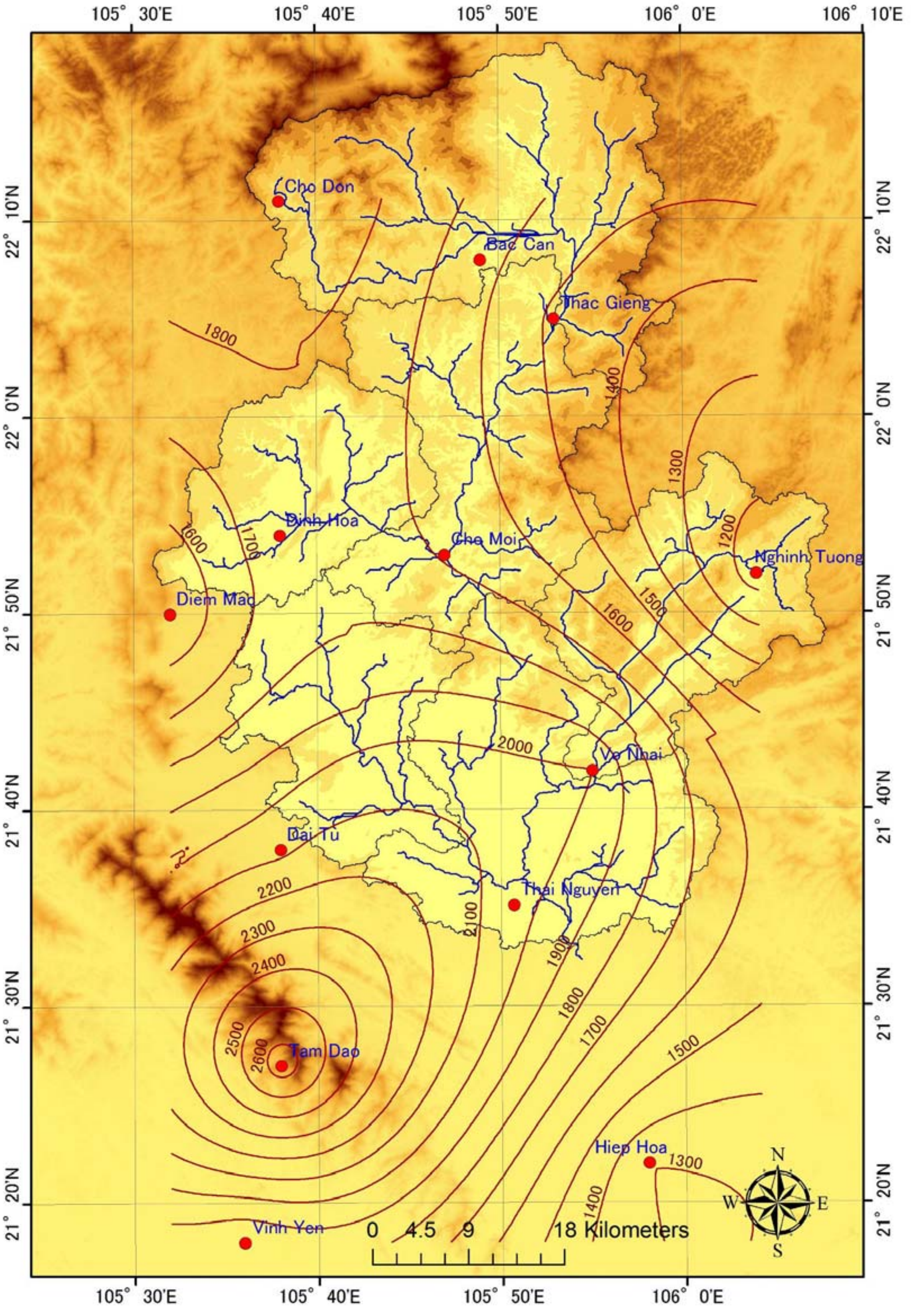


Figure 2-5 Distribution of annual rainfall as space of the Upper Cau River basin (source: HMDC)

In the Upper Cau River basin, topography strongly affects to rainfall and evaporation:

- In the summer (rainy season), high-pressure systems are expanded northward from the Southern Hemisphere. Atmospheric conditions in North Vietnam are governed by air masses coming from the Highs over Indian Ocean and the subtropical High over the South China Sea (Figure 2-6). The two systems bring moist air and monsoon rains. However, heavy rains mainly occur in July and August in association with tropical depressions, highly unstable conditions around the Intertropical Convergence Zone and cyclones, which frequently appear in the South China Sea and move westward striking the West Pacific coast (Hien et al., 2002). Summer monsoon comes from the South China Sea to the study area with the direction southeast-northwest, meet high moutains in the southwest (Tam Dao mountain) (Figure 2-5) and northern part of the basin, and makes high rainfall area in the southwest and north of the basin. The Northeast and Eastern parts of the basin is lower rainfall areas because the moutains in these area have parallel direction with summer moonsoon.

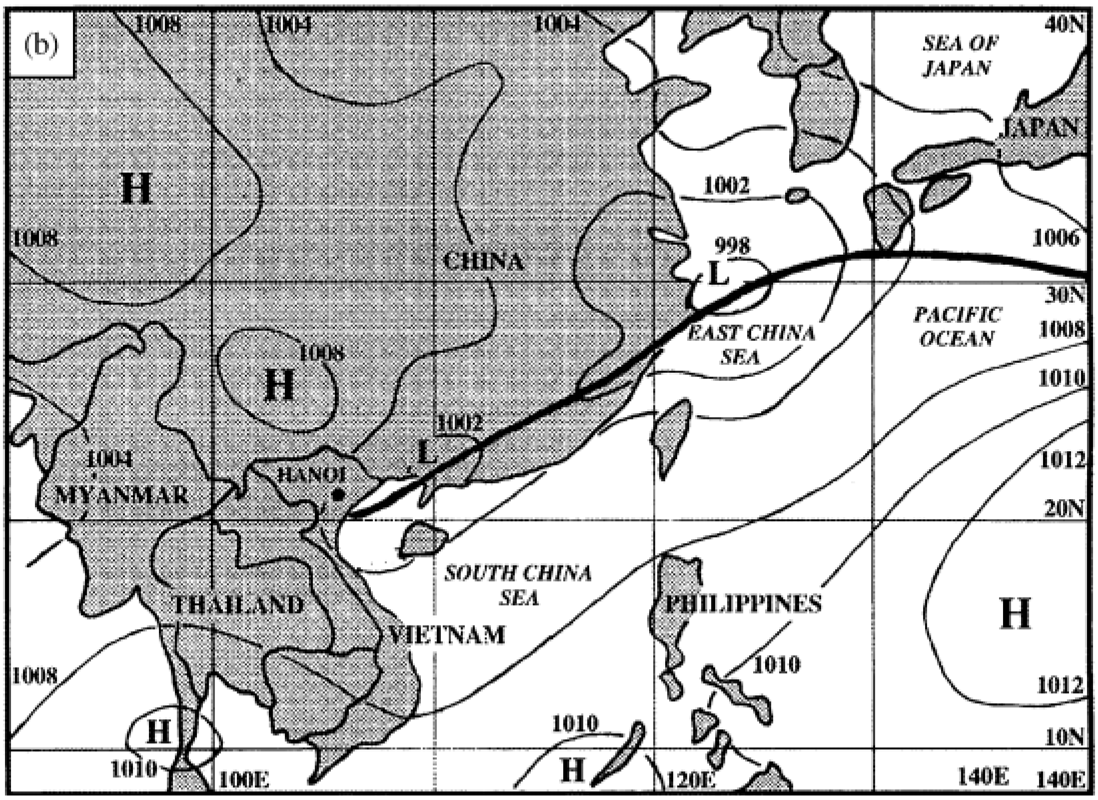


Figure 2-6 High-pressure systems in East Asia in summer (Hien et al., 2002)

- In the winter (dry season), atmospheric conditions are alternately affected by air masses from the Highs over Siberia and East China Sea (Figure 2-7). Continental air from the Siberia High yields low temperature and stable atmospheric conditions. Air humidity depends on the trajectory (continental or marine) of air masses from the source origin to North Vietnam. From October to December, northerly to northeasterly flow coming from the inland of China brings dry and cold air. Conversely, from January to March/April, with the Siberia High system frequently shifted to the East, air masses have to travel a long way over the Pacific Ocean before reaching North Vietnam via the Gulf of Tonkin. Northeasterly flow of moist-laden air results in smog, low stratus cloudiness and drizzle (Hien et al., 2002)

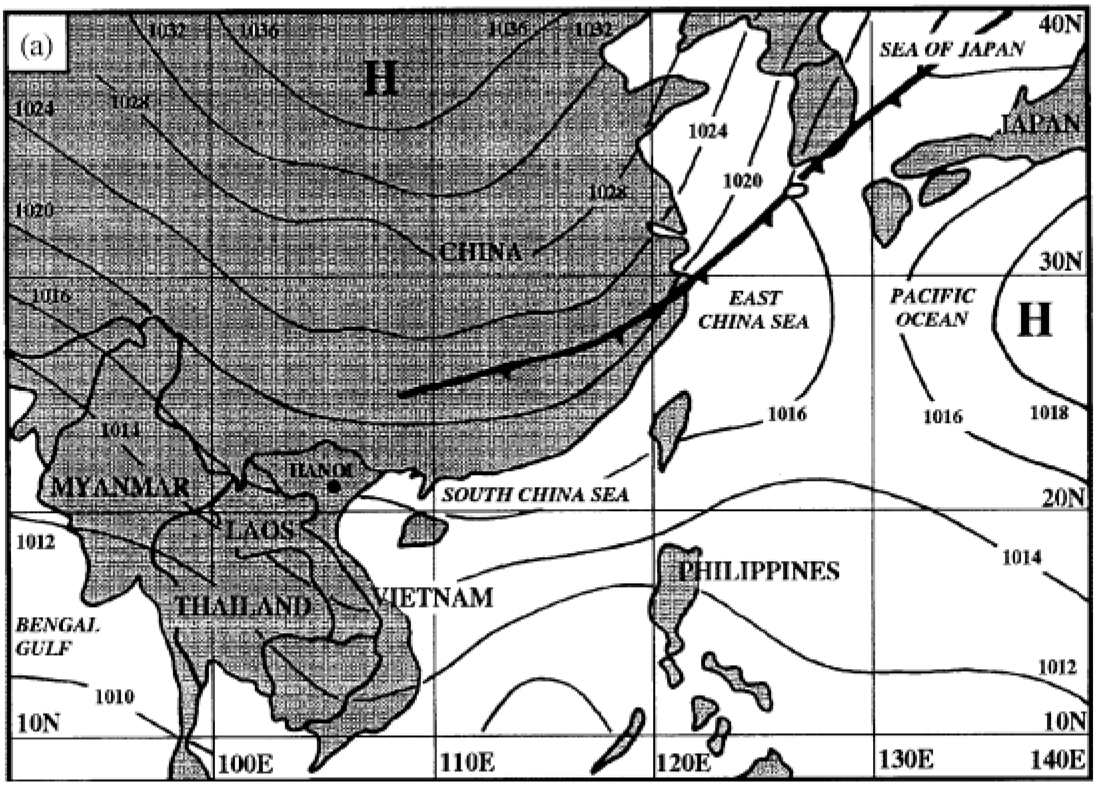


Figure 2-7 High-pressure systems in East Asia in winter (Hien et al., 2002)

2.1.3.2. Runoff

Due to unevenly rainfall distribution, according to flow regime, there are two seasons in a year: flood season and dry season. Flood season is from June to October and accounts for 70-80 percent of total annual flow. Dry season lasts 7 to 8 months, from November to May next year and accounts for only 20-30 percent of total annual flow. The three exhausted months are January, February and March, and only accounts for 5.6 to 7.8 percent of total annual flow (IMHEN, 2006).

2.1.4. Water use zoning in the Upper Cau river basin

The Upper Cau river basin is divided into 6 sub-areas: Thac Rieng, Cho Moi, Cho Chu, Song Du, Vo Nhai, and Dong Hy (Table 2-1 and Figure 2-8). This division based on characteristics of water resources, irrigation systems, water users on the Upper Cau River basin (IMHEN, 2008). There are two sub-areas located in Bac Can province, and four others located in Thai Nguyen province of Vietnam.

- Thac Rieng sub-area includes territory of five communes of Cho Don District (Bac Can province), Bac Can town, and Bac Thong District. Total land is 75,922 ha.
- Cho Moi sub-area includes whole territory of Cho Moi District (Bac Can province) with total land is 52,088 ha
- Cho Chu sub-area includes territory of 17 communes, one town of Dinh Hoa District (Thai Nguyen province) with total land is 38,598 ha.
- Song Du sub-area includes territory of Phu Luong District (Thai Nguyen province), six communes of Dai Tu District (Thai Nguyen province). Total land is 47,183 ha.
- Vo Nhai sub-area includes territory of six communes of Vo Nhai District (Thai Nguyen province) with total land is 48,576 ha.
- Dong Hy sub-area includes territory of whole Dong Hy District (Thai Nguyen province) with total land is 45,775 ha.

Table 2-1 Six sub-areas in the Upper Cau river basin

No	Area	Province	Total area (hectares)
1	Thac Rieng	Bac Can	75,922
2	Cho Moi	Bac Can	52,088
3	Cho Chu	Thai Nguyen	38,598
4	Song Du	Thai Nguyen	47,183
5	Vo Nhai	Thai Nguyen	48,576
6	Dong Hy	Thai Nguyen	45,775
Total			308,142

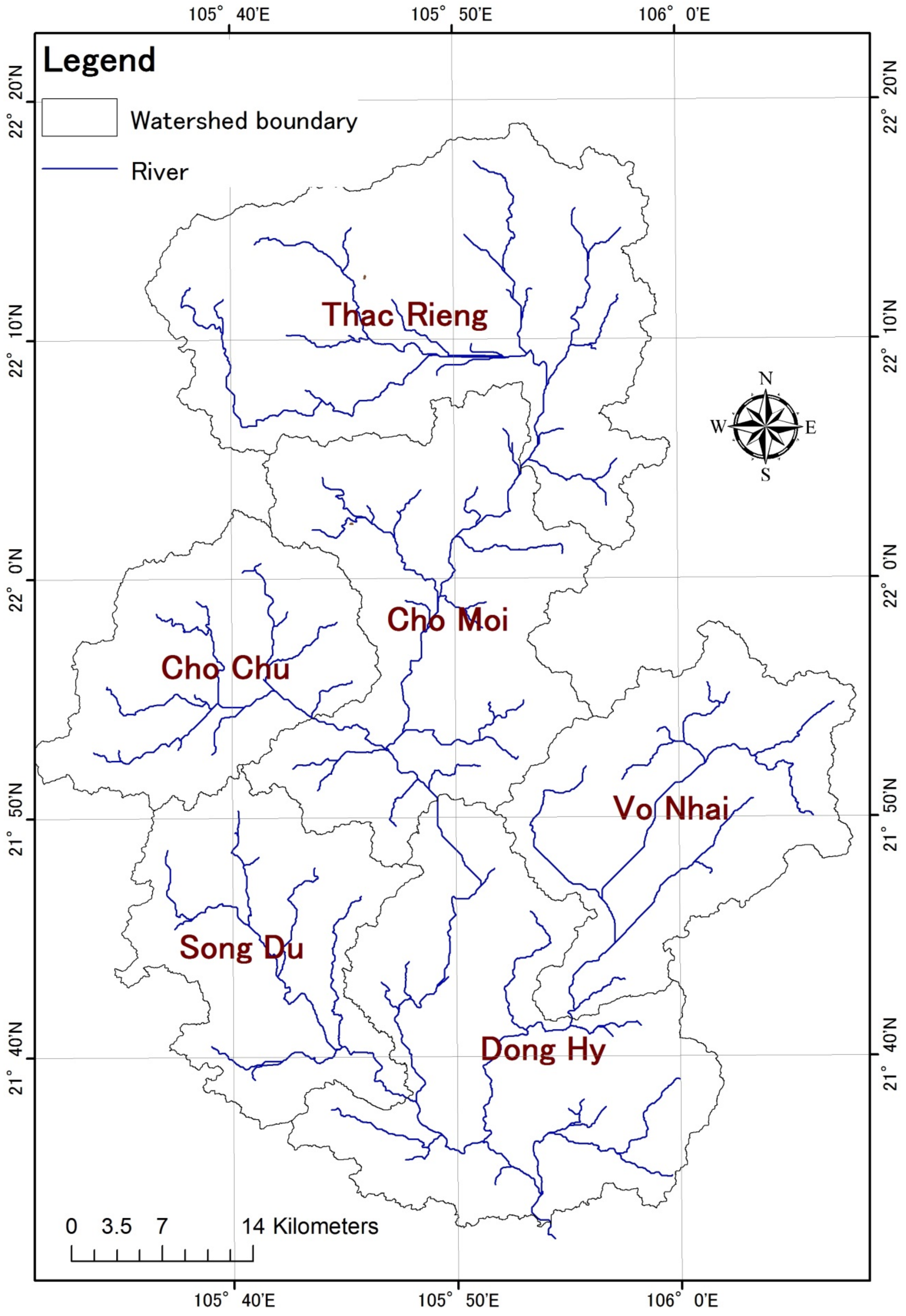


Figure 2-8 Six sub-areas in the Upper Cau River basin

2.2. Methodology

2.2.1. Climate change scenarios for Vietnam

The climate change scenarios for Vietnam were developed by using the software MAGICC/SCENGEN 5.3 (Model for the Assessment of Greenhouse-gas Induced Climate Change/A Regional Climate SCENario GENerator). MAGICC and SCENGEN are coupled. Where MAGICC carries through calculations at the global-mean level using the same upwelling-diffusion, energy-balance climate model that developed by Intergovernmental Panel on Climate Change (IPCC). SCENGEN uses these results to produce spatially detailed information on future changes in temperature, precipitation. The results of this couple model are temperature and rainfall with 5x5 degree latitude/longitude grid resolution.

Two important meteorological elements, rainfall and air temperature, were computed and analyzed (IMHEN, 2010). On the Upper Cau river basin, there are available climate change data for three meteorology station: Bac Can, Dinh Hoa, and Thai Nguyen (Figure 2-5). However, data of seven rainfall stations and one evaporation station surround the basin was also used to increase data quality for calculation (it will be explained detail in the next part of content (2.2.2)).

2.2.1.1. Rainfall

The general trend of change in precipitation in the Upper Cau river basin is upward in all three climate change scenarios at three stations. However, there are differences among three scenarios: an A2 scenario shows the highest change, then B2 and B1 in order.

The tendency of annual rainfall in three climate change scenarios is shown in Figure 2-9 to Figure 2-11. In compare with baseline period, annual rainfall at Thai Nguyen station increases 168 mm/year (8.3%) (A2 scenario), 141 mm/year (7.0%) (B2 scenario), and 100 mm/year (5.0%) (B1 scenario). Annual rainfall at Dinh Hoa station increases 120mm/year (7.1%) (A2), 101 mm/year (6.0%) (B2), 72 mm/year (4.2%) (B1). Similarly at Bac Can station, 76 mm/year (4.8%) (A2), 63 mm/year (4.0%), and 45 mm/year (2.9%) (B1).

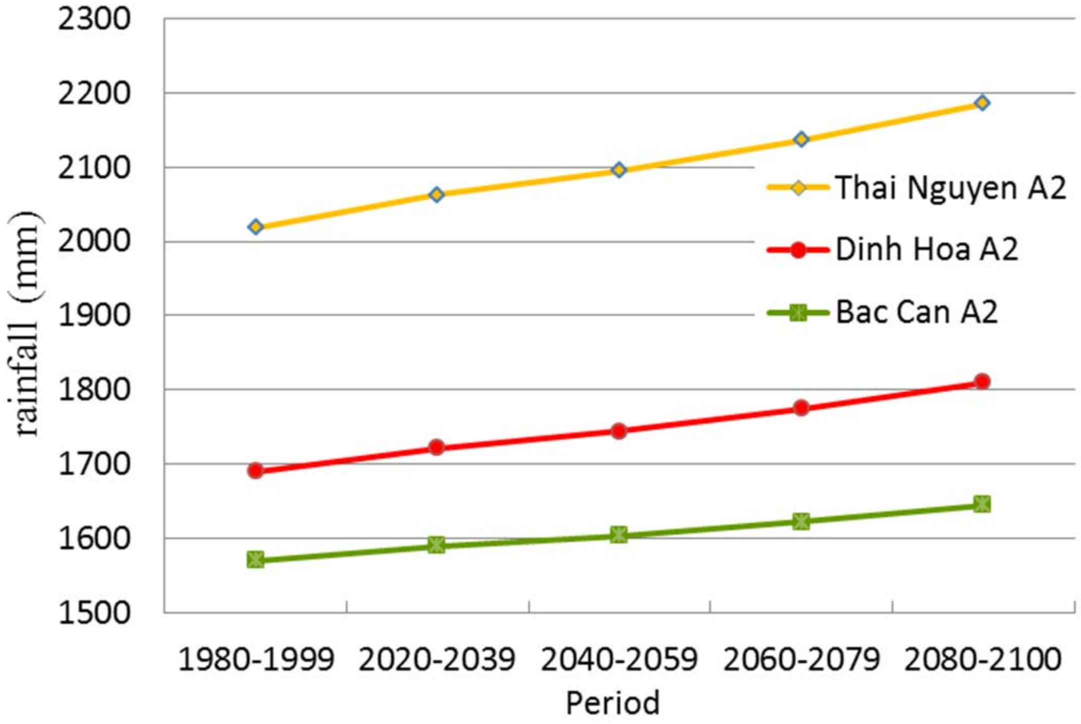


Figure 2-9 Increasing trend of average annual rainfall to A2 climate change scenario

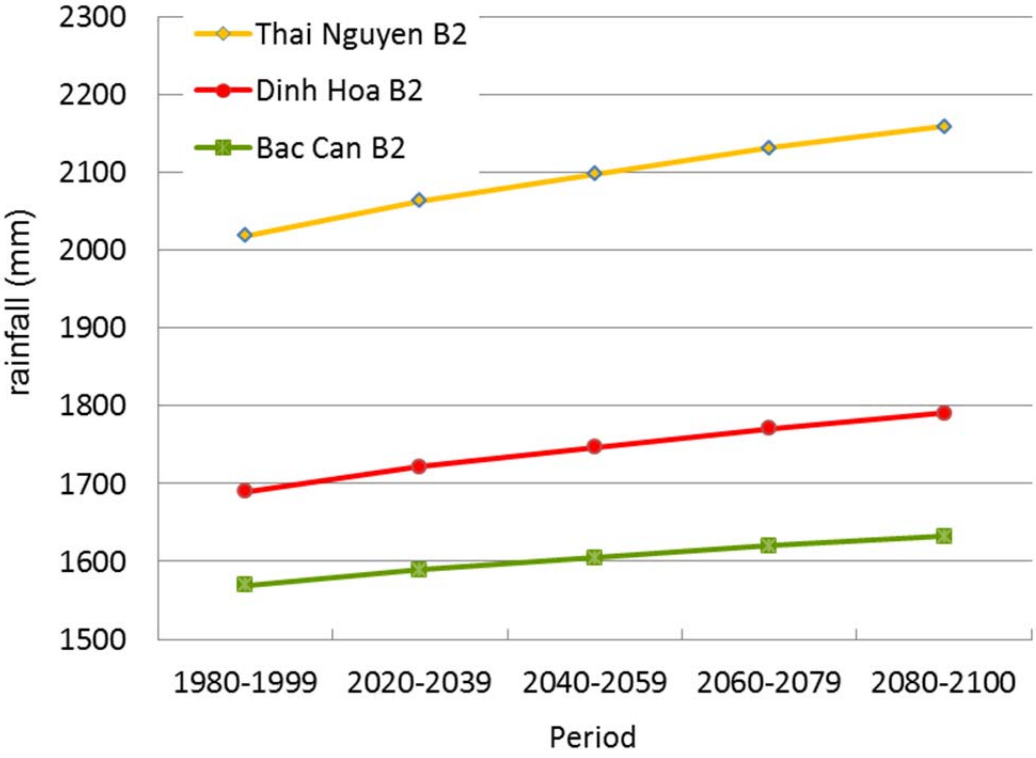


Figure 2-10 Increasing trend of average annual rainfall to B2 climate change scenario

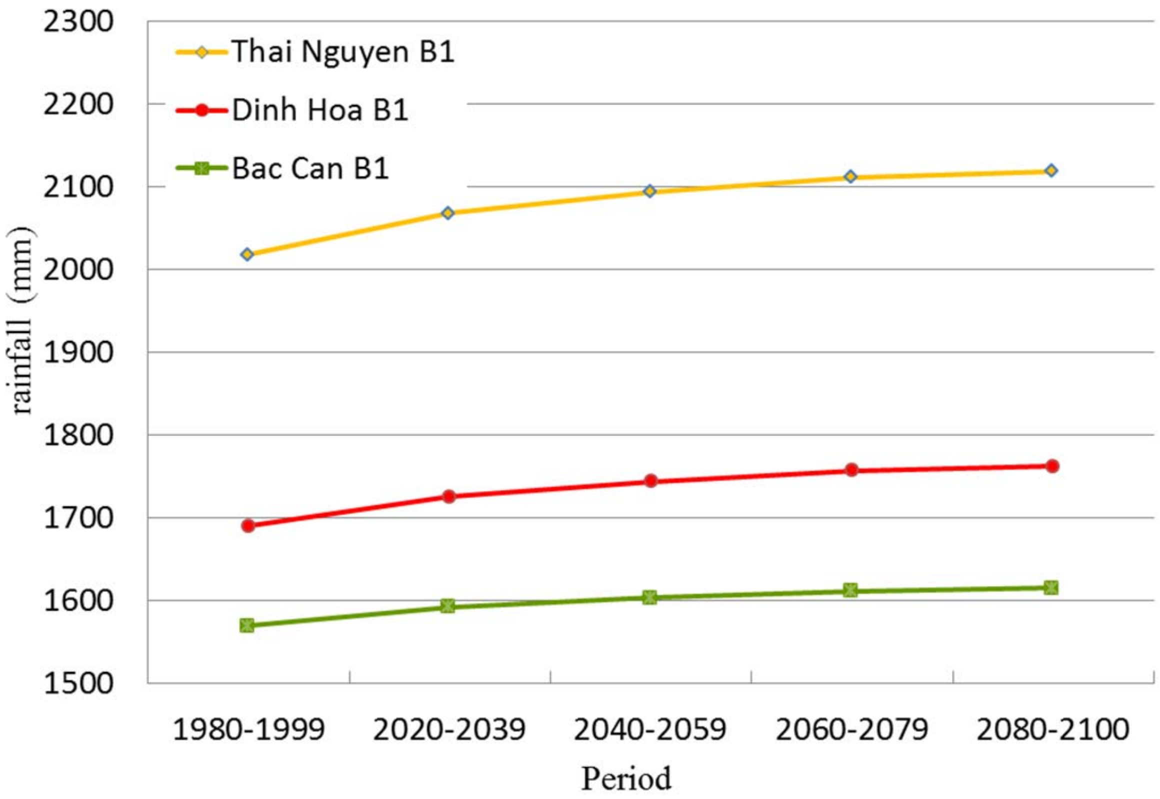


Figure 2-11 Increasing trend of average annual rainfall to B1climate change scenario

Considering of seasonal change, there is an increasing trend of rainfall in rainy season and a decreasing trend in dry season; the range of change depends on the climate change scenarios. For example, A2 scenario is always stronger increasing than B2 in rainy season and decrease faster in dry season; B2 is stronger increasing than B1 in rainy season, and decrease faster in dry season. It shows that climate change may lead more disaster in the future: flood in the rainy season, drought in the dry season.

In rainy season, the increase in rainfall in A2 scenario is larger than B2 and B1 scenarios. For example, at Thai Nguyen station, rainfall in the period of 2080-2100 is 9.2% (A2), 7.8% (B2), and 5.5% (B1) larger than baseline period (1980-1999); at Dinh Hoa station are 10.6% (A2), 8.9% (B2), and 6.3% (B1); at Bac Can station are in the order 7.4% (A2), 6.2% (B2), and 4.4% (B1). From those numbers, rainfall at Dinh Hoa has more change than in two other stations. Rainfall in the North of basin (Bac Can station) has smallest changes. The tendency of rainy season rainfall in three climate change scenarios is shown in Figure 2-12 to Figure 2-14

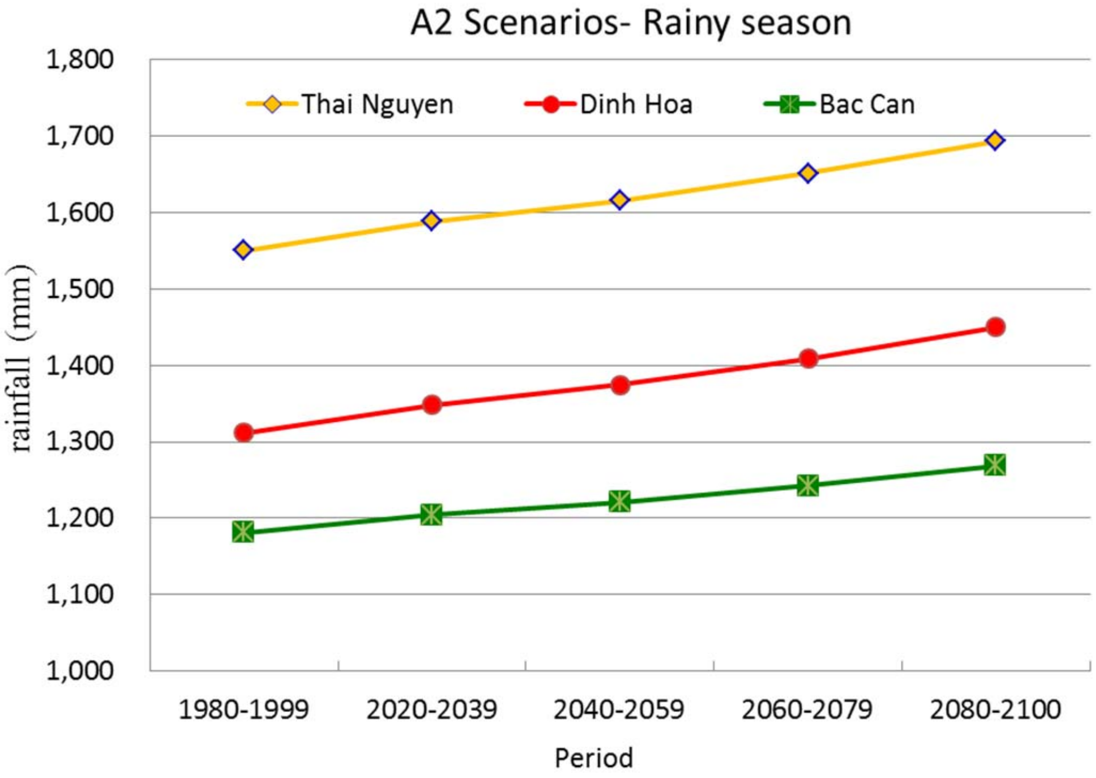


Figure 2-12 Increasing trend of average rainfall in rainy season to A2 climate change scenario

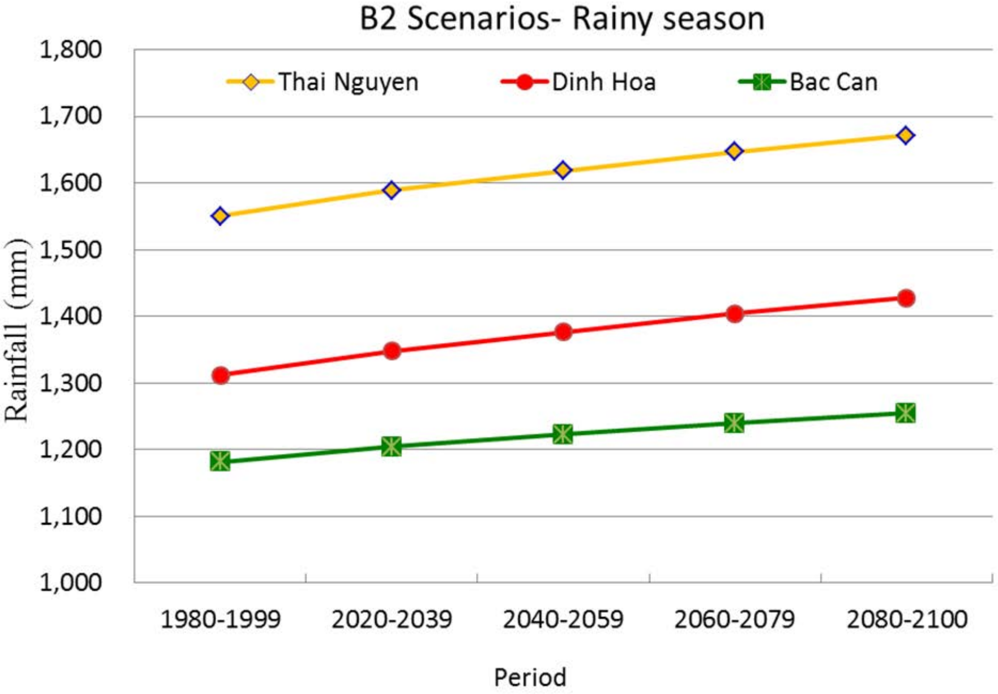


Figure 2-13 Increasing trend of average rainfall in rainy season to B2 climate change scenario

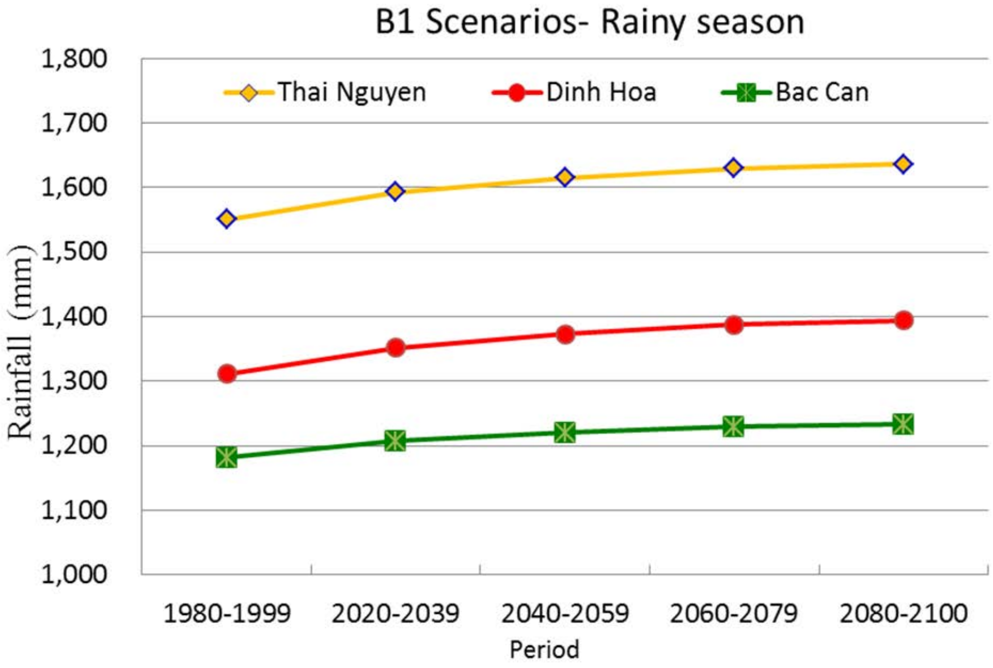


Figure 2-14 Increasing trend of average rainfall in rainy season to B1 climate change scenario

In dry season, average rainfall at all three stations show the decrease tendency over the periods from the baseline to the end of 21st century. The largest change can be seen at Dinh Hoa station with (-4.5%) (A2), (-3.7%) (B2), (-2.5%) (B1) at the end of 21st century, in comparison with baseline. Two other stations have smaller changes. The tendency of dry season rainfall in three climate change scenarios is shown in Figure 2-15 to Figure 2-17.

