Deterministic hydrological modelling for flood risk assessment and climate change in large catchment. Application to Vu Gia Thu Bon catchment, Vietnam

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Thèse dirigée par *Philippe GOURBESVILLE*

soutenue le 11 Septembre 2015

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ABSTRACT

Climate change due to the increase of greenhouse gas emissions is considered to be one of the major challenges to mankind in the 21st century. It will lead to changes in precipitation, atmospheric moisture, increase in evaporation and probably a higher frequency of extreme events. The consequences of these phenomena will have an influence on many aspects of human society. Particularly at river deltas, coastal regions and developing countries, the impacts of climate change to socio-economic development become more serious. So there is a need for a robust and accurate estimation of the variation of natural factors due to climate change, at least in the hydrological cycle and flooding events to provide a strong basis for mitigating the impacts of climate change and to adapt to these challenges.

Vietnam is located in the region of the south East Asia monsoon. As most of the population work in agriculture and inhabitants essentially concentrate at the coastal plain, Vietnam is expected to be one of the countries most heavily affected by the consequences of climate change in the end of 21st century. These challenges urge Vietnam to have suitable policies which help to improve public awareness, as well as capacity to respond to climate change. In order to provide complete insights for local authority to establish better adaptation strategies against the climate change, the PhD thesis focuses on simulating the long term variation of runoff factors for a river system in central Vietnam, the Vu Gia Thu Bon river.

The first part of this study concentrates on constructing a hydrological model which becomes an efficient tool for assessing the variation of stream flow in the future. Due to its advantages, the fully deterministic distributed hydrological model, which is expected to overcome the difficulties in hydrological modelling at large catchment and the lack of data, is chosen for applying in Vu Gia Thu Bon catchment. The model is set up over Vu Gia Thu Bon catchment, approximately 10,350 km^2. This model considers mostly the runoff factors, from surface flow to groundwater flow, from infiltration to evapo-transpiration. This model is calibrated and validated against daily data and monthly data in the period of 1991-2000 and 2001-2010, respectively. The second part is to evaluate the impact of climate factor changes on runoff at the end of the 21st century. For this purpose, 3 climate scenarios (CCSM3.0, MIROC- 3.2, ECHAM 5) for the period 2091-2100 were estimated from the present observations of the period 1991-2000 by using delta change factors obtained from downscaling process. These scenarios were input to the validated hydrological model for determining the runoff in the future. The change tendency is shown by the difference in the present and future peak flow, base flow and return period. In the third part, a hydraulic model has been developed for the flood prone area (1,780 km^2) to map the inundation area corresponding with the previously described streamflow variations. Scale variability of inundation area under the impact of climate change was evaluated to demonstrate the severe consequences of global warming at Vu Gia Thu Bon catchment. Finally, flood and land use maps are analyzed to estimate damages caused by the streamflow increase.

RESUME

Le changement climatique dû à l'augmentation des émissions de gaz à effet de serre est considéré comme l'un des principaux défis pour les êtres humains dans 21$^{\text{ème}}$ siècle. Il conduira à des changements dans les précipitations, l'humidité atmosphérique, augmentation de l'évaporation et probablement augmenter la fréquence des événements extrêmes. Les conséquences de ces phénomènes auront une influence sur de nombreux aspects de la société humaine. Particulièrement à deltas des fleuves, les régions côtières et les pays en développement, les impacts du changement climatique au développement socio-économique sont plus graves. Donc, il y a une nécessité d'avoir une estimation robuste et précise de la variation des facteurs naturels dus au changement climatique, au moins dans les événements de cycle et d'inondation hydrologiques pour fournir une base solide pour atténuer les impacts du changement climatique et s'adapter à ces défis.

Le Vietnam est situé dans la région de la mousson en Asie du Sud. La plupart de la population travaille dans l'agriculture et habitants essentiellement se concentrer à la plaine côtière, le Vietnam est prévu l'un des pays les plus durement touchés par les conséquences du changement climatique à la fin du 21$^{\text{e}}$ siècle. Ces défis exhorter le Vietnam d'avoir une des politiques appropriées qui contribuent à améliorer la sensibilisation du public, ainsi que la capacité à répondre aux changements climatiques. Afin de donner un aperçu complet de l'autorité locale d'établir de meilleures stratégies d'adaptation contre le changement climatique, la thèse accent sur la simulation de la variation à long terme des facteurs de ruissellement pour un système de rivière au Vietnam système fluvial central, Vu Gia Thu Bon.

La première partie de cette étude se concentre pour construire un modèle hydrologique qui est l'outil d'évaluation de la variation de débit d'eau à l'avenir. En raison de ses avantages, le modèle hydrologique distribué totalement déterministe, qui devrait à surmonter les difficultés dans la modélisation hydrologique aux grands bassins versant et aux zones manquée données, est choisi pour appliquer dans Vu Gia Thu Bon bassin versant. Le modèle est mis en place au cours Vu Gia Thu Bon versant, à environ 10,350 km^2. Ce modèle considère la plupart des facteurs de ruissellement, de l'écoulement de surface vers les eaux souterraines flux, de l'infiltration de l'évapo transpiration. Ce modèle est calibré et validé avec les données quotidiennes et les données mensuelles pour la période de 1991-2000 et 2001-2010, respectivement. La deuxième partie est d'évaluer l'impact des changements des facteurs climatiques à ruisseler à la fin du 21^{e} siècle. A cet effet, trois scénarios climatiques (de CCSM3.0, MIROC- 3.2, ECHAM 5) dans la période de 2091 à 2100 ont été calculés sur la base d'observation actuelle de la période de 1991 à 2000 en utilisant les facteurs de changement delta lesquelles l'obtention du processus de régionalisation. Ces scénarios ont été saisis au modèle hydrologique validé pour déterminer la course au large à l'avenir. La tendance de changement est montrée par la différence dans le présent et l'avenir de débit de pointe, le débit de base et la période de retour. En troisième partie, un modèle hydraulique ont été développés pour les inondations zone sujette (1,780 km^{2}) pour cartographier la zone d'inondation correspondant à des variations de flux ci-dessus. Échelle variabilité de zone d'inondation sous l'impact du changement climatique a été évaluée à démontrer des conséquences catastrophiques du réchauffement climatique à Vu Gia Thu Bon bassin versant. En dernière partie, la carte des inondations et de l'utilisation des terres carte sont analysés afin de compter les dommages causant l'augmentation du débit des cours d'eau.

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This thesis is the end of my journey in obtaining my Ph.D. I have not traveled in a vacuum in this journey. This thesis has been kept on track and been seen through to completion with the support and encouragement of numerous people including my well-wishers, my friends, colleagues and various institutions. At the end of my thesis, I would like to thank all those people who made this thesis possible and an unforgettable experience for me. At the end of my thesis, it is a pleasant task to express my thanks to all those who contributed in many ways to the success of this study and made it an unforgettable experience for me.

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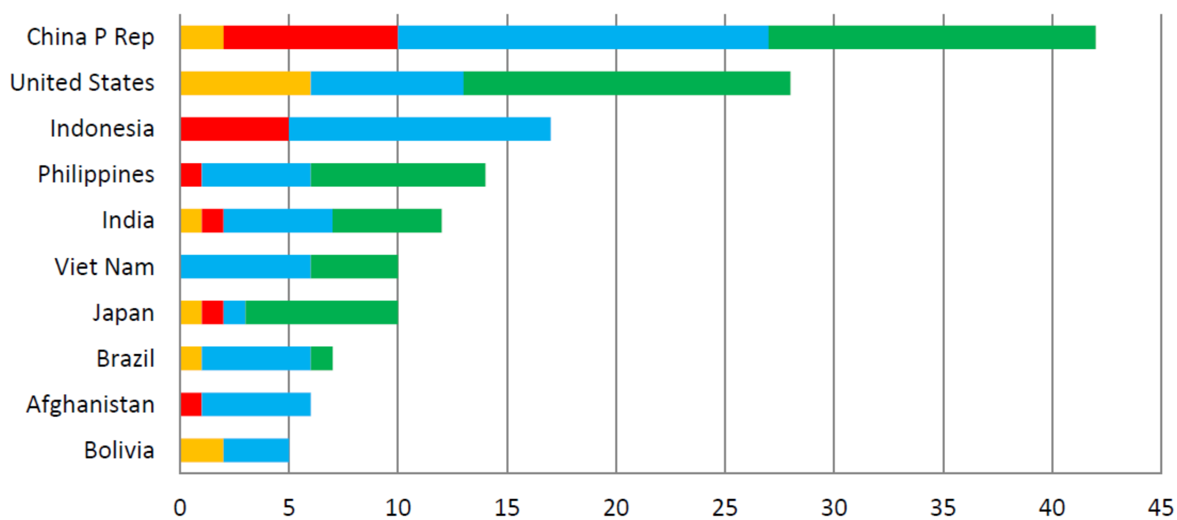
Chapter 1 INTRODUCTION

1.1 Context

The natural environment is obviously the human living space. All components of natural environment such as climate, weather, and natural resource, have an influence on human survival and economic activity (Johnson *et al.*, 1997). However, beside positive effects, the natural environment includes natural hazards, which frequently bring undesirable impacts to human society. In the last decade (2003-2013), there are annually 383 natural disaster events globally, which killed a significant number of people (98,923) and made more than 205.13 million victims. Like other indicators, natural disaster claimed 153.24 billion US$ from worldwide economy (Guha-sapir *et al*., 2013). These figures demonstrate the catastrophic characteristic of natural disasters.



	Bolivia	Afghanistan	Brazil	Japan	Viet Nam	India	Philippines	Indonesia	United States	China P Rep
Climatological	2		1	1		1			6	2
Geophysical		1		1		1	1	5		8
Hydrological	3	5	5	1	6	5	5	12	7	17
Meteorological			1	7	4	5	8		15	15

Figure 1.1 Top 10 counties by number of reported events in 2013(Guha-sapir et al., 2013)

Amongst these natural disasters, disasters related to hydrological factors, such as flood and wet mass movement, have become the most common and destructive. Each year, this kind of natural disaster causes tremendous losses and social disruption worldwide. The following statistics are used to show the damage of extreme flood events during the last century. In 1913 at Ohio, US statewide flooding of rivers killed at least 428 people. In 1953 in spring season, northwest Europe, storm followed by floods devastated North Sea coastal areas, Netherlands hit hardest 1794 dead; In August, 1954 in Teheran, Iran flood rains resulted in some 10,000 deaths; On December, 1959, in Fréjus, France flood caused by collapse of Malpasset Dam left 412 dead. On November, 1970 in Est of Pakistan: 20,099 kill by cyclone-driven tidal wave from bay of Bengal and over 100,000 people missing. During the months of 1971, in Ha Noi, Viet Nam heavy rains flooded the Red river delta, killing 100,000 people. August 1975, an estimated 80,000 to 200,000 people killed by flood and subsequent time in Yangtze River. 1988, heaviest monsoon in 70 years killed more than 1,300. Floods inundated three-fourths of country, leaving 30 million homeless. During the summer of 1997, Central and Northeast China heavy flooding of Yangtze river killed more 3,000 and left 14 million homeless, estimated damages exceeded US$ 20 billion. In the year of 1999, southwest Mexico, heavy rains killed at least 360 people, and on November and December Viet Nam, devastating floods caused US$ 285 million in damage and killed more than 700 people, in the same in northern Venezuela, heavy rains caused catastrophic flooding and mudslide, killing an estimated 5,000 to 20,000 people. On February 2000, Southeast Africa, deadly floods in Mozambique and Zimbabwe, killing more than 700 people and leaving 280,000 homeless, and at least 235 people dead in Thailand, Laos, Viet Nam and Cambodia. The summer of 2002 is registered with more than 2,000 deaths in China, India, Nepal and Bangladesh by flooding. In 2004, flood killed more than 2,000 people in Dominican Republic and Haiti, and 1,800 dead in India, Nepal and Bangladesh. in February 2005, flooding in Afghanistan, India, and Pakistan killed more than 800 people, and July, a record 37 in rain of in a 24 hour period and a week of monsoon rains left 1,000 dead in western India. In 2007, monsoon rain and flooding left 660 people dead. On July 2010, Massive flooding in Pakistan, following two days of record rainfall, kills over 1,600 people. In 2011, Floods caused by Tropical Storm Washi kill 1 268 people in Philippine. And lastly May 2014, Serbia, Bosnia and Herzegovina, the countries are hit with the heaviest rains and flooding in over a century. At least 44 people are killed in the flood. In the 21,610 people killed by natural disaster in 2013, deaths from flood had the largest share (9,819), representing 45.4 % of global disaster mortality. This phenomena have had negative effects on people's lives (32 million deaths) and the world economy which lost around 53.2 billion

US$ over last years Besides the tangible damage, the flood also brings to people the intangible consequences (Markantonis & Meyer, 2011) which are not traded in in a market and are far more difficult to assess in monetary terms. Through the impact above, we might recognize the severe characteristics of flood hazard to human development.

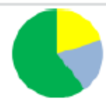
Country	Disaster distribution	No. of deaths	Country	Disaster distribution	Deaths per 100 000
Philippines		7750	St Vincent and the Grenadines		11.89
India		7119	Philippines		7.88
China P Rep		1395	St Lucia		3.29
United Kingdom		772	Solomon Is		1.78
Pakistan		730	Somalia		1.61
Japan		400	Cambodia		1.32
Mexico		223	Bolivia		1.27
United States		212	United Kingdom		1.20
Cambodia		200	Zimbabwe		0.88
Viet Nam		200	South Sudan		0.88

Figure 1.2 Top 10 counties in the terms of disaster mortality in 2013 and distributed by type (Guha-sapir *et al.*, 2013)

Even the destructivity of flood disaster, the people could not eliminate completely the natural negative impacts to human development. It always ask the human to look for the way to adapt well with natural hazard, so it has been proposed to understand as much as possible the substance of these natural phenomenon. Based on these knowledge, we might find out an efficient model as well as mitigate highly the damaging effects. However, these works require lots of human strength as well as social investment.

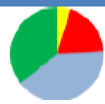
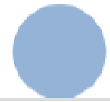
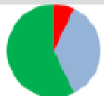
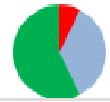
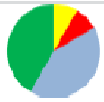
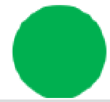
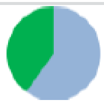
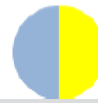
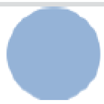
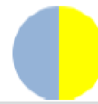
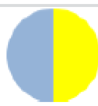
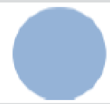
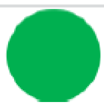
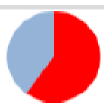
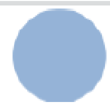
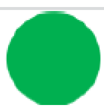
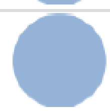
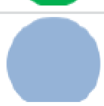
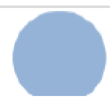
Country	Disaster distribution	No. of victims (millions)	Country	Disaster distribution	Victims / pop. (%)
China P Rep		27.47	St Lucia		93.27
Philippines		25.67	Philippines		26.09
India		16.72	Israel		24.85
Viet Nam		4.13	Zimbabwe		15.62
Thailand		3.52	Namibia		15.00
Zimbabwe		2.21	Czech Rep		12.36
Israel		2.00	Marshall Is		12.13
Pakistan		1.70	St Vincent and the Grenadines		11.98
Bangladesh		1.53	Cambodia		9.91
Cambodia		1.50	Lao P Dem Rep		8.48

Figure 1.3 Top 10 countries by victims in 2013 and distributed by disaster type (Guha-sapir *et al.*, 2013)

Unfortunately, the regions, where have been hugely influenced by flood hazards, are mostly poor and developing countries. The geographical location, meteorological condition, poor infrastructure, the low awareness of people, the lack of governmental policy towards flood disaster are seen as leading factors which have made the flood consequences at these countries become more devastating and more catastrophic. Amongst of the top 10 countries, in terms of disaster mortality in 2013, five countries are classified as low income or low middle income economies. The statistics in 2013 show that Asia is the continent which will affected mostly by natural disasters with around 40.7 % events, 82.3 % of global reported disaster mortality, more than 90.1% of global disaster victims (Guha-sapir *et al.*, 2013). And between 1987 and 1997, 44% of all flood disasters worldwide affected Asia, claiming 228 000 lives, roughly 93% of all flood related deaths worldwide (Bich *et al*., 2011).

Nowadays, Natural movement happens more frequently in an abnormal trend and seems to unfollow the previous rules. These changes come from its interior property as well as the consequences of the impacts of human activities. These negative variations seemly make increasing the destructivity of natural catastrophe towards human being. In recent years, the negative effects of natural disasters are apparently more severe and more catastrophic. The graphs in Figure 1.4 show the dramatic increase of natural disasters in the 3 last decades.

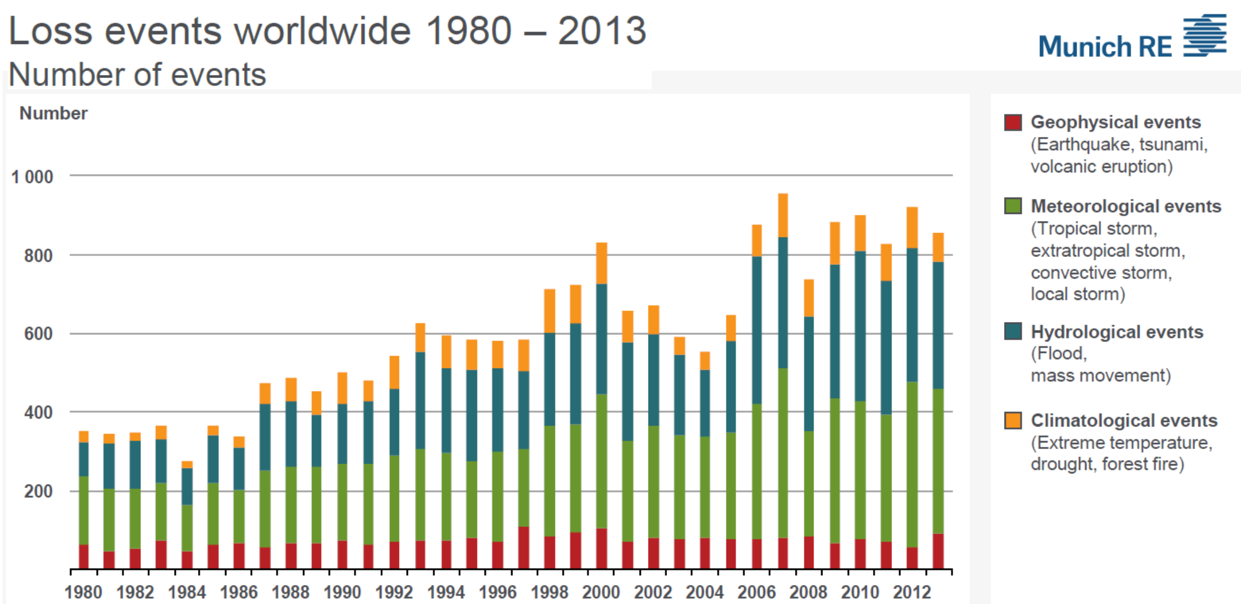


Figure 1.4 Statistics of loss events worldwide 1980 -2013 (http://preventionweb.net/go/36162)

One of suitable explications for these increases is Climate change. This terminology appeared late 1950s (Agrawala, 1998). There are a lot of definitions of this phenomenon but commonly it could be understood as a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any changes in climate over time whether due to natural variability or as a result of human activity (IPCC, 2007). The climate change is related closely with global warming phenomenon caused mostly by the increasing concentration of green gases in the atmosphere (EPA, 2014). Reasons of greenhouse gases emission can be classified in two types, natural variability and human impact. The first type is seen as a normal part of the Earth's natural variability, which is related to the interactions among the atmosphere, ocean, and land, as well as changes in the amount of solar radiation reaching the earth.

The geologic record includes significant evidence for large-scale climate changes in Earth’s past (NOAA National Weather Service, 2007). The natural variability is believed to be a main factor which helps the life exist on the earth. However, in recent years, with the economic development and the industrialization, humans have created a huge influence on global warming, at least in late 1950s, human activities have released large amounts of carbon dioxide and others greenhouses gases into the atmosphere. This leads to the planet warm up so quickly. Climate change is estimated like one of biggest challenges to the human beings due to serious impacts on production, life and environment on a global scale. Higher temperature and sea level rising will cause inundation and water salinity which can bring negative effects to agriculture and high risks to industry and socio-economic systems in the future. This problem has been predicted to continue leading to comprehensive and deep changes in global development and security especially energy, water, food, society, job, diplomacy, culture, economy and trade.