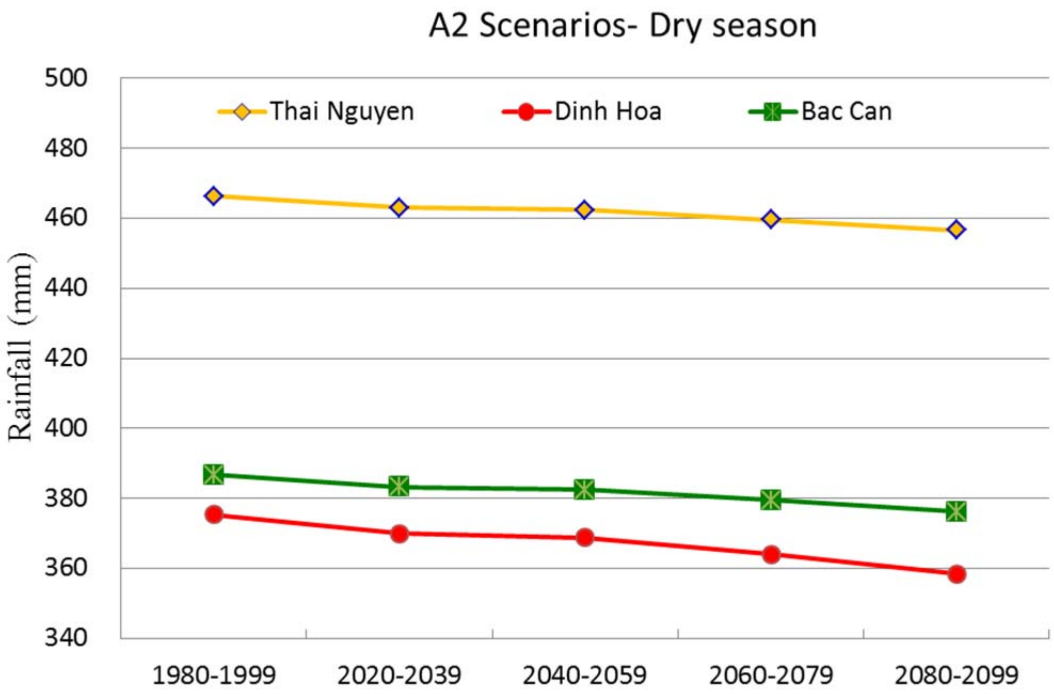


Figure 2-15 Decreasing trend of average rainfall in dry season to A2 climate change scenario

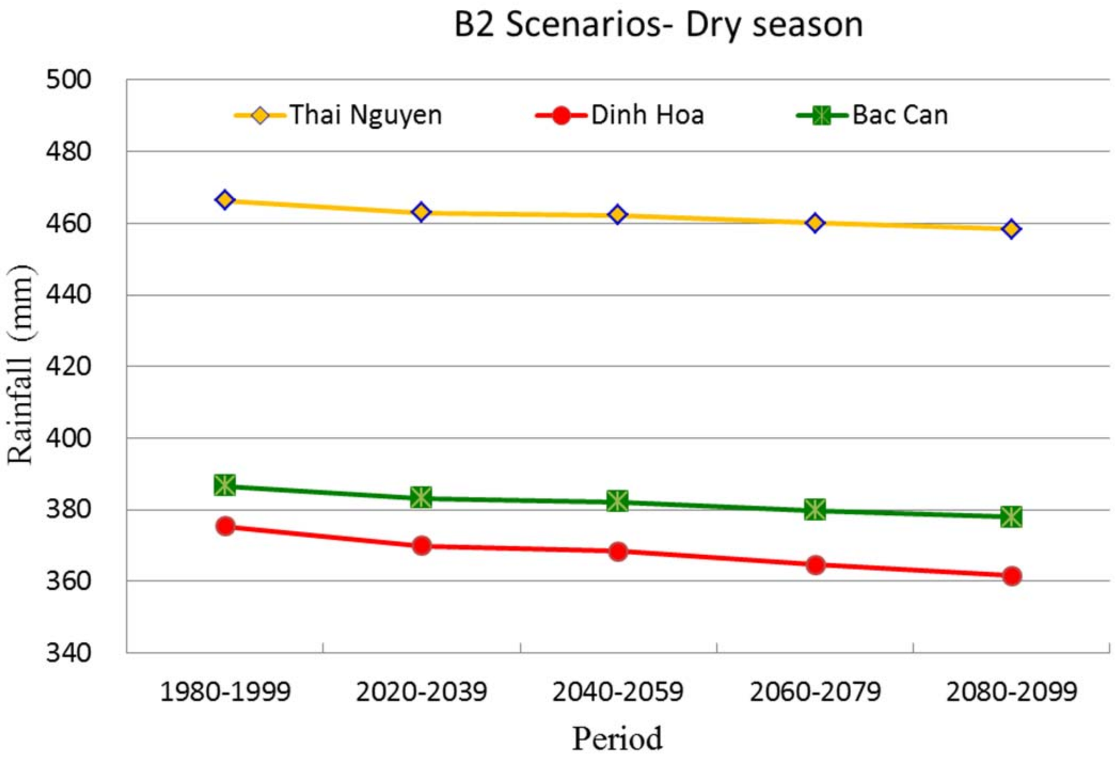


Figure 2-16 Decreasing trend of average rainfall in dry season to B2 climate change scenario

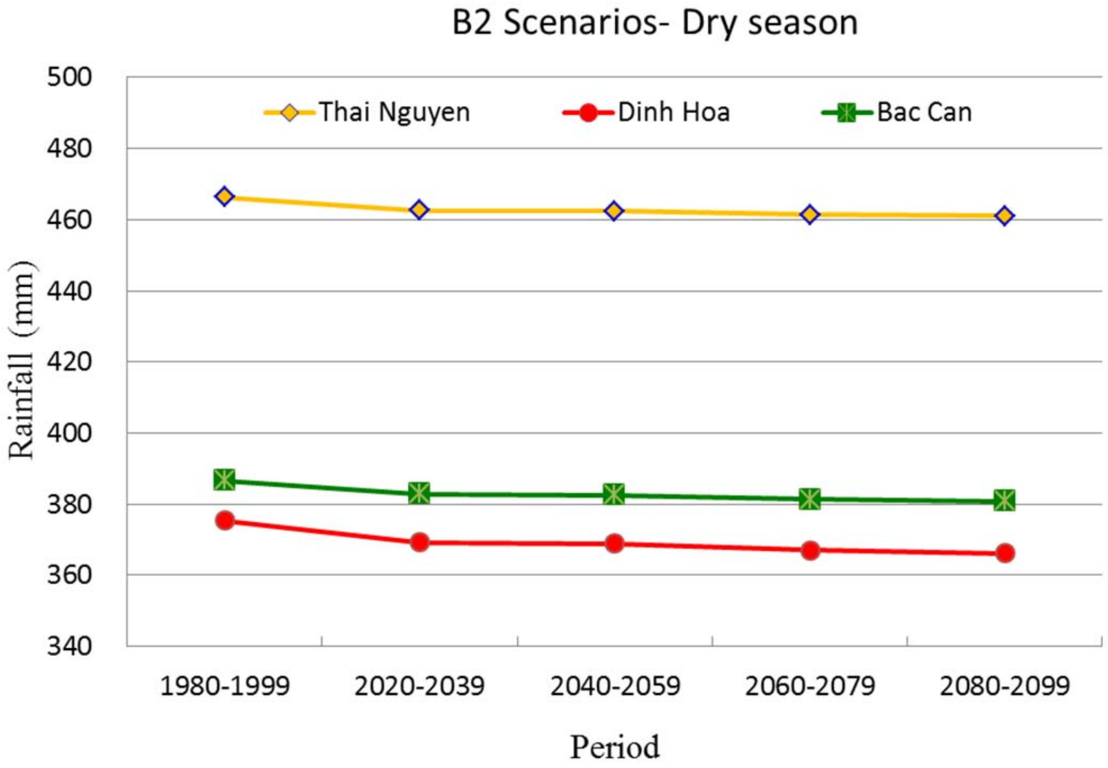


Figure 2-17 Decreasing trend of average rainfall in dry season to B1 climate change scenario

2.2.1.2. Potential evaporation

Potential evaporation is an important factor of hydrological cycle leading to the changes in flow in the basin. In this study, potential evaporation was used from two sources. In baseline period (1980-1999), observation data was used. In future periods (2020-2099), this study uses the potential evaporation developed by Institute of Meteorology, Hydrology, and Environment (2009) in the project of "Impacts of climate change on water resources and adaptation measures".

The average of annual potential evaporation for each period from 2020 to 2099 (Figure 2-18 to Figure 2-20) shows the increasing trend in the entire basin and at all the three scenarios. In comparison with baseline period, at the last period of 21st century (2080-2099), the difference can reach 18% (Dinh Hoa station, A2 scenario); the lowest change is also reach to 10% (Bac Can station, B1 scenario).

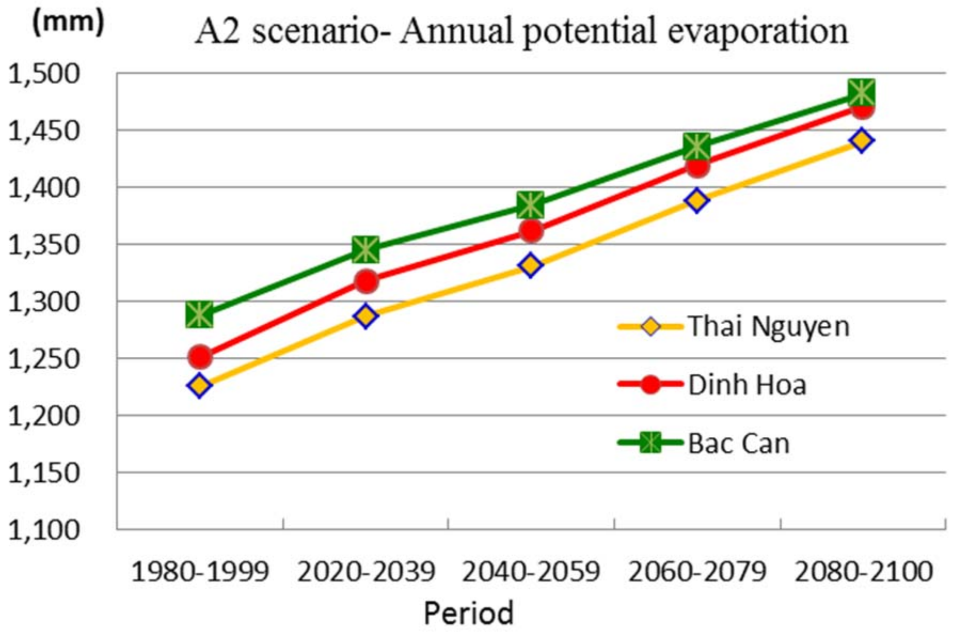


Figure 2-18 Increasing trend of average annual potential evaporation to A2 climate change scenario

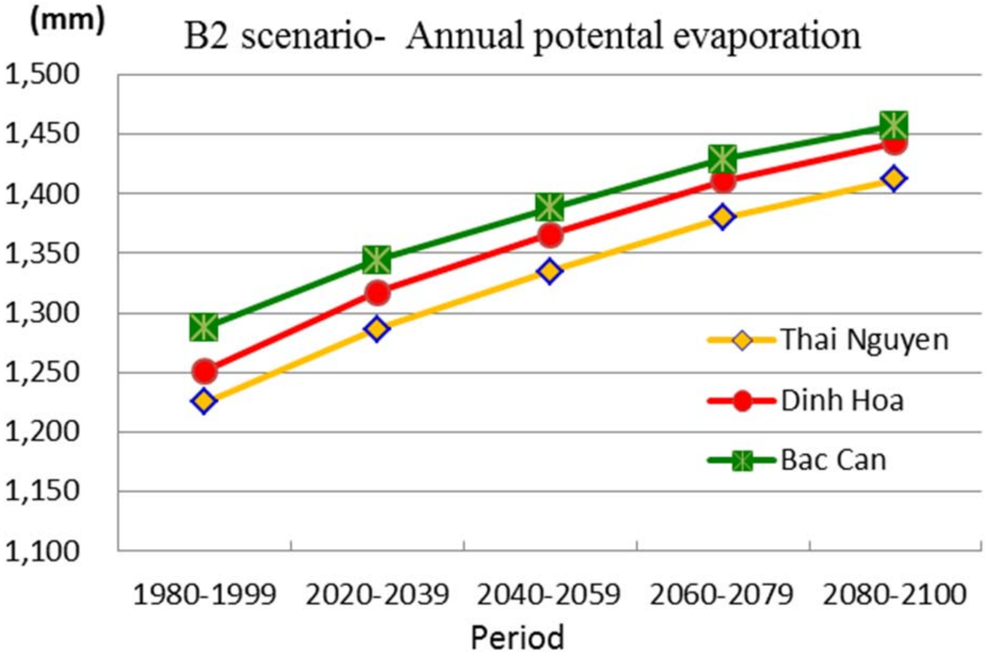


Figure 2-19 Increasing trend of average annual potential evaporation to B2 climate change scenario

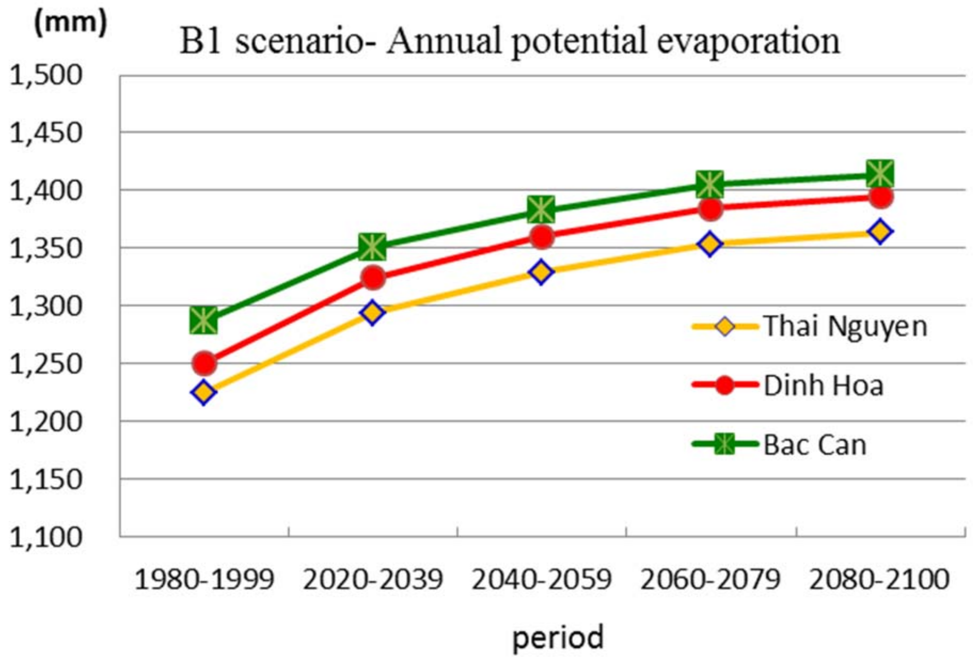


Figure 2-20 Increasing trend of average annual potential evaporation to climate change scenarios

The increase in potential evaporation causes increasing moisture loss on the basin when rainfall in the dry months decreases in general, resulting in reduction of low flows. Meanwhile, with increased water demand for irrigation, water shortage will be more serious (IMHEN, 2010).

2.2.2. Methods

The study was implemented based on the steps shows in Figure 1-3.

The study has rainfall and potential evaporation (in climate scenarios (A2, B2, B1) developed by IMHEN from 2020 to 2099, and observation data in period 1980-1999). These data are point data at meteorological stations. Then, the Inverse Weighting Method (IDW) was applied to interpolate to areal rainfall and potential evaporation in the study area. The areal meteorological data is input of CROPWAT model and NAM model. CROPWAT model calculates water demand for irrigation, NAM model calculates river flow. The results from the two models are inputs of water allocation model MIKE BASIN to assess impacts of climate change on water allocation in the study area.

2.2.2.1. Interpolation of rainfall and potential evaporation

The dense network of observation will help the estimation of the spatial distribution of meteorological data become more accurate, but it requires expensive costs for installation and operation. Therefore, the estimation of point data at unrecorded positions is necessary (Goovaerts, P., 2000). In the study area, climate change data of rainfall and potential evaporation is available for three stations Bac Can, Dinh Hoa, Thai Nguyen (Figure 2-5). The study applied three methods to interpolate them for the entire basin. Then the best one was selected for the study. The first method is relation of rainfall and potential evaporation with elevation, the second method is Thiessen Polygon method, and the last one is Inverse Distance Weighting method.

a. <u>Relation of rainfall and potential evaporation with elevation</u>

The idea of method is to find the relation of rainfall, potential evaporation with elevation, and then to apply to find these data on unknown point. Annual rainfall and potential evaporation were applied to find the relationship between rainfall and elevation, and potential evaporation and elevation. Rainfall data of 13 stations (1973, 1975-1981) and potential evaporation (1981, 1982) of nine stations in and around the study area were chosen. The position of meteorological stations are shown in Figure 2-21. The data used to estimate the relation between rainfall and evaporation with elevation is shown in Table 2-2.

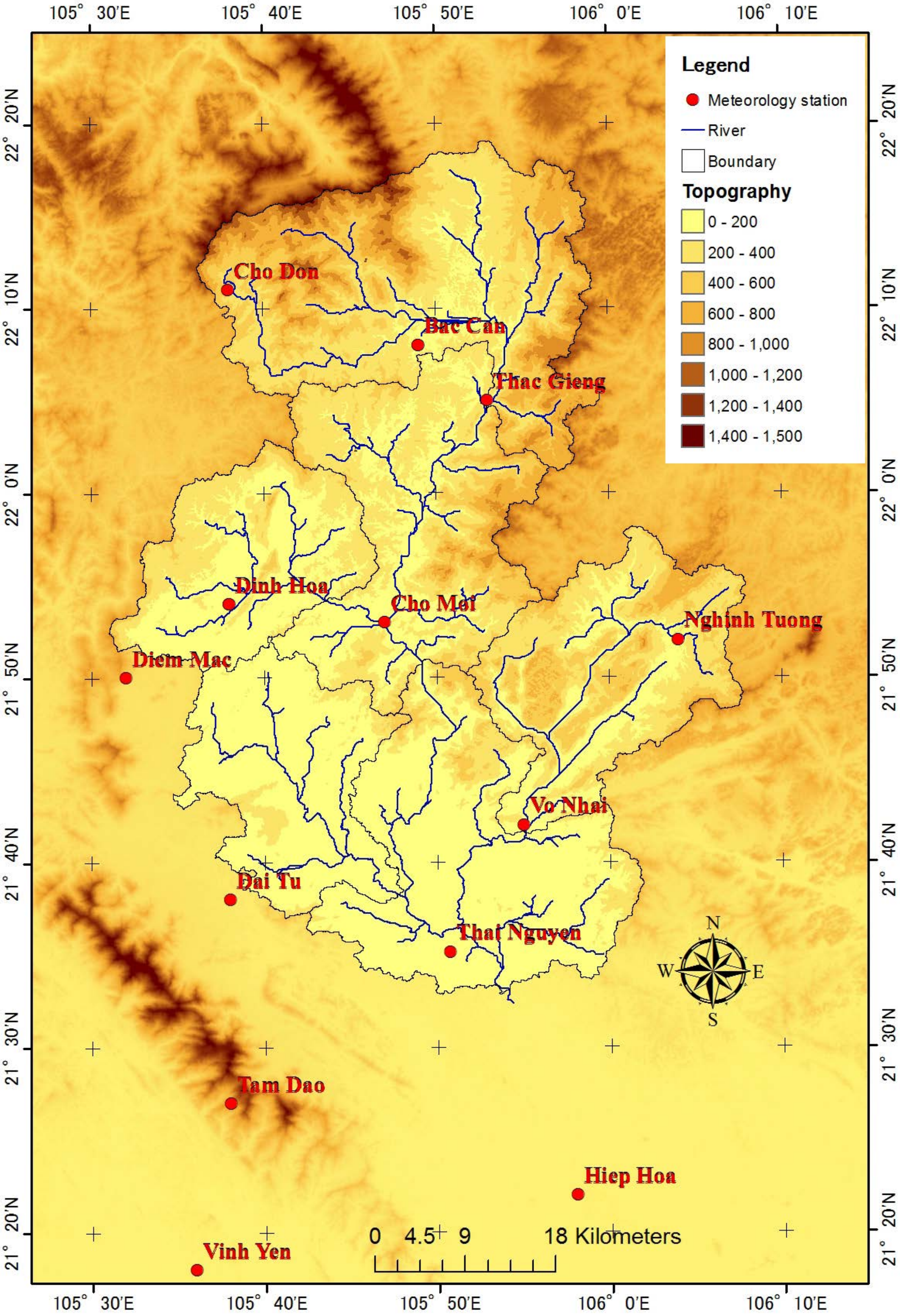


Figure 2-21 Meteorological stations were used to find the relation of rainfall and evaporation with elevation

Table 2-2 Data for estimate correlation of rainfall, potential evaporation and elevation

No	Station	Elevation (m)	Rainfall (mm)	Potential evaporation (mm)
1	Bac Can	174	1,637	704
2	Dinh Hoa	220	1,776	817
3	Thai Nguyen	36	2,095	1,010
4	Vinh Yen	10	1,797	865
5	Hiep Hoa	5	1,304	972
6	Dai Tu	50	2,077	717
7	Tam Dao	897	2,659	527
8	Cho Don	380	1,891	666
9	Nghinh Tuong	67	1,147	
10	Thac Rieng	98	1,482	
11	Diem Mac	41	1,508	
12	Vo Nhai	125	2,002	825
13	Cho Moi	160	1,690	

Data in the Table 2-2 was applied to estimate the relationship of elevation and rainfall. The result is shown in the Figure 2-22:

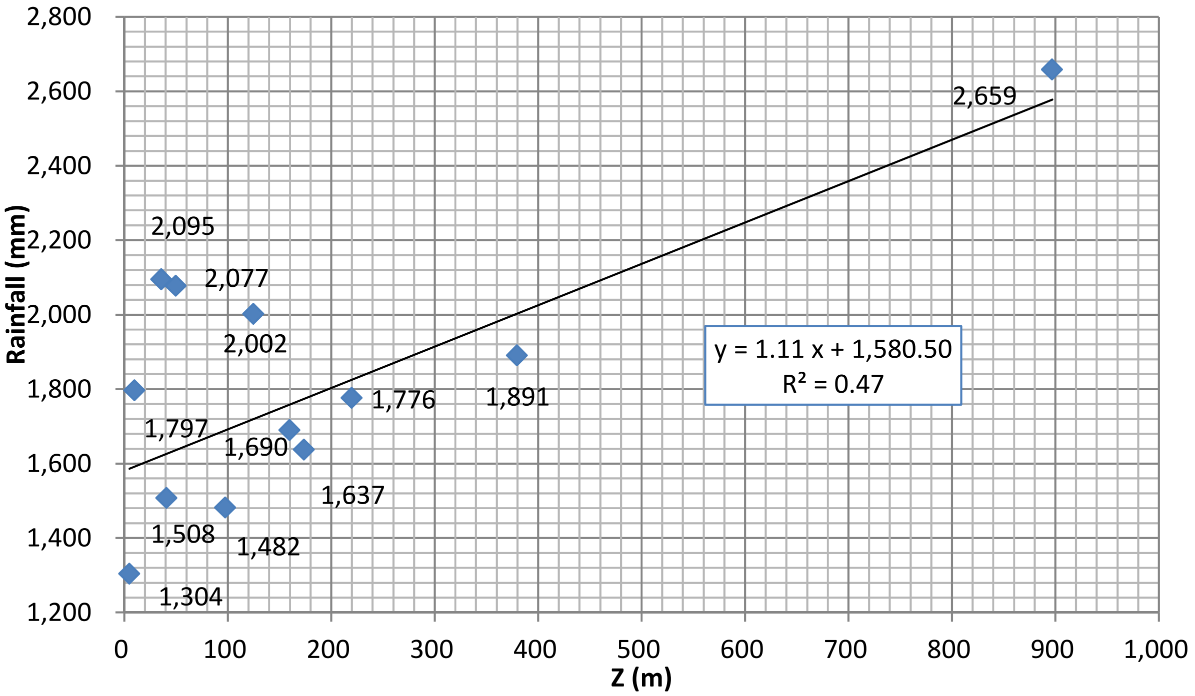


Figure 2-22 The relationship of rainfall and elevation

The relationship of elevation and potential evaporation was estimated based on the data in the Table 2-2. The result is shown in Figure 2-23:

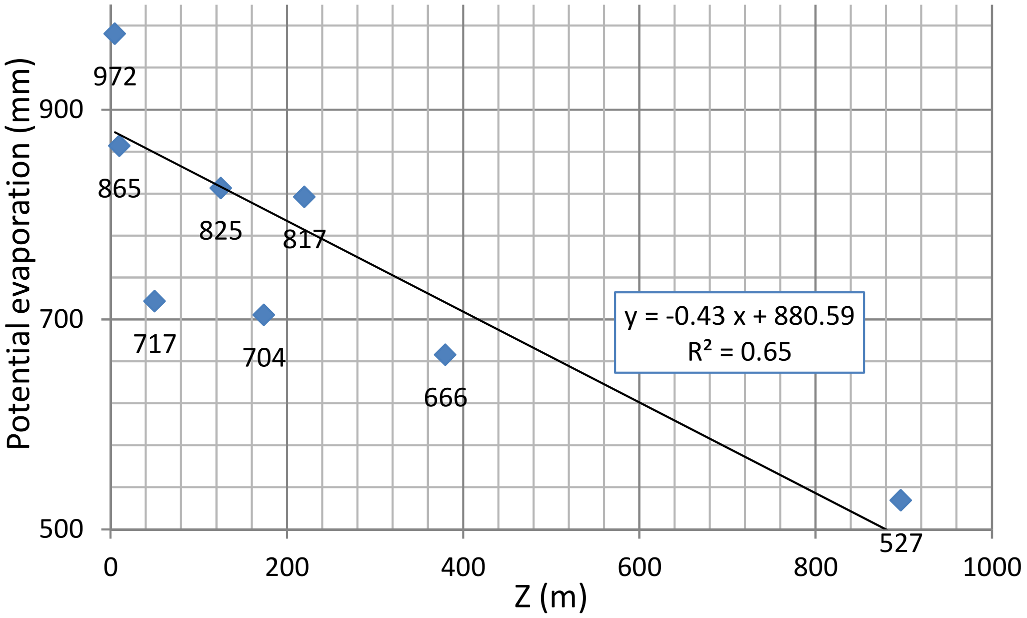


Figure 2-23 The relationship of potential evaporation and elevation

The results show that there are relationship of rainfall and potential evaporation with elevation in the Upper Cau River basin. These relations can be explained by following formulas:

$$y = ax + b \qquad (2.1)$$

where a and b are coefficients shown in Table 2-3.

Table 2-3 Coefficients in the formula describle relationship between rainfall and potential evaporation with elevation

Relation	a	b
Rainfall-Elevation	1.1118	1580.5
Potential evaporation- Elevation	-0.4327	880.59

b. Thiessen polygon method

Thiessen polygon method applies the rainfall data at a station to all parts of the drainage area that are nearer to that station than to any other station. The drainage area is divided by first connecting stations by straight lines, then drawing perpendiculars at the center points of theses connecting lines (Whitney, 1929)

In this study, 10 rainfall stations and eight potential evaporation stations were used to create areal meteorology data. Figure 2-24 and Figure 2-25 show the Thiessen polygons method applied for the Upper Cau River basin.

Thiessen Polygon method is very simple to apply without any difficult technic. However, the Upper Cau River basin has complex conditions of meteorological elements affected by monsoon, topography. Therefore, this method cannot describe accurate the variation of rainfall and potential evaporation in the basin. For example, rainfall in the south of basin (near Thai Nguyen station) is high rainfall area, but in the east of basin is low rainfall area (Vo Nhai sub-area); Thiessen Polygon method includes almost part Vo Nhai sub-area is high rainfall region. It will lead to the wrong results of calculation in the next steps. If there is dense network of observation, this method can be used. However, this study area exist thin observation network.

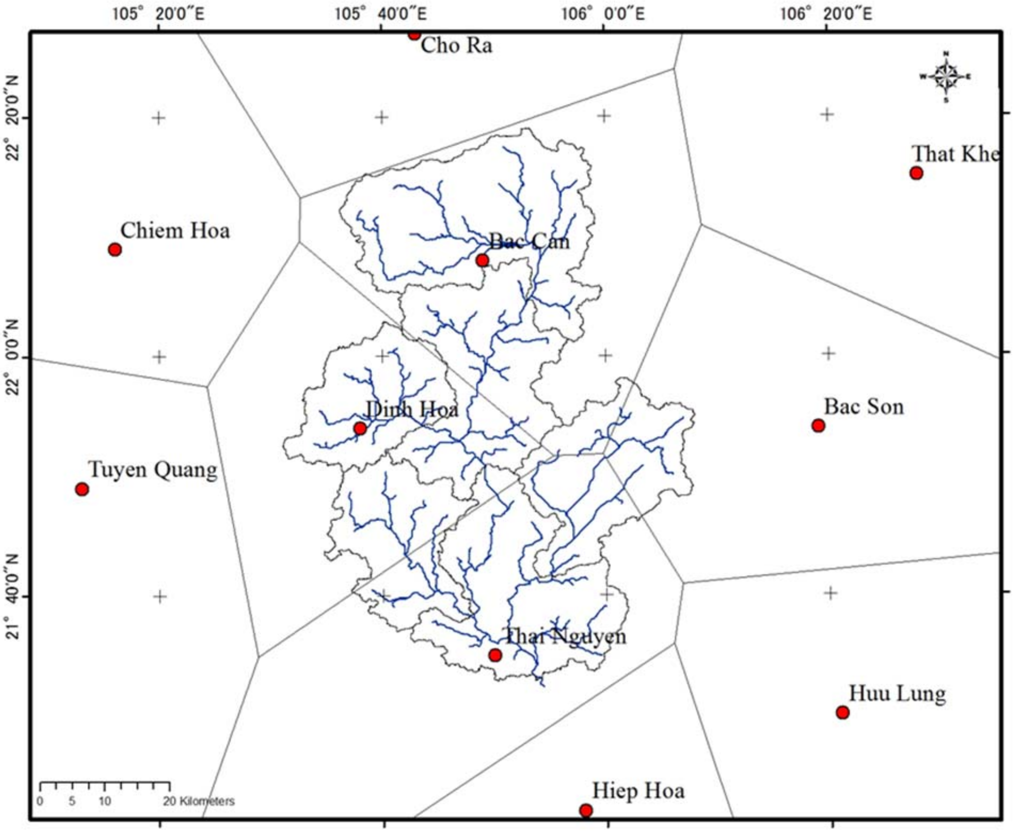


Figure 2-24 Areal rainfall create by Thiessen method

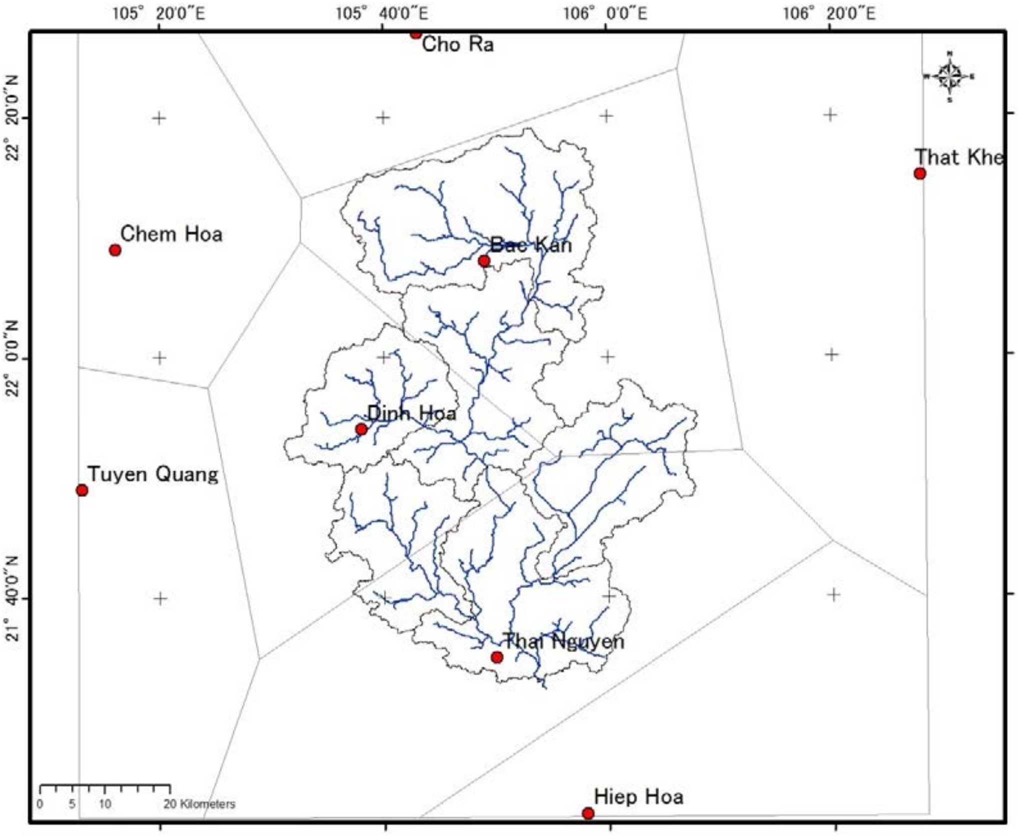


Figure 2-25 Areal potential evaporation create by Thiessen method

c. Inverse distance weighting method

The inverse distance weighting (IDW) method, a deterministic spatial interpolation model, is one of the more popular methods adopted by geoscientists and geographers partly (Lu and Wong, 2008). With this method, the property at each unknown location will be calculated by the formula:

$$P_i = \frac{\sum_{j=1}^{G} P_j / D_{ij}^{n}}{\sum_{j=1}^{G} 1/ D_{ij}^{n}} \qquad (2.2)$$

where P_i is the property at location i; P_j is the property at sampled location j; D_{ij} is the distance from i to j; G is the number of sampled locations; and n is the inverse-distance weighting power (in this study, n=2).

- The study used data of 10 rainfall stations from 1980 to 1999 to interpolate rainfall in the Upper Cau River basin.

- Potential evaporation displays in Figure 2-27 was interpolated by using of data from 1980 to 1999 of eight stations inside and around the basin. However, there are only four stations (Bac Can, Dinh Hoa, Thai Nguyen, and Hiep Hoa) with available potential evaporation data in the three climate change scenarios. Then, the study compares interpolated results of average annual potential evaporation from 1980 to 1999 from eight stations and from four stations. The result of comparison in Figure 2-28 shows that there is little difference from two approaches, especially in the north and west of the basin. Therefore, it was decided that the study used data of four potential evaporation stations to interpolate potential evaporation for whole the basin.

IDW method gives better results in compare with the two others. It can describe the change of rainfall and potential evaporation smoothly in space. With this method, we can see clearly the change from the high rainfall area in the south and the west part of the basin to the low rainfall area in the east of the basin.