According to the Fourth Assessment Report of the Intergovernmental Committee for Climate Change (IPCC, 2007) (R K Pachauri & Reisinger, 2007) the average surface temperature of the Earth is likely to increase from 1.1 to 6.4°C by the end of the 21st century, relative to 1980-1999, 1.8°C to 4.0°C with the best estimate of IPCC, (2007) also forecasts a global average sea level rise of between 0.18m and 0.59m in the period 2080 to 2099, related to the years 1980 to 1999 (Table 1.2). It will lead to changes in precipitation, atmospheric moisture, increase in evaporation and probably raise the frequency of extreme events. These changes may strongly affect many factors on a global scale. The variation of temperature and rainfall is expected to result in changes in the hydrological cycle. As a result, many areas will be inundated and saltwater intrusion in coastal area will become more serious. Natural disasters such as storms and floods will increase in terms of frequency and severity, which will cause damages in many areas. On the other hand, dry seasons may start earlier and will be more violent (Nguyen et al., 2009) .Based on the estimation of river runoff variability of 1200 catchments on all over the world, Arnell, (2003) predicted that by the 2020s, the change in runoff due to climate change in approximately a third of catchments is less than that due to natural variability by the 2080s this fall to between 10% and 30%. The change leads to runoff increases in high latitudes, east Africa and south and east Asia, and decreases in southern and eastern Europe, western Russia, north Africa and the Middle East, central and southern Africa, much of North America, much of south America, and south and east Asia. The consequences of these phenomenon will have an influence on human society e.g the reduction of agriculture production, increased risk on animals, the destruction of infrastructure, socio-economic damages, enhanced water conflicts, poverty, war... Stern, (2008) shows that the costs of extreme weather alone could reach 0.5% - 1% of world GDP by the middle of the century, and will keep rising as the world continues to warm. In Europe the costs of a 100 year storm event could double by the 2080s with climate change ($50/€40 billion in the future compared with $25/€20 billion today), while average storm losses were estimated to increase by only 16% – 68% over the same period. Economic loss suffered by the Pacific region could range from 2.9% to as high as 12.7% of annual GDP by 2100 (ADB, 2013) .

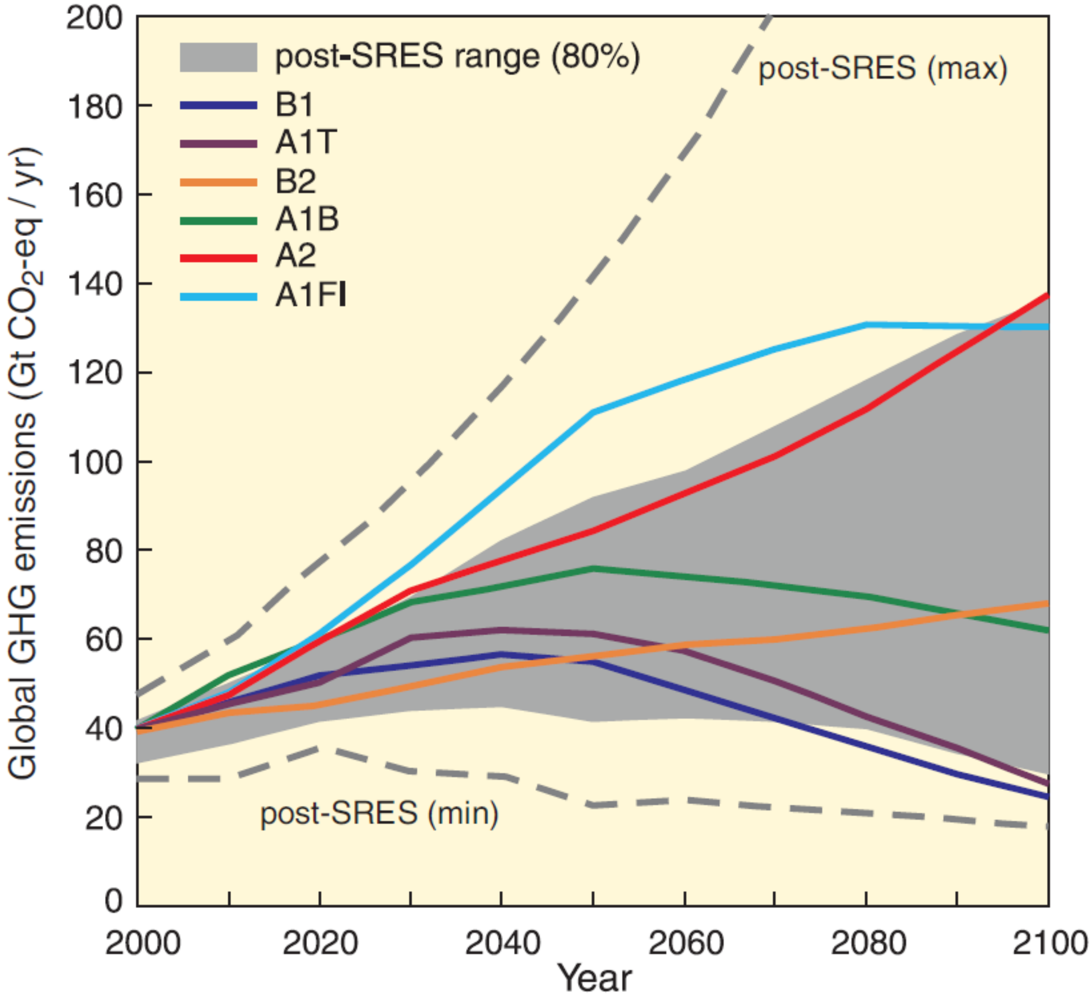


Figure 1.5 Global GHG emissions (in $GtCO_2$-eq per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (colored lines) and 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post- SRES scenarios. The emissions include CO_2, CH_4, N_2O and F-gases. {WGIII 1.3, 3.2, Figure SPM.4} (Barker *et al*., 2007)

Table 1.1. The human and economic losses from disasters of Viet Nam in the period of 1989-2011 (http://www.wpro.who.int/vietnam/topics/emergencies/factsheet/en/#)

Year	Deaths including missing	Injured	People affected	Houses destroyed	Houses damaged	Total estimated damage US$ (1,000)
1989	959	1,359	5,635,000	84,283	5,824	21,000
1990	384	308	510,000	10,614	1,112	725
1991	492	236	316,478	14,989	1,335	57,200
1992	287	33	178,234	7,320	1,445	66,100
1993	270	52	41,520	25,154	13,974	75,000
1994	361	34	393,000	5,917	6,093	253,300
1995	269	51	423,000	9,747	1,288	107,200
1996	1,056	591	1,051,206	74,856	17	751,420
1997	3,692	907	3,697,225	108,749	1,181	887,000
1998	647	97	2,520,665	13,380	17,406	121,900
1999	799	576	7,039,150	52,583	30,495	309,500
2000	592	215	5,027,505	12,198	7,432	291,035
2001	392	95	1,785,895	10,602	13,817	171,900
2002	147	116	2,733,500	75,739	76,914	284,200
2003	148	81	402,946	6,441	9,504	105,000
2004	231	23	535,951	4,766	16,725	38,000
2005	324	31	851,900	3,320	23,037	346,370
2006	579	2,010	2,994,720	75,010	140,855	1,099,000
2007	353	322	1,599,755	13,465	42,081	981,000
2008	411	163	776,330	5,148	9,945	673,500
2009	356	1,006	3,607,820	65,034	170	1,065,200
2010	221	103	1,522,710	6,054	Not available	704,700
2011	76	2	Not available	222	94,465	92,300

Climate change will affect everyone but developing countries will be hit hardest, soonest and have the least capacity to respond. South East Asia is particularly vulnerable to the impacts of climate change with its extensive, heavily populated coastlines, large agricultural sectors and large sections of the population living under $2 or even $1 a day. The study by the ADB on the economics of climate change for South East Asia is the first regional report on the impacts, vulnerabilities, costs, opportunities and policy options for South East Asia, and, on this regional scale, globally. In southeast Asia, this number could reach to 6.7% of annual GDB by 2100 (ADB, 2009). Particularly at river deltas, coastal regions and developing countries, the impacts of climate change to socio-economic development are more serious.

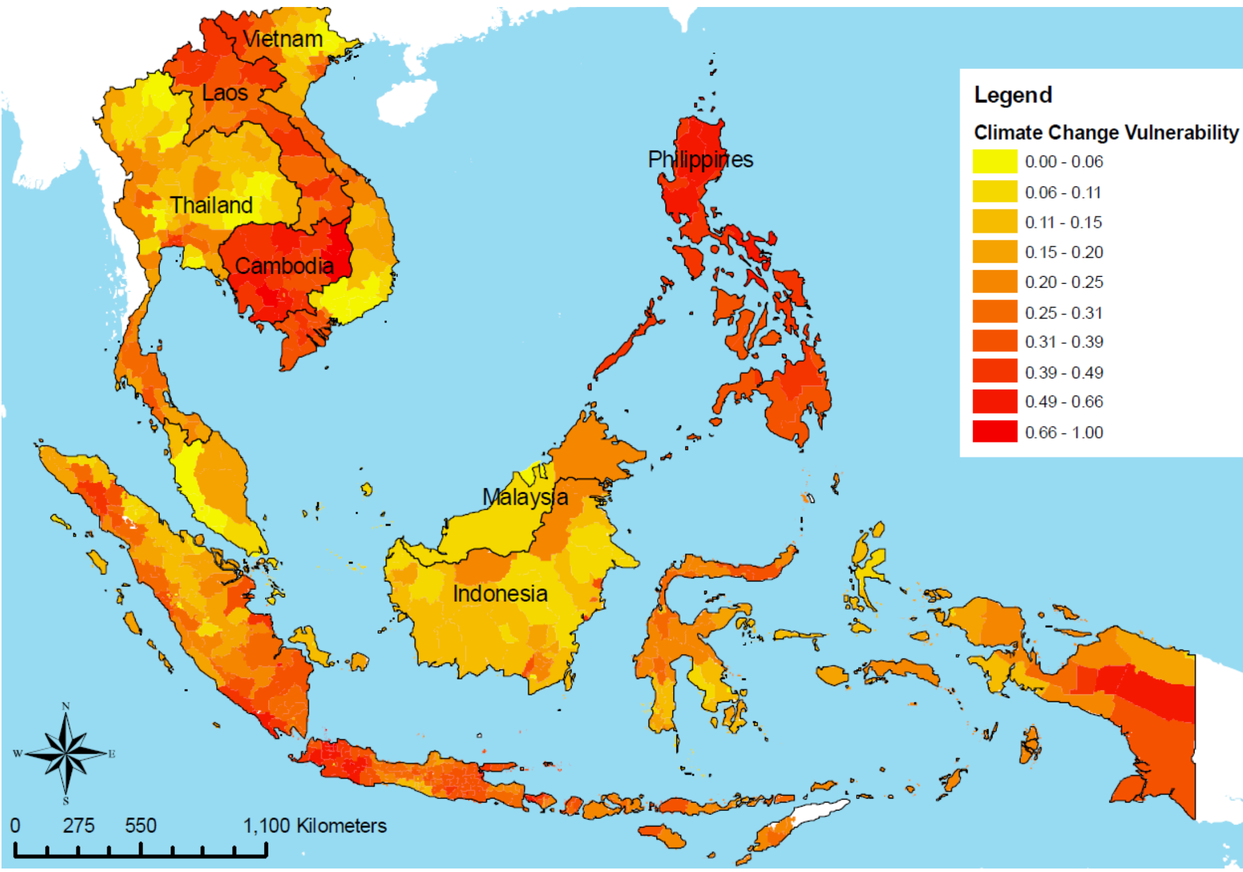


Figure 1.6. Climate change Vulnerability map over Southeast Asia (Economy and Environment Program for Southeast Asia)

It is a very welcome contribution for policymakers, businesses, academics and civil society. It increases the national understanding in each country of the challenge of development in the face of a more hostile climate. It provides important perspectives on the regional interdependencies of climate change impacts and policies and thus can help in the pooling of regional resources to address shared challenges; for example, the development of public goods for adaptation (including new technologies, disaster and risk management and water resource management) in the region. This is particularly important, given that the climate is likely to change significantly in South East Asia in the next 20 or 30 years.