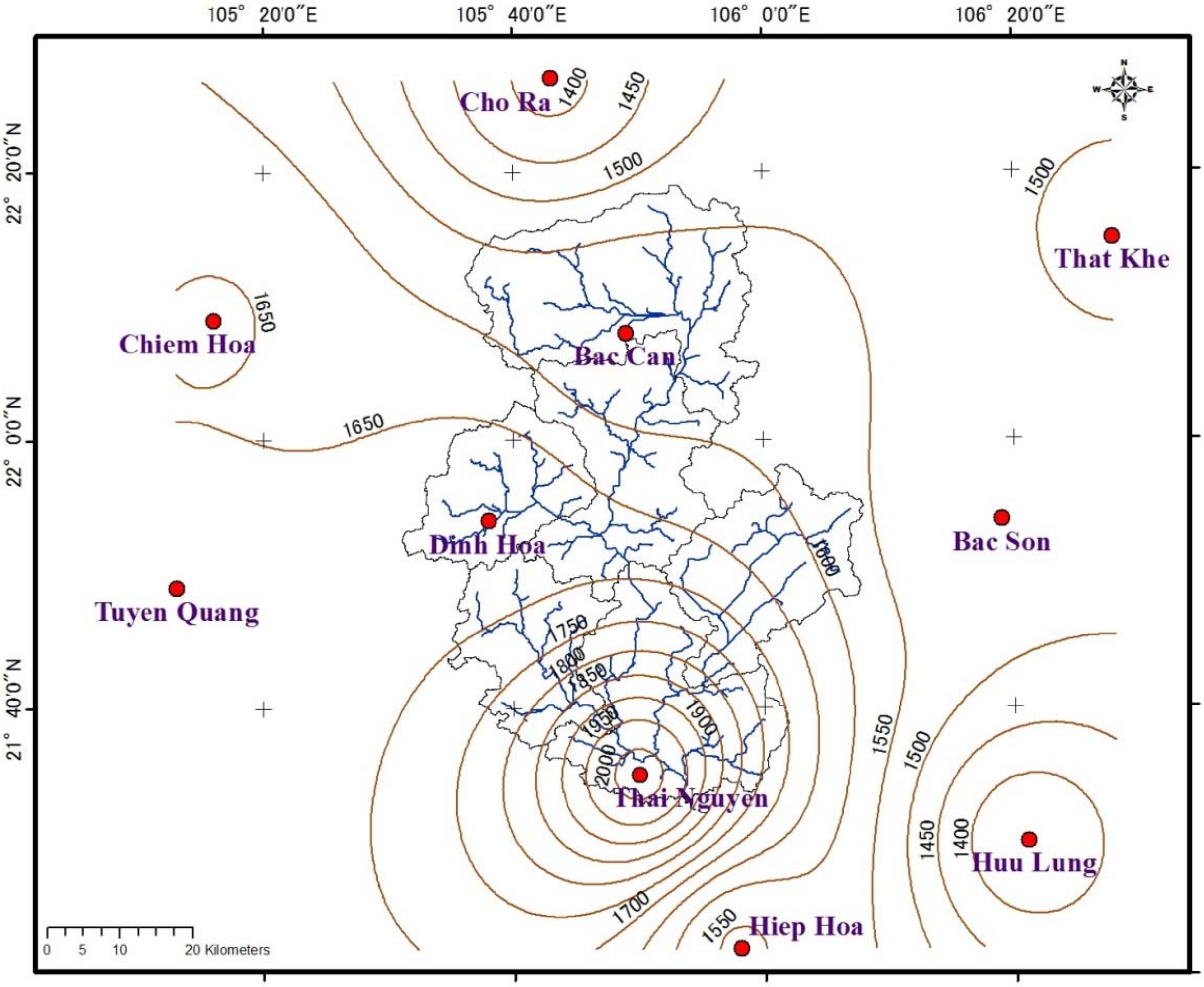


Figure 2-26 Areal rainfall create by IDW interpolation method

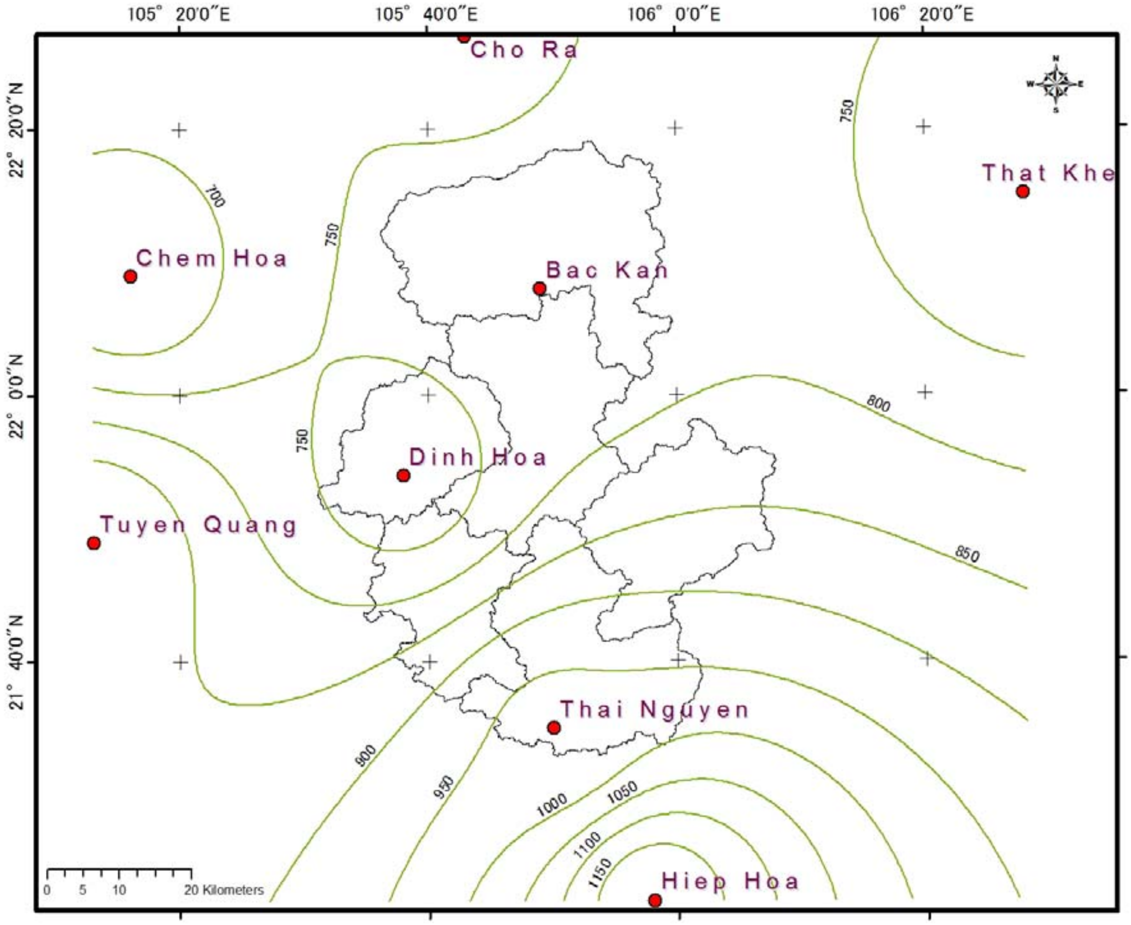


Figure 2-27 Areal potential evaporation create by IDW interpolation method

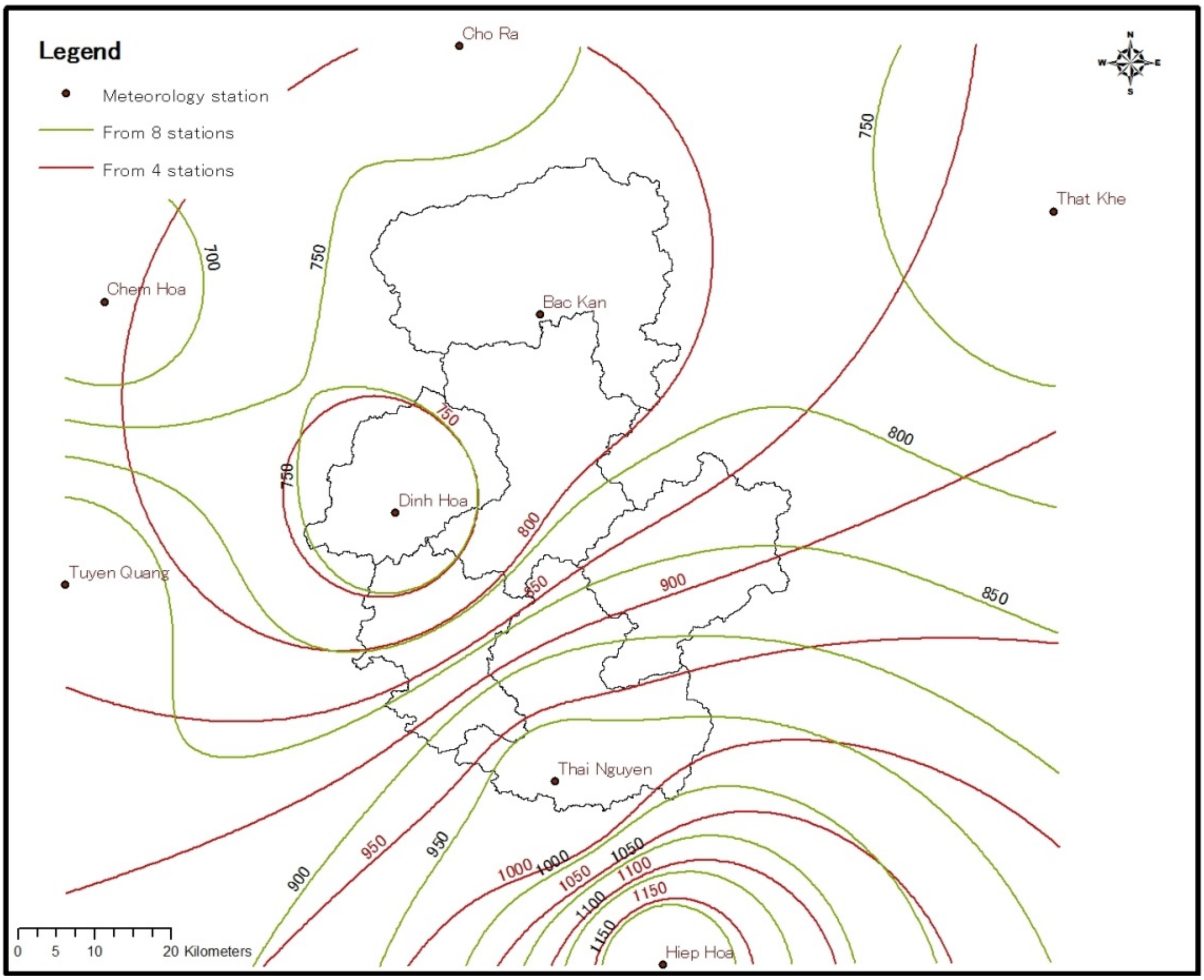


Figure 2-28 Comparison of interpolated potential evaporation from eight station and from four stations

d. Comparison of three methods

The study has to choose one from the three methods to interpolate rainfall and potential evaporation at unknown point in the basin:

- Relationship of rainfall and potential evaporation with elevation were found. However, rainfall and potential evaporation in the basin is complicated and depend on many other factors such as: wind direction and topography direction. Therefore, this method cannot reflect accurately rainfall and potential evaporation in the basin. For example: In the low elevation in the south of the basin has the highest rainfall, the low rainfall can be seen at high mountainous area in the east of the basin.
- Thiessen polygon method is simple method but it cannot be applied for the area with complex meteorological regime and lack of observation points as in the Upper Cau River basin. This method is suitable for the relatively flat and expansive areas (Taesombat and Sriwongsitanon, 2009).
- IDW method gives better results than two above methods. It can reflect the change of rainfall and potential evaporation int the basin with relatively accuracy. However, because of lack data in the high mountainous area in the northwest of the basin, IDW cannot interpolate high rainfall area in that region.

The study chose IDW as the method to interpolate rainfall and potential evaporation in the Upper Cau River basin with cell size is 5×5 km.

e. Improvement of rainfall interpolated data in north of the basin

IDW method was chosen for interpolating rainfall and potential evaporation data in the basin. However, there is no sample point in the high rainfall areas in higher mountainous in northwest part of the basin in climate change scenarios, which will lead to inaccuracy of the interpolated results. Therefore, the correlation and regression equation between Bac Can station and Cho Don station which in the high rainfall area of the northwest part of the basin (Figure 2-30). Then, rainfall at Cho Don station in climate change scenarios (2020-2099) will be calculated to the rainfall at Bac Can station.

Monthly rainfall from 1970 to 1980 of the two rainfall station was applied to estimate the correlation. The result in Figure 2-29 shows that there is a strongly correlation between the two stations with correlation coefficient of 0.93 and R^2 of 0.86.

With this strong correlation, rainfall at Cho Don station can be estimated by rainfall at Bac Can station as formula in Figure 2-29. The daily rainfall data at Cho Don station was calculated to climate change scenarios A2, B2 and B1.

Results of average annual rainfall (1980-1999) were interpolated by IDW method and it is shown in Figure 2-30, which appears more accurate than the result shows in Figure 2-26 because it express the high rainfall area in the northwest of the basin.

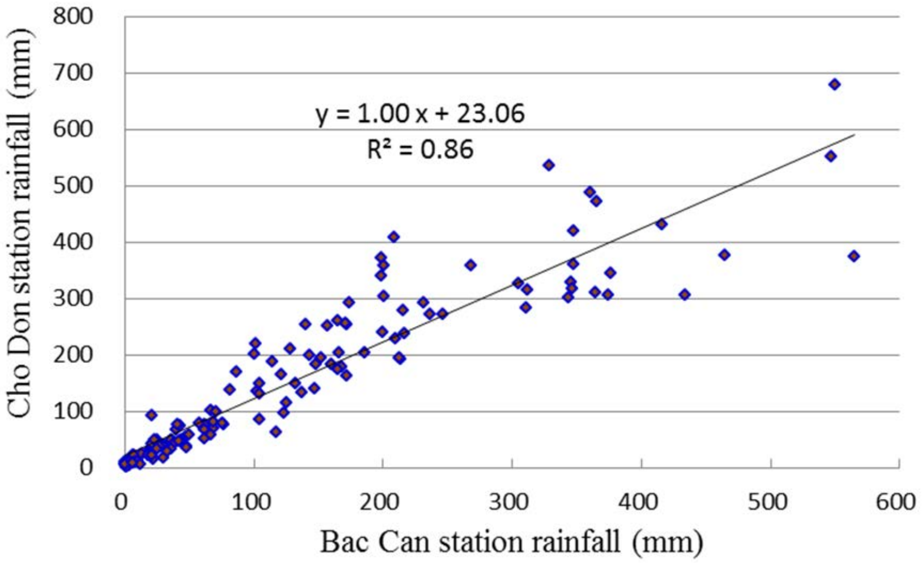


Figure 2-29 Correlation of rainfall at Cho Don and Bac Can station

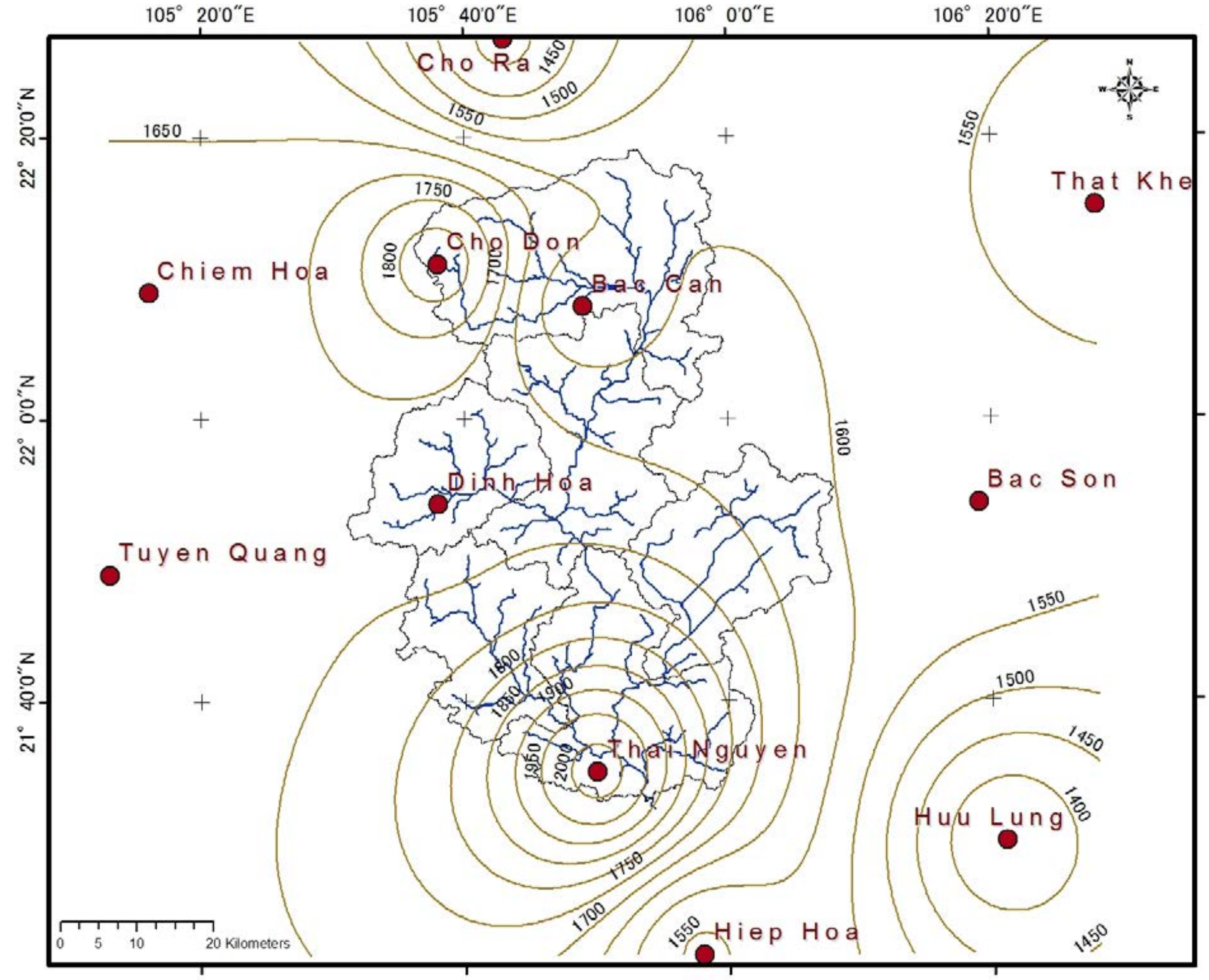


Figure 2-30 Areal rainfall create by IDW interpolation method after the improvement

2.2.2.2. Water demands

There are four important water demands calculated in this study, including water demand for industry, water demand for domestic use, water demand for livestock, and water demand for irrigation.

a. Water demand for industry

Water demand for industry (W_{in}) is calculated based on data of industrial zones and reference of water supply standard for area unit. Industrial water demand includes the needs of the industrial zone with standard (S_{in}): 50 – 80 m^3/ha/day (IMHEN, 2008). The areas of industrial zone (A_{in}) on the Upper Cau River basin in the year of 2000 were referenced to a project by IMHEN in 2008 (Table 2-4). In the basin, there is no industrial zone in two sub-areas (Vo Nhai and Cho Chu).

The water demand for industrial zone in the Upper Cau River basin was calculated as in equation (2.2):

$$W_{in}= A_{in} \times S_{in} \tag{2.2}$$

Table 2-4 Industrial zone in the Upper Cau River basin

No	Sub-area	Name of industrial zone	Area (ha)
1	Thac Rieng	Nam Bang Lung	100
2		Ban Thi	33.15
3		Xuat Hoa	100
4		Ban Ang	37.8
5		East of Bac Kan town	50
6		West of Bac Kan town	100
7		North of Bac Kan town	100
8	Cho Moi	Thanh Binh	500
9		Cam Giang	50
10	Song Du	Du - Dong Dat	25
11		Phan Me	12
12		Son Cam	50
13	Dong Hy	Cao Ngan	25.2

b. Water demand for domestic use

Water demand for domestic use (W_{do}) calculation based on some criteria such as the population, water use of person per day.

This study applies the water standard for domestic (S_{do}) use by Ministry of Construction (1997) (Table 2-6). Population (P_{do}) was collected from the socioeconomic statistical data of 671 districts, towns and cities under the authority of provinces in Vietnam (2006) (Table 2-5). Then, water demand for domestic use was calculated as in equation (2.3):

$$W_{do} = P_{do} \times S_{do} \tag{2.3}$$

Table 2-5 Population in sub-areas of the Upper Cau River basin

No	Sub-area	Population
1	Thac Rieng	68,477
2	Cho Moi	36,090
3	Cho Chu	61,439
4	Song Du	141,947
5	Vo Nhai	31,762
6	Dong Hy	117,727
Total		457,442

Table 2-6 Water demand standard for domestic use (MOC, 1997)

Level of area	Standard (l/day/person)
Urban level 1	150
Urban level 2	120
Urban level 3	100
Rural area	60

where: according to Vietnamese Government decree namely 42/2009/NĐ-CP:

- Urban area level 1: Population > 500,000, population density > 10,000 /km^2, Non-agriculture population > 85%.
- Urban area level 2: Population > 300,000, population density > 8,000 /km^2, Non-agriculture population > 80%.

- Urban area level 3: Population > 150,000, population density > 6,000 /km^2, Non-agriculture population > 75%.

c. Water demand for livestock

Water demand for livestock (W_{li}) includes water requirements for daily life, and to clean living place. To calculate the water demand for livestock (the demand for this popular domestic livestock such as cattle, pigs and poultry), water use standard (S_{li}) (l/ head/day) was selected according to the TCVN 4454:1987 (Table 2-7). The population of livestock (P_{li}) was collected from the socioeconomic statistical data of 671 districts, towns and cities under the authority of provinces in Vietnam (2006) (Table 2-8).

Table 2-7 Water use standard for livestock in the Upper Cau river basin

No	Livestock	Standard (l/head/day)
1	Cattles	80
2	Pig	25
3	Poultry	2

Table 2-8 Population of livestock in the Upper Cau River basin

No	Area	Cattles	Pig	Poultry
1	Thac Rieng	33,927	55,588	387,000
2	Cho Moi	12,371	17,884	145,000
3	Cho Chu	15,711	38,242	447,000
4	Song Du	38,665	104,480	1,025,000
5	Vo Nhai	15,915	28,654	242,000
6	Dong Hy	16,844	45,187	435,000
Total		133,433	290,035	2,681,000

Based on the current status of livestock in the province and water use standards, the study calculated water requirements for livestock for each area as in equation (2.4):

$$W_{li} = P_{li} \times S_{li} \qquad (2.4)$$

d. Water demand for irrigation

Water demand for rice was calculated based on water balance formula:

$$IRR = (ETc + LPrep + Prep) - Peff \quad \text{(mm/day)} \qquad (2.5)$$

Water demand for maize is calculated based on water balance formula:

$$IRR = (ETc + Prep) - Peff \quad \text{(mm/day)} \qquad (2.6)$$

where:

IRR: irrigation requirements (mm/day)

ETc: Crop evapotranspiration (mm/day)

LPrep: Land preparation depth (mm)

Prep: Infiltration (mm/day)

Peff: Effective rainfall (mm)

According to the formula, there are 4 important factors should be found:

- Crop evapotranspiration: $ETc = Kc \times ETo$

Where: *Kc:* crop coefficient, was selected as Vietnam standard (TCVN 8641:2011) for Northern Part of Vietnam (Table 2-9).

Table 2-9 *Kc* for rice and maize in Northern Part of Vietnam

	Kc in each development stage					
	Initial	Growth stage	Middle	End stage	Harvest	Average
Rice						
Winter-spring	1.03	1.13	1.23	1.12	1.12	1.13
Summer-Autumn	1.14	1.27	1.26	1.17	1.17	1.13
Maize						
	0.3-0.5	0.7-0.8	1.05-1.10	1.00-1.15	0.95-1.10	

ETo: The study used *ETo* for climate change scenarios from IMHEN (2009)

- Effective rainfall: According to Dastane (1974), effective rainfall refers to the percentage of rainfall which becomes available to crops. Ineffective rainfall is that portion which is lost by surface run-off, unnecessary deep percolation losses, the moisture remaining in the soil after the harvest of the crop and which is not useful for next season's crop.

There are many ways to calculate effective rainfall. In this study, references from project report of IMHEN (2008) and paper of Nhu et al. (2010), the study chose the formula of FAO/AGLW:

$$\begin{cases} Peff = 0.6P - 10 \text{ for Pmonth} \leq 70\text{mm} \\ Peff = 0.8P - 24 \text{ for Pmonth} > 70\text{mm} \end{cases} \quad (2.7)$$

- Infiltration:

$$Prep = K \times t \quad (2.8)$$

where: K is infiltration rate (mm/day) and t is time (day). In the study, infiltration was calculated based on experiment formula:

$$Prep = 126.83 \times t^{-0.8045} \text{ (Dat, 2011)} \quad (2.9)$$

- Land preparation depth: According to Klein and Zaid (2002), "the purpose of land preparation is to provide the necessary soil conditions which will enhance the successful establishment of the young offshoots or the tissue culture plants received from the nursery". In this study, land preparation depth was sellected from Vietnam standard namely TCVN 8641:2011 with *LPrep* = 30-50 mm.

2.2.2.3. Rainfall-runoff model

a. Theory basis of NAM model

Rainfall-runoff models are effective tools to predict the response of a basin with a given amount of rainfall. Running the rainfall-runoff model is a pre-processing step in MIKE BASIN that creates the runoff time series for the specified catchments.

The NAM Model is one of classical lumped conceptual models of the rainfall-runoff process. It was developed oriGially as a daily simulation model at the Technical University of Denmark (Nielsen, Hansen, 1973). NAM is an abbreviation for "Nedbor-Afstromings Model"," a Danish phrase meaning "precipitation runoff model." The hydrological NAM Model simulates the rainfall runoff process that occurs at the watershed scale (Moore et al., 2007). Precipitation and potential evapotranspiration are two major input parameters. Surface characteristics, root zone storage, runoff coefficient are important parameters to define the basin characteristics.

A lumped conceptual model of the NAM Model treats each sub catchment as a unit. NAM simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment with the following parameters: surface and root zone parameters (maximum water content in surface storage U_{max}, maximum water content in root zone storage L_{max}, overland flow runoff coefficient CQ_{OF}, time constant for interflow CK_{IF}, time constant for routing interflow and overland flow CK_{12}, root zone threshold value for overland flow T_{OF}, root zone threshold value for interflow T_{IF}), groundwater parameters (baseflow time constant CK_{BF}, root zone threshold value for groundwater recharge T_G). Snow module was not considered in this study.

The routine for overland flow, interflow, and baseflow, shown in Figure 2-31, is based on the linear reservoir.

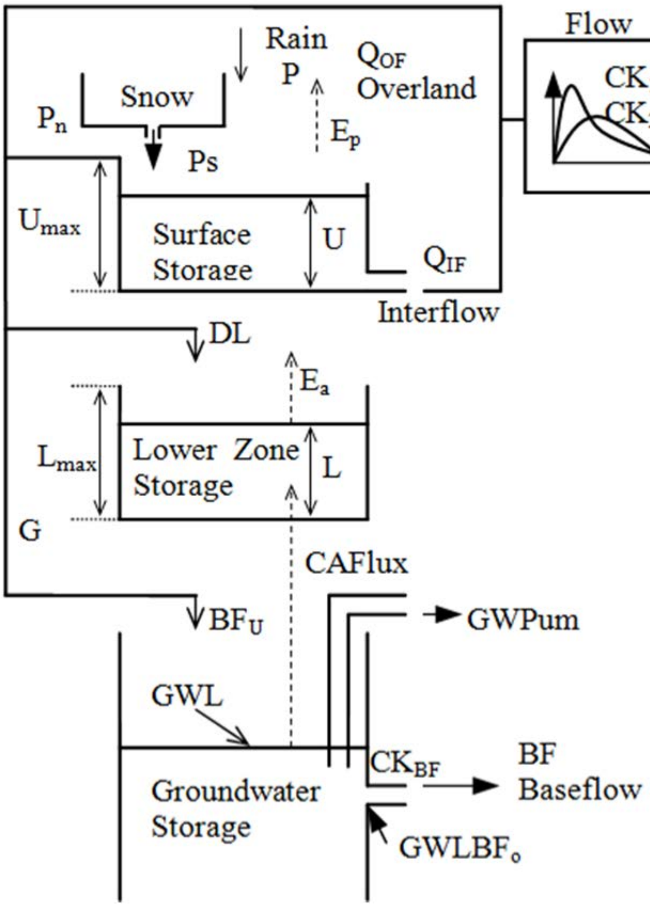


Figure 2-31 Structure of the NAM model (DHI, 2007)

Moisture intercepted on vegetation as well as water trapped in depressions and in the uppermost, cultivated part of the ground is represented as surface storage. U_{max} denotes the upper limit of surface water storage.

Evapotranspiration demand is initially met at the potential rate from the surface storage. If moisture content, U, in the surface storage is less than this requirement, the remaining fraction is assumed to be withdrawn by root activity from the lower zone storage at an actual rate, *Ea*. The value *Ea* is set to be proportional to potential evapotranspiration, *Ep*, according to:

$$E_{\mathrm{a}} = E_{\mathrm{p}} \frac{L}{L_{\max}} \tag{2.10}$$

where *L* and L_{max} are the actual and maximum possible moisture contents, respectively, in the lower zone storage.

When the surface storage spills, $U \geq U_{\max}$, the excess maximum water, P_n, induces overland flow as well as infiltration. Q_{OF} denotes the part of P_n that contributes to overland flow. Q_{OF} is assumed to be proportional to P_n and to varies linearly with the relative soil moisture content, L/L_{max}, of the lower zone storage.

Then, overland flow, Q_{OF}, is determined as:

$$\begin{cases} Q_{\mathrm{OF}} = CQ_{\mathrm{OF}} \dfrac{L_{t-1}/L_{\max} - T_{\mathrm{OF}}}{1 - T_{\mathrm{OF}}} P_{\mathrm{n}} & \text{for } L_{t-1}/L_{\max} > T_{\mathrm{OF}} \\ Q_{\mathrm{OF}} = 0 & \text{for } L_{t-1}/L_{\max} \leq T_{\mathrm{OF}} \end{cases} \tag{2.11}$$

where *L* denotes the soil moisture content of the lower zone storage, CQ_{OF} and T_{OF} are the positive constants less than unity and without dimension, and *t* is time.

Interflow contribution, Q_{IF}, is assumed to be proportional to *U* and to vary linearly with the relative moisture content, L/L_{max}, of the lower zone storage. Q_{IF} is determined as:

$$\begin{cases} Q_{\mathrm{IF}} = CQ_{\mathrm{IF}} \dfrac{L_{t-1}/L_{\max} - T_{\mathrm{IF}}}{1 - T_{\mathrm{IF}}} U_t & \text{for } L_{t-1}/L_{\max} > T_{\mathrm{IF}} \\ Q_{\mathrm{IF}} = 0 & \text{for } L_{t-1}/L_{\max} \leq T_{\mathrm{IF}} \end{cases} \tag{2.12}$$

where CQ_{IF} is the time constant for interflow and T_{IF} is the root zone threshold value for interflow.

The proportion of excess rainfall, P_n, that does not run off as overland flow infiltrates into the lower zone storage representing the root zone. A portion *DL* of the amount of infiltration, $P_n - Q_{OF}$, is assumed to increase soil moisture content, *L*, in the lower zone. *G* is assumed to percolate deeper and recharge groundwater storage.

$$\begin{cases} G = (P_{\mathrm{N}} - Q_{\mathrm{OF}}) \dfrac{L_{t-1}/L_{\max} - T_{\mathrm{G}}}{1 - T_G} & \text{for } L_{t-1}/L_{\max} > T_{\mathrm{G}} \\ G = 0 & \text{for } L_{t-1}/L_{\max} \le T_{\mathrm{G}} \\ DL = (P_{\mathrm{N}} - Q_{\mathrm{OF}}) - G & \end{cases} \tag{2.13}$$

where T_G is the root zone threshold value for groundwater recharge.

Percolation, G, is routed through a linear reservoir with the time constant, CK_{BF}, before reaching the groundwater table as recharge, BFu.

Base flow is determined as:

$$BF_{\mathrm{u}(t)} = BF_{\mathrm{u}(t-1)} \cdot e^{(-\frac{t}{CK_{\mathrm{BF}}})} + G_t (1 - e^{(-\frac{t}{CK_{\mathrm{BF}}})}) \tag{2.14}$$

Based on meteorological data input, the NAM Model produces watershed runoff and other information about the land phase of the hydrological cycle such as temporal variation in evapotranspiration, soil moisture content, groundwater recharge, and groundwater levels. The resulting watershed runoff is conceptually divided into overland flow, interflow, and baseflow components (DHI, 2007).

b. Calculation of discharge for each sub-area in the Upper Cau River basin

In the basin, there are discharge data at two points in the baseline period: Thac Rieng station and Gia Bay station (Figure 2-32). However, Gia Bay station has data in whole baseline period, but Thac Rieng station has avaiable data only in two years (1980, 1981). Therefore, the study used discharge data of 1980 at Thac Rieng for calibration, data of 1981 for verification to find the parameters of basin; Gia Bay station has longer data. Thus discharge data of 1980-1990 were used for calibration, and data of 1991-1999 for the verification.

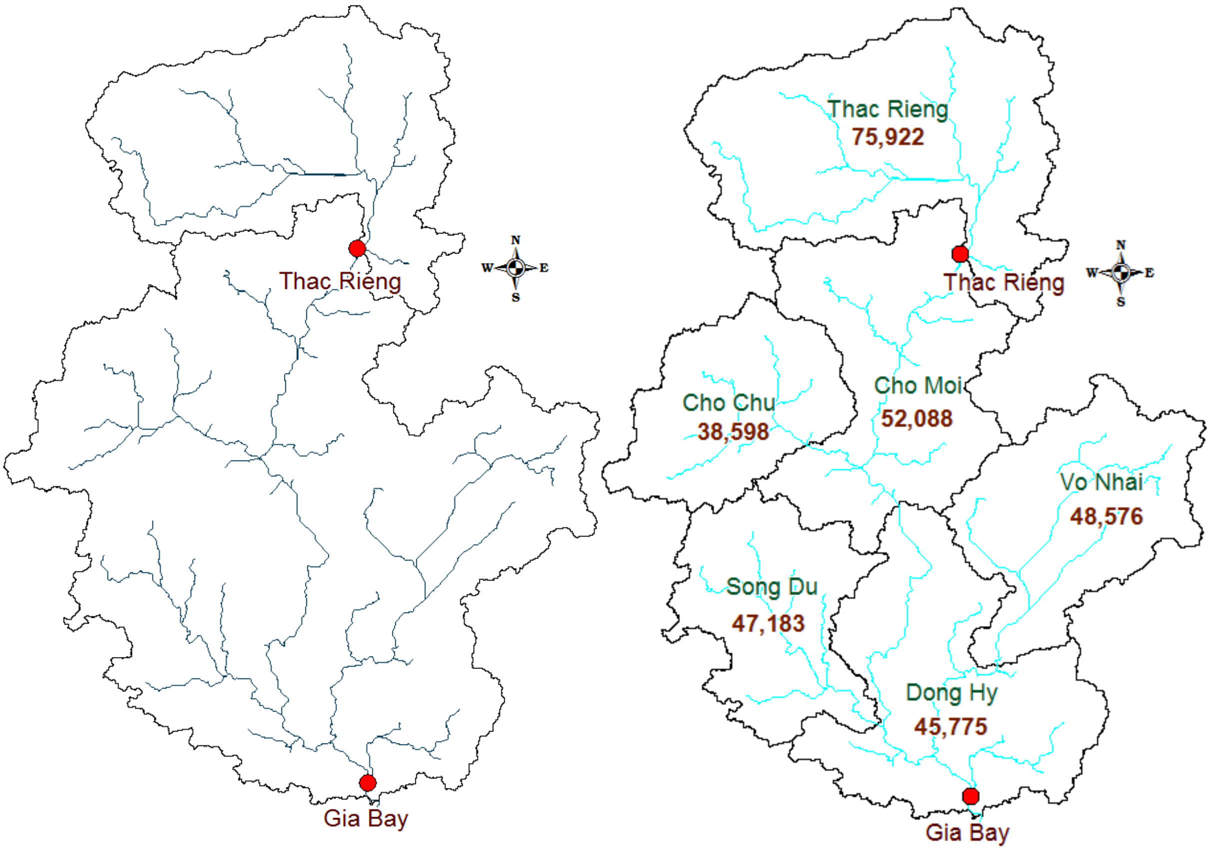


Figure 2-32 Hydro stations and six sub-areas in the Upper Cau River basin

Discharge in sub-areas which lacks observation discharge data, were calculated based on area ratio of each sub-area (A_{sub}) with area of upstream of Gia Bay station (A_{GB}). With Discharge at Gia Bay station (Q_{GB}) and its upstream watershed area of 2,760 km^2, discharges of Cho Chu sub-area (Q_{CC}), Cho Moi sub-area (Q_{CM}), Song Du sub-area (Q_{SD}), Dong Hy sub-area (Q_{DH}), Vo Nhai sub-area (Q_{VN}) were calculated by formula:

$$Q_{sub} = Q_{GB}\frac{A_{sub}}{A_{GB}} \qquad (2.15)$$

where A_{sub} is area of sub-area, A_{GB} is upstream area of Gia Bay station (Table 2-10)

Table 2-10 Area of the sub-areas in the basin and upstream area of Gia Bay station

Q_{sub}	A_{sub} (ha)	A_{GB} (ha)
Q_{CC}	38,598	276,000
Q_{CM}	52,088	276,000
Q_{SD}	47,183	276,000
Q_{DH}	45,775	276,000
Q_{VN}	48,576	276,000

c. Calibration and verification of the model

In this study, a comparison of simulated discharge accuracy with observed discharge was expressed by the error indicators Nash-Sutcliffe coefficient (E_2), and root mean square error (RMSE).

$$E_2 = 1 - \frac{\sum_{i=1}^{N} \left[Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i}\right]^2}{\sum_{i=1}^{N} \left[Q_{\mathrm{obs},i} - \overline{Q_{\mathrm{obs}}}\right]^2} \tag{2.16}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i}\right]^2} \tag{2.17}$$

Parameters of basin of Thac Rieng and Gia Bay station were found by trial-error method and the results is shown in Table 2-11.