Table 1.2 Projected global average surface warming and sea level rise at the end of the 21st century (Barker et al., 2007).

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:
a) These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity, and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs) as well as observational constraints.
b) Year 2000 constant composition is derived from AOGCMs only.
c) All scenarios above are six SRES marker scenarios. Approximate CO_2-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the WGI TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550ppm, respectively.
d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5°C.

There is a need to have a robust and accurate estimation of variation of natural factors due to climate change, at least in the hydrological cycle and flooding events to provide a strong basis for mitigating the impacts of climate change and adapt to these challenges.

1.2 Challenges in central Vietnam

Vietnam is situated in the region of the south East Asia monsoon, so this country frequently suffers from natural disasters. It is estimated as one of the most disaster-prone countries in the world. The country suffers from many kinds of natural disasters. Like other parts of the world, among the disasters, flood is ranked first in terms of affected areas, severity, frequency and losses it causes to society. In the past, a large inundation in 1945 led to famine for a long period and caused more than two million deaths. In 1964, large floods caused inundation of large areas in Central Vietnam from Quang Binh to Phu Yen. In 1971 the historical largest flood broke down dykes and caused severe inundation in many provinces in Bac Bo plain. Also in Central Vietnam, flood in Ca and La rivers broke down dykes and led to the severe inundation in 1978. A large flood caused inundation in

Vu Gia - Thu Bon, Huong and Tra Khuc rivers in 1999 caused significant losses in human life and property in Da Nang City, and in Thua Thien Hue, Quang Nam, and Quang Ngai provinces. Additionally, Viet Nam is still a developing country with many social economic problems such as the infrastructure is underdeveloped, people’s awareness with natural disasters is still weak. Consequently, Viet Nam is estimated being in the countries which are high vulnerability versus natural disaster. As statistic, during the period 1989-2009, the natural disaster annually killed around 510 people and caused damage of more than 5,175 billion VND.

Moreover, natural disasters in Vietnam are forecasted to increase in term of frequency and intensity in the next year. It will cause serious damages for the country. In addition, with a coastline of around 3,440 Km and most of the population work in agriculture and inhabitants essentially concentrate at the coastal plain, Vietnam is among the countries most heavily affected by the consequences of climate change. In the last report of ADB about the economy of climate change for southeast Asia, this agency projects that Viet Nam is likely to suffer more from climate change than the global average and Viet Nam could suffer a loss equivalent to more than 6% of GDP annually by 2100, more than double the global average loss (ADB, 2013). According to the assessment of Vietnam government, in late 21st century, Vietnam's yearly mean temperature will increase from 2°C to 3°C, the total yearly and seasonal rainfall will increase while the rainfall in dry seasons will decrease, the sea level could rise 0.75m to 1m compared to the 1980-1999 period. About 10% to 12% of Vietnam's population will be directly impacted and country could lose around 10% of GDP (Viet Nam government, 2011). These challenges urge Vietnam to have suitable policies and measures to improve public awareness, as well as capacity to respond to climate change.

Table 1.3: Statistic of disaster damages in Central Vietnam in recent year.
(Source: Flood prevention center in Vietnam central region)

Year	Dead (Persons)	Injured (Persons)	Missing (Persons)	Domicile	Class room	Hospital	Property (Million USD)
1999	737	476	56	1,043,029	6,344	95	350
2004	77	53	33	228,010	635	81	349
2007	47	122	2	32,580	296	68	97.5
2009	303	1,308	9	373,740	7,423	158	1,094

1.3 Aims and objectives of the research

Efforts to aid the local population to strengthen its adaptive competence against natural disasters, also could mitigate the impact of climate change on regional socio economic conditions, this study focuses on the objectives as follows:

1. Construct a hydrological model to simulate the hydrology in Vu Gia Thu Bon catchment which is one of the large catchments located at coastal region of Viet Nam central. The objective is seen as the first and most fundamental to study the hydrological regime of a catchment. For this objective, a model, which could translate as accurately as possible the hydrologic characteristic of the catchment by using mathematic method, is established. The model will be calibrated and validated against observed data to prove the model efficiency. Based on validated model, the modeler can simulate different scenarios corresponding to parameter changes. From the simulated results, modelers could represent historic events and predict the change trend of hydrological factors in study catchment.

2. Assess the long term variation of runoff factors in the Vu Gia Thu Bon river system under the impact of climate change. The second objective concentrates on analyzing the change tendency in the future of runoff factor in the catchment. By applying the statistical laws to predicted run off, the analysis might help to find out the future extreme events. The extreme events are analyzed in this study including flood and drought events which might affect significantly the social economic development of catchment. Besides, the seasonal shift phenomena is also dissected to give a concrete view of change in the future hydrological regime.

3. Realize flood modellings which could present detailed flood maps and scale effects under the effect of climate change.

4. Evaluate the hydrological risks, the impact on hydrological disaster and propose the solution to adapt with the variation of climate.

1.4 Research strategy

Regarding to the hydrological catastrophe, constructing the prevention plan for natural disasters related to climate change requires accurate assessments in this domain. For the moment, most estimations about climate change at global scale, as well as at regional scale are likely to base on scenarios from the Intergovernmental Committee for Climate Change (IPCC – 2007) (Barker *et al*., 2007). From these climate scenarios, the challenge is to derive and generate realistic forecasts for the hydrological processes. This task is challenging and requests many steps before reaching the objective which could be the flood frequency changes in order to improve design and mitigation measures. In the case of large catchments, this analysis is an essential tool for the development of master plans and for the development of a real strategy on land use and economic development. The challenge consists in creating a coherent chain of tools, with a sufficient accuracy, being able to start from the data produced by the Global Circulation Models (GCM) and to generate hydrographs in the analyzed catchment for the new climate conditions.

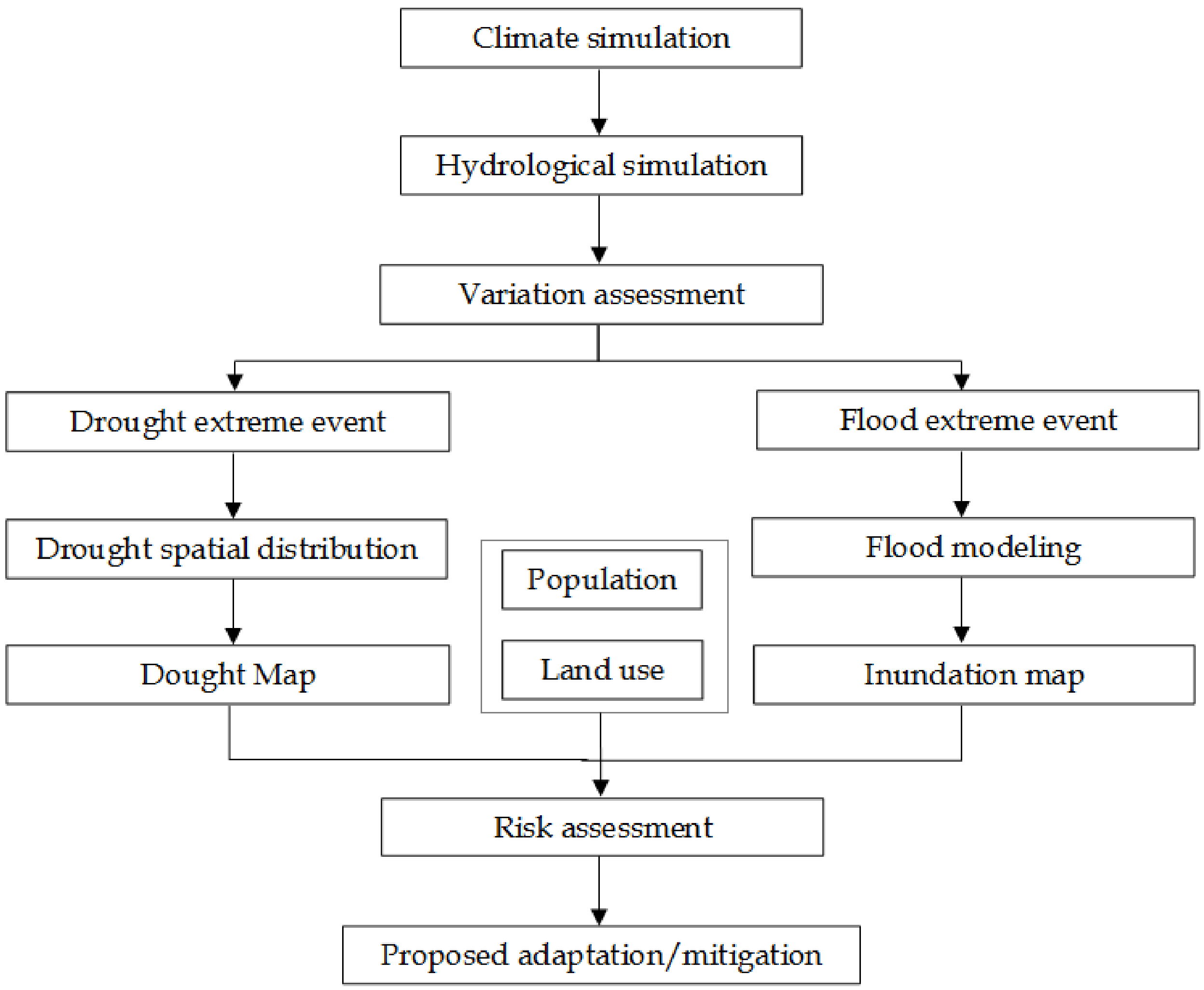


Figure 1.7. Proposed methodology for estimating the impact of climate change.

A research strategy is outlined to complete all study objectives (Figure 1.7). This conceptual strategy is developed referred on a study that was applied successfully to assess the climate change in Europe. However, in this study, it is transformed and completed in order to evaluate overall variations in the hydrological regime in the future at developing countries, particularly to be suitable with this study area. The strategy of Rojas *et al.,* (2013) , which was applied to European countries, mainly focussed on the flood extreme events. Nevertheless, in a developing region like this catchment, the economy depends significantly on agriculture so the drought risk assessment is also important to predict the impact of climate change towards the regional social economic development. Both disasters in this study, flood and drought, are defined based on the results of hydrological simulation by using different statistical law.