Table 2-11 Parameters of NAM model at Thac Rieng station

Parameters	U_{max}	L_{max}	CQ_{OF}	CK_{IF}	$CK_{1.2}$	T_{OF}	T_{IF}	T_G	CK_{BF}
Thac Rieng	10	100	0.348	200.1	21.9	0	0.001	0	1003
Gia Bay	10	100	0.525	200.1	26.2	0.173	0	0	3998

The results of calibration and validation at Thac Rieng station are shown in Figure 2-33 and Figure 2-34 (where: red line indicates observed runoff, and black line indicates simulated runoff).

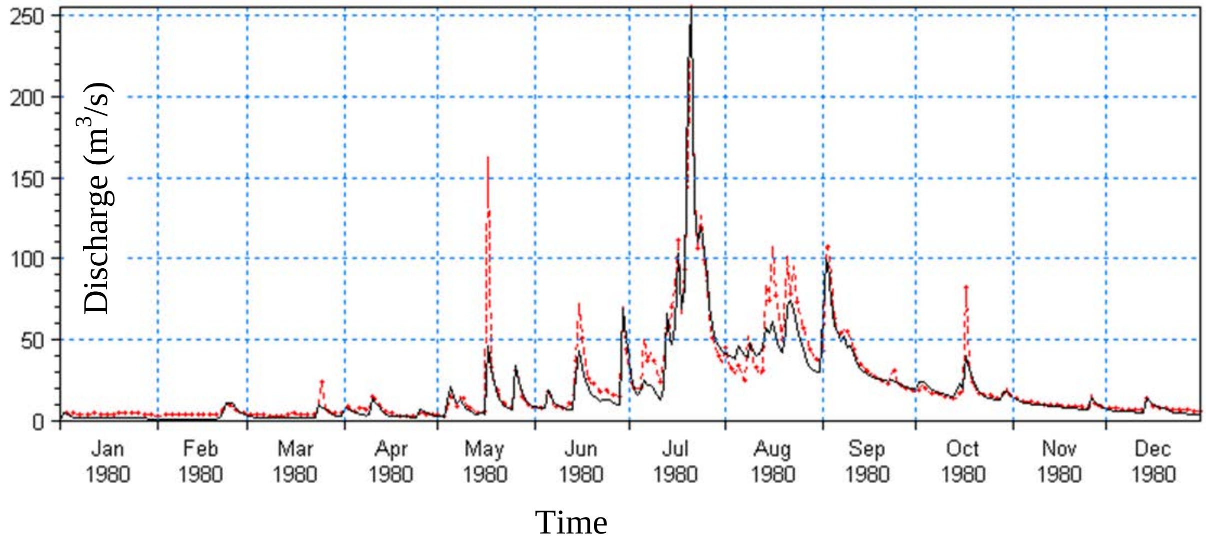


Figure 2-33 Calibration result of NAM model at Thac Rieng station (unit: m^3/s)

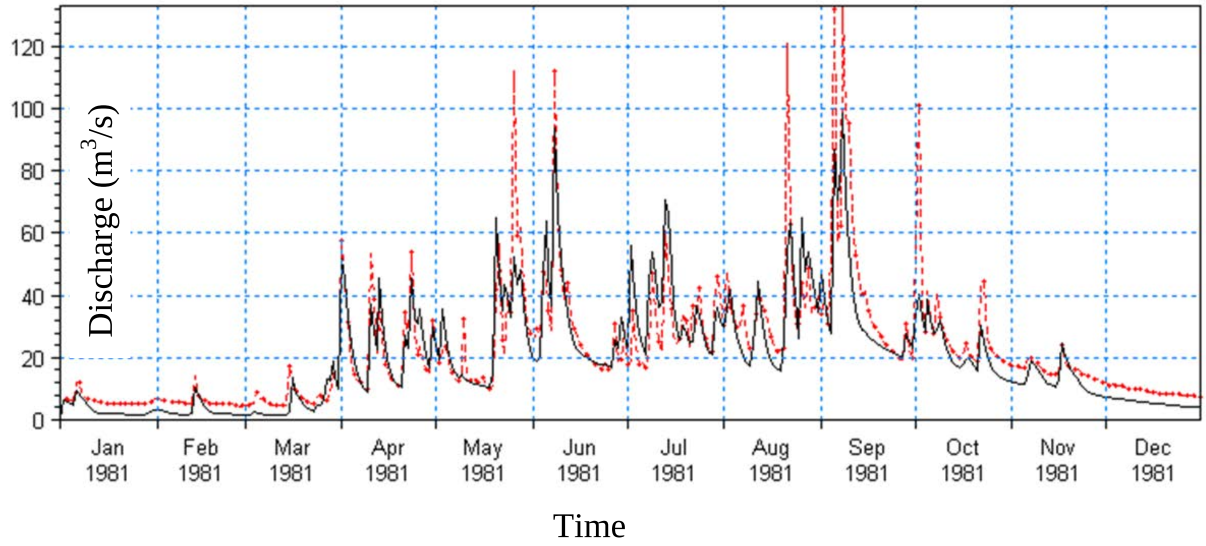


Figure 2-34 Validation result of NAM model at Thac Rieng station (unit: m^3/s)

——— : observed runoff ——— :simulated runoff

The results of calibration and validation at Gia Bay station are shown in Figure 2-35 and Figure 2-36 (where: red line indicates observed runoff, and black line indicates simulated runoff).

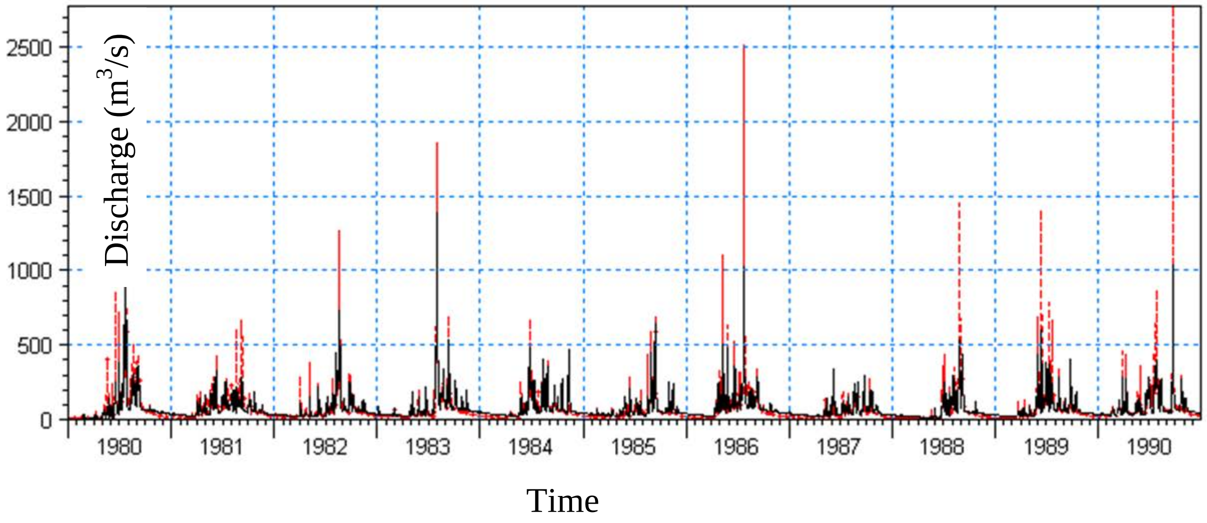


Figure 2-35 Calibration result of NAM model at Gia Bay station (unit: m^3/s)

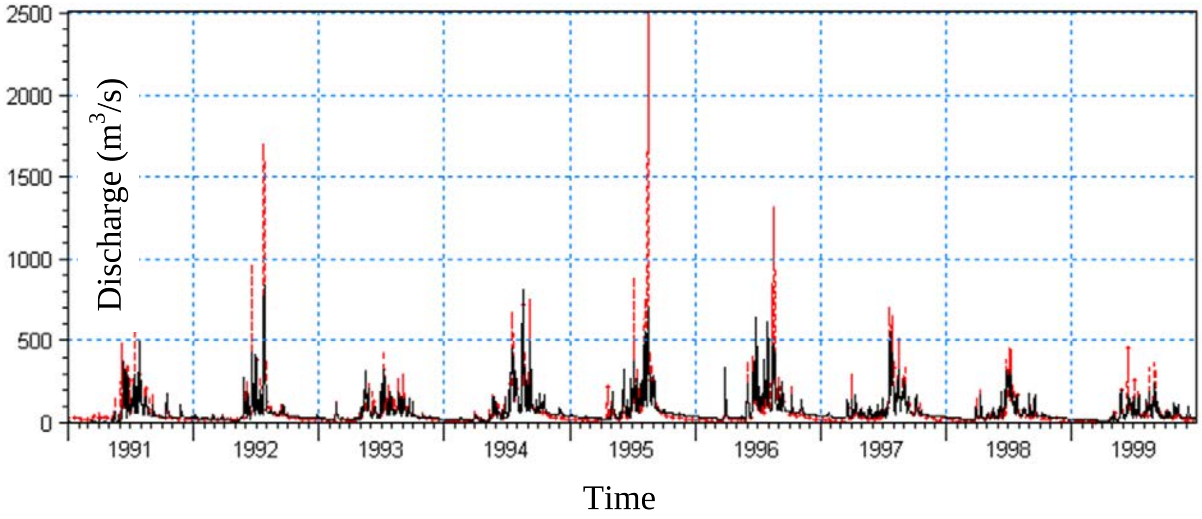


Figure 2-36 Validation result of NAM model at Gia Bay station (unit: m^3/s)

— : observed runoff — :simulated runoff

The results of error indicators for NAM model are listed in Table 2-12:

Table 2-12 The results of error indicators for NAM model in calibration and validation

Parameters	Calibration		Validation	
	Thac Rieng (1980)	Gia Bay (1980-1990)	Thac Rieng (1981)	Gia Bay (1991-1999)
E_2	0.88	0.71	0.75	0.70
RMSE (m^3/s)	9.91	71.42	9.72	59.31

The results from Figure 2-33 to Figure 2-36, and from Table 2-12 show acceptable accuracy in simulated discharge at Thac Rieng and Gia Bay station. Therefore, the study can use the parameters in Table 2-12 for calculating of flow in the climate change scenarios.

2.2.2.4. Water allocation model

a. Overview of the model

MIKE BASIN is a tool for water resources management, and more exactly it is a tool to calculate the optimal balance between water demand and available water amount. It supports the managers in choosing suitable development scenarios, exploitation, and protection of water resources in the future (Thai, 2010).

MIKE BASIN is structured as a network model in which the rivers and their main tributaries are represented by a network consisting of branches and nodes. The branches represent individual stream sections while the nodes represent confluence, locations where certain water activities may occur or important locations where model results are required (DHI, 2007).

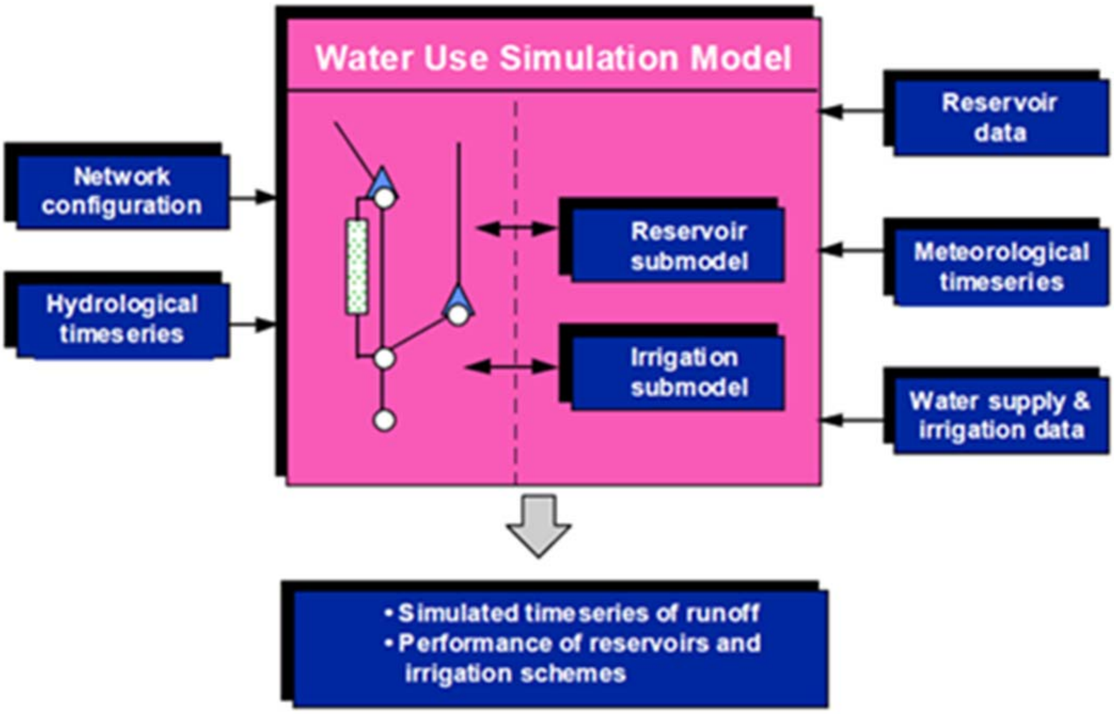


Figure 2-37 Concept of MIKE BASIN for water allocation modeling (DHI, 2007)

Node interaction is explained as Figure 2-38 and equations (2.19):

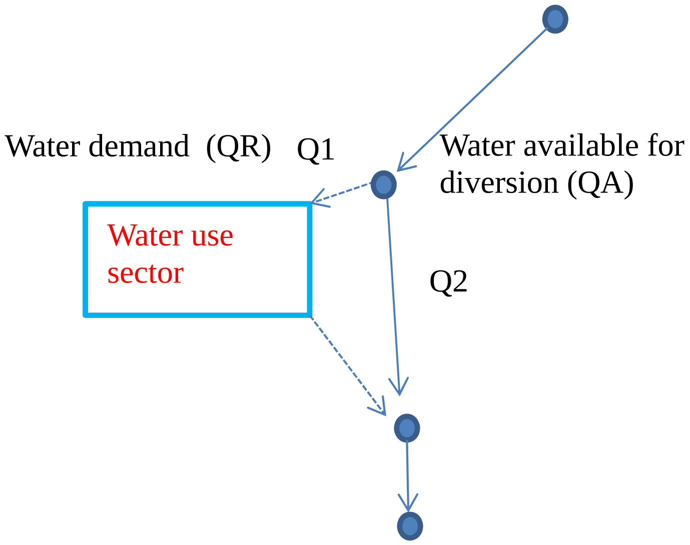


Figure 2-38 Node interaction in MIKE BASIN model

Q1 and *Q2* calculated as (2.18) equation:

$$\begin{cases} Q1 = min(QA, QR) \\ Q2 = QA - Q1 \end{cases} \tag{2.19}$$

where:

Q1: Actual water supply for water use area

QA: Water available for diversion

Q2: Water to downstream

Incoming water and water consumption are the basic data input in Water allocation model setup. Incoming water was calculated by NAM model. Water consumptions which include irrigation, domestic, industrial, and livestock were calculated in water demand section.

The output of Water allocation model is discharge available at each note.

b. Water use zoning

The basin is divided into six water use zones, and scheme of intake water of each zone is displayed in the Figure 2-39 and Figure 2-40.

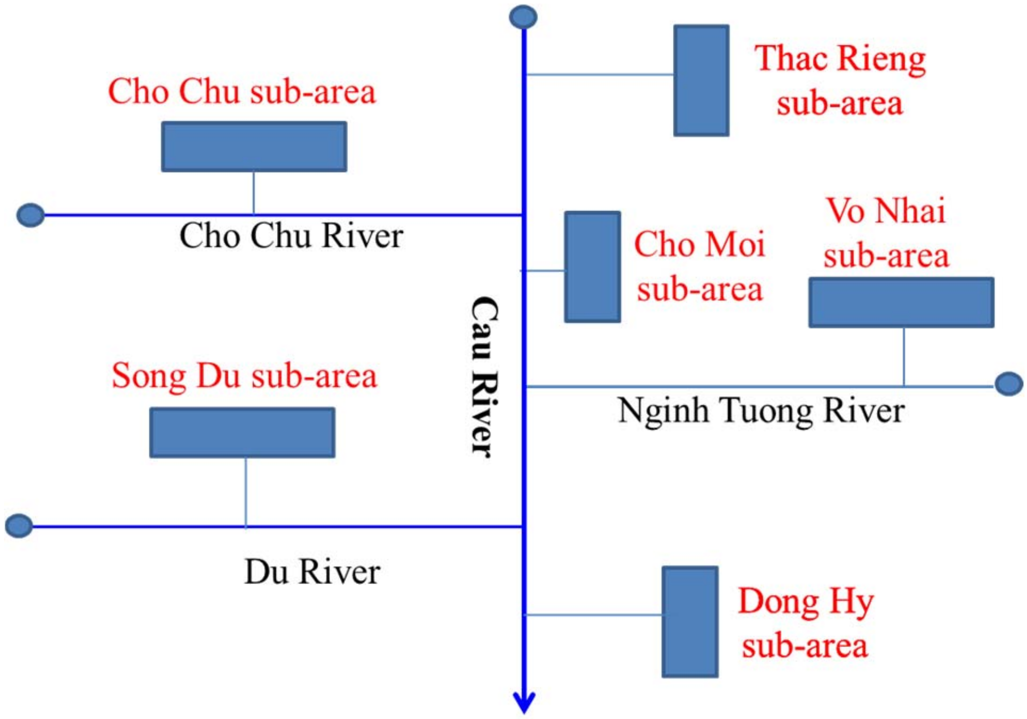


Figure 2-39 Scheme of the basin in water allocation model

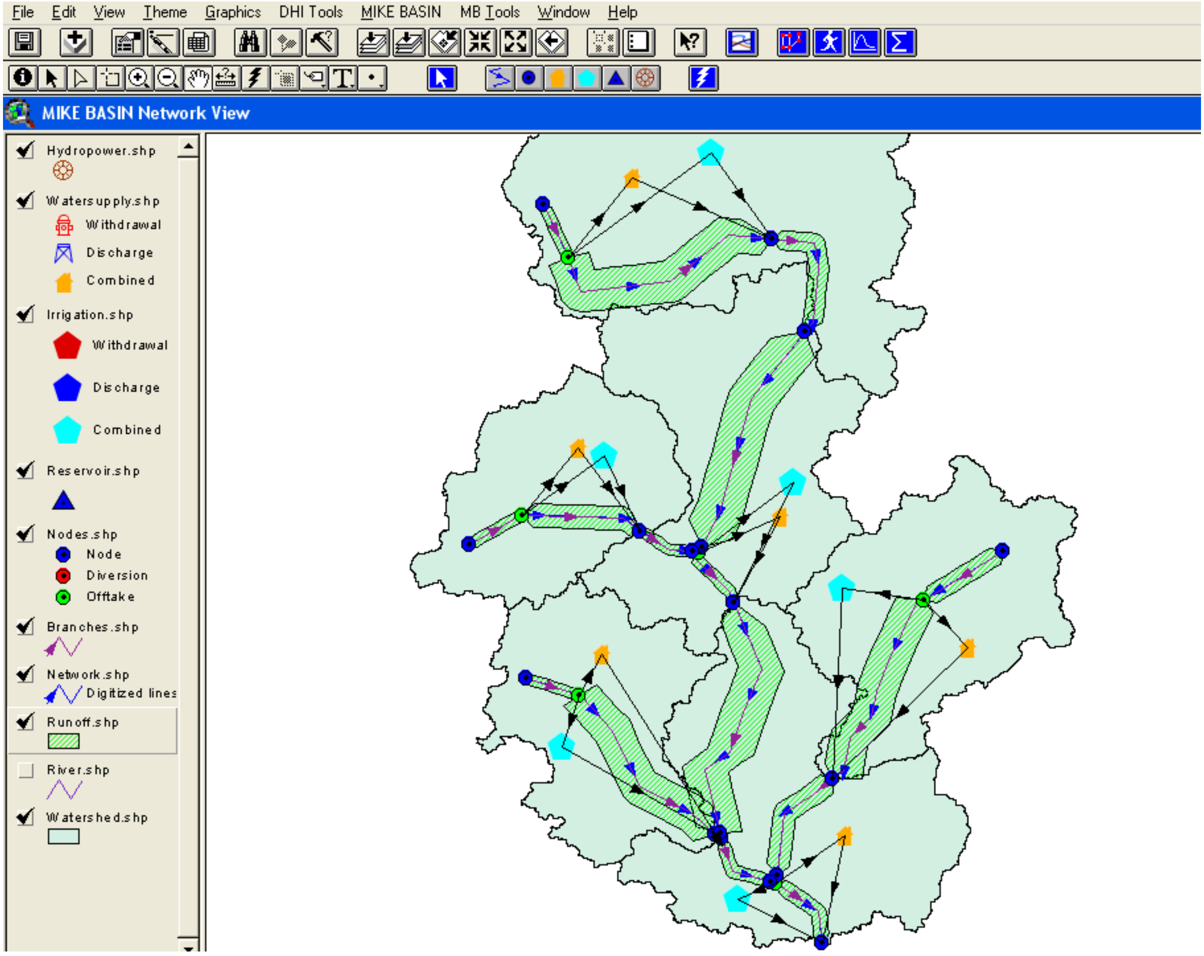


Figure 2-40 The Upper Cau River basin in MIKE BASIN model

c. Boundary conditions of model

- Inflow at nodes was calculated by rainfall-runoff NAM model
- Water demand in six water use areas were calculated as water demand for domestic use, industry, livestock, and irrigation.

d. Priority principle at water division node

This study was based on the article No 54 of law on Water resources of Vietnam and National Water Resources Strategy towards the year 2020 (NWRS) to set priority for division node in MIKE BASIN model. According to article No 54, in the water shortage situation, water allocation policy must give the priority to domestic purpose; other purposes will be allocated as the rate defined in water resources management planning of each river basin and must ensure the equitable as well as appropriate principle. NWRS indicates that the appropriate and fair allocation and sharing of water resources among sectors are ensured, industries and localities, while priority is given to domestic use. Uses of high economic benefits and environmental flows are also ensured. In summary, the priority order for water user using water resources is as below:

- The first priority is given to domestic uses.
- The second priority is given to ensuring water for ecosystem and environmental flow at downstream area.
- The third priority is given to ensuring water for industrial zones.
- The fourth priority is given to ensuring water for livestock.
- The last priority is given to ensuring water for irrigation.

e. Water for ecosystem and environmental flow

In this study, environmental flow was referenced in the Project: Master plan for water resources in Cau River basin (IMHEN, 2008).

Table 2-13 Environmental flow in the Upper Cau River basin

No	Station	Environmental flow (m^3/s)
1	Gia Bay	6.30
2	Thac Rieng	1.65

Chapter 3 Results and discussion

3.1. The tendency change of natural flow to climate change scenarios

The natural flows were determined at Gia Bay and Thac Rieng by using the rainfall-runoff model Mike NAM. The results are shown from Figure 3-1 to Figure 3-4. The results showed an increasing trend of annual flows throughout the periods for all 3 scenarios A2, B2 and A1 (Figure 3-5). The flows also vary according to different season with a considerable rise in rainy season (Figure 3-9), but a decreasing trend in dry season (Figure 3-13).

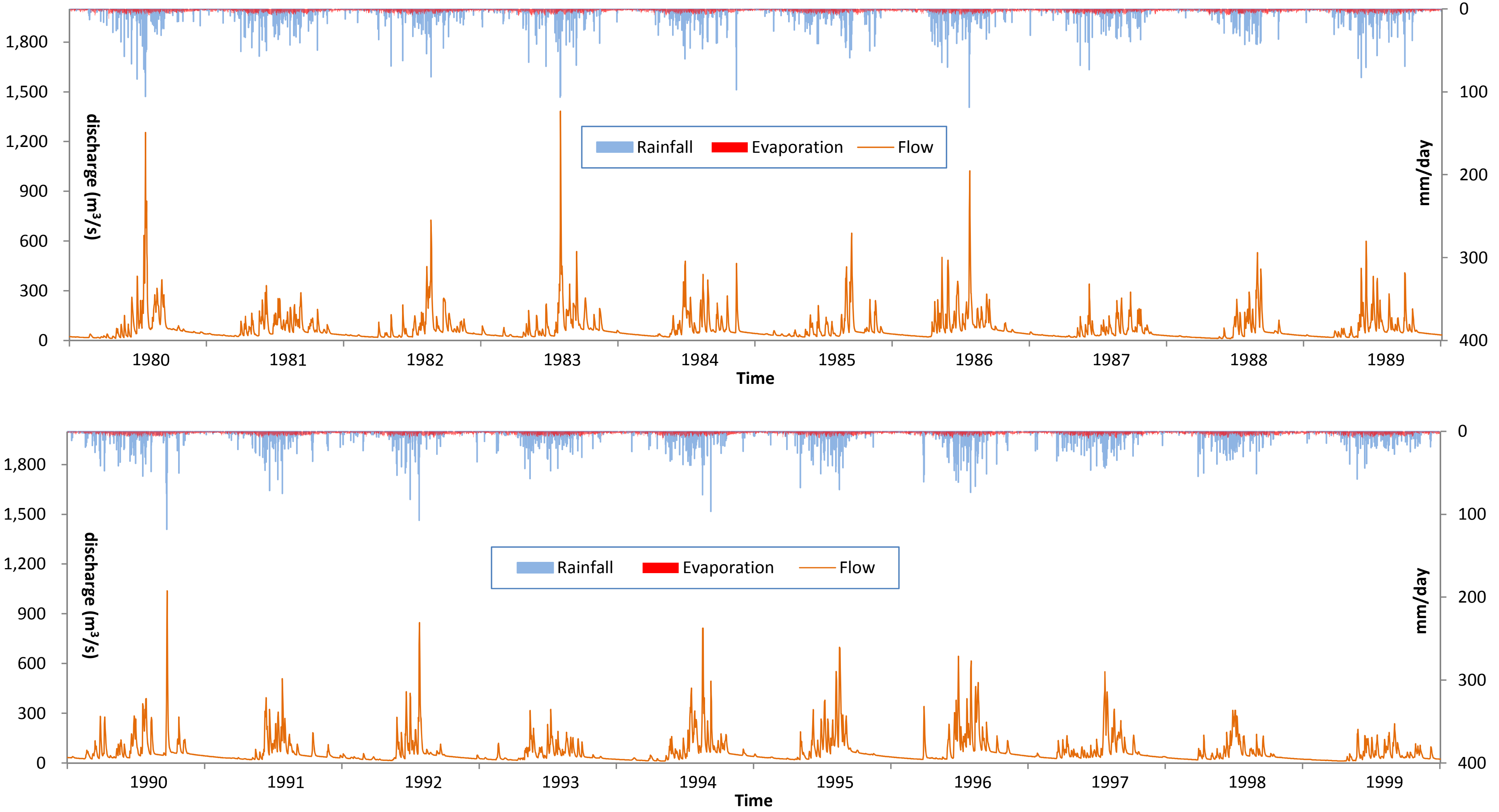


Figure 3-1 Discharge simulation from NAM model in baseline period

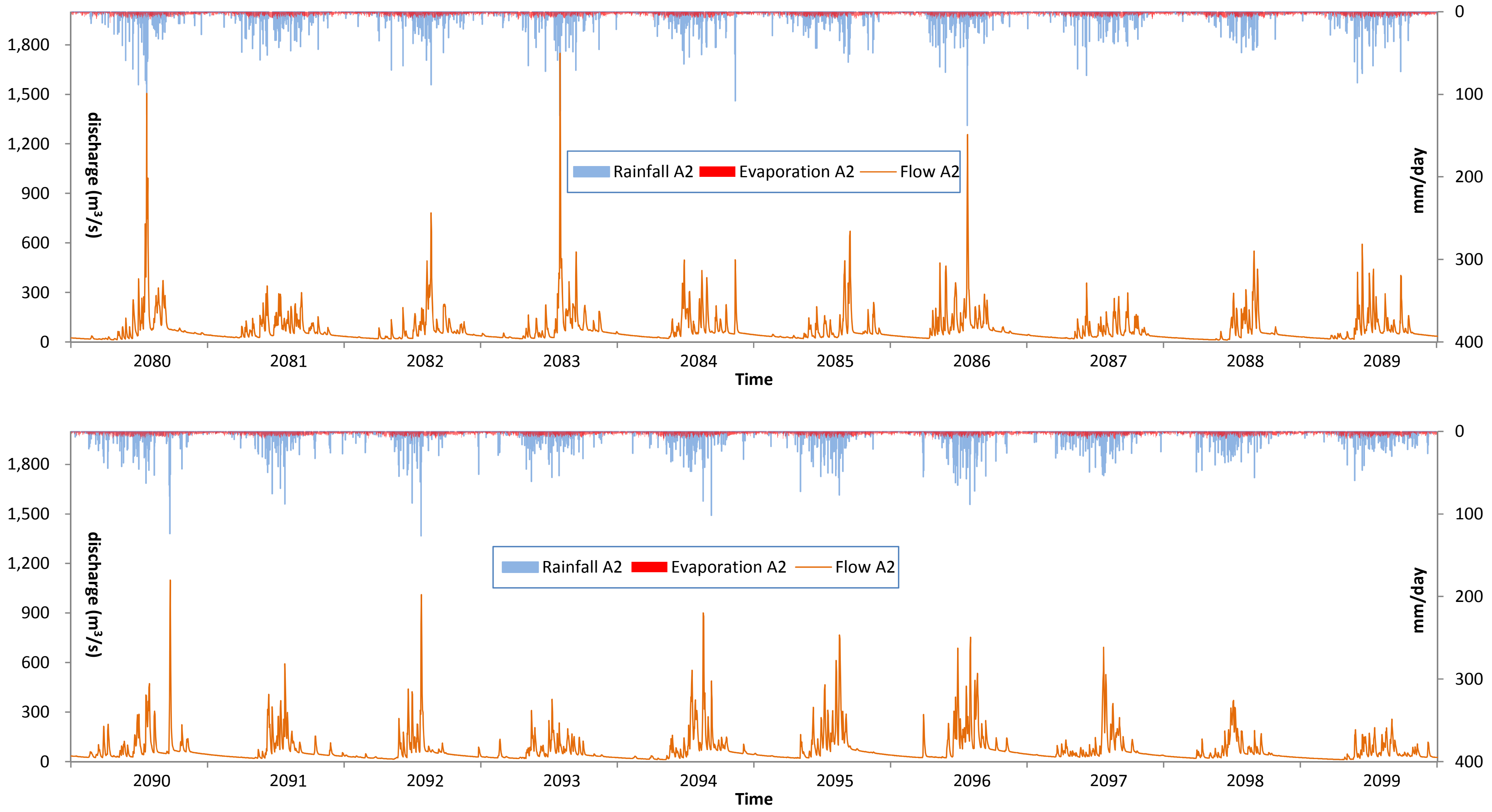


Figure 3-2 Discharge simulation from NAM model in the period of 2080-2099 in A2 scenario

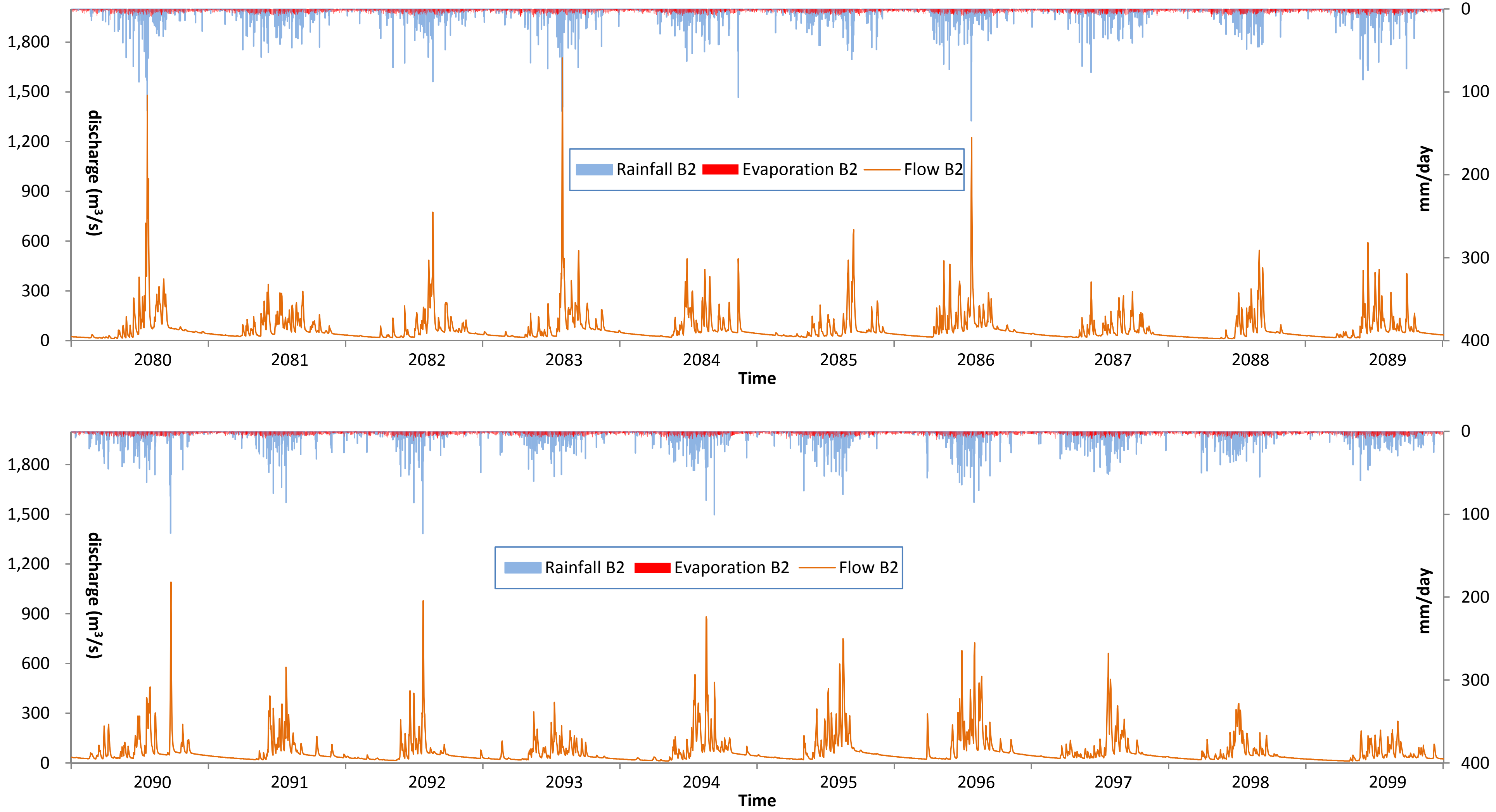


Figure 3-3 Discharge simulation from NAM model in the period of 2080-2099 in B2 scenario

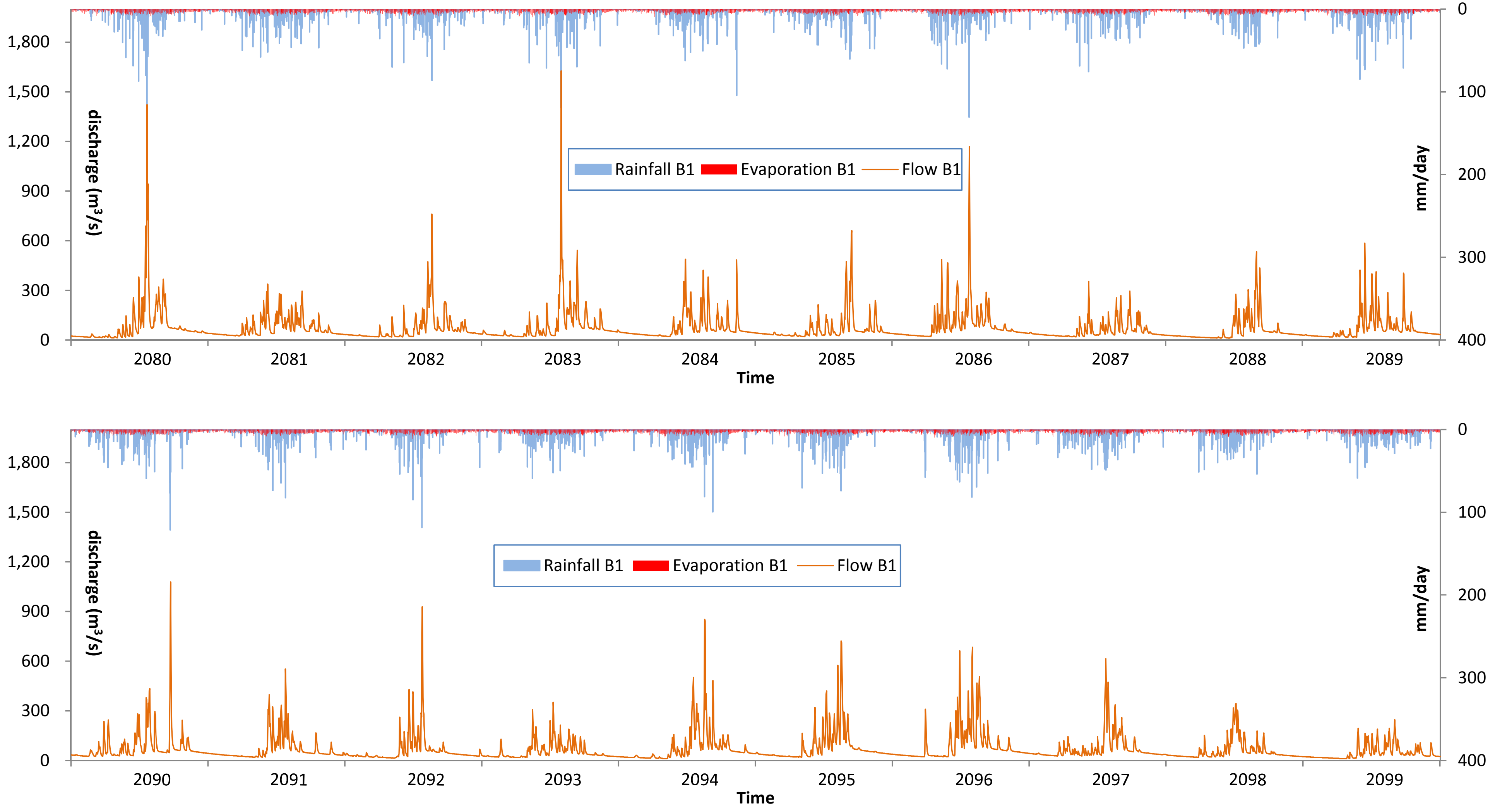


Figure 3-4 Discharge simulation from NAM model in the period of 2080-2099 in B1 scenario

3.1.1. Annual flow

The changes of annual flow at Thac Rieng and Gia Bay in 3 scenarios are shown in the Figure 3-5 and Table 3-1.

Under the impact of climate change context, the annual flows go upward slightly in 3 scenarios for Thac Rieng and Gia Bay station. The highest increase of discharge is found at A2 scenario with the rate of 2.7% for Thac Rieng and 3.7% for Gia Bay, while the smallest increase is at B1 scenario with the rate of 0.8% for Thac Rieng and 1.6% for Gia Bay. In B2 scenarios, the flow rises by 1.9% for Thac Rieng and 2.9% for Gia Bay.

The gentle rise in flow is explained by the higher annual potential evaporation compared to the smaller annual rainfall. While the maximum increase rate of annual rainfall is just about 6.1% (in A2 scenario), the maximum increase rate of annual potential evaporation (ETo) reaches 17.4%, and actual evaporation (ET) reaches 8.7% (in A2 scenario) (Figure 3-6 to Figure 3-9).

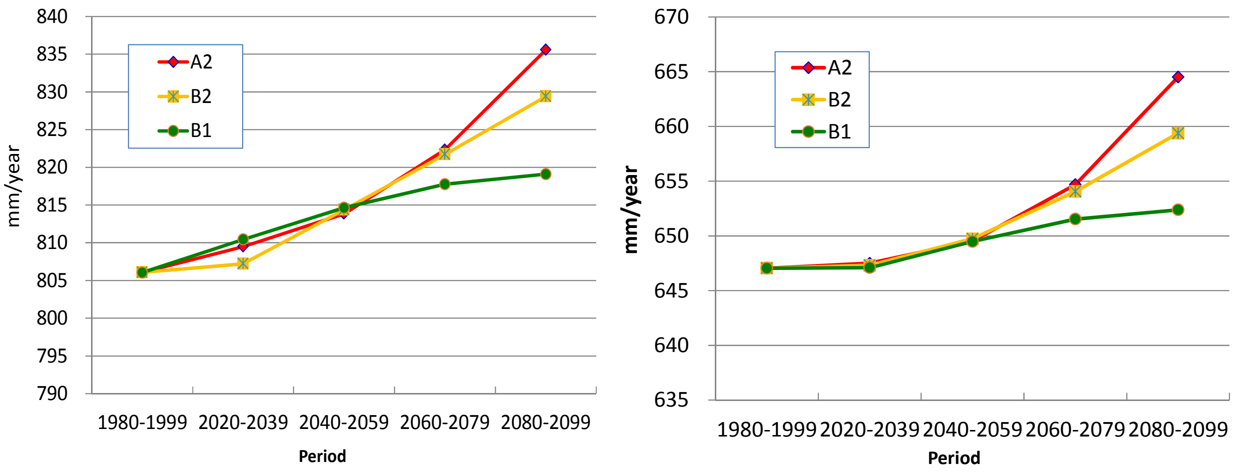


Figure 3-5 Average annual flow at Gia Bay station (left) and Thac Rieng station (right)

Table 3-1 Average annual flow at Gia Bay and Thac Rieng Station

Sub-Area	Gia Bay	Thac Rieng
A2 Scenario (Unit: mm/year)		
1980-1999	806	647.0
2020-2039	809	647.5
2040-2059	814	649.5
2060-2079	822	654.7
2080-2099	836	664.5
B2 Scenario (Unit: mm/year)		
1980-1999	806	647.0
2020-2039	807	647.3
2040-2059	814	649.7
2060-2079	822	654.1
2080-2099	829	659.4
B1 Scenario (Unit: mm/year)		
1980-1999	806	647.0
2020-2039	810	647.1
2040-2059	815	649.5
2060-2079	818	651.5
2080-2099	819	652.4

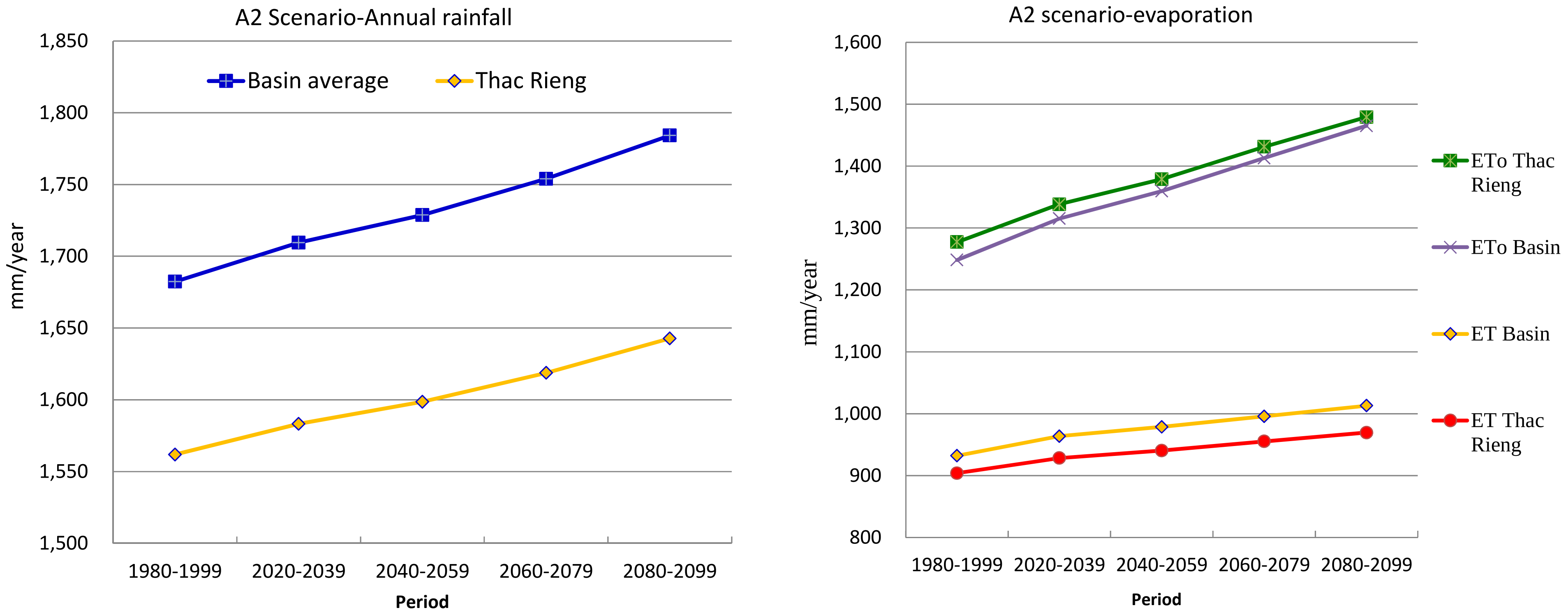


Figure 3-6 Change tendency of annual rainfall (left) annual evaporation (right) at each sub-areas in A2 scenario

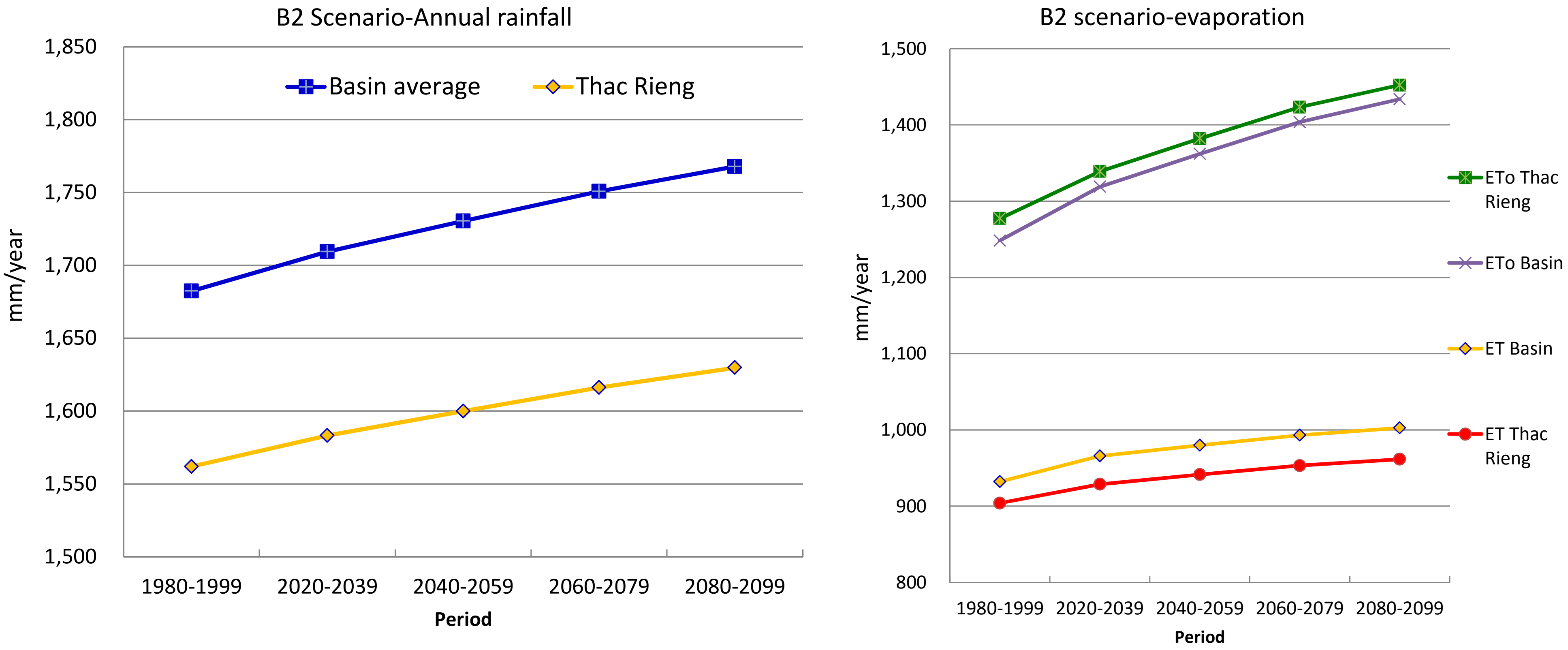


Figure 3-7 Change tendency of annual rainfall (left) annual evaporation (right) at each sub-areas in B2 scenario

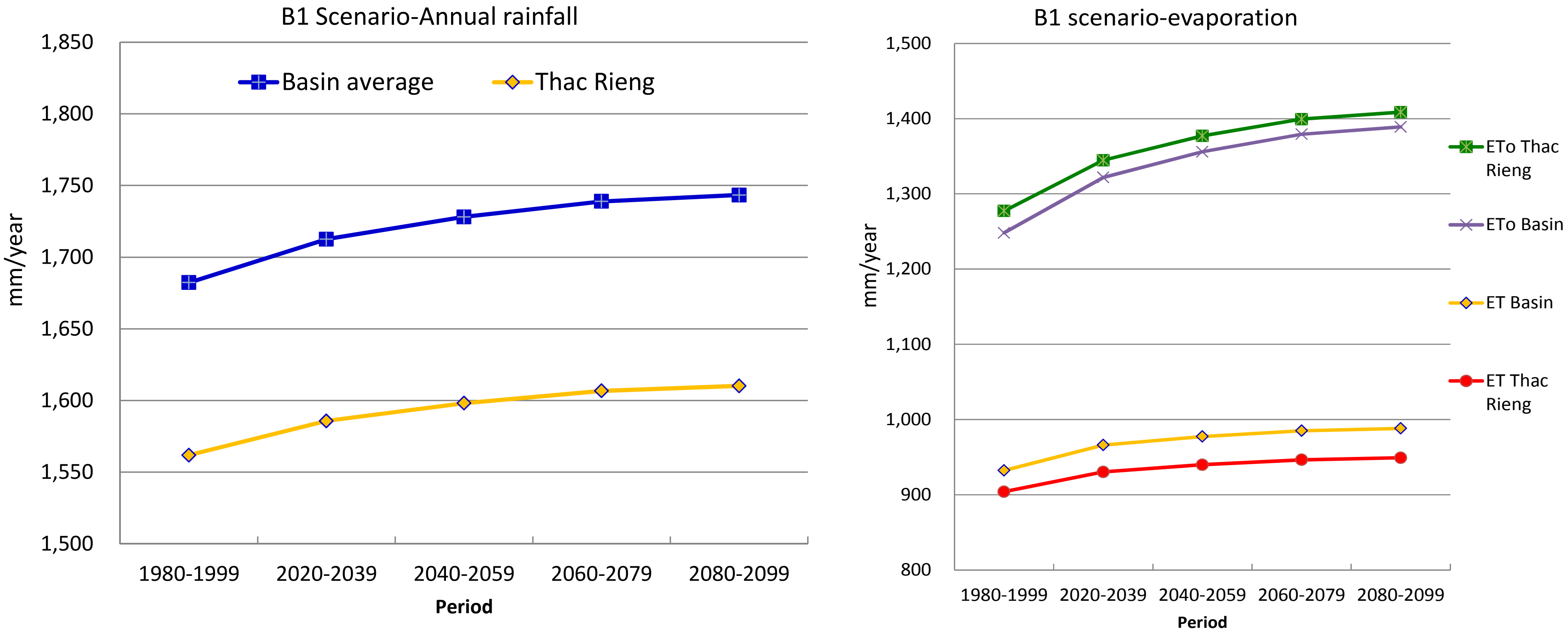


Figure 3-8 Change tendency of anuual rainfall (left) annual evaporation (right) at each sub-areas in B1 scenario

3.1.2. Flow in rainy season

The changes of flow in rainy season at Thac Rieng and Gia Bay in 3 scenarios is shown in the Figure 3-9 and Table 3-2.

Similar with the manner of annual flow but with bigger magnitude, there is a considerable rise of flow in rainy season in 3 scenarios for Thac Rieng and Gia Bay station. A2 scenario is recognized as the worst case with the maximum increase of discharge at the rate of 5.9% for Thac Rieng and 5.5% for Gia Bay. In contrast, the B1 scenario is found with the minimum increasing rate of 2.9% for Thac Rieng and 2.6% for Gia Bay. In B2 scenario, the flow rises by 4.7% and 4.4% for the 2 hydro stations.

The big rise of flow in rainy season is explained by the intensive rainfall and the decline of potential evaporation in comparison with the annual values. In this season, while the maximum increase rate of rainfall is about 10% (in A2 scenario), the maximum increase rate of potential evaporation is 12.3%, and the actual evaporation is 10.9% (A2). The tendency change of rainfall, potential evaporation and evaporation are shown in Figure 3-10 to Figure 3-12.

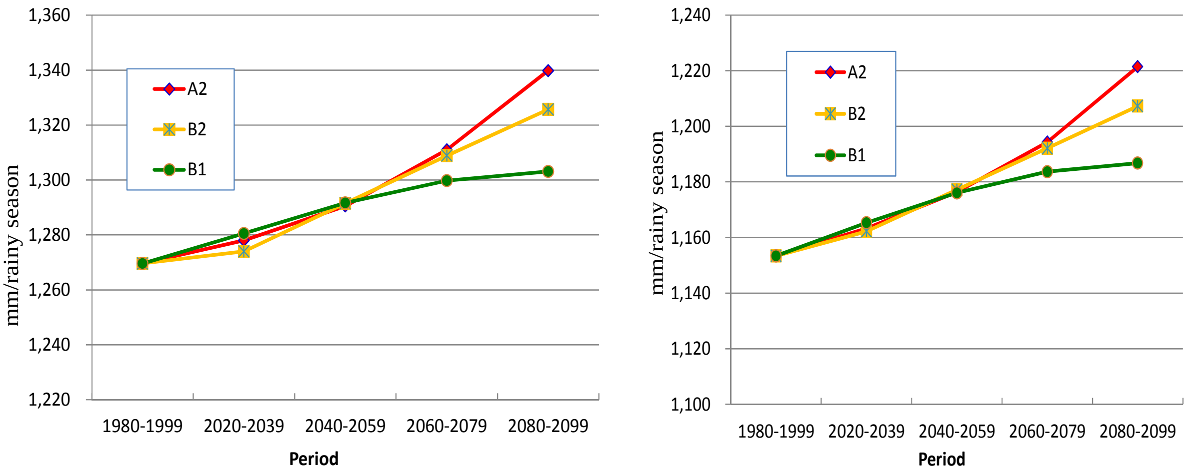


Figure 3-9 Average rainy season's flow at Gia Bay station (left) and Thac Rieng station (right)

Table 3-2 Average flow at Gia Bay and Thac Rieng Station in Rainy Season

Sub-Area	Gia Bay	Thac Rieng
A2 Scenario (Unit: mm/rainy season)		
1980-1999	1270	1153
2020-2039	1278	1163
2040-2059	1291	1176
2060-2079	1311	1194
2080-2099	1340	1221
B2 Scenario (Unit: mm/rainy season)		
1980-1999	1270	1153
2020-2039	1274	1162
2040-2059	1292	1177
2060-2079	1309	1192
2080-2099	1326	1207
B1 Scenario (Unit: mm/rainy season)		
1980-1999	1270	1153
2020-2039	1281	1165
2040-2059	1292	1176
2060-2079	1300	1184
2080-2099	1303	1187

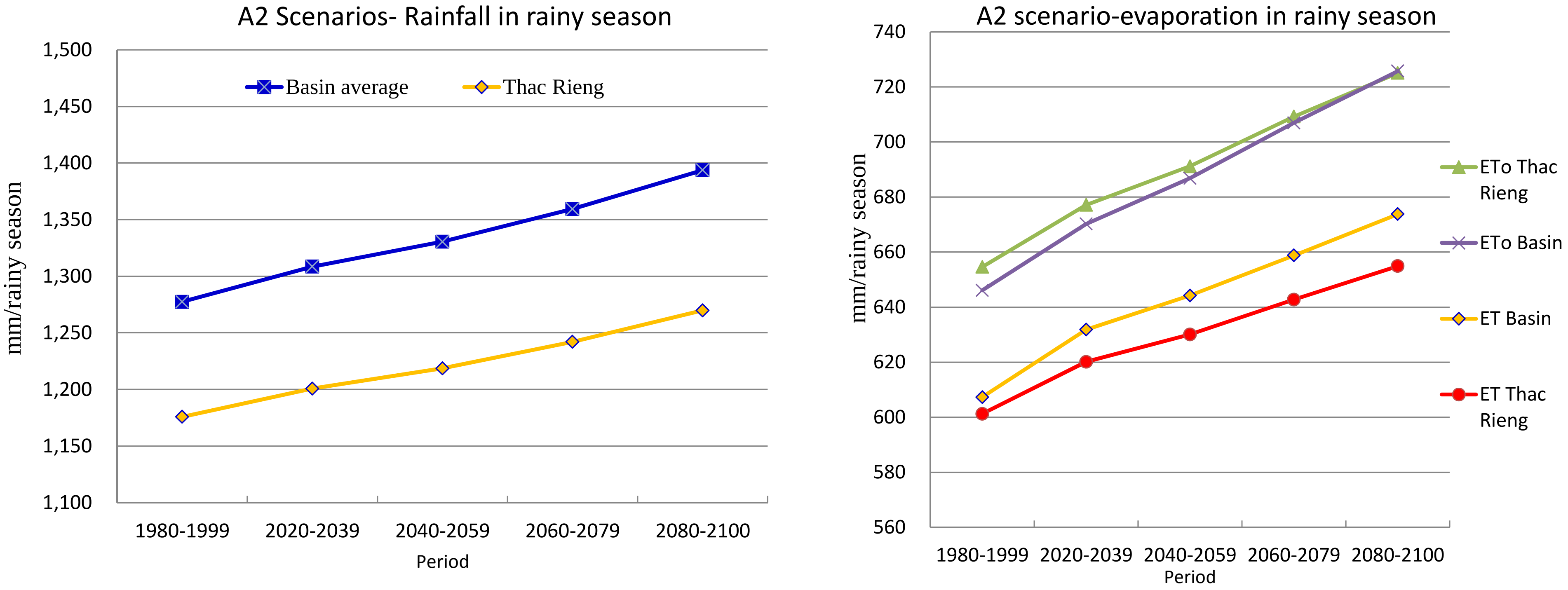


Figure 3-10 Change tendency of rainfall (left) evaporation (right) in rainy season at each sub-areas of A2 scenario

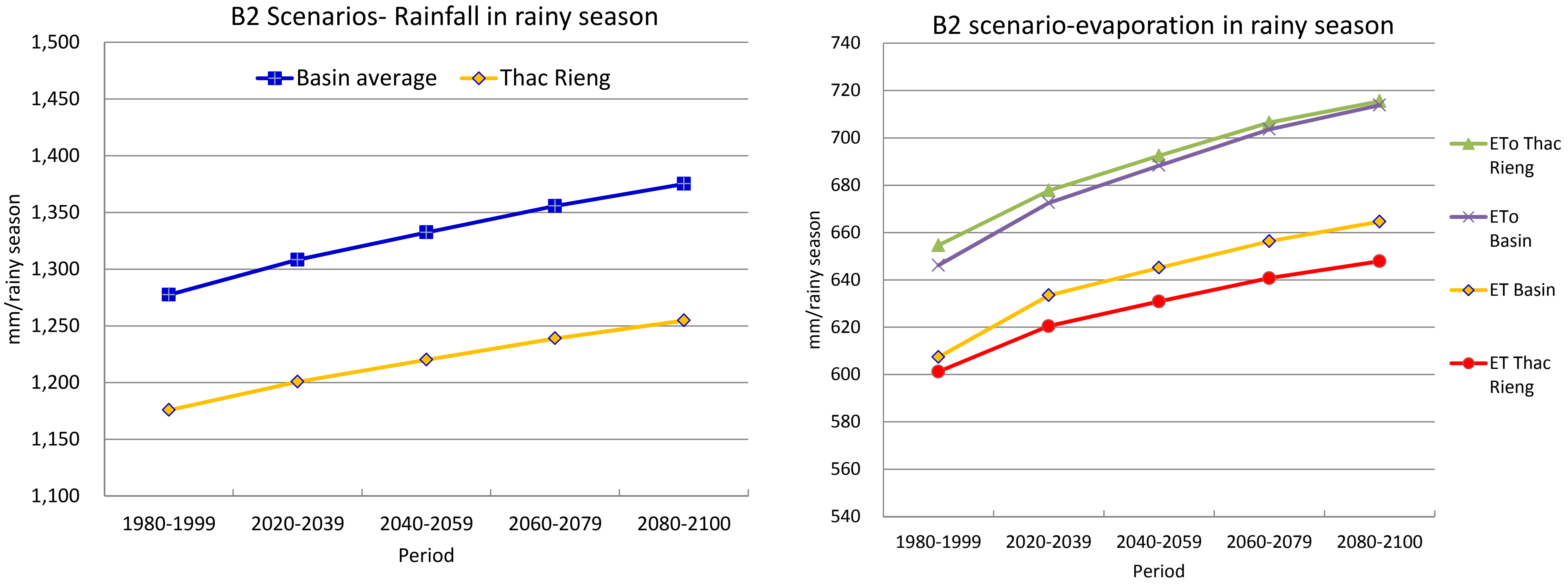


Figure 3-11 Change tendency of rainfall (left) evaporation (right) in rainy season at each sub-areas of B2 scenario

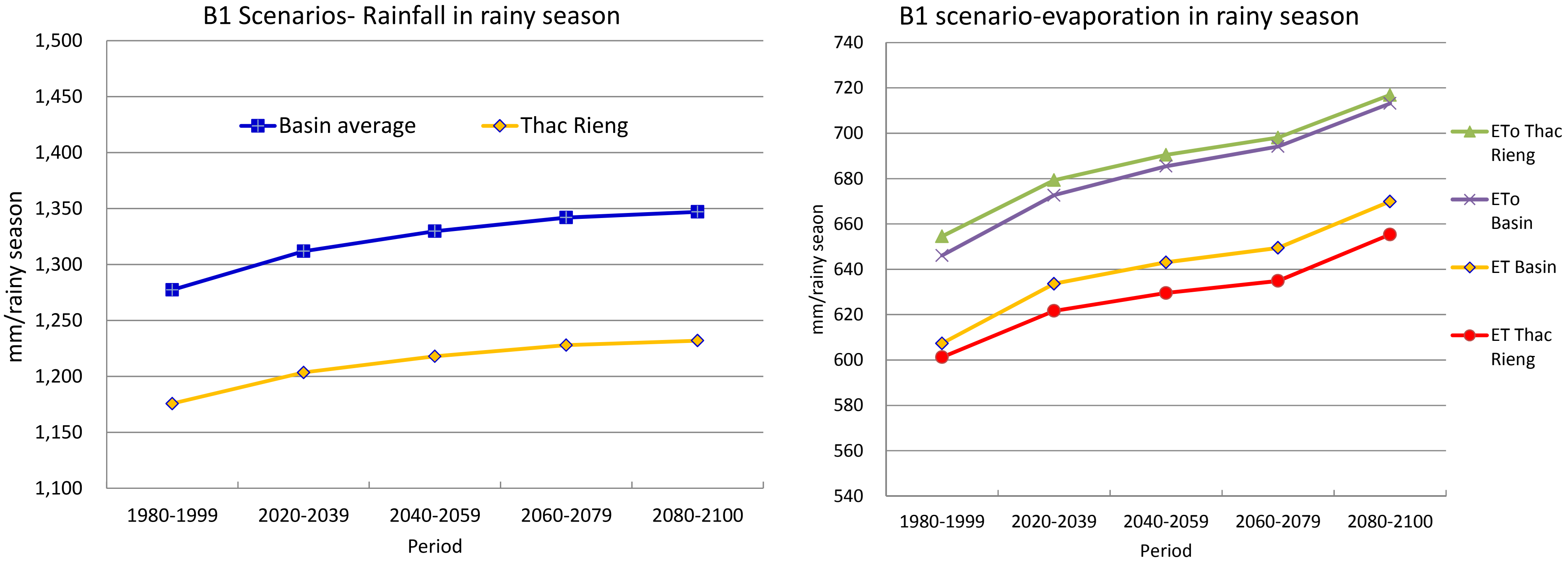


Figure 3-12 Change tendency of rainfall (left) evaporation (right) in rainy season at each sub-areas of B1 scenario

3.1.3. Flow in dry season

The changes of flow in rainy season at Thac Rieng and Gia Bay in 3 scenarios are shown in the Figure 3-13 and Table 3-3.

On the contrary to the manner of annual flow and flow in rainy season, there is a huge recession of flow in dry season in three scenarios for Thac Rieng and Gia Bay station. A2 scenario is recognized as the worst case with the maximum decrease of discharge at the rate of approximately 7.3% for Thac Rieng and 3.4% for Gia Bay. In contrast, the B1 scenario is found with the minimum decreasing rate of 5.9% for Thac Rieng and 2.5% for Gia Bay. In B2 scenario, the flow falls by 6.8% for Thac Rieng and 3.0% for Gia Bay.

The downward trend of flow in dry season is explained by the big drop of rainfall incorporated with the intensive increase of potential evaporation. In this season, the maximum decrease rate of rainfall in the basin (basin average) is about 3.3% (A2) and the maximum increase rate of potential evaporation reaches 18.7% (A2), and actual evaporation reaches 4.4% (A2). The tendency change of rainfall, potential evaporation and actual evaporation are shown in Figure 3-14 to Figure 3-16.