The proposed approach could be then formulated as follow:

- GCM produces data according to different climate scenarios;
- The data are transformed through downscaling methods in order to fit with the catchment size and the requested scale for hydrological analysis;
- A deterministic distributed hydrological model, validated under actual climate conditions, is then used for future climate simulation;
- The new simulated flood and drought events are analyzed and compared with the frequencies observed for the actual conditions;
- The differences between actual and future conditions allow assessing the potential impact of climate change.

The added value of this approach is on the use of a deterministic distributed hydrological model which offers the possibility to asses in an accurate way the consequences of future conditions. The main hypothesis, that could be easily accepted, is that the hydrological processes simulated under the actual climate will keep a similar dynamic in the future.

1.5 Structure of the thesis

In order to concretize the research strategy shown in Figure 1.7, the thesis is organized in six chapters which roughly adhere to the principal objectives

Chapter 1 introduces the context of natural disasters, flood risk and climate change, in global and Viet Nam scale. The chapter also presents the objectives of research and suggested solutions to accomplish these objectives. Chapter 2 describes generally the Vu Gia Thu Bon catchment, the hydrological characteristic and data situation in this model. This part also includes the analysis related to the uncertainty of the lack of data when doing this study. Chapter 3 and chapter 4 aim to prepare necessary tools for modeling the impact of climate change to stream flow and flood plain in Vu Gia Thu Bon catchment. In those chapters, chapter 3 is presumed as the focus to solve the first objective of thesis. This chapter concentrates on establishing a perfected hydrological model that could describe much as much possible the hydrological regime in the study area. In this chapter, the hydrological process will be presented broadly to serve for this purpose. It also compares the efficiency of each kind of model to choose the best one for simulating the hydrological process. The selected model – deterministic distributed model will be dissected more details about the mathematical algorithm and its components, and analyzed the data requirement and the uncertainty. Chapter 4 focuses on the flood modeling. It will also compare to choose the best model for flood modeling, the coupling 2D/1D model. Model component, data requirement and the uncertainty are also analyzed for this kind of model. Chapter 5 will present the methodology to simulate the impact of climate change to this catchment. This will sketch several points about Global Circulation Model, Regional Circulation Model and explain why we need to apply the downscaling step for the climate data. The part also defines the climate scenarios which will be applied for estimating the change in the future. These scenarios will be input in validated hydrological model to evaluate the change in the future. The future stream flow will be analyzed by using several statistical laws to find out the extreme events, as flood and drought events. The run off variations will be put in flood model to present the change in flood plain. Based on these changes, flood and drought risks are determined by overlapping with the land use and population distribution. From these risks, the basic adaptation and mitigation will be proposed. Chapter 6 will summary the principal conclusion of the study, highlight the contribution of the research and suggest recommendations for further study.

Chapter 2 THE VU GIA THU BON CATCHMENT

The chapter describes generally the Vu Gia Thu Bon catchment. It also provides the Meteo-hydrological characteristic, social economy and natural disaster of the catchment. The chapter as well communicates the challenge of local people towards natural phenomena at present and in the future. Difficulties in simulating the hydrological cycle of this catchment are likewise discussed in this chapter to find out the best solution for these problems.

2.1 General

The Vu Gia Thu Bon is a large river system in central region of Viet Nam which originates on the eastern side of the Truong Son mountain range and drains to the ocean near the cities of Da Nang and Hoi An (Figure 2.1). The river basin covers 10,350 km^2 and extends from 14°90´to 16°20´N and from 107°20´to 108°70´E. The basin surrounded by Cu De basin to the north; Laos to the west; Tra Bong Basin (part of the Se San Basin) to the south; Tam Ky basin to the east and eastern sea. (RETA 6470, 2011).

This system has two main rivers, i.e., the Vu Gia and Thu Bon rivers that flow through many complex topographies, the relatively narrow mountainous area with a maximum elevation of 2,600 m at Ngoc Linh mountain that features a large number of steep tributaries, and the flat coastal zone at downstream prone to annual flooding consisting of a complex interconnected coastal river system.

Due to mountainous and hilly area accounts for a large area of over 60% of the total area, the Vu Gia Thu Bon river basin lies at elevation of 552m and has an average slope of 25%. The river and stream network, which is typical for this region in mountainous areas, is really complex. However, due to its geological structure, the horizontal dissection of the basin is not much thus its river and stream network is undeveloped with the river density of 0.47km/km^2. The upper of the basin has a slope of over 30%; due to it consists of granite slopes and sharp mountain peaks, the river and stream network can be expanded in low areas and constant flows are not seen in the mountain slopes, the average density of rivers is 0.38km/km^2. In the downstream area, the rivers flow within coastal low-lying plains where are composed of sandy and red soils so the rivers run tenuously, with the density of 0.57km/km^2. The river network in the basin has tributaries grade IV and its 78 tributaries with the main stem of over 10 km are divided into 4 grade: 19 – graded I, 360-grade II, 22-grade III and 2-grade IV (Vu *et al*., 2011).

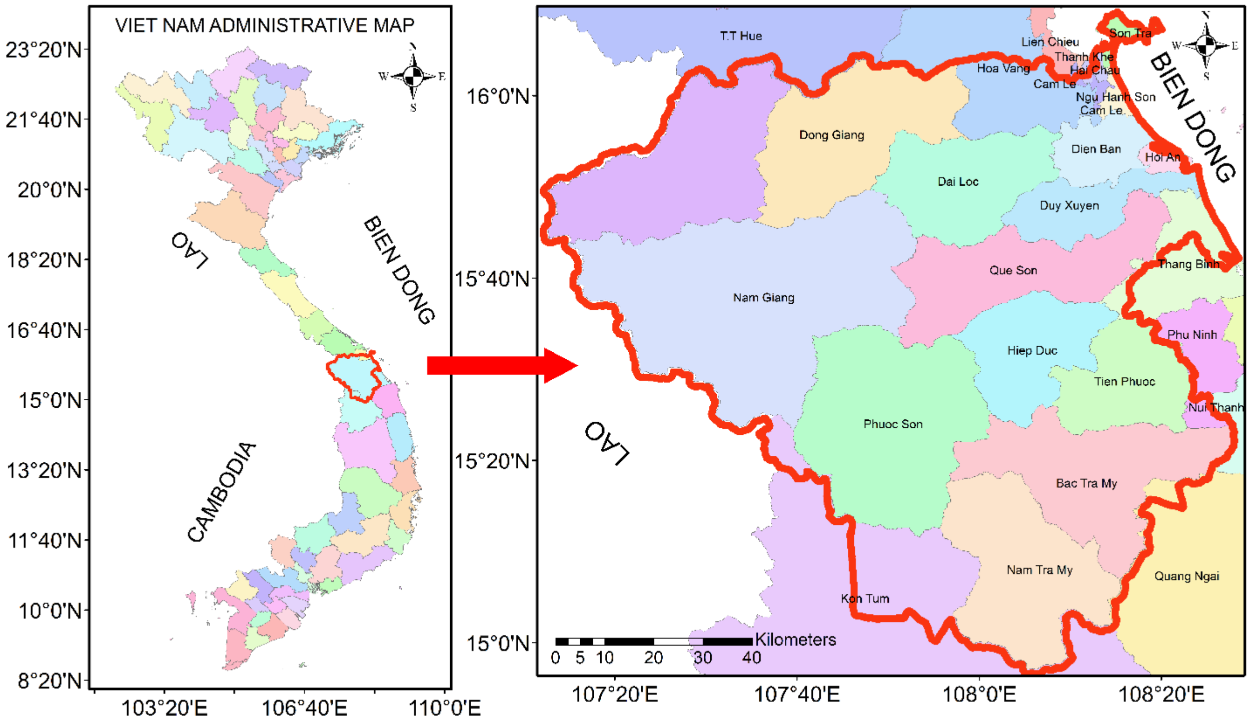


Figure 2.1 Vu Gia - Thu Bon catchment.

2.2 Hydro meteorological characteristics.

The system locates at a tropical monsoon climate region where weather phenomena, rain and storm happen so complicatedly. The region's climate divides clearly into two seasons, warm winters, dry summers affected by dry westerly winds and a strong monsoon impacted rainy season with typhoons. The climate pattern in Vu Gia Thu Bon basin is influenced by Truong Son mountain with quite high rainfall. The average humidity is 84%. Northeast winds flow from October to March with an average velocity of 6 to 10 m/s. Southern, southeast, and southwest winds flow from May to August with an average velocity of 4 to 6 m/s. The average temperature is 25.4°C (Dang, 2009).The rainfall is obtained in an average of 2,612mm (in relevant to 27 billion m^3 precipitation). The precipitation has shown increasing trends from north to south, from the low elevation area to the high one. The mean annual rainfall ranges significantly from 2000 mm in central and downstream areas to more than 4,000 mm in southern mountainous areas. However, there is a difference in season, 65 – 80% of the annual rainfall drops in September – December. Seriously, the 40-50% of total annual rainfall drops in two months, October and November (RETA 6470, 2011). It leads to the flood disaster occurring frequently at this period. Due to the difference in rainfall distribution, the flow in Vu Gia Thu Bon varies significantly between seasons. The flood season generally lasts from October to December corresponding with the highest rainfall period. The flow in this short time occupies approximately 62.5 to 69.2% the total yearly flow.