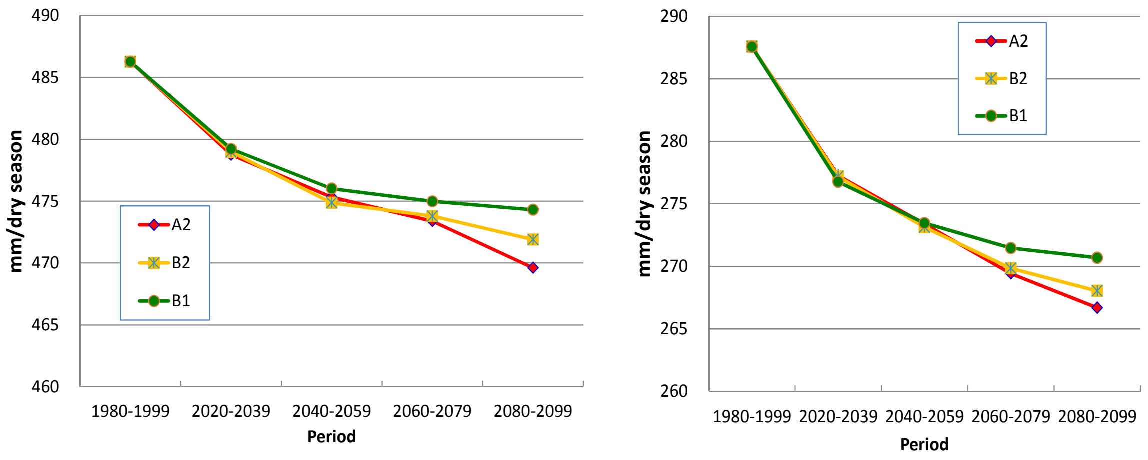


Figure 3-13 Average dry season's flow at Gia Bay station (left) and Thac Rieng station (right)

Table 3-3 Average flow at Gia Bay and Thac Rieng Station in Dry Season

Sub-Area	Gia Bay	Thac Rieng
A2 Scenario (Unit: mm/dry season)		
1980-1999	486	288
2020-2039	479	277
2040-2059	475	273
2060-2079	473	269
2080-2099	470	267
B2 Scenario (Unit: mm/dry season)		
1980-1999	486	288
2020-2039	479	277
2040-2059	475	273
2060-2079	474	270
2080-2099	472	268
B1 Scenario (Unit: mm/dry season)		
1980-1999	486	288
2020-2039	479	277
2040-2059	476	273
2060-2079	475	271
2080-2099	474	271

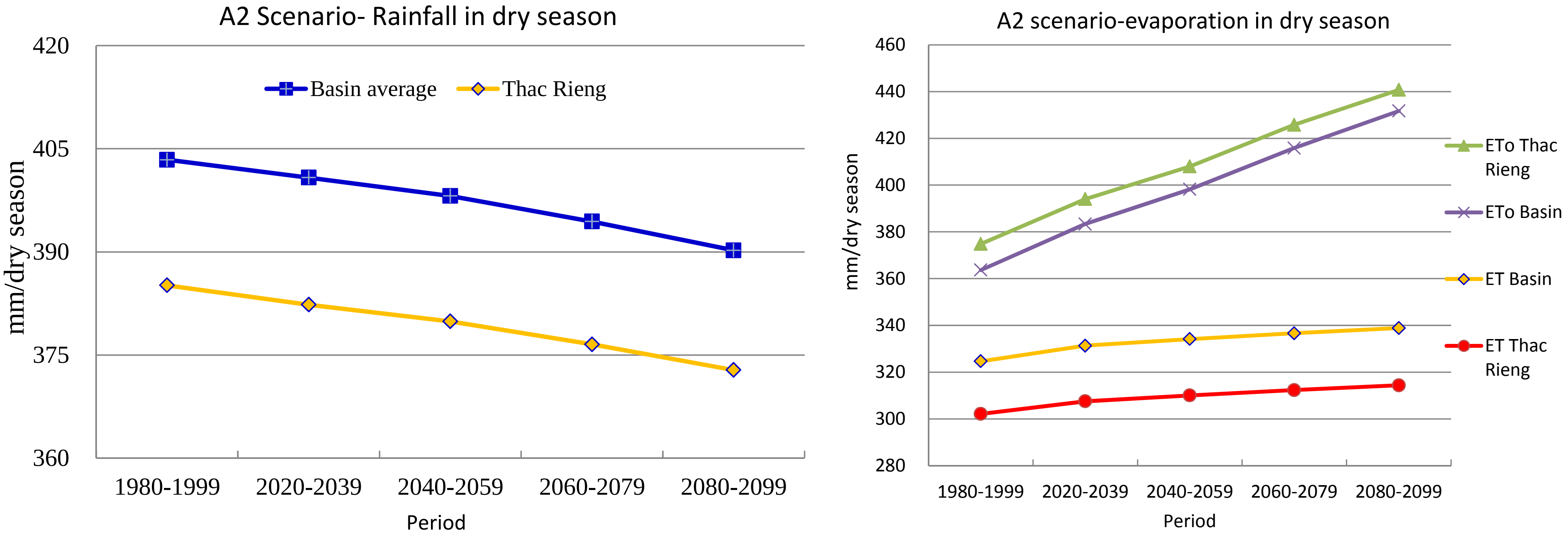


Figure 3-14 Change tendency of rainfall (left) evaporation (right) in dry season at each sub-areas of A2 scenario

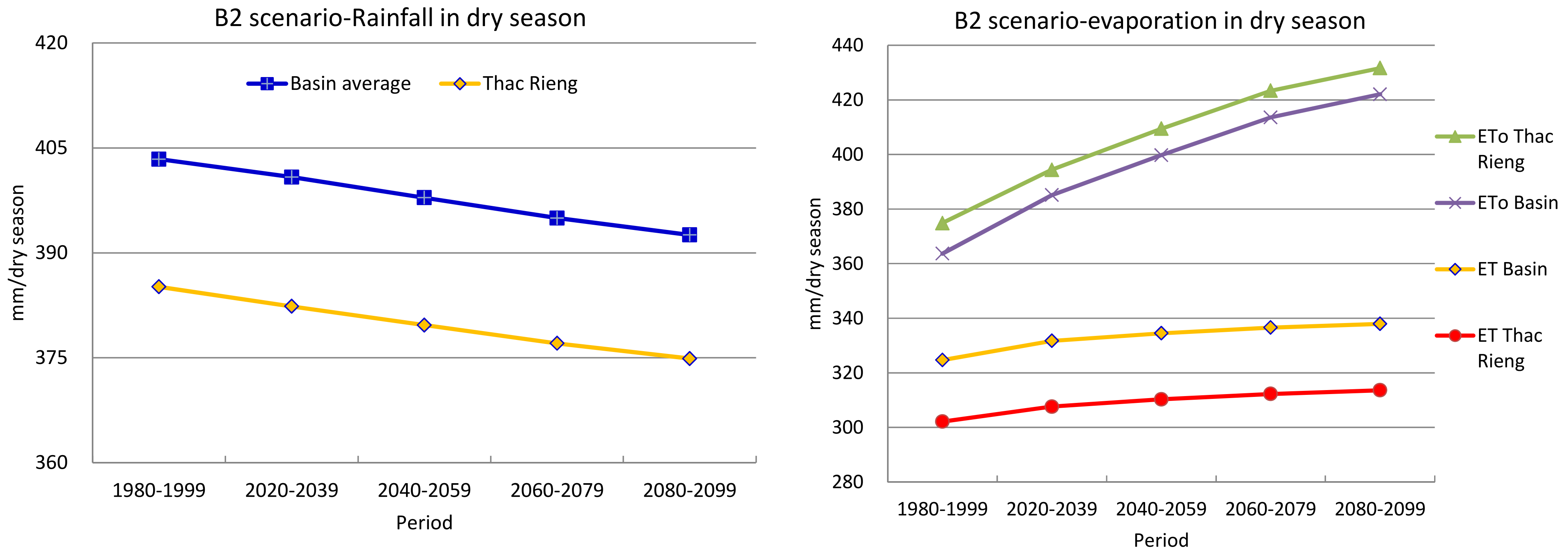


Figure 3-15 Change tendency of rainfall (left) evaporation (right) in dry season at each sub-areas of B2 scenario

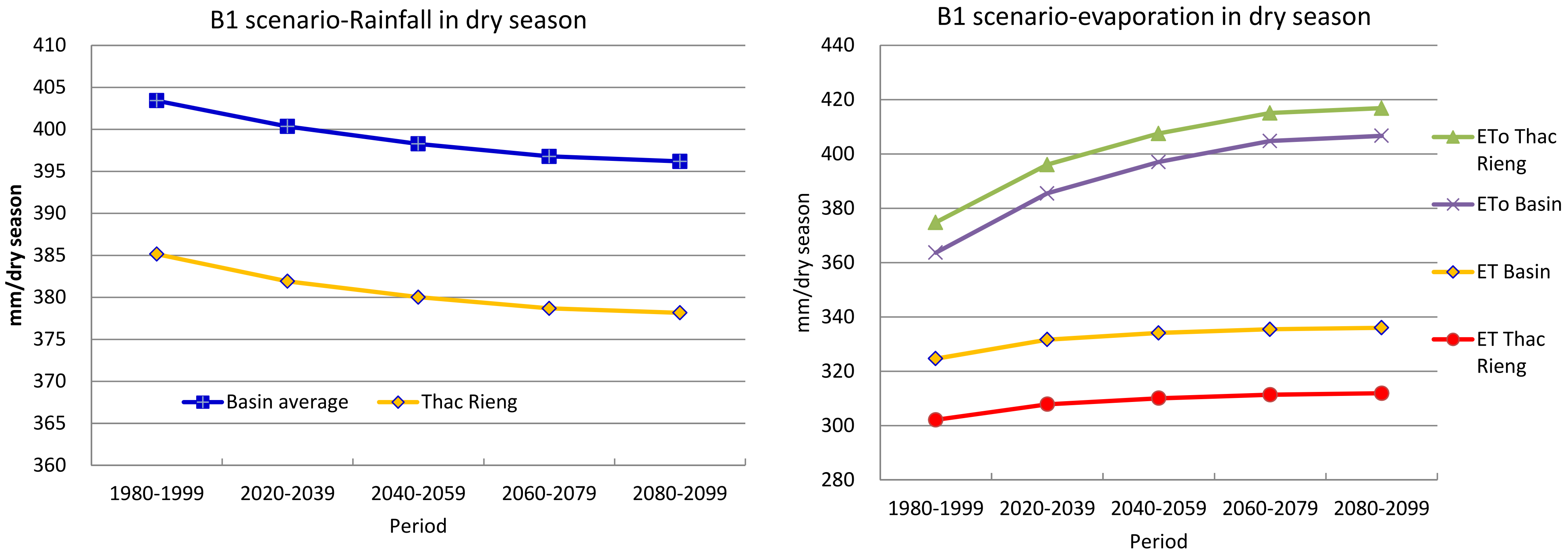
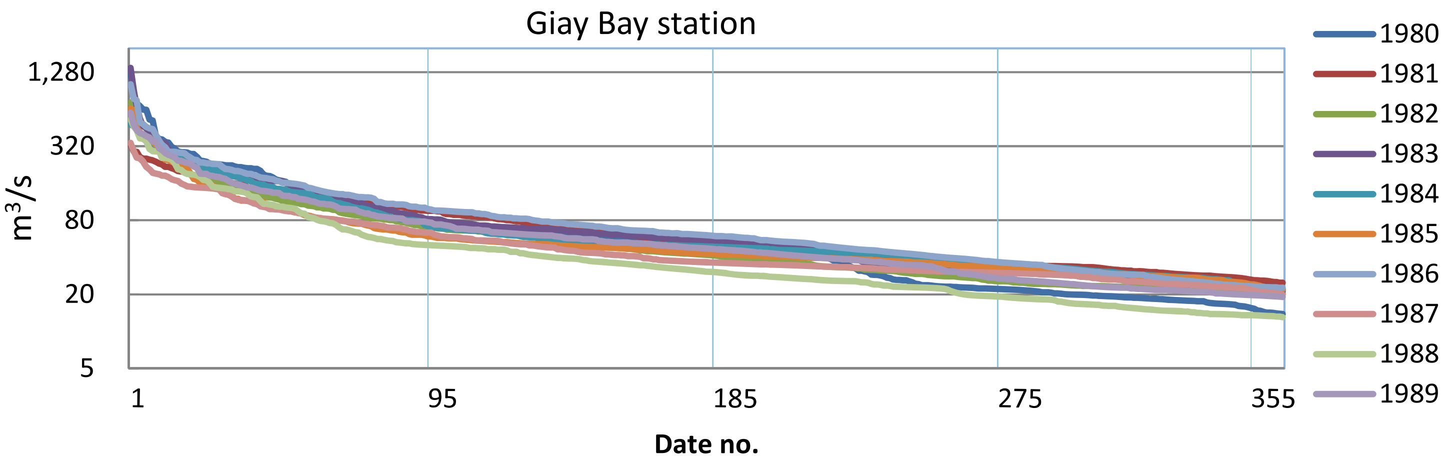


Figure 3-16 Change tendency of rainfall (left) evaporation (right) in dry season at each sub-areas of B1 scenario

3.1.4. Change of peak and low flow in the basin

Change of peak and low flow in the Upper Cau River basin was accessed based on flow duration curves. In a discharge duration curve, the 365 daily discharges for one year are arranged in descending order. The left side of the curve indicates daily discharges at times of high water, and the right side indicates daily discharges at times of low water. According to Noguchi et al., (2005), abundant runoff, ordinary runoff, low runoff, and scanty runoff are defined as the daily runoff on 95th, 185th, 275th, and 355th largest flow data of a year for flow regime characteristics.

The flow duration curves of the Upper Cau River basin are shown in Figure 3-17 to Figure 3-20.



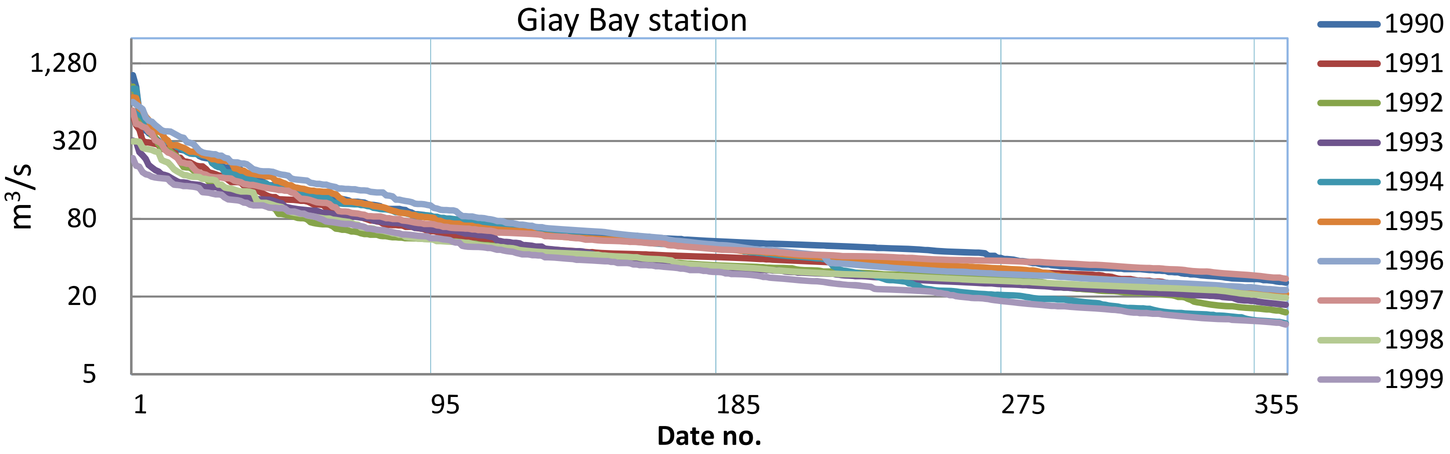
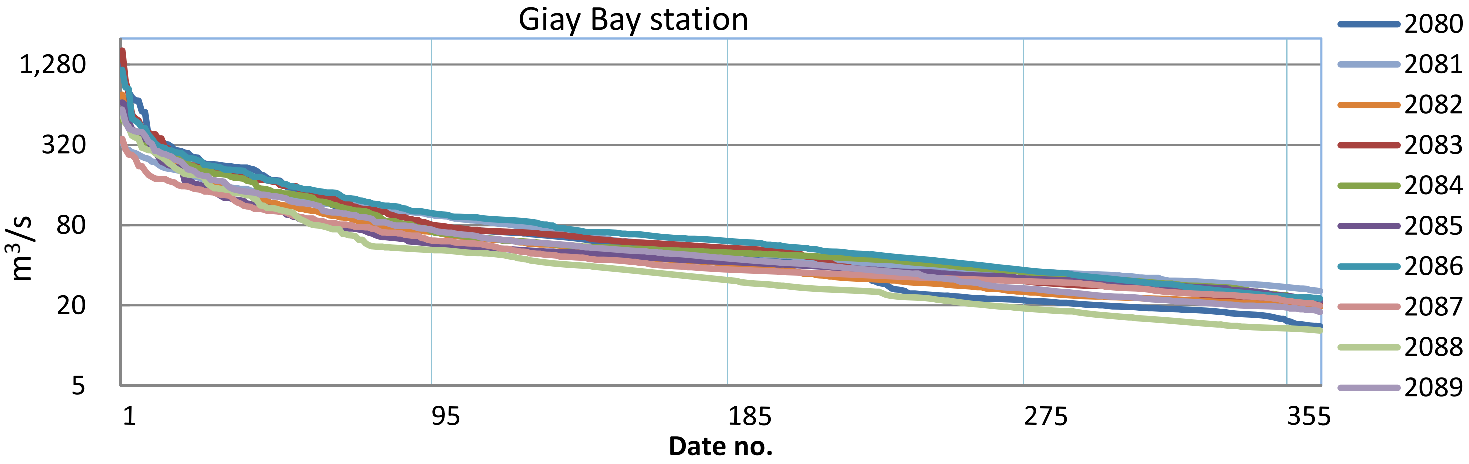


Figure 3-17 Flow duration curves at Gia Bay station in baseline period



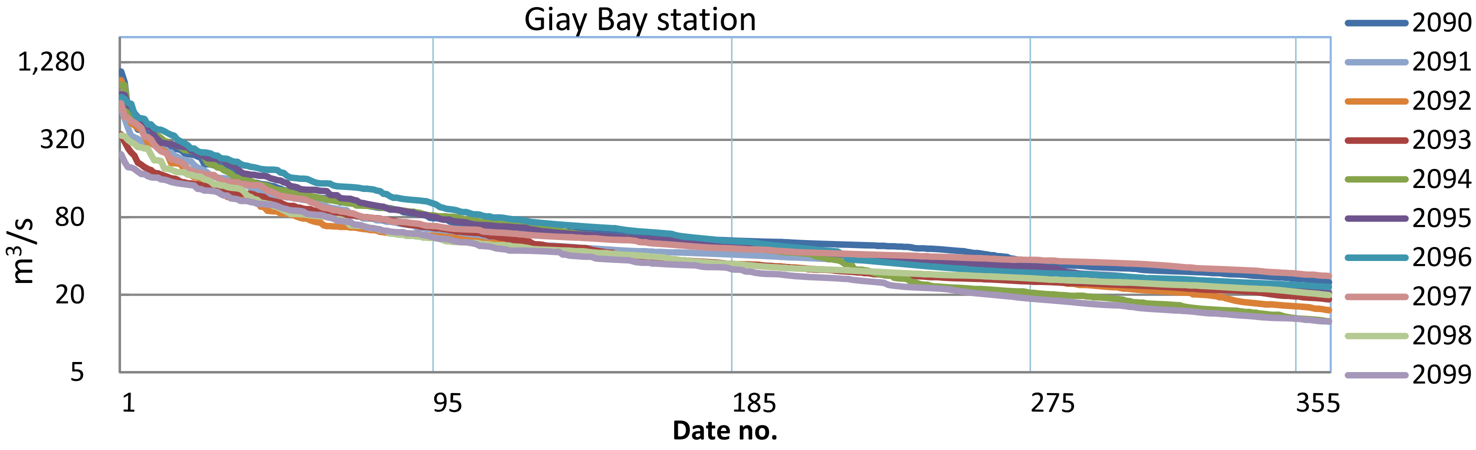
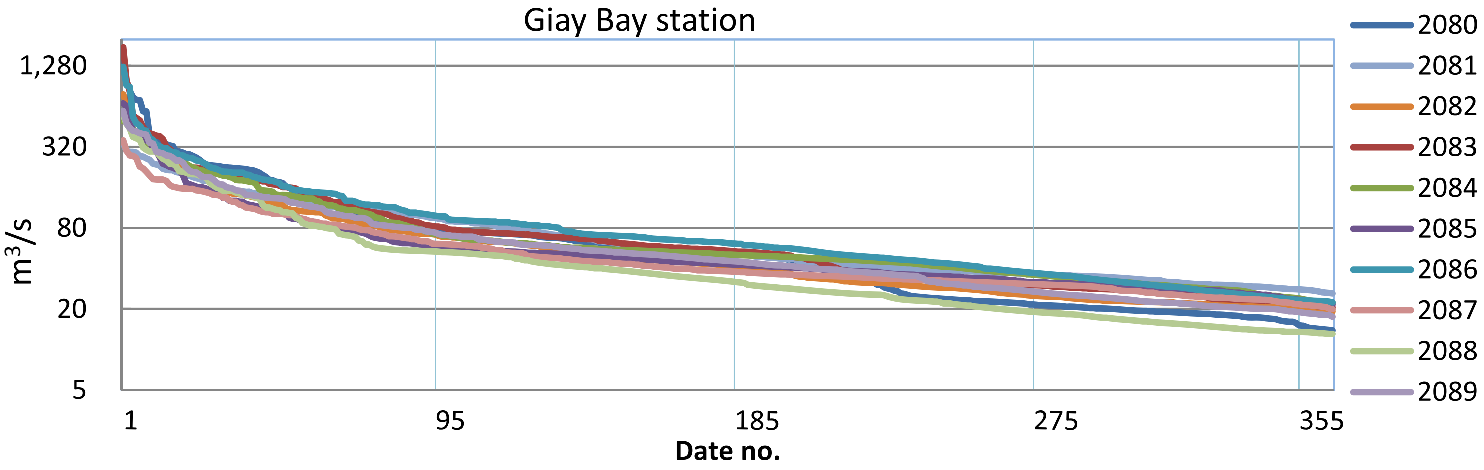


Figure 3-18 Flow duration curves at Gia Bay station in 2080-2099 period-B1 scenario



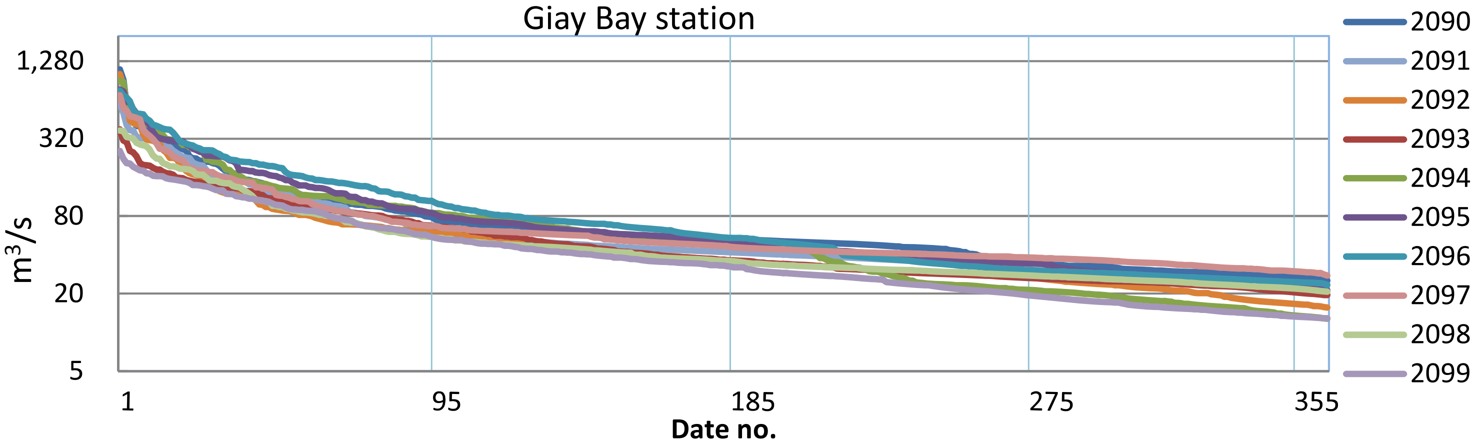


Figure 3-19 Flow duration curves at Gia Bay station in 2080-2099 period-A2 scenario

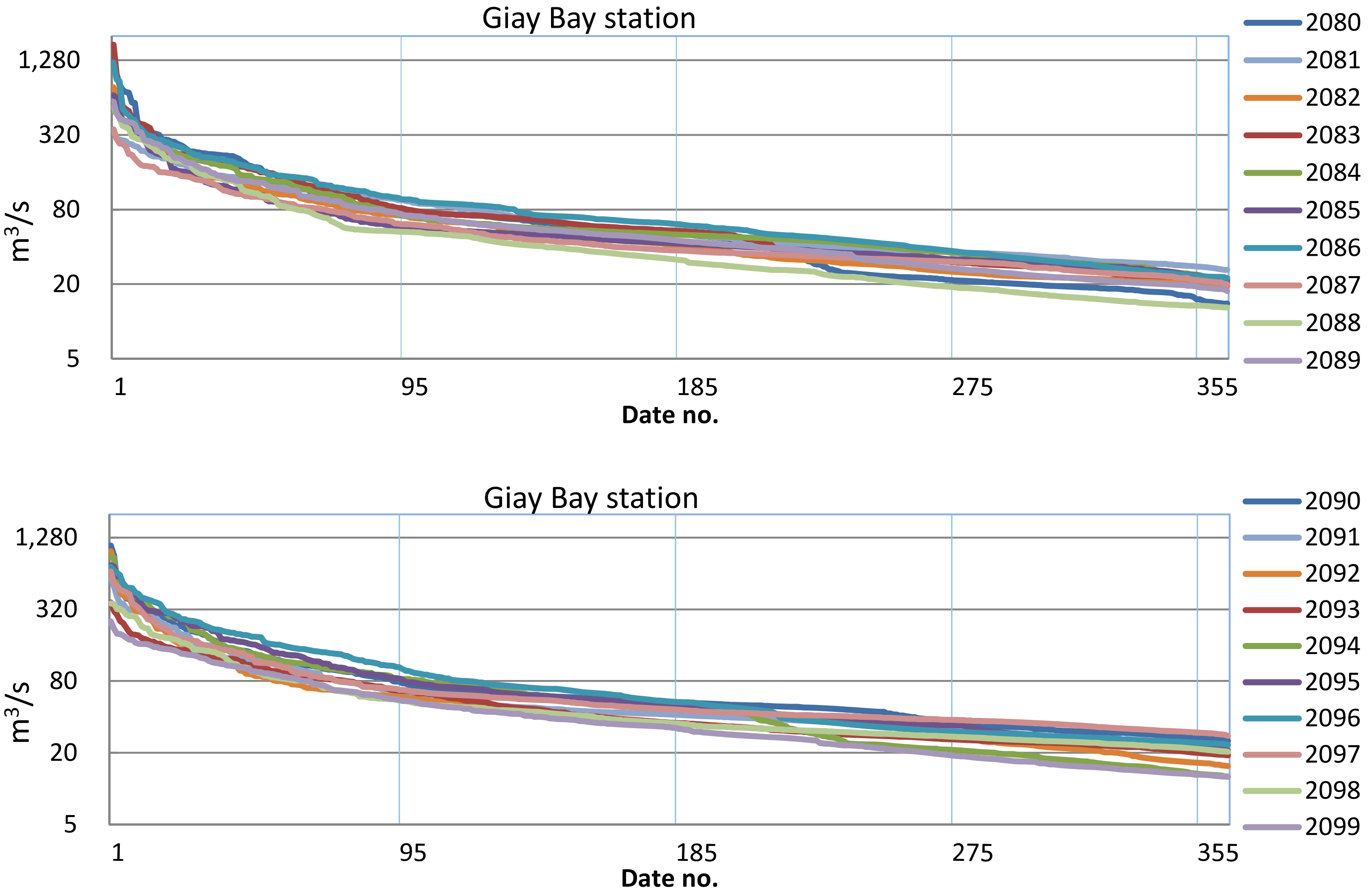


Figure 3-20 Flow duration curves at Gia Bay station in 2080-2099 period-B2 scenario

In this study, the minimum flow-duration curve of each period was estimated from duration curves of years in this period. These curves show the minimum boundary of river flow change under the impacts of climate change. These curves are shown in Figure 3-21 to Figure 3-23. From the curves, the differences are quite small among the periods in climate change scenarios. It can be the results to small change of water deficit through periods in the same climate change scenario.

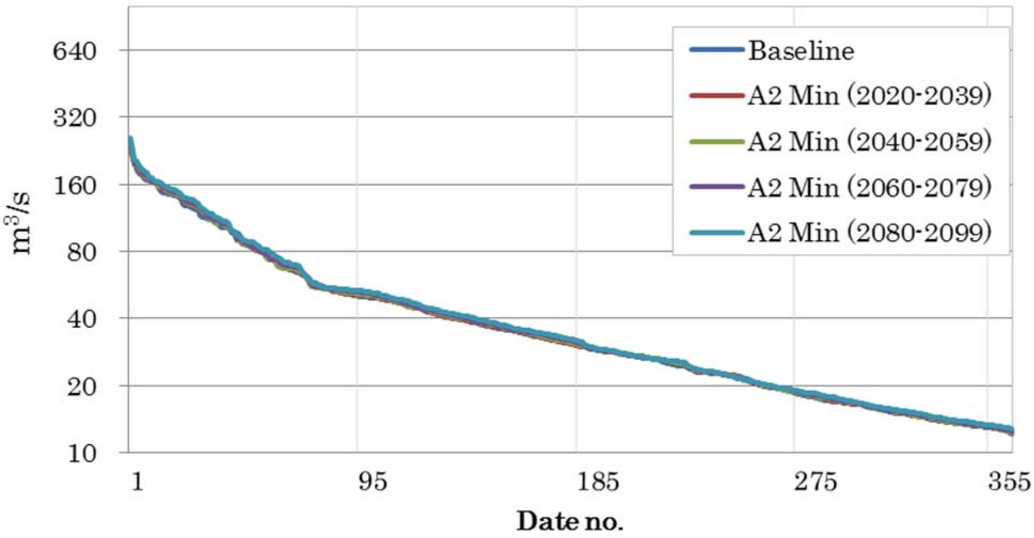


Figure 3-21 Minimum of flow duration curves in A2 scenario

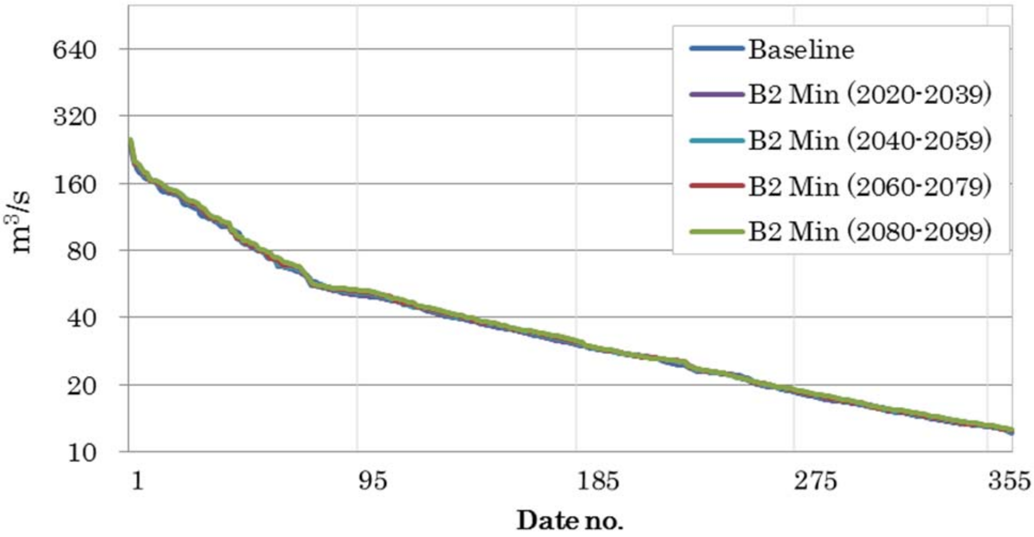


Figure 3-22 Minimum of flow duration curves in B2 scenario

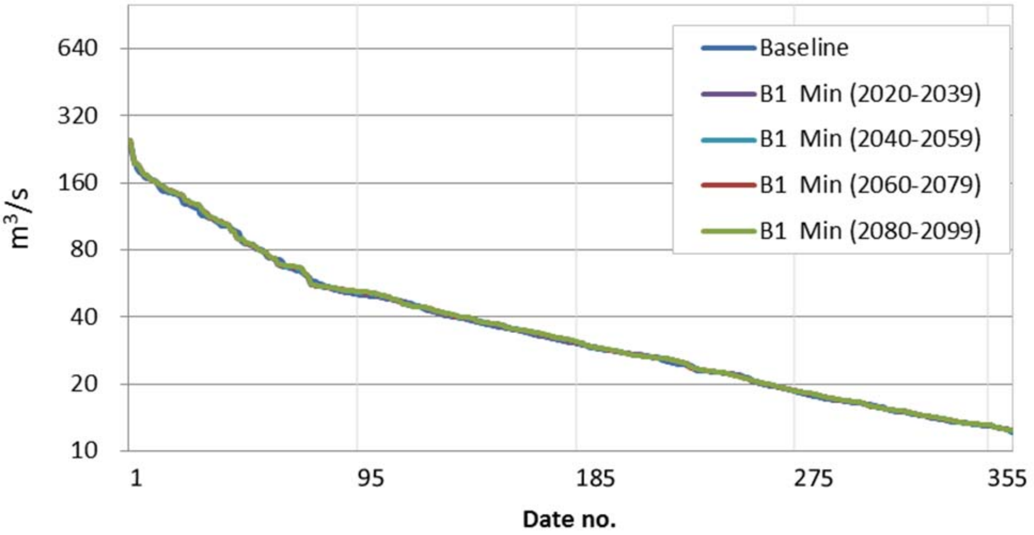


Figure 3-23 Minimum of flow duration curves in B1 scenario

3.2. The tendency change of water demand to climate change scenarios

In Vietnam, irrigation places the largest burden on water resources and it is estimated to be over 82% of total water utilization (Gebretsadik, 2012). Therefore, in this study, impacts of climate change on water demand will be focused with an assumption that water demand for industry, domestic use and livestock are kept as the same with baseline period (1980-1999). The study considers that only water demand for irrigation will change under the impacts of climate change.

3.2.1. Water demand for domestic use

Water demand for domestic use was calculate base on the equation (2.3). In the equation, population data was collected from the Socio-economic statistical data of 671 districts, towns and cities under the authority of provinces in Vietnam (2006) as in the Table 2-5; water demand standard for domestic use in Table 2-6. The Upper Cau River basin is listed is rural area, thus water supply standard for domestic use is 60 l/day/person.

The results of water demand for domestic use are shown in Table 3-4. According to the table, with population are over 100.000 people, water demand for domestic use of Song Du and Dong Hy sub-areas rank first and second with 8,517 m^3/day (Song Du) and 7,064 m^3/day (Dong Hy). Cho Moi and Vo Nhai sub-areas which has less population than other sub-areas, water demand for domestic use rank the lowest with 2,165 m^3/day (Cho Moi), 1,906 m^3/day (Vo Nhai).

Table 3-4 Water demand for domestic use in the Upper Cau River basin

No	Sub-area	Population	Water demand (m^3/day)
1	Thac Rieng	68,477	4,109
2	Cho Moi	36,090	2,165
3	Cho Chu	61,439	3,686
4	Song Du	141,947	8,517
5	Vo Nhai	31,762	1,906
6	Dong Hy	117,727	7,064
Total			27,447

3.2.2. Water demand for industry

Water demand for industry was calculted as the equation (2.2). In this equation, water demand for industry in the study area was estimated based on area of industrial zones, and water supply standard for industry. In the basin, there are four areas (Thac Rieng, Cho Moi, Song Du, Dong Hy) have industrial zones (Table 2-4 and Table 3-5).

Water demand for industry is shown in Table 3-5. According to the table, water demand for industry of Thac Rieng and Cho Moi sub-areas is highest with 36,461 m^3/day (Thac Rieng), 38,500 m^3/day (Cho Moi). Water demand for industry in Song Du and Dong Hy sub-ares are quite small with 6,090 m^3/day (Song Du), 1,764 m^3/day (Dong Hy).

Table 3-5 Water demand for industry in the Upper Cau River basin

No	Name of sub-area	Area (ha)	Water demand (m^3/day)
1	Thac Rieng	521	36,461
2	Cho Moi	550	38,500
3	Song Du	87	6,090
4	Dong Hy	25.2	1,764
Total			82,815

3.2.3. Water demand for livestock

Water demand for livestock was calculated as the equation (2.4). Three kinds of important livestock were considered in the study: cattle, pig, and poultry. Number of each kind of livestock which were collected from the statistical book of the Socioeconomic statistical data of 671 districts, towns and cities under the authority of provinces in Vietnam (2006). Water use standard was used as in Table 2-7.

The results of water demand for livestock are shown in Table 3-6. Total water demand for livestock in the Upper Cau River basin is 23,288 m^3/day which includes 10,675 m^3/day for castles, 7,251 m^3/day for pig, and 5,362 m^3/day for poultry.

Table 3-6 Water demand for livestocks in the Upper Cau River basin

No	Area	Water demand (m^3/day)			
		Cattles	Pig	Poultry	Total
1	Thac Rieng	2,714	1,390	774	4,878
2	Cho Moi	990	447	290	1,727
3	Cho Chu	1,257	956	894	3,107
4	Song Du	3,093	2,612	2,050	7,755
5	Vo Nhai	1,273	716	484	2,474
6	Dong Hy	1,348	1,130	870	3,347
Sum		10,675	7,251	5,362	23,288

3.2.4. Water demand for irrigation

3.2.4.1. Irrigation areas in the Upper Cau River basin

Crop area is an important element related to water demand for irrigation. If there is large crop area, water demand for irrigation will increase. On the contrary, small crop area will lead to less water demand for irrigation.

The Upper Cau River basin is divided into 6 irrigation areas: Thac Rieng, Cho Moi, Cho Chu, Song Du, Vo Nhai, and Dong Hy. In those areas, there are two main crops were considered (rice and maize). There are two cultivation seasons for both rice and maize: winter-spring season (WS) and summer-autumn (SA) season. Areas for rice cultivation are different in different season (Table 3-7).

Table 3-7 Irrigation areas in the Upper Cau River basin

No	Area	Province	Total area (ha)	WS Rice (ha)	SA Rice (ha)	Maize (ha)
1	Thac Rieng	Bac Can	75,922	1,667	2,325	1,291
2	Cho Moi	Bac Can	52,088	922	1,682	1,657
3	Cho Chu	Thai Nguyen	38,598	2,272	2,931	684
4	Song Du	Thai Nguyen	47,183	3,657	4,685	1,615
5	Vo Nhai	Thai Nguyen	48,576	525	1,218	700
6	Dong Hy	Thai Nguyen	45,775	2,202	3,836	1,639
Total			308,142	11,245	16,677	7,586

3.2.4.2. Schedule of cultivation

Two main crops were considered in the study are rice and maize. There are two cultivation seasons for each crop (Table 3-8): winter-spring (WS) season and summer-autumn (SA) season.

The cultivation time of both rice and maize are the same with 120 days in WS season and 110 days in SA season. In WS season, starting date is in February, and harvesting date is in June. In SA season, starting date is in July, and harvesting date is in September (rice) and October (maize).