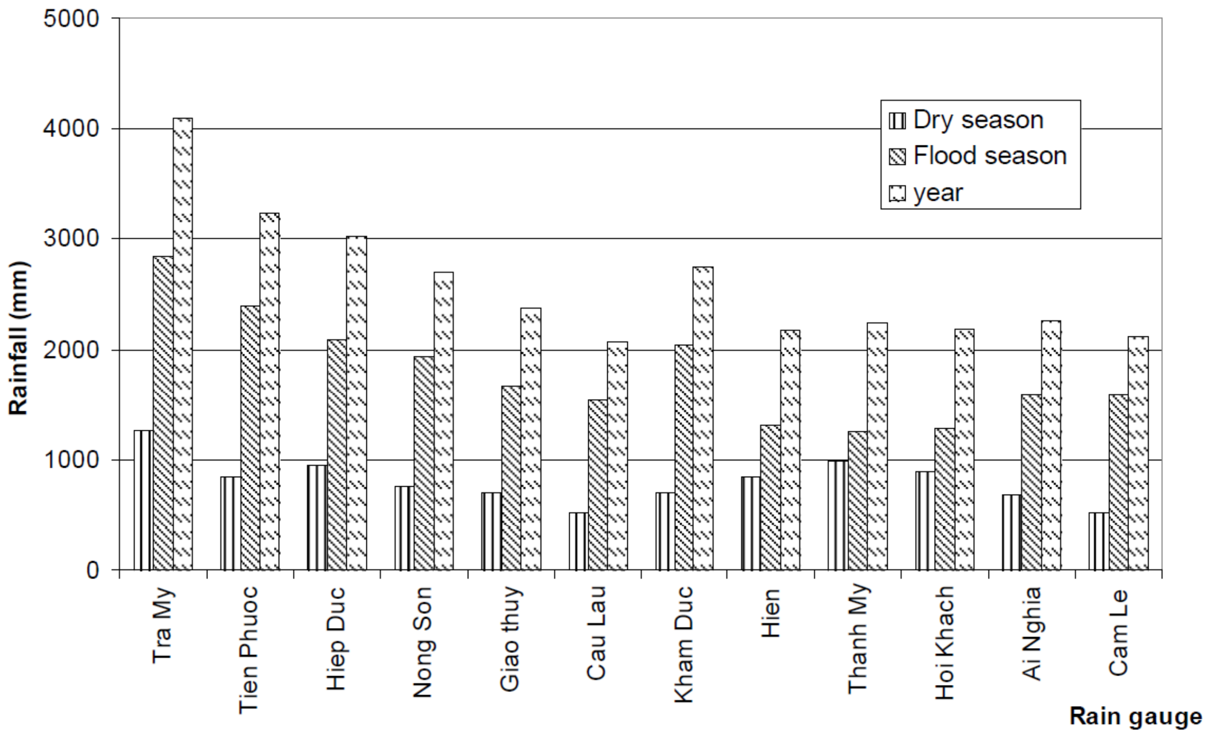


Figure 2.2 Total annual, monsoon season and dry season rainfall observed in different rain gauges in Vu Gia – Thu Bon river basin (Dang, 2009)

The combination of big flow intensity happening in short time and slope topography leads to the flood catastrophe in the catchment is high intensity, short occurrence time, large amplitude and sharp crest. Every year, floods hit this catchment in 4-5 times, even 7 – 8 times in the Vu Gia – Thu bon river system. And as the statistic over previous time, they accounted that more than 50% flood events are higher than dangerous warning flood lever. Highest floods are often seen in October and November, that are caused by various weather patterns such as hurricanes, tropical depression, cold air, northeast monsoon resulting in heavy rains for many days, while water permeability of soil is saturated because early floods, rains and water level in rivers and streams is dramatically high(Vu et al., 2011).

Table 2.1 Properties of flood flows of rivers in Quang Nam (Vu et al., 2011)

Properties		Thạnh Mỹ (1,850 km^2)	Nông Sơn (3,155 km^2)
Season	Characteristic		
Flood season	Q (m3/s)	300	734
	M(l/s/Km2)	162	233
	Time of occurrence	10-12	10-12
	% compared to the year	62.6	68.2
Highest month	Q (m3/s)	385	978
	M(l/s/Km2)	208	310
	Time of occurrence	11	11
	% compared to the year	26.7	30.3

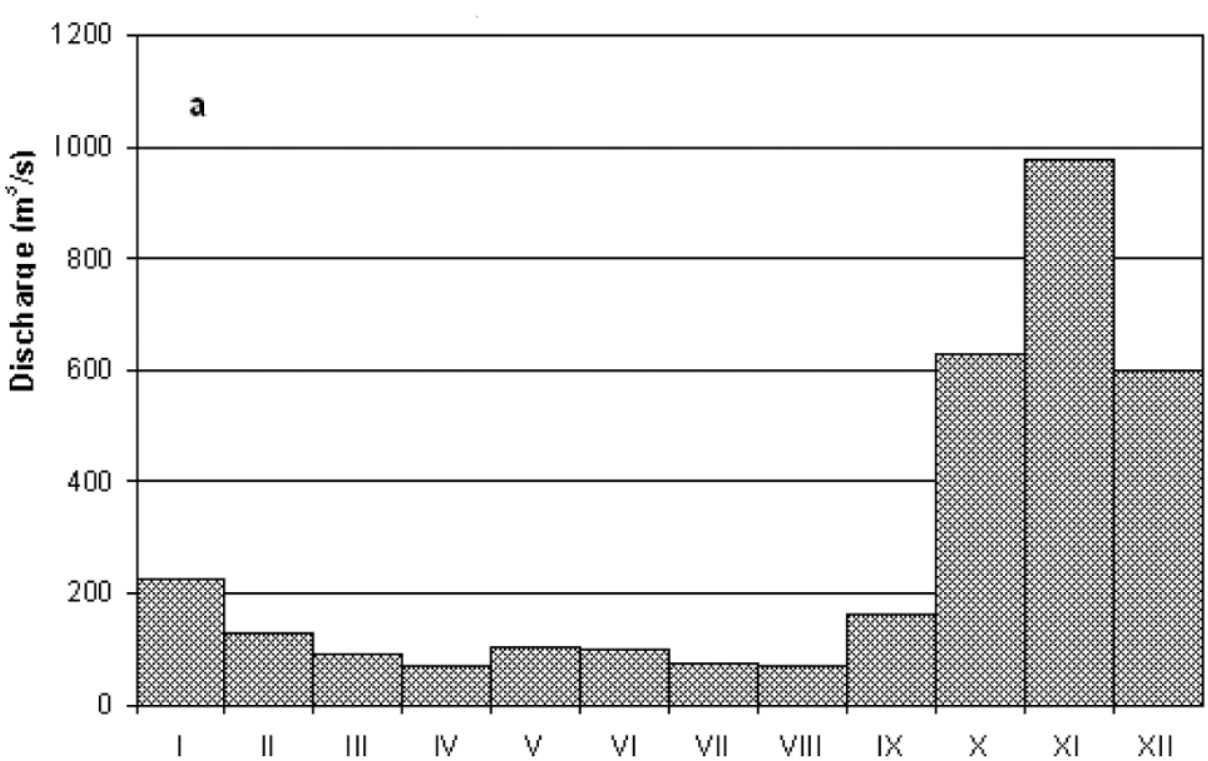


Figure 2.3 Average monthly flow at Nong Son station (Dang, 2009)

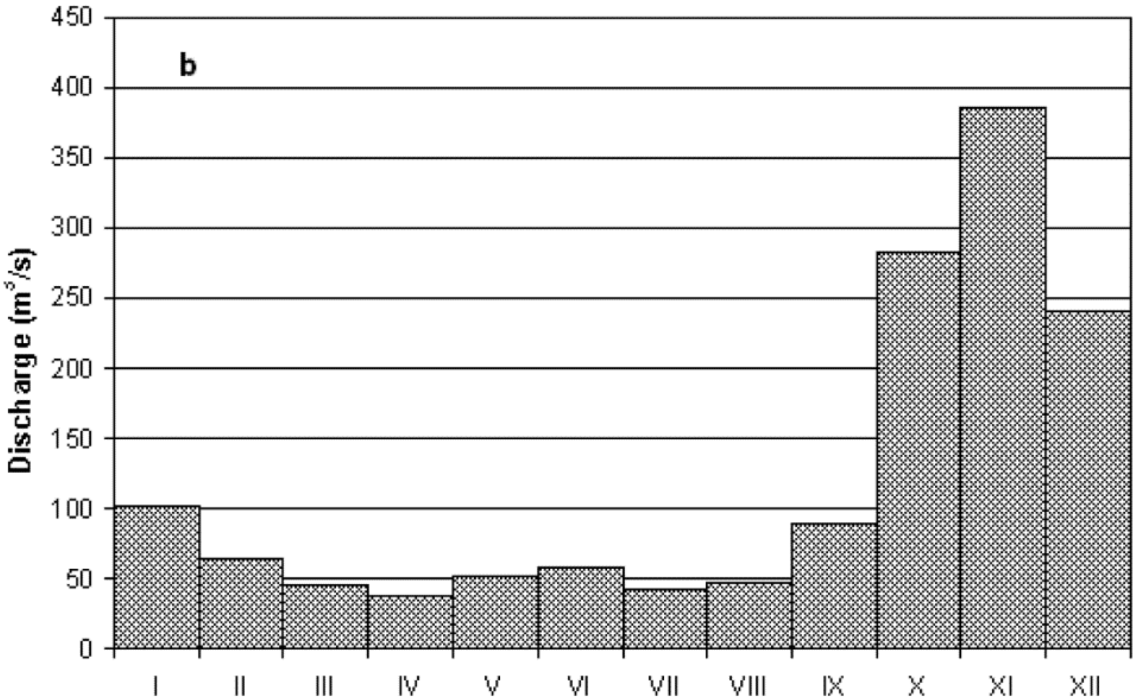


Figure 2.4 Average monthly flow at Thanh My station (Dang, 2009)

Conversely, the dry season lasts in the remaining period when the rainfall is only 20- 35 % of annual amount. The driest period usually falls in the period of February and April. The precipitation measures annually in this time around 3-5% of total rainfall. The sub chronic floods usually come in the May and June under the secondary rainfall peak, which is pronounced towards the north-western part of the area.

Table 2.2. Properties of dry season flow of rivers in Quang Nam(Vu et al., 2011)

Properties		Thạnh Mỹ (1,850 km2)	Nông Sơn (3,155 km2)
Season	Characteristic		
Dry season	Q (m^3/s)	59.9	114
	M(l/s/Km^2)	32.4	36.1
	Appearance time	1-9	1-9
	% compared to the year	37.4	31.8
Driest month	Q (m^3/s)	38.1	68
	M(l/s/Km^2)	20.6	21.6
	Appearance time	4	8
	% compared to the year	2.65	2.11

2.3 Economy and livelihoods

The study area is considered as the most dynamical economic region in Vietnam central. This region has experienced active changes with an average growth rate of 10 per cent and an economic structure of high transformation towards industrialization and modernization (Nguyen, 2011). The regional economy consists of many composition, agriculture, forestry, fishery, industry, handicraft and services. However, the regional economy still depends strongly on agriculture. The labor in this sector occupies more than 52% of total labor market. In agricultural sector, the cropping activities account 70% of the total value of agricultural output. Rice is the dominant staple crop and is mainly planted in the lowland areas. The planted areas for other staple crops, including maize, sweet potato and cassava are relatively small, being also mainly concentrated on the lowland districts and some midland districts near lowland areas (Nguyen, 2011) .The industry has been developed but the proposition of this component in local economy is still small. Mostly, the industrial zone concentrates on Da Nang city and coastal areas. Tourism and service are quite small. These economic parts have not been adequately developed towards regional potentiality while there are many celebrated world cultural heritages such as Hoi An ancient town, My Son Temple in this river basin.

Figure 2.5a. Labor structure, 2.5b. Sector contributions to the economy of Quang Nam province in 2014 (Quang Nam, 2014).

The population in the region reaches 1,472,000 persons in 2014. GDP per capita is around 1670 USD and the rate of poverty households is 12,1% (GDP per person is lower 225 USD) (Quang Nam, 2014).

2.4 Vulnerability

Due to the violence of climatological events, the fragile economic condition and the underdeveloped infrastructure, the natural disasters related to river flow deeply affect the population in this region. In addition, the farming habits formed agricultural production and cultural customs also have a negative influence on the prevention of inhabitants against natural catastrophes. Furthermore, local authorities although have made efforts to prepare for these disasters and to overcome the damage, these works seem still insufficient. They have not yet had a complete strategy to help population avoid the catastrophic effects. Consequently, the population in central Vietnam, especially in Vu GiaThu Bon basin, annually sustains considerable damages to people and property. The socio-economy of this region is strongly affected by natural disasters. As a result, the flood and inundation are seen as the biggest disaster for the catchment. The hydrological catastrophe causes many damages towards the human's lives and property over catchment. In ten years, it left 602 people dead; 33 missing; 1,550 injured and costed VND 9,578 billions in damage to property and infrastructures (Vu et al., 2011).

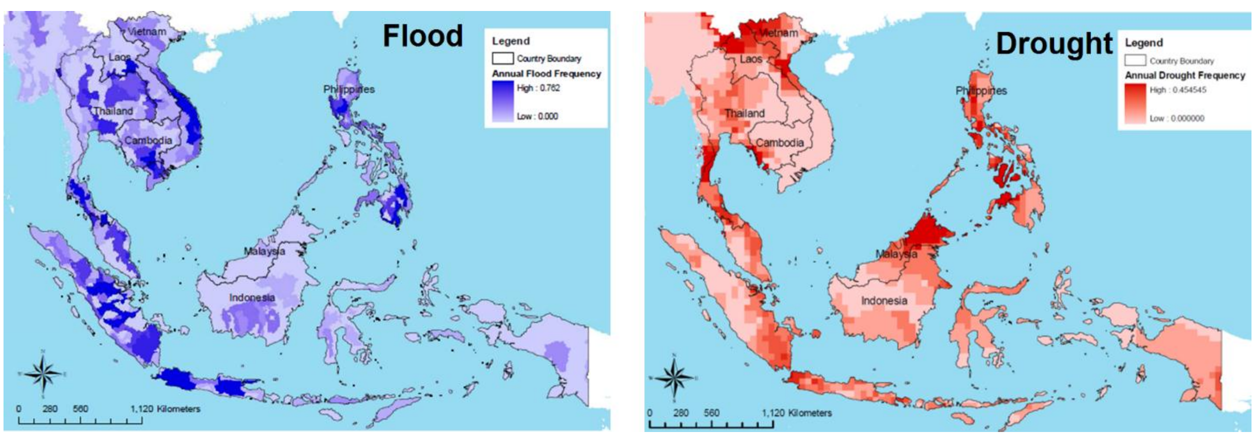


Figure 2.6 Flood and drought frequency at Southeast Asia (event per year from 1980-2000) (Yusuf & Francisco, 2009)

According to recent five years statistics from 2003 to 2007, flood and storm disaster loses in Quang Nam province are estimated average up to 6.26% of the GDP. In years with excessive rain and flood, losses can sum up to 18-20% of the GDP and severely crash human lives and property (Vu *et al*., 2011). Moreover, similar to other regions in Viet Nam, Vu Gia Thu Bon's economy depends greatly on agriculture, particularly on rice production. As a result, the run off regime of this river system not only affects socio economy in flood season, but also causes impacts on water resources, drought disaster, and salinity in dry season. According to the prediction of IPCC's scenario, under the impact of global warming, sea level increase, the change in hydrological cycle, flood and drought disaster, abnormal phenomenon such as phenomena El Nino and La Nina in Vu Gia Thu Bon basin will happen more frequently and more extremely (Nguyen, 2011). It makes the consequences of natural disasters to people, livelihood, social economic development become more severe.

2.5 Historical flood disasters

Due to the hydrological feature and vulnerability of Vu Gia Thu Bon catchment, the flood catastrophe frequently occurs and causes severe damages for local population and economy in history. In 1964, a flood event lasted in many days of beginning November and caused the inundation overall the catchment. This historical flood killed more than 6000 people, destroyed a lot of villages.

The flood happening in one week of November 1999 inundated heavily the downstream districts of Quang Nam province and Da Nang city, especially mostly areas were sunk deeply at 1.0-2.0m water depth in many days. The water overflowed the road, railway. Many locations and villages were isolated. The traffic and communication were interrupted. Almost all of the lakes in the catchment passed the designed capacity. They faced broken risk and led to destroy many inhabitant areas. In 1999, the flood killed 118 people and damaged 758 VND billions for local economy (Table 1.3). Although the local authority have had many solutions to reduce actively the impact of natural disasters, the flood event in 2007 inundated heavily 125 per 233 communes of Quang Nam. It affected roughly to 200,000 households. Communication and power supply were cut off in many areas. Most roads there were blocked, transportation on the highway 1A was obstructed for 40 hours. The damage caused by this flood is very great. In total, 47 people were killed; the infrastructures were damaged dramatically. These natural catastrophes in this year cost about 2,000 VND billion. Recently, in 2009, after several heavy rainfall and tropical low pressure, many parts of region were sunk completely in water. People and property were damage severely. The event killed 52 habitants, collapsed 5,200 houses, around 3,500 VND billion were lost. These damages have been very substantial with the underdeveloped economy as Vu Gia Thu Bon catchment (Nguyen, 2011; RETA 6470, 2011; Vu *et al*., 2011).

2.6 Data availability

2.6.1 Topography and river geometry

The topography data is generally required for distributed hydrological and hydraulic modelling. However, this kind of data is rarely available at large catchment and poor countries. Nowadays, there are a lot of online DEMs. Although their accuracy is still a big question but these free data sources are very helpful for areas with the lack of data. For example, the famous free data source of topography is SRTM DEM of NASA which can easily download from the website http://www.cgiar-csi.org/. As information introducing at this website, this DEM covers over 80% of the globe. This data is currently distributed free of charge by USGS and available for downloading from the National Map Seamless Data Distribution System, or the USGS ftp site. The SRTM data is available as 3 arc second (approx. 90m resolution) DEMs. One arc second data product was also produced, but it is not available for all countries. The vertical error of the DEM's is reported to be less than 16m. The data currently being distributed by NASA/USGS contains "no-data" holes where water or heavy shadow prevented the quantification of elevation. These are generally small holes, which nevertheless render the data less useful, especially in hydrological modelling fields. From origin, resample data with 250m, 500m, 1000 m also released on this website. The accuracy of this DEM has been demonstrated in many previous projects. The second source of free topography data is 30 m ASTER GDEM which is joint product developed and made available to the public by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It is generated from data collected from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), a space borne earth observing optical instrument. The ASTER GDEM covers land surfaces between 83°N and 83°S. Although, The ASTER GDEM is newer and is built with smaller grid size than SRTM DEM, its quality is not as confident as SRTM DEM. Hence, using ASTER GDEM is not popular as SRTM DEM. Besides that, there are DEMs which benefit from two projects of LUCCi and Vie 08-P1. The first from LUCCi covers overall Vu Gia Thu Bon catchment. This data presents topography at the catchment with 15 m resolution. The second has smaller grid size than the first one, 10m. Unfortunately, it only expresses for Quang Nam province. The lack of data is an important part of this catchment which contains the downstream part of Vu Gia branch. However this data is very helpful for constructing the river geography at upstream parts.

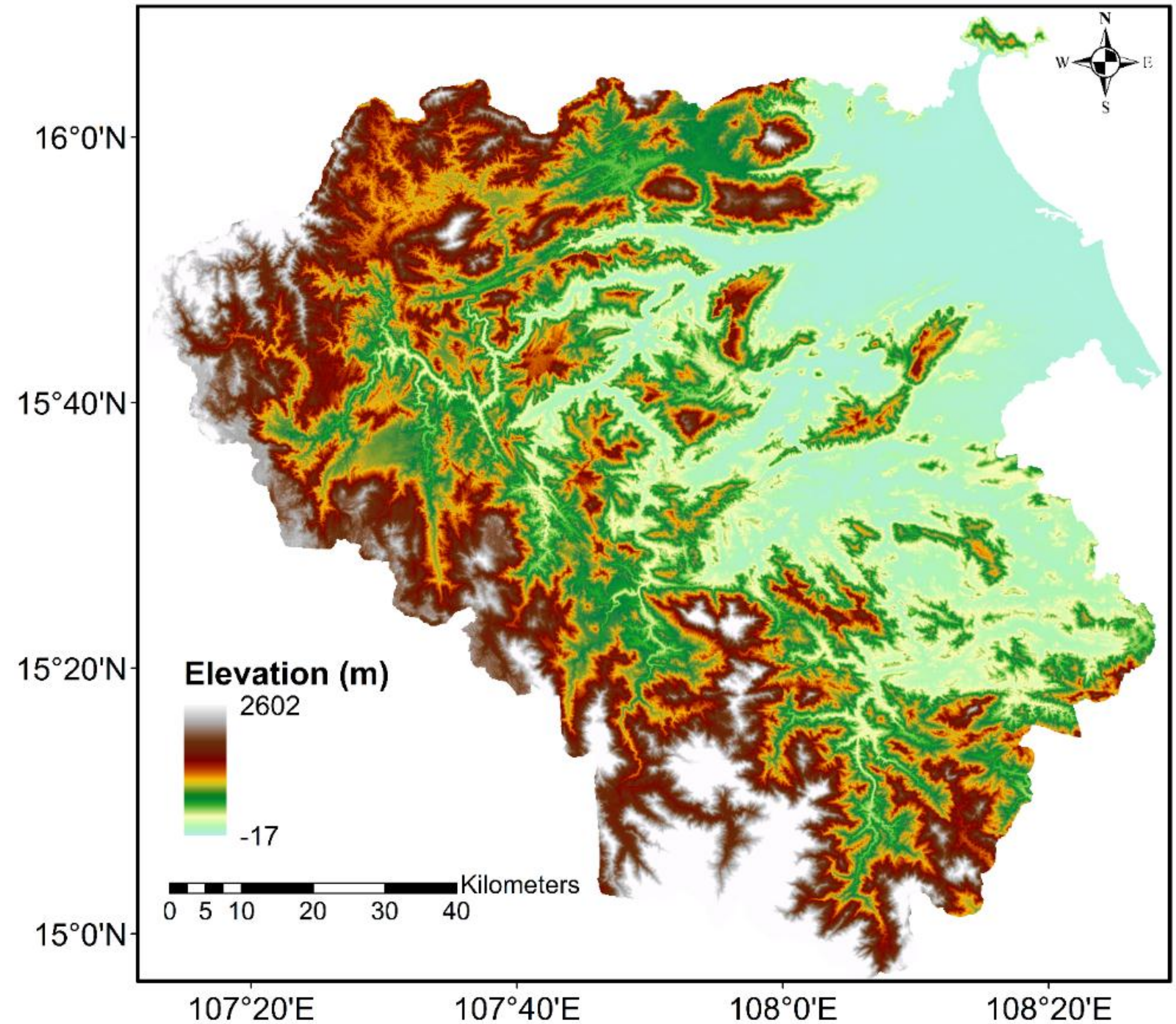


Figure 2.7: Topography as 15m DEM resolution from LUCCi project.