Table 3-8 Schedule of cultivation activities in the Upper Cau River basin (source: IMHEN, 2008)

Winter-Spring season					
Rice			Maize		
Starting date	Harvesting date	Number of days	Starting date	Harvesting date	Number of days
15-February	13-June	120	10- February	8-June	120
Summer-Autumn season					
10-July	27-September	110	25-June	12-October	110

3.2.4.3. Water demand for irrigation

Based on rainfall and potential evaporation data which were observed in the baseline period and were given by the three climate change scenarios (2020-2099), water demand for irrigation rice and maize areas, in the Upper Cau River basin was calculated for given schedule of cultivation. The results of irrigation calculation (Figure 3-24 to Figure 3-26, and Table 3-9) shows increasing trend of water demand in A2, B2, and B1 scenarios. The highest change can be seen in the A2 scenario, and the lowest change can be seen in the B1 scenario. Among six sub-areas, value of water demand for irrigation in the Upper Cau River basin follows the order from the lowest to the highest: Vo Nhai, Cho Moi, Thac Rieng, Cho Chu, Dong Hy, and Song Du. In relation to the annual water demand for each sub-area, the trend goes upward in 3 scenarios but with different magnitudes.

a. Annual irrigation water demand

The irrigation demand of A2 scenario is the highest in the three climate change scenarios and is shown by the Figure 3-24 with considerable increasing rate of about 12% for Thac Rieng and Dong Hy, 13% for Vo Nhai, 14% for Cho Moi and Cho Chu, and 16% for Song Du. The increasing of water demand is strongly affected by the change of rainfall and crop evaporation. In A2 scenario, average annual rainfall increases but water demand for irrigation also increases. The comparison between changes of rainfall and those of crop evaporation will give the answer. The largest change of rainfall in the basin ranges from 5.2% to 6.6% in comparison with the baseline, but the largest changes of crop evaporation in the basin are from 13.2% to 16.0%. The higher increasing of average annual crop evaporation than average annual rainfall is the main cause of increase of average annual water demand.

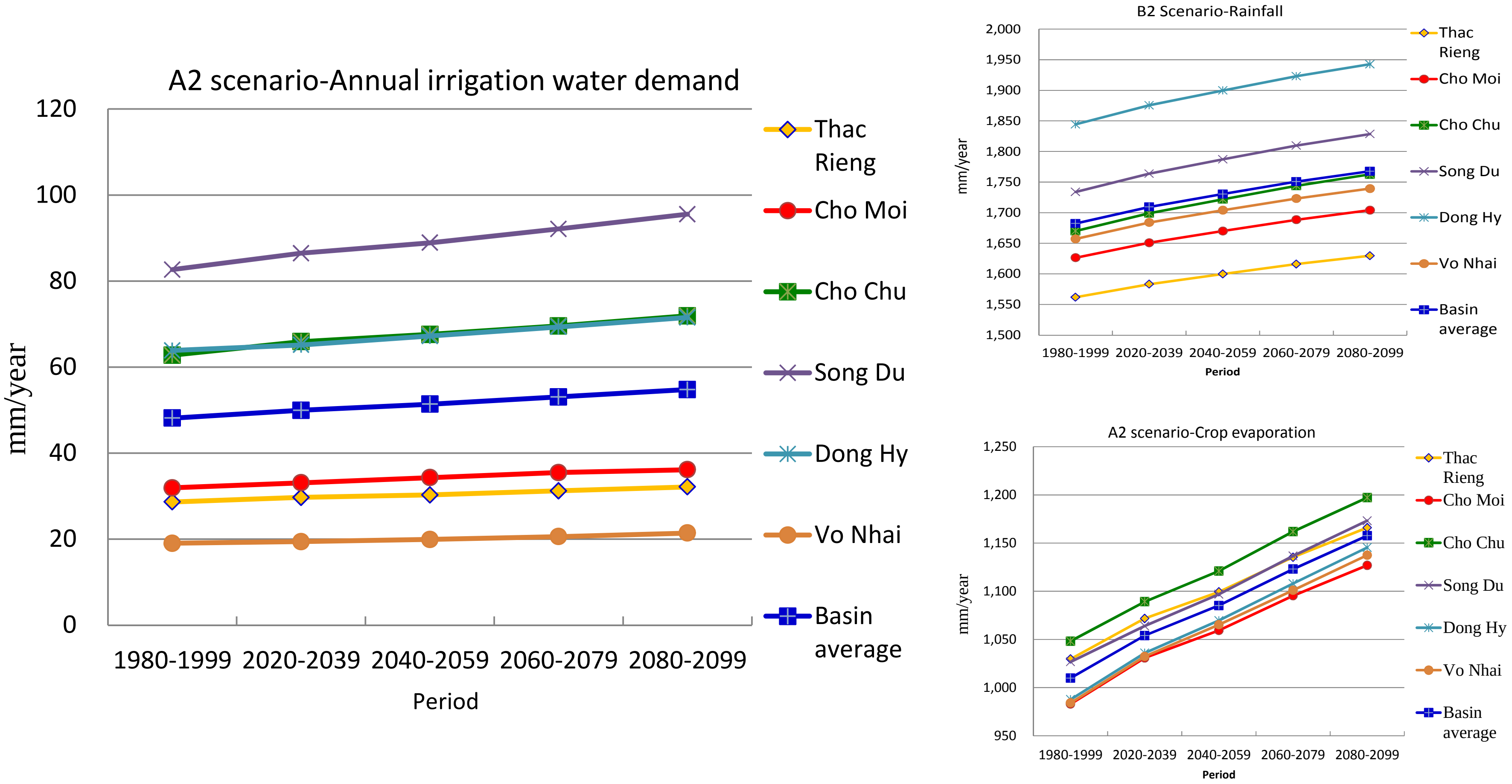


Figure 3-24 Average annual water demand for irrigation, rainfall and potential evaporation in A2 scenario

Water demand for irrigation in B2 scenario is shown in Figure 3-25. The irrigated water demand for B2 scenario is followed by that for A2 with lower rates but is still counted as large changes ranging from approximately 10% for Thac Rieng, Dong Hy and Vo Nhai, 12% for Cho Moi, 13% for Cho Chu and Song Du. In the B2 scenario, average annual rainfall in the last period (2080-2099) increases from 4.3% to 5.5% in comparison with the baseline, while average annual crop evaporation increase from 11.4% (Thac Rieng sub-area) to 13.5% (Dong Hy sub-area).

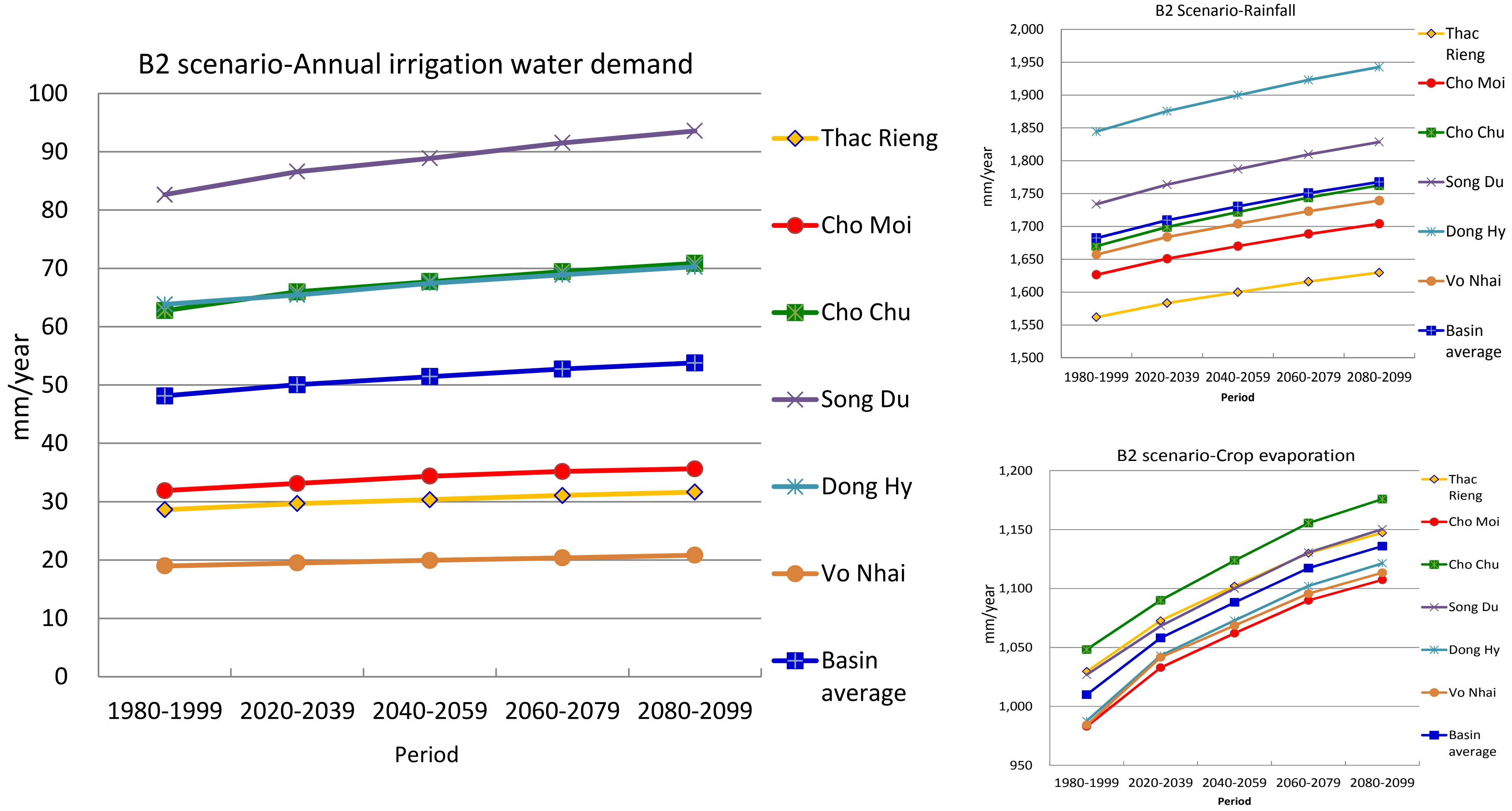


Figure 3-25 Average water demand for irrigation, rainfall and potential evaporation in B2 scenario

In three climate change scenarios, B1 has also increasing tendency of irrigation water demand, but with slower rate than the two other scenarios (Figure 3-26). For the period of 2080-2099, the increasing rate of six sub-areas ranges from 4.0% (Vo Nhai) to 8.6% (Song Du) in compare with baseline period. The cause can be seen from the change of rainfall and crop evaporation: the maximum increasing rate of rainfall in each sub-area from 3.1% (Thac Rieng) to 4.0% (Cho Chu), while maximum increasing rate of crop evaporation in each sub-area from 10.3% (Thac Rieng) to 12.9% (Dong Hy).

The detail of average annual water demand for irrigation in the Upper Cau River Basin is shown in the Table 3-9. Considering of average change rate of rainfall and potential evaporation in climate change scenarios (2020-2099), average of annual rainfall in whole basin has average increasing rate of 3.7% (A2), 3.4% (B2), and 3.1% (B1); that for crop evaporation is 14.6% (A2), 12.5% (B2), and 12.0% (B1). From that numbers, it is reason why water demand for irrigation increase and the increasing rate are different in three climate change scenarios.

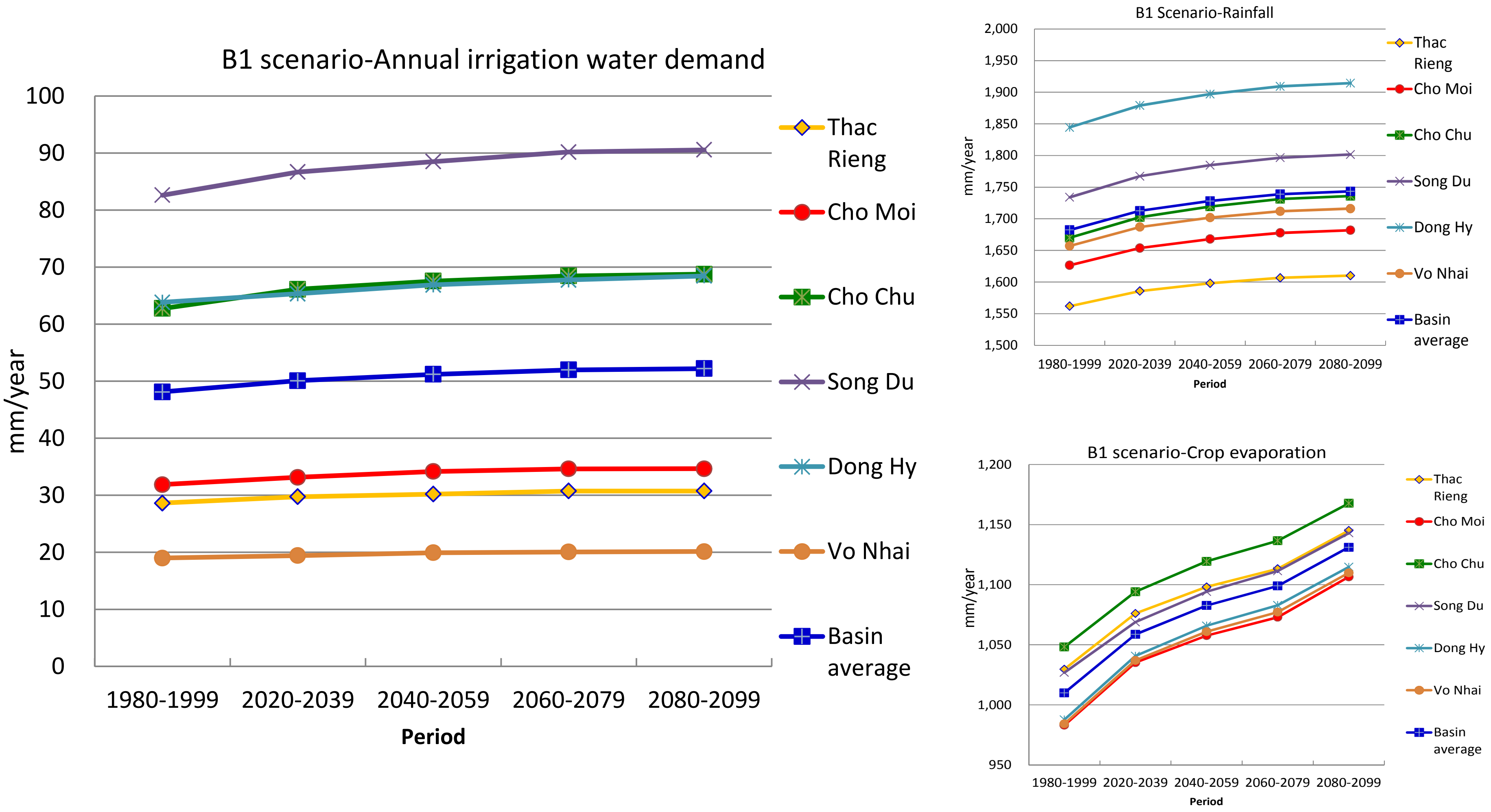


Figure 3-26 Average water demand for irrigation, rainfall and potential evaporation in B1 scenario

Table 3-9 Average annual water demand for irrigation in the Upper Cau River Basin

Sub-Area	Thac Rieng	Cho Moi	Cho Chu	Song Du	Dong Hy	Vo Nhai
Scenario A2 (unit: mm/year)						
1980-1999	28.6	31.9	62.8	82.6	63.8	19.0
2020-2039	29.7	33.1	65.9	86.4	65.1	19.4
2040-2059	30.2	34.3	67.6	88.9	67.2	19.9
2060-2079	31.2	35.4	69.5	92.1	69.3	20.6
2080-2099	32.1	36.1	71.9	95.5	71.5	21.4
Scenario B2 (unit: mm/year)						
1980-1999	28.6	31.9	62.8	82.6	63.8	19.0
2020-2039	29.7	33.1	66.0	86.6	65.5	19.5
2040-2059	30.3	34.4	67.7	88.9	67.5	19.9
2060-2079	31.1	35.2	69.4	91.5	68.9	20.4
2080-2099	31.6	35.6	70.9	93.6	70.3	20.8
Scenario B1 (unit: mm/year)						
1980-1999	28.6	31.9	62.8	82.6	63.8	19.0
2020-2039	29.8	33.2	66.1	86.7	65.3	19.4
2040-2059	30.2	34.2	67.6	88.5	66.9	19.9
2060-2079	30.8	34.6	68.5	90.2	67.8	20.1
2080-2099	30.8	34.7	68.8	90.6	68.5	20.1

b. Dry season irrigation water demand

In Vietnam, dry season lasts 7 to 8 months, from November to April next year. In similar manner with annual demand, the trend of irrigation water requirement in dry season shows an upward tendency in all six sub-areas in the Upper Cau River basin for all 3 scenarios of climate change. In dry season, the decline of rainfall and intensive evaporation lead to the lack of irrigation water. Therefore, the water requirement in dry season is high and accounts for a large portion of annual water demand.

Figure 3-27 to Figure 3-29 show the highest water demand in A2 scenario and lowest need of water in B1 scenario. From these figures, the demand in dry season is also varied among different areas and ranked from the lowest to highest as Vo Nhai, Cho Moi, Thac Rieng, Cho Chu, Dong Hy and Song Du. In Song Du sub-area, the dry season water demand increases by 19.3 % for A2, 16.2 % for B2, and 11.9% for B1 throughout the periods and reaches the highest rate of about 51.8 mm/dry season at last period (A2). In the contrast, the water is required at lowest rate of about 9.8 mm/dry season at last period (A2) in Vo Nhai but the trends are still accounted for a considerable rise of 20.2 % for A2, 14.5 % for B2 and 8.0 % for B1. Other sub-areas are listed in the middle rate of dry season's water requirement. In Cho Moi, the increases in water demand are 19.4 % for A2, 17.3% for B2 and 13.0% for B1. In Thac Rieng, the increase rates are 16.6 % for A2, 12.8 % for B2 and 9.9 % for B1 scenario. Water demand in Cho Chu is estimated as an upward trend by 18.7 %, 16.0 % and 11.9 % for A2, B2 and B1 respectively. Dong Hy's water demand also goes up with the rates of 13.8 %, 11.6 %, and 8.5 % for A2, B2 and B1.

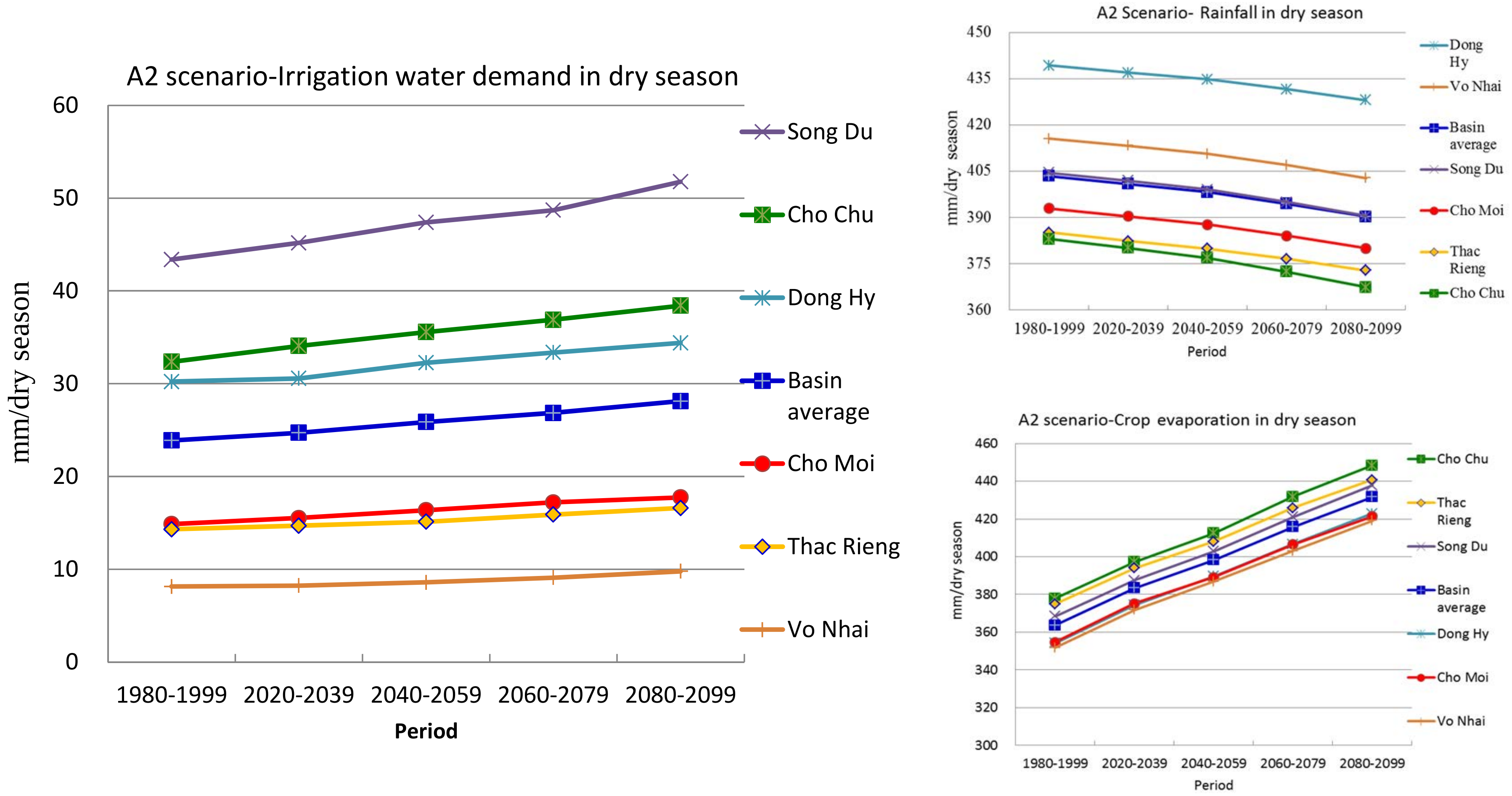


Figure 3-27 Average water demand for irrigation, rainfall and potential evaporation in A2 scenario in dry season

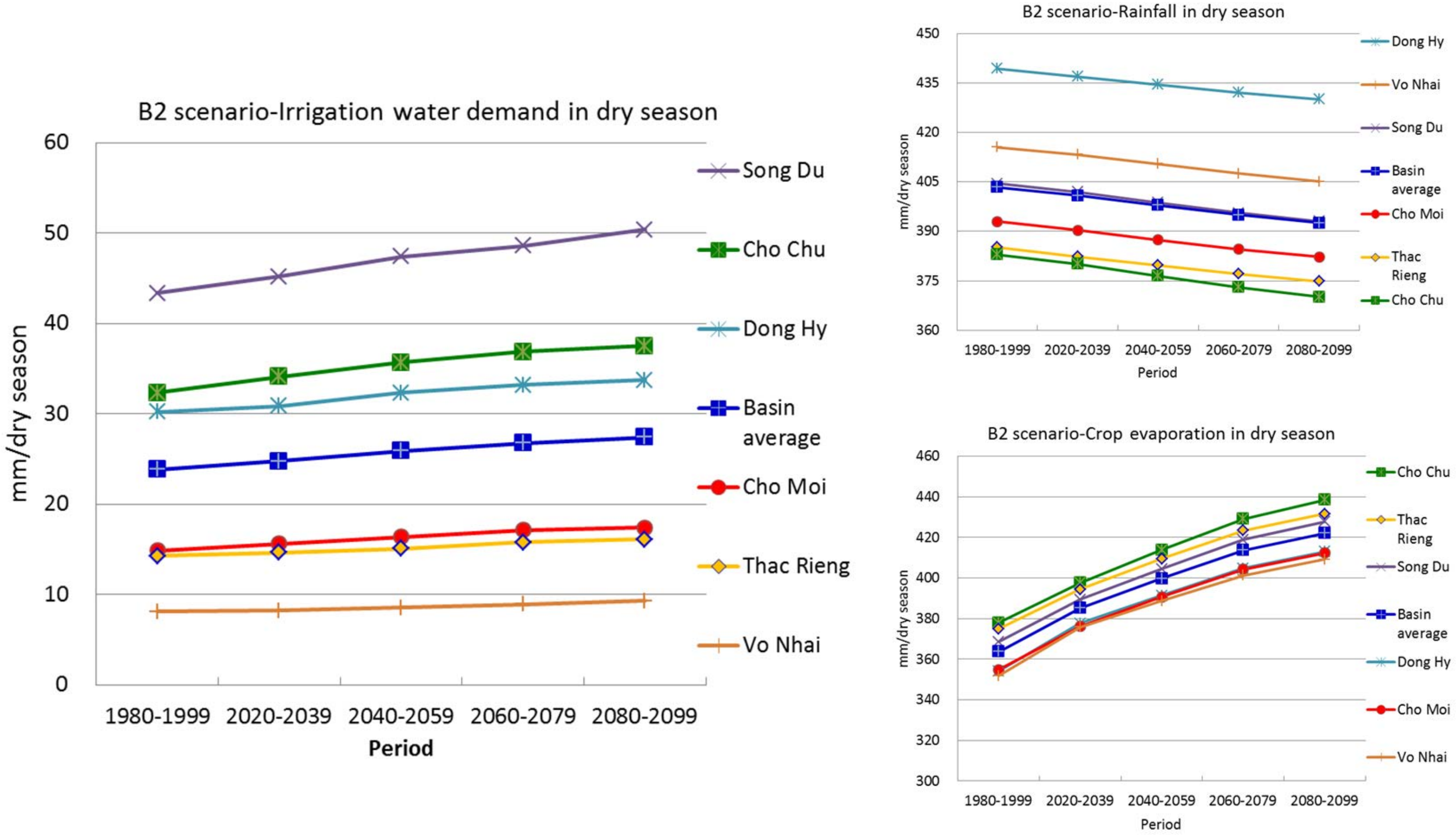


Figure 3-28 Average water demand for irrigation, rainfall and potential evaporation in B2 scenario in dry season

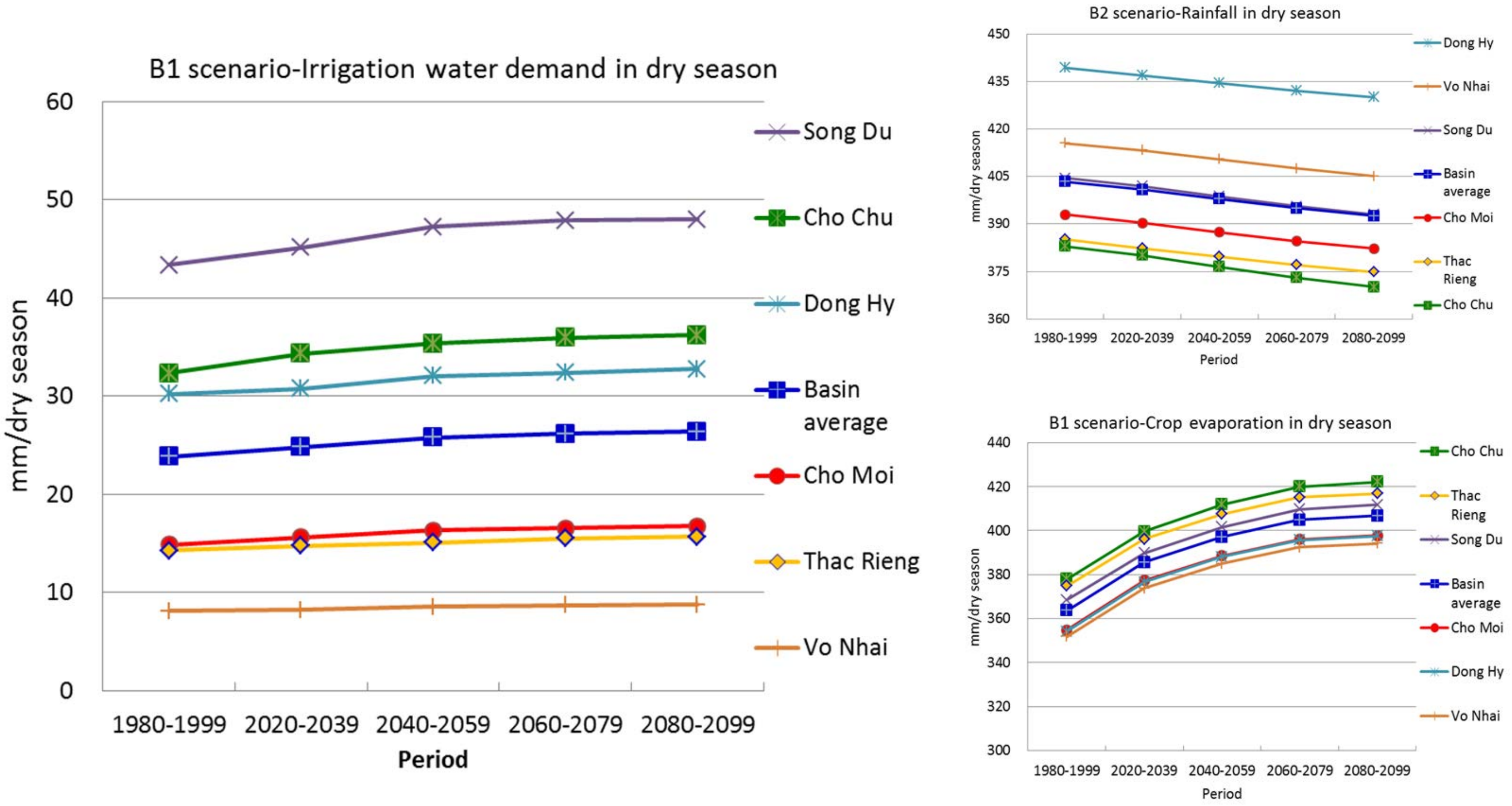


Figure 3-29 Average water demand for irrigation, rainfall and potential evaporation in B1 scenario in dry season

c. Rainy season irrigation water demand

In rainy season from May to October, the trend for water demand is also illustrated as upward lines for all three climate change scenarios. According to Figure 3-30 to Figure 3-32, the greatest demand of irrigation water is found in A2 scenario while the smallest need of water is in B1 scenario. From these figures, the demand in rainy season is also varied among different sub-areas and ranked from the lowest to highest as Vo Nhai, Thac Rieng, Cho Moi,Cho Chu, Dong Hy and Song Du.

In rainy season, the high emission A2 scenario is also the worst case of water shortage. Over the periods, water demand in this case rises by 6% at Vo Nhai, 7% at Thac Rieng, 8% at Cho Moi, 10% at Dong Hy and Cho Chu and 11% at Song Du.

There is also a rising trend of the water demand of medium emission B2 scenario in rainy season by 5% at Vo Nhai, 6% at Cho Moi, 7% at Thac Rieng, 9% at Dong Hy and Cho Chu and 10% at Song Du.

The low emission B1 is recognized as the sustainable scenario with the small increase in rainy season water demand of 4% at Vo Nhai and Thac Rieng, 5% at Cho Moi, 6% at Dong Hy, 7% at Cho Chu and 9% at Song Du.

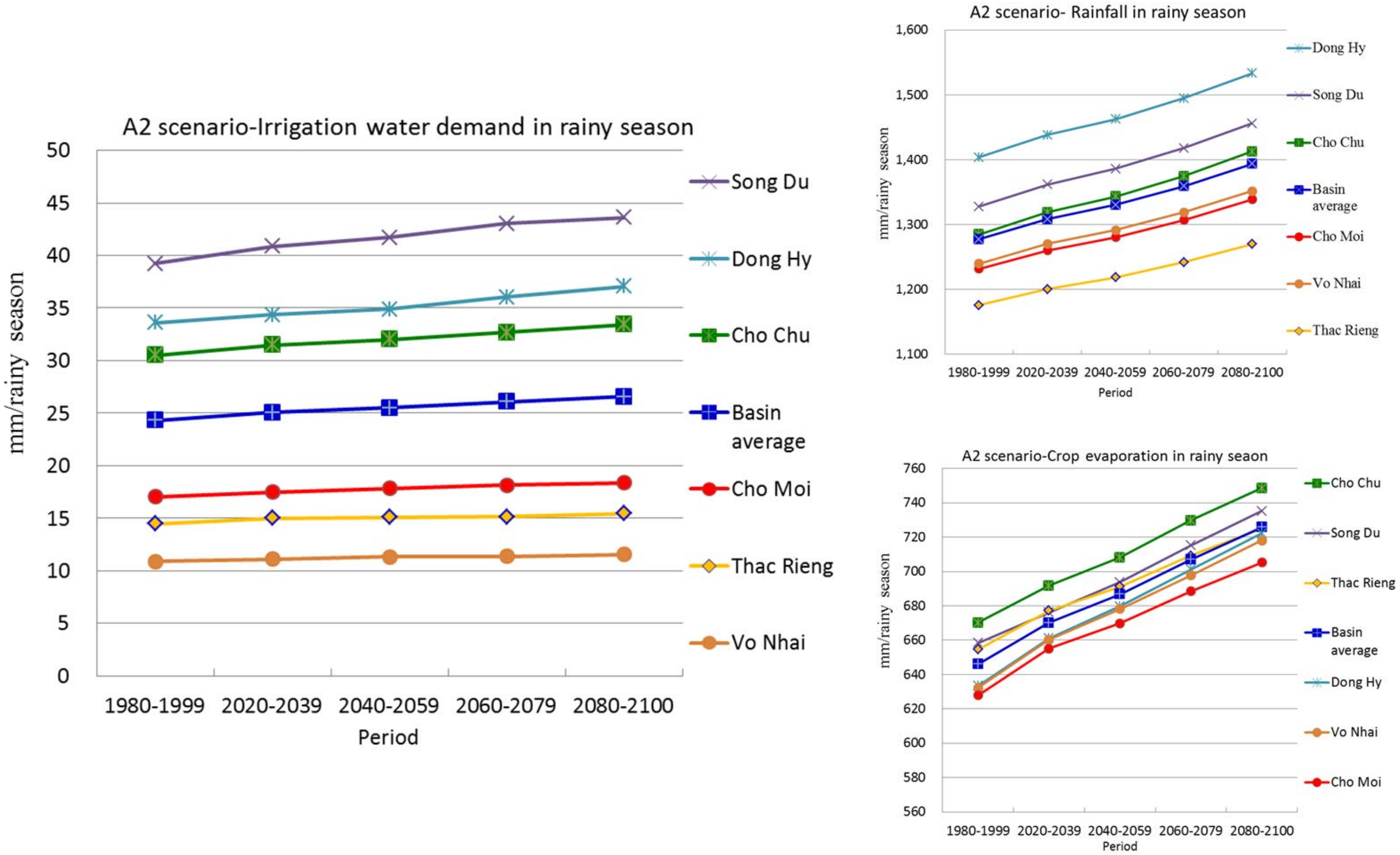


Figure 3-30 Average water demand for irrigation, rainfall and potential evaporation in A2 scenario in rainy season

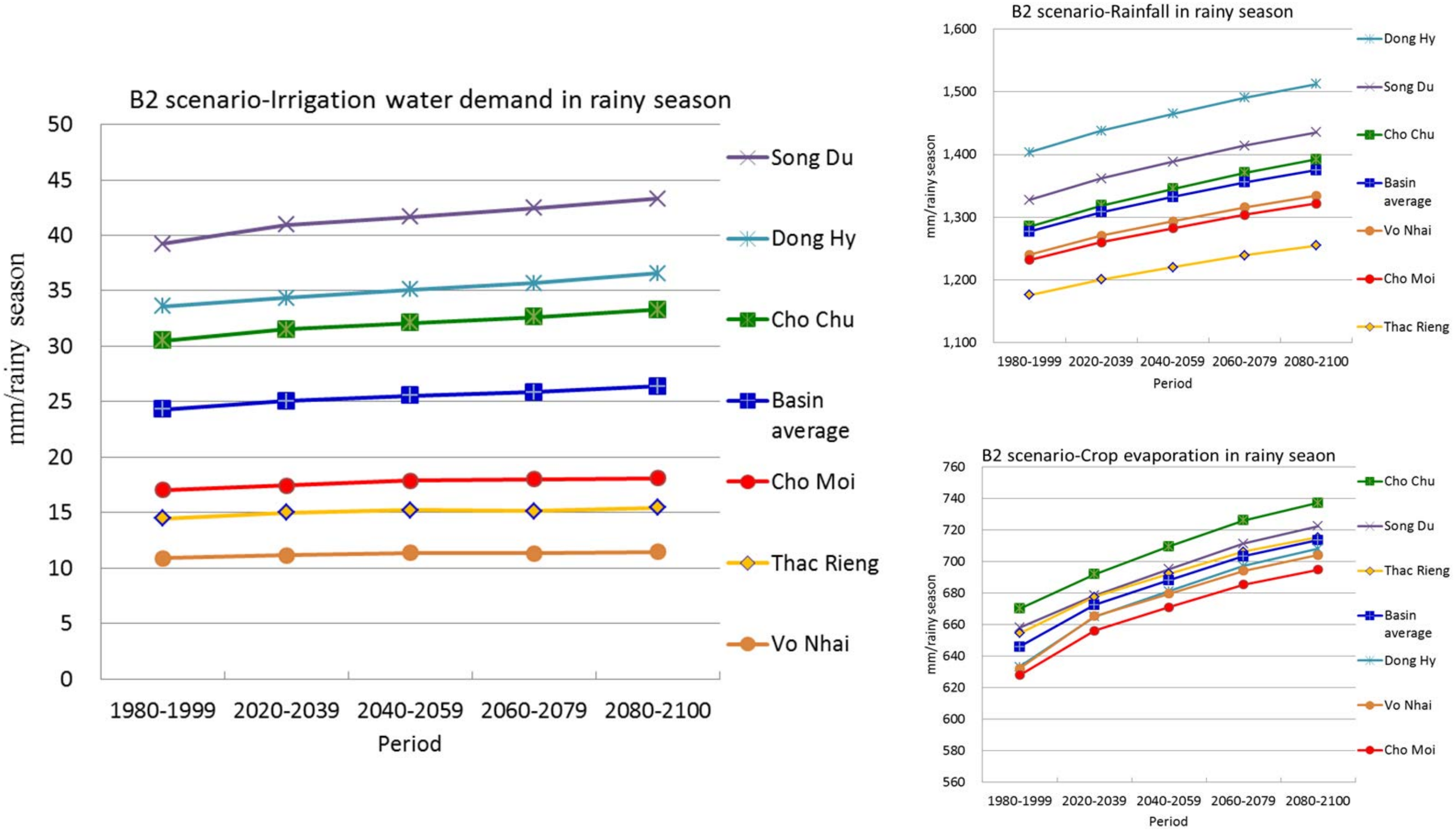


Figure 3-31 Average water demand for irrigation, rainfall and potential evaporation in B2 scenario in rainy season

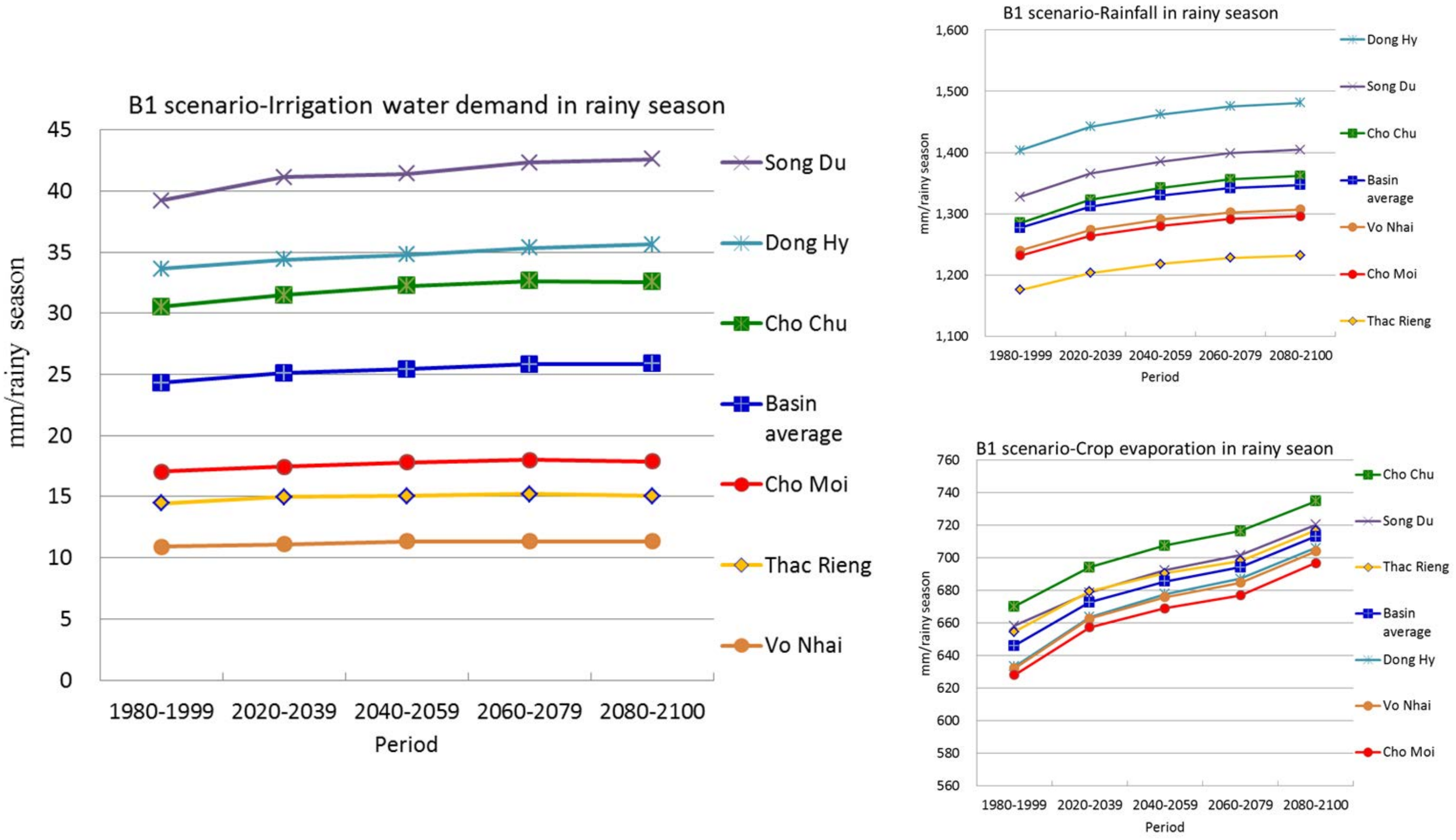


Figure 3-32 Average water demand for irrigation, rainfall and potential evaporation in B1 scenario in rainy season

3.3. The tendency change of water allocation to climate change scenarios

MIKE BASIN model was applied to calculate the balance between water demand and supply water from river. The result from the model is water deficit of each water use sector at each of six sub-areas in the Upper Cau River basin.

In all the three climate change scenarios, water demand for domestic use, industry, and livestock is fully supplied. Water deficit for irrigation happen in four sub-areas (Thac Rieng, Cho Chu, Song Du , and Dong Hy) in all three climate change scenarios. However, water shortage happen only in dry season from October to April, and more concrete that from February to April. The reason of this result comes from distribution of rainfall in year, and the cultivation activities. From February to April, it is the dry season with small total rainfall (Figure 2-4) in compare with other months in rainy season. At that time is also the starting time of rice and maize cultivation (Table 3-8), and these activities require large amount of water. In rainy season, water deficit does not happen, because rainfall is large, and river flow is abundant.

3.3.1. Irrigation water deficit in Thac Rieng sub-area

The total irrigation water deficit in Thac Rieng sub-area is shown in Table 3-10 and Figure 3-33.

Table 3-10 Total irrigation water deficit in Thac Rieng sub-area in climate change scenarios

Period	A2 (10^6m^3/year)	B2 (10^6m^3/year)	B1 (10^6m^3/year)
1980-1999	0.88	0.88	0.88
2020-2039	1.02	1.02	1.02
2040-2059	1.15	1.14	1.12
2060-2079	1.24	1.21	1.18
2080-2099	1.34	1.26	1.21

In the baseline period (1980-1999), shortage of water demand for irrigation in Thac Rieng sub-area is about 0.88 million m^3/year. This average shortage has increasing trend in all three climate change scenarios. In the last period (2080-2099), it rises to 1.34 million m^3/year (A2), 1.26 million m^3/year (B2), and 1.21 million m^3/year (B1). It means that water shortage in A2 grows up to 52% in comparison with that in baseline period. Similarly it is 43% in B2 and 38% in B1 scenario.

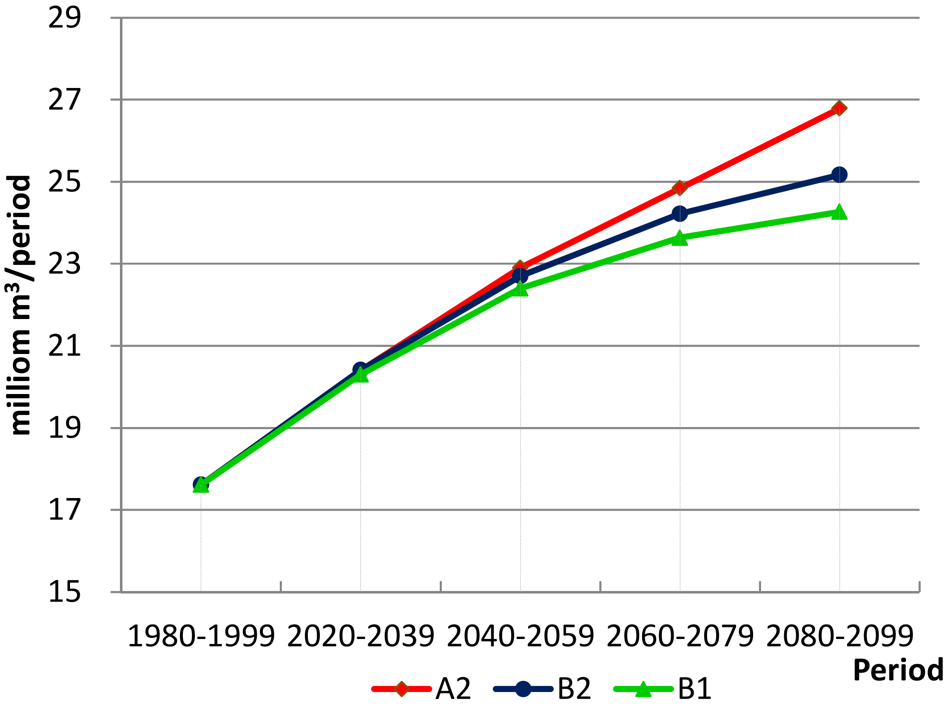


Figure 3-33 Increasing tendency of irrigation water deficit in Thac Rieng sub-area in climate change scenarios

The increasing of water shortage in Thac Rieng sub-area can be explain by the decreasing of river flow in dry season (Figure 3-5, Figure 3-9, Figure 3-13): 7.3% (A2), 6.8% (B2), 5.9% (B1), and the grow up of water demand in this area: 16% (A2), 12.8% (B2), and 9.9% (B1).

3.3.2. Irrigation water deficit in Cho Chu sub-area

The total irrigation water deficit in Cho Chu sub-area is shown in Table 3-11 and Figure 3-34.

In three first periods from 2020 to 2079, the deference of water shortage in three climate change scenarios is very small, expecially from 2020 to 2059; but the deference can be seen clearly in the last period where there is the significant increase of water shortage in A2 scenario (64.1%), and slow increase in B1 scenario (46.5%).

Table 3-11 Total irrigation water deficit in Cho Chu sub-area in climate change scenarios

Period	A2 ($10^6 m^3$/year)	B2 ($10^6 m^3$/year)	B1 ($10^6 m^3$/year)
1980-1999	2.44	2.44	2.44
2020-2039	2.92	2.92	2.90
2040-2059	3.21	3.20	3.20
2060-2079	3.61	3.57	3.38
2080-2099	4.01	3.77	3.58

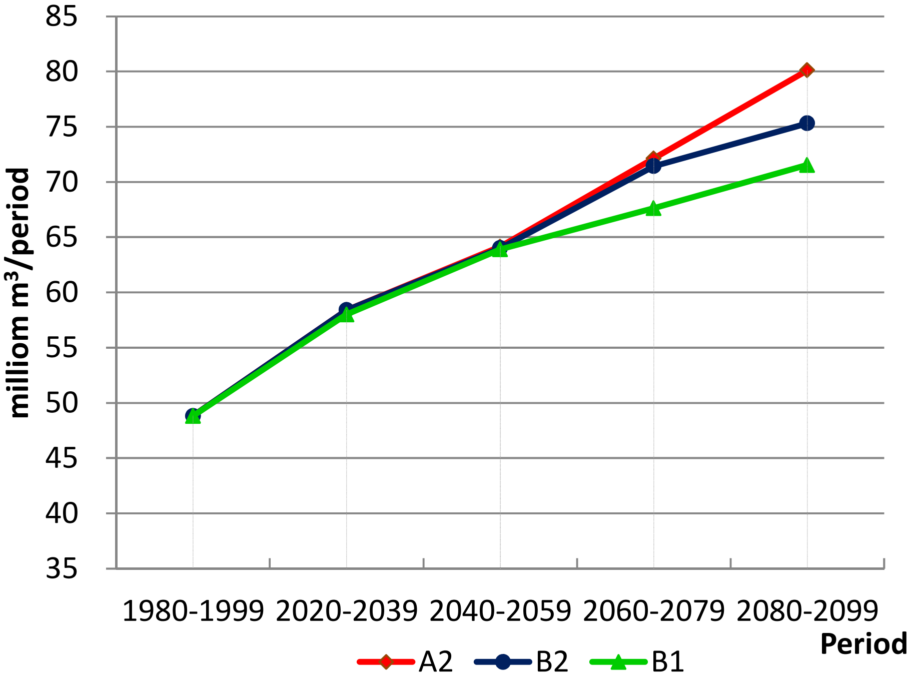


Figure 3-34 Increasing tendency of irrigation water deficit in Cho Chu sub-area in climate change scenarios

In Cho Chu sub-area, water demand in dry season has increasing tendency in all three climate change scenarios: 14.5% (A2), 12.9% (B2), and 9.6% (B1) , while natural flow has decreasing tendency in this season (Figure 3-5, Figure 3-9, Figure 3-13): 3.4% (A2), 3.0% (B2), and 2.5% (B1). The result of these change is the rising trend of water deficit in the sub-area.

3.3.3. Irrigation water deficit in Song Du sub-area

The total irrigation water deficit in Song Du sub-area is shown in Table 3-12 and Figure 3-35.

Song Du sub-area has largest cultivation area of rice and maize in the Upper Cau River basin, and the area also has highest water deficit in comparison with other sub-areas. Average water deficit in baseline period is 6.3 million m^3/year. This number increases after each period of climate change scenarios and reach the highest value in the last period in each scenario. In the last period (2080-2099), the average water shortage in the sub-area is 9.5 million m^3/year (A2), 9.0 million m^3/year (B2), and 8.5 million m^3/year (B1).

Table 3-12 Total irrigation water deficit in Song Du sub-area in climate change scenarios

Period	A2 ($10^6 m^3$/year)	B2 ($10^6 m^3$/year)	B1 ($10^6 m^3$/year)
1980-1999	6.28	6.28	6.28
2020-2039	7.42	7.39	7.38
2040-2059	7.94	7.90	7.90
2060-2079	8.69	8.57	8.27
2080-2099	9.49	8.99	8.45

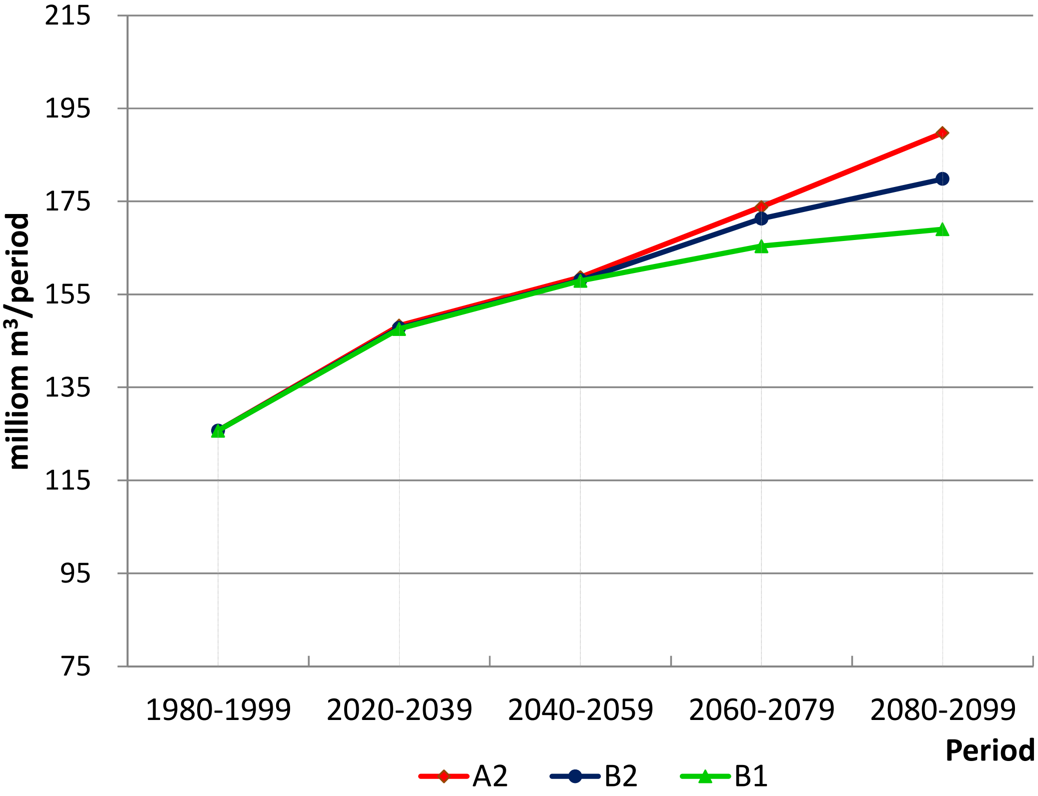


Figure 3-35 Increasing tendency of irrigation water deficit in Song Du sub-area in climate change scenarios

In Song Du sub-area, water demand in dry season has increasing tendency in all three climate change scenarios: 19.3% (A2), 16.2% (B2), and 10.6% (B1) , while natural flow has decreasing tendency in this season (Figure 3-5, Figure 3-9, Figure 3-13): 3.4% (A2), 3.0% (B2), and 2.5% (B1). The result of these change is the rising trend of water deficit in the sub-area. In addition, Song Du sub-area has largest cultivation areas of rice and maize in the Upper Cau River basin, thus water demand for irrigation in this area is highest. The result is huge amount of water deficit in this sub-area.

3.3.4. Irrigation water deficit in Dong Hy sub-area

The total irrigation water deficit in Cho Chu sub-area is shown in Table 3-13and Figure 3-36.

Dong Hy sub-area has the second largest cultivation area of rice and maize (2,202 ha winter-spring rice, 3,836 ha summer-autumn rice and 1639 ha maize), but its water shortage is small: average 0.22 million m^3/year in baseline period), and highest is 0.66 million m^3/year (in the last period of A2 scenario). It can be explained from the geography of Dong Hy sub-area. This sub-area located in the downstream of the Upper Cau River basin with water contribution of Cau River, Nghinh Tuong River and Du River. Therefore, this sub-area has more abundant water sources than other sub-areas. Morever, Dong Hy area is also located in the high rainfall area (with average around 2,000 mm/year (1980-1999)).

The increasing of water shortage in Dong Hy sub-area can be explain by the grow up of water demand in this area: 13.8% (A2), 11.6% (B2), and 8.5% (B1), and the decreasing of river flow in dry season (Figure 3-5, Figure 3-9, Figure 3-13): 7.3% (A2), 6.8% (B2), 5.9% (B1). However, although Dong Hy rank the second largest for cultivation area, the water deficit are small. That result come from located position of the sub-area: Dong Hy sub-area located in high rainfall region (Figure 2-30), and in the downstream of the Upper Cau River basin where collects water from upstream and other branches (Du river, Cho Chu river, Nghinh Tuong river). Therefore, water in this sub-area is abundant.

Table 3-13 Total irrigation water deficit in Dong Hy sub-area in climate change scenarios

Period	A2 ($10^6 m^3$/year)	B2 ($10^6 m^3$/year)	B1 ($10^6 m^3$/year)
1980-1999	0.22	0.22	0.22
2020-2039	0.32	0.31	0.31
2040-2059	0.43	0.43	0.41
2060-2079	0.55	0.53	0.48
2080-2099	0.66	0.59	0.53

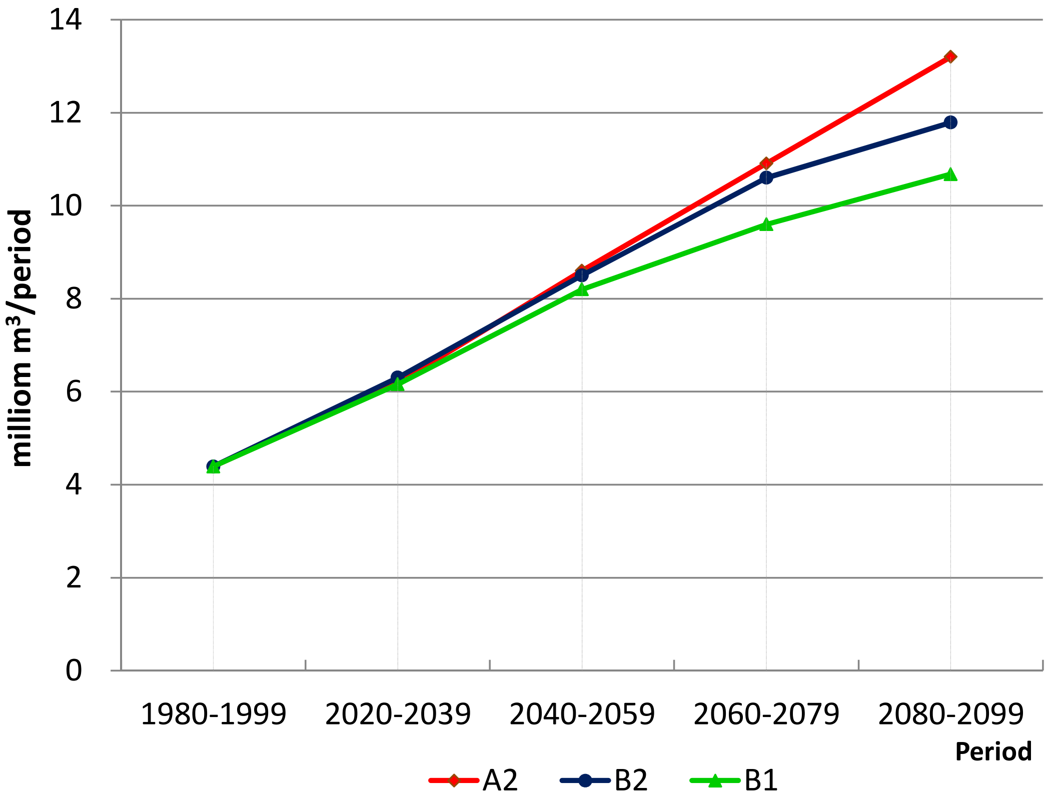


Figure 3-36 Increasing tendency of irrigation water deficit in Dong Hy sub-area in climate change scenarios

Chapter 4 Conclusions

The Cau River basin which is an important river in The Thai Binh river system is one of the large river basins in the North of Vietnam. Total catchment is 6,030 km^2 in area. The Upper Cau River basin with the total area of 308,142 km^2 is located in Bac Can and Thai Nguyen province. The water resources of Cau River Basin is really abundant with high annual rainfall and runoff. Because of uneven distribution of rainfall over time and space, water exploitation and use is truly difficult and challenged. Under the impacts of climate change, rising risk of non-uniform in water distribution appears in the basin. Therefore, the study has investigated into the impacts of 3 climate changes scenarios (high emission A2 scenario, medium emission B2 scenario, low emission B1 scenario) to the water demand for irrigation, river flow, and water allocation within Cau River Basin.

The most important inputs of the study are rainfall and potential evaporation data from climate change scenarios. Rainfall data in climate change scenario were interpolated by the IDW method based on data at 10 rainfall stations (three inside and seven stations outside the basin). Potential evaporation data were interpolated also by the IDW method from four potential evaporation stations. The resolution of the IDW method applied in this study is 5×5 km. In addition to these data, estimates of rainfall at higher mountain region was made by donating relationship between Bac Can station and Cho Don station. The result of interpolated data shows a strong increasing trend of potential evaporation in both rainy season and dry season. The result of rainfall shows increasing trend in rainy season, and decreasing trend in dry season.

In relation to the changes of flow under the climate change context, the discharging vary complicated manner with the increasing trend of annual flow and flows in rainy season, but with decreasing tendency of dry season’s flow. It means that floods occur more frequently with larger amount of discharges in rainy season, while water shortage and drought would be more serious in dry season corresponding to the increasing level of emission from climate change context. However, the change in natural flow is quite small in compare with baseline period: the maximum increasing is 5.9% (A2 scenario) at Thac Rieng station (in Thac Rieng sub-area) in rainy season, maximum decreasing is 7.3% (A2 scenario) at at Thac Rieng station in dry season.

The study assumed that water demand for domestic use, industry, and livestock do not change for the period adopted in climate change scenarios in order to investigate only the effects of climate change. All changes in water demand depend on changes of irrigation requirement. The results of the study show that there is an upward trend in water demand with the increasing magnitude from B1 to B2 and the highest A2. In six water use zones (six sub-areas), Song Du sub-area has the highest water demand for irrigation due to the large area of cultivation and change in rainfall and potential evaporation.

Under the impacts of climate change, the Upper Cau River basin faces rising tendency of water shortage. However, water supply for domestic use, industry, and livestock is always sufficient; water shortage in the basin belongs to irrigation requirement. In the six water use zone, Vo Nhai and Cho Moi sub-area have enough water for every requirements; water shortage happen in the four sub-areas (Thac Rieng, Cho Chu, Song Du, and Dong Hy) with different magnitude. Song Du sub-area has the highest average water deficit about 6.3 million m^3/year in baseline period, and rise to 9.5 million m^3/year in the last period of A2 scenario (2080-2099).

Water shortage happens in dry season when river flow goes down, rainfall is small, and potential evaporation is high. In rainy season when rainfall is high, total rainfall is large, and thus the water shortage was not happen.

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Appendices

A-1. Summary water balance results

The summary results are shown in the table A-2 to A-10. According to the tables, the water deficit was calculated from MIKE BASIN model and from the formula (Water deficit = (*Riir+Rin+Rli+Rdo)-(Qa-Qe)*) are different. The cause of this result can come from basin conditions such as land cover, soil; or the study did not cover enough elements in the basin. This information is very important; therefore it should be solved in the next research. One of recommendation is to compare the parameters as in the table A-1.

A-1 Comparison of calculation results from MIKE BASIN model and the equation

No	MIKE BASIN	This table
Irrigation requirements, *Rirr*		48
Water demand for industry, *Rin*		10
Water demand for livestock, *Rli*		2.8
Water demand for domestic, *Rdo*		3.3
River discharge, *Qa*		932
Environmental Flow, *Qe*		74
Water deficit		**-667.8**

A-2 Annual results of water balance in the Upper Cau River basin in A2 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		1,682	1,784	101.9	6.1
River discharge, *Qa*		806	836	29.5	3.7
	Basin evaporation, *Ea*	932	1,013	80.8	8.7
Irrigation requirements, *Rirr*		48	55	6.6	13.8
	Potential Evaporation	*1,248*	*1,465*	216.9	17.4
	Crop Evaporation	*1,010*	*1,158*	147.7	14.6
	Infiltration	*51*	*51*	0.0	0.0
	Effective rainfall	1,109	1,191	82.1	7.4
Water demand for industry, *Rin*		10	10	0.0	0.0
Water demand for livestock, *Rli*		2.8	2.8	0.0	0.0
Water demand for domestic, *Rdo*		3.3	3.3	0.0	0.0
Water deficit =(*Riir+Rin+Rli+Rdo)-(Qa-Qe)*	From MIKE BASIN	**3.6**	**5.6**	**6.7**	**10.5**
	From formula	**-667.8**	**-690.6**	**-22.9**	**3.4**
Environmental Flow, *Qe*		74	74	0.0	0.0

A-3 Annual results of water balance in the Upper Cau River basin in B2 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		1682	1768	85	5.1
River discharge, *Qa*		806.1	829.4	23	2.9
	Ea	932.2	1002.6	70	7.6
Irrigation requirements, *Rirr*		48.1	53.8	6	11.8
	Potential Evaporation	1248.3	1433.7	185	14.9
	Crop Evaporation	1009.9	1135.9	126	12.5
	Infiltration	***51***	***51***	0	0.0
	Effective rainfall	1108.7	1177.4913	69	6.2
Water demand for industry, *Rin*		10	10	0	0.0
Water demand for livestock, *Rli*		2.8	2.8	0	0.0
Water demand for domestic, *Rdo*		3.3	3.3	0	0.0
Water deficit =*Riir+Rin+Rli+Rdo-(Qa-Qe)*	From MIKE BASIN	**3.6**	**5.3**	6	8.9
	From formula	**-667.8**	**-685.4**	-18	2.6
Environmental Flow, *Qe*		74	74	0	0.0

A-4 Annual results of water balance in the Upper Cau River basin in B1 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		1682	1743	61	3.6
River discharge, *Qa*		806.1	819.1	13	1.6
	Ea	932.2	988.2	56	6.0
Irrigation requirements, *Rirr*		48.1	52.2	4	8.5
	Potential Evaporation	1248.3	1389.1	141	11.3
	Crop Evaporation	1009.9	1131.2	121	12.0
	Infiltration	51.0	51.0	0	0.0
	Effective rainfall	1108.7	1157.7	49	4.4
Water demand for industry, *Rin*		9.8	9.8	0	0.0
Water demand for livestock, *Rli*		2.8	2.8	0	0.0
Water demand for domestic, *Rdo*		3.3	3.3	0	0.0
Water deficit =*Riir+Rin+Rli+Rdo-(Qa-Qe)*	From MIKE BASIN	3.6	5.0	4	6.4
	From formula	-667.8	-676.7	-9	1
Environmental Flow, *Qe*		74	74	0	0.0

A-5 Rainy season results of water balance in the Upper Cau River basin in A2 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		1,277	1,394	117.0	9.2
River discharge, *Qa*		1,270	1,340	70.0	5.5
	Ea (for NAM model)	629	703	74.0	11.8
Irrigation requirements, *Rirr*		24	27	2.3	9.5
	Potential Evaporation	682	770	88.0	12.9
	Crop Evaporation	646	726	80.0	12.4
	Infiltration	21	21	0	0
	Effective rainfall	902	995	93.0	10.3
Water demand for industry, *Rin*		4	4	0.0	0.0
Water demand for livestock, *Rli*		1.2	1.2	0.0	0.0
Water demand for domestic, *Rdo*		1.4	1.4	0.0	0.0
Water deficit	From MIKE BASIN	0	0	0.0	0
	From this table	-1,208.5	-1,276.2	-67.7	5.6
Environmental Flow, *Qe*		30.5	30.5	0.0	0.0

A-6 Rainy season results of water balance in the Upper Cau River basin in B2 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		1277	1375	98	7.7
River discharge, *Qa*		1270.0	1326.0	56	4.4
	Ea (for NAM model)	629.0	694.0	65	10.3
Irrigation requirements, *Rirr*		24.3	26.4	2	8.6
	Potential Evaporation	682.0	758.0	76	11.1
	Crop Evaporation	646.0	714	68	10.5
	Infiltration	21	21	0	0
	Effective rainfall	902.0	980	78	8.6
Water demand for industry, *Rin*		4	4	0	0.0
Water demand for livestock, *Rli*		1.2	1.2	0	0.0
Water demand for domestic, *Rdo*		1.4	1.4	0	0.0
Water deficit	From MIKE BASIN	**0**	**0**	0	0
	From this table	**-1,208.5**	**-1,262.4**	-54	4.5
Environmental Flow, *Qe*		30.5	30.5	0	0.0

A-7 Rainy season results of water balance in the Upper Cau River basin in B1 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		1277	1347	70	5.5
River discharge, *Qa*		1270.0	1303.0	33	2.6
	Ea (for NAM model)	629.0	692.0	63	10.0
Irrigation requirements, *Rirr*		24.3	25.8	2	6.2
	Potential Evaporation	682.0	740.0	58	8.5
	Crop Evaporation	646.0	713.0	67	10.4
	Infiltration	21	21	0	0
	Effective rainfall	902.0	958.0	56	6.2
Water demand for industry, *Rin*		4	4	0	0.0
Water demand for livestock, *Rli*		1.2	1.2	0	0.0
Water demand for domestic, *Rdo*		1.4	1.4	0	0.0
Water deficit	From MIKE BASIN	**0**	**0**	0	0
	From this table	**-1,208.5**	**-1,240.0**	-32	3
Environmental Flow, *Qe*		30.5	30.5	0	0.0

A-8 Dry season results of water balance in the Upper Cau River basin in A2 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		403	390	-13.0	-3.2
River discharge, *Qa*		486	470	-16.0	-3.3
	Ea (for NAM model)	325	339	14.0	4.3
Irrigation requirements, *Rirr*		24	28	4.2	17.6
	Potential Evaporation	568	694	126.0	22.2
	Crop Evaporation	364	432	68.0	18.7
	Infiltration	30	30	0.0	0.0
	Effective rainfall	196.0	186.0	-10.0	-5.1
Water demand for industry, *Rin*		6	6	0.0	0.0
Water demand for livestock, *Rli*		1.6	1.6	0.0	0.0
Water demand for domestic, *Rdo*		1.9	1.9	0.0	0.0
Water deficit	From MIKE BASIN	3.6	5.6	2.0	55.6
	From this table	-410.2	-390.0	20.2	-4.9
Environmental Flow, *Qe*		42.7	42.7	0.0	0.0

A-9 Dry season results of water balance in the Upper Cau River basin in B2 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		403	393	-10	-2.5
River discharge, *Qa*		486.0	472.0	-14	-2.9
	Ea (for NAM model)	325.0	338.0	13	4.0
Irrigation requirements, *Rirr*		23.9	27.4	4	14.6
	Potential Evaporation	568.0	676.0	108	19.0
	Crop Evaporation	364.0	422	58	15.9
	Infiltration	30	30	0	0.0
	Effective rainfall	196.0	188	-8	-4.1
Water demand for industry, *Rin*		6	6	0	0.0
Water demand for livestock, *Rli*		1.6	1.6	0	0.0
Water demand for domestic, *Rdo*		1.9	1.9	0	0.0
Water deficit	From MIKE BASIN	3.6	5.3	2	47.2
	From this table	-410.2	-392.7	18	-4.3
Environmental Flow, *Qe*		42.7	42.7	0	0.0

A-10 Dry season results of water balance in the Upper Cau River basin in B1 scenario at Gia Bay station

		1980-1990	2080-2099	Difference	Difference
		mm	mm	mm	%
Rainfall		403	396	403	396
River discharge, *Qa*		486	474	486	474
	Ea (for NAM model)	325	336	325	336
Irrigation requirements, *Rirr*		24	26	24	26
	Potential Evaporation	568	649	568	649
	Crop Evaporation	364	407	364	407
	Infiltration	30	30	30	30
	Effective rainfall	196	189	196	189
Water demand for industry, *Rin*		6	6	6	6
Water demand for livestock, *Rli*		1.6	1.6	1.6	1.6
Water demand for domestic, *Rdo*		1.9	1.9	1.9	1.9
Water deficit	From MIKE BASIN	3.6	5.0	3.6	5.0
	From this table	-410	-396	-410	-396
Environmental Flow, *Qe*		43	43	43	43