The river network in this catchment is very complicated and affects significantly on the regional socio economic development. However, the profile of this river system has not been yet measured completely. It causes many difficulties for studying hydrological and hydraulic phenomena related to this system. At study area, data for river profile only exists at downstream part (186 cross sections). This data is inherited from the last study. However, the density of this data is not very high. Average 1 km long of river is represented by 1 cross section. Moreover, they mainly concentrated on two principal branches, Vu Gia and Thu Bon. Consequently, the characteristics of river are not clear enough to simulate accurately the hydrological and hydraulic phenomenon of the river system, at least with the mountainous regions. The issue was solved by relying on the DEM 10 m of Vie 08-P1 project.

2.6.2 Land use and soil maps

This area covers 10,350 Km^2 and situates at a dynamic region which has a diversified economic structure. Thus, the land use map also varies frequently. Determining a general land use map over time have met many difficulties. Currently, there are a lot of land use maps which come from locality or online sources. Nevertheless, their contents are not concrete to evaluate the consequence of flood events and to determine the roughness coefficient in the catchment. The land use map was selected for this study originated from LUCCI project. This data was resampled to 9 kinds of land uses (Figure 2.8). The proportion of each land use is shown in Table 2.3. This map is transferred into raster data under different resolutions to make it suitable with calculated objectives.

Table 2.3. Percentage of land use at Vu Gia Thu Bon catchment

Land use	Percentage (%)
Unused mountain land	11.48
Natural forest	49.20
Planted forest	12.85
Rural settlement	10.53
Annual crops	4.69
Rice	6.32
Urban	1.70
Perennial crops	2.95
Water body	0.28

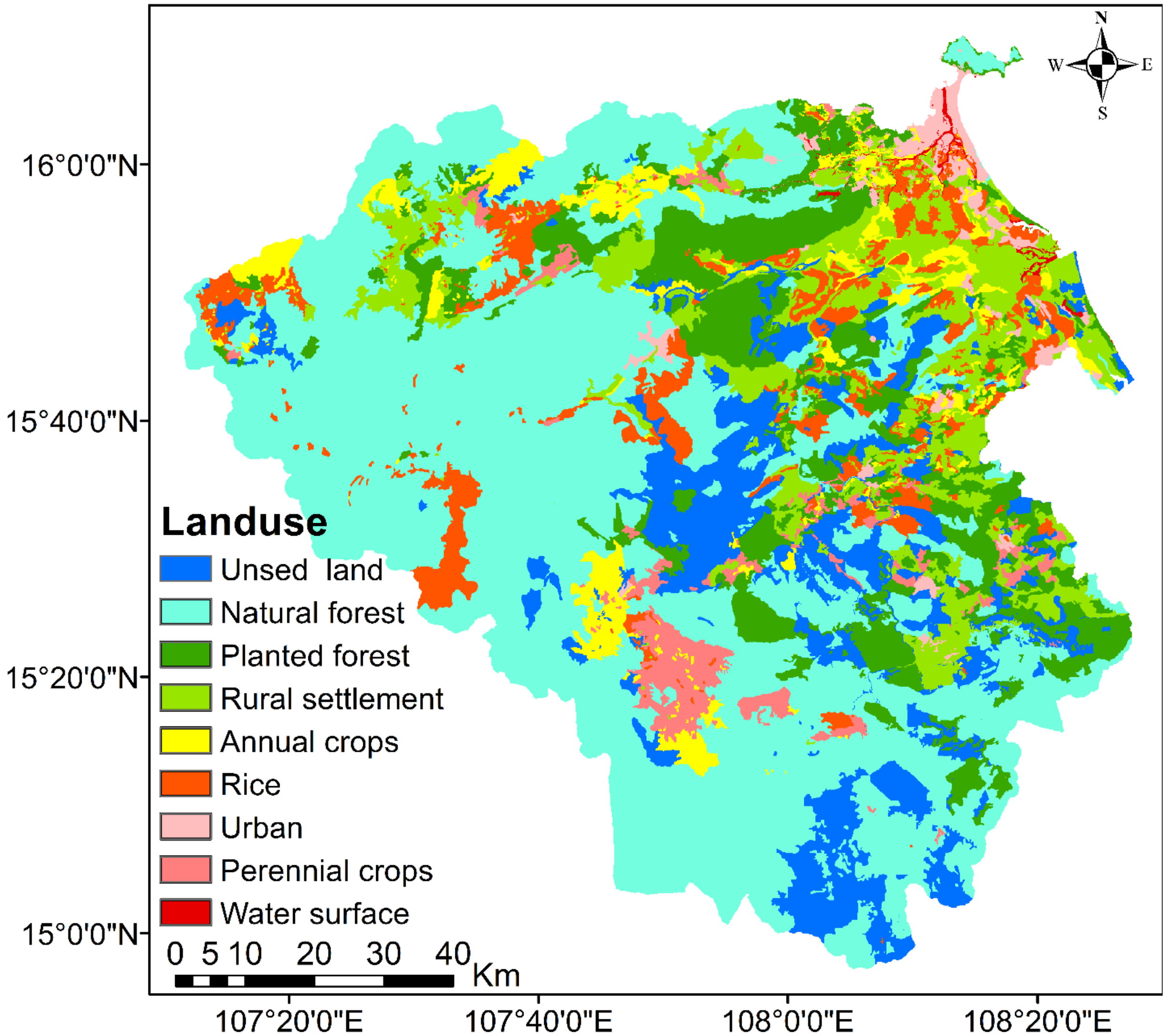


Figure 2.8: Land use map at Vu Gia Thu Bon catchment.

Table 2.4. Percentage of soil at Vu Gia Thu Bon catchment.

Soil type	Percentage (%)
Clay	34.61
Silt loam	48.72
Loamy sand	11.54
Light clay	2.73
Sand	2.40

The soil map is supplied by Vie 08-P1 project which describes 44 types of soil of catchment. This map is resampled to 5 principal soils types as the Figure 2.9. In these components, clay and silt loam are more than 80 % of total (Table 2.4). Hence, they are judged to be two factors deciding on the infiltration and base flow in this catchment.

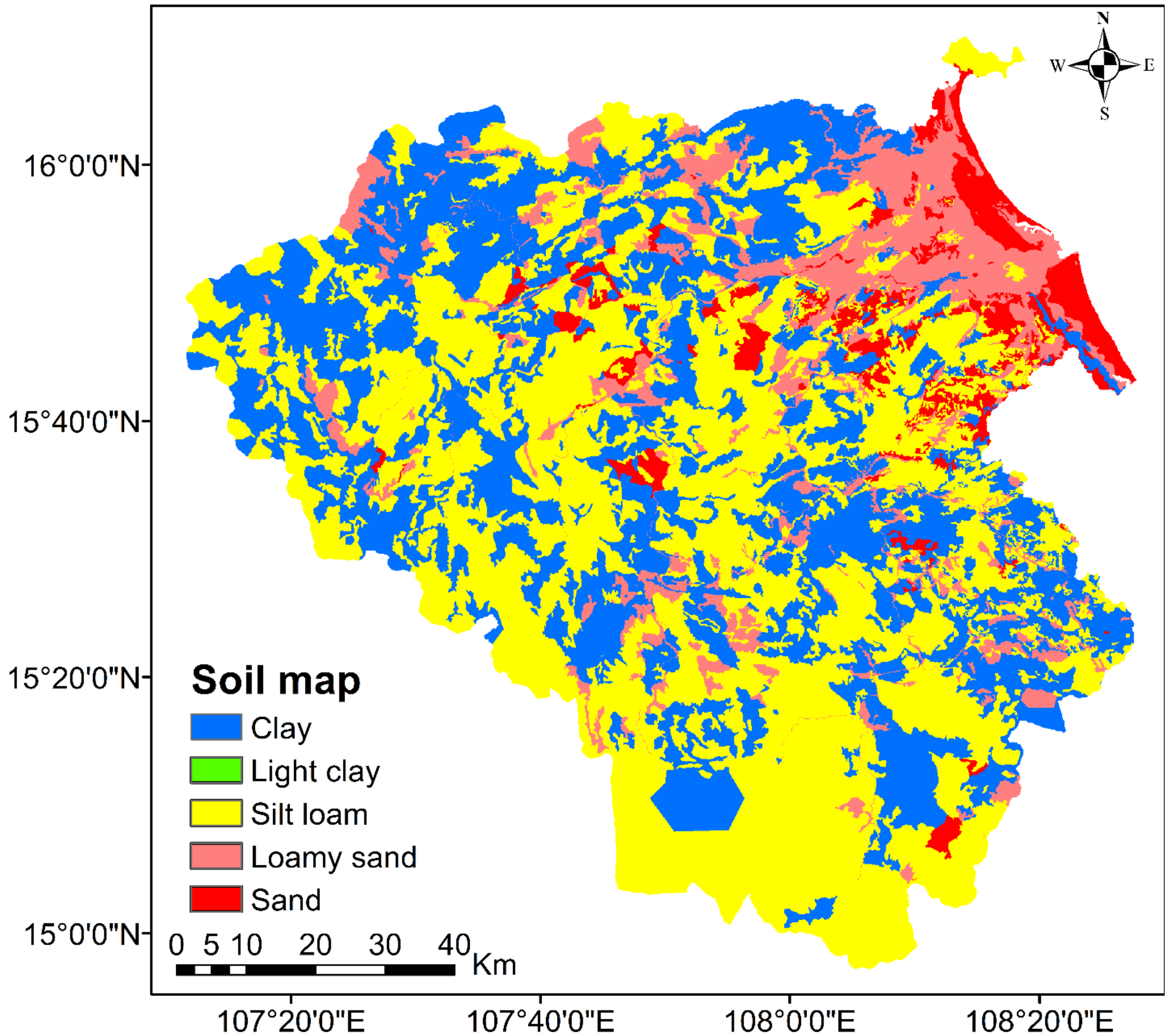


Figure 2.9: Soil map at Vu Gia Thu Bon catchment.

2.6.3 Ground water

The ground water data is provided by the Central Viet Nam Division of Water Resources Planning and Investigation. This data is described preliminary ground water distributed situation of Quang Nam and Da Nang via two reports. These reports also accompany by the ground water level process at 27 wells over catchments. However, most of the holes are in flat area, concentrating mainly on the downstream parts. There is not any hole being mountainous area.

2.6.4 Hydrometric data

The data is supported by the Hydro meteorological Center in mid central Viet Nam. The Availability of data type is listed in the Figure 2.10.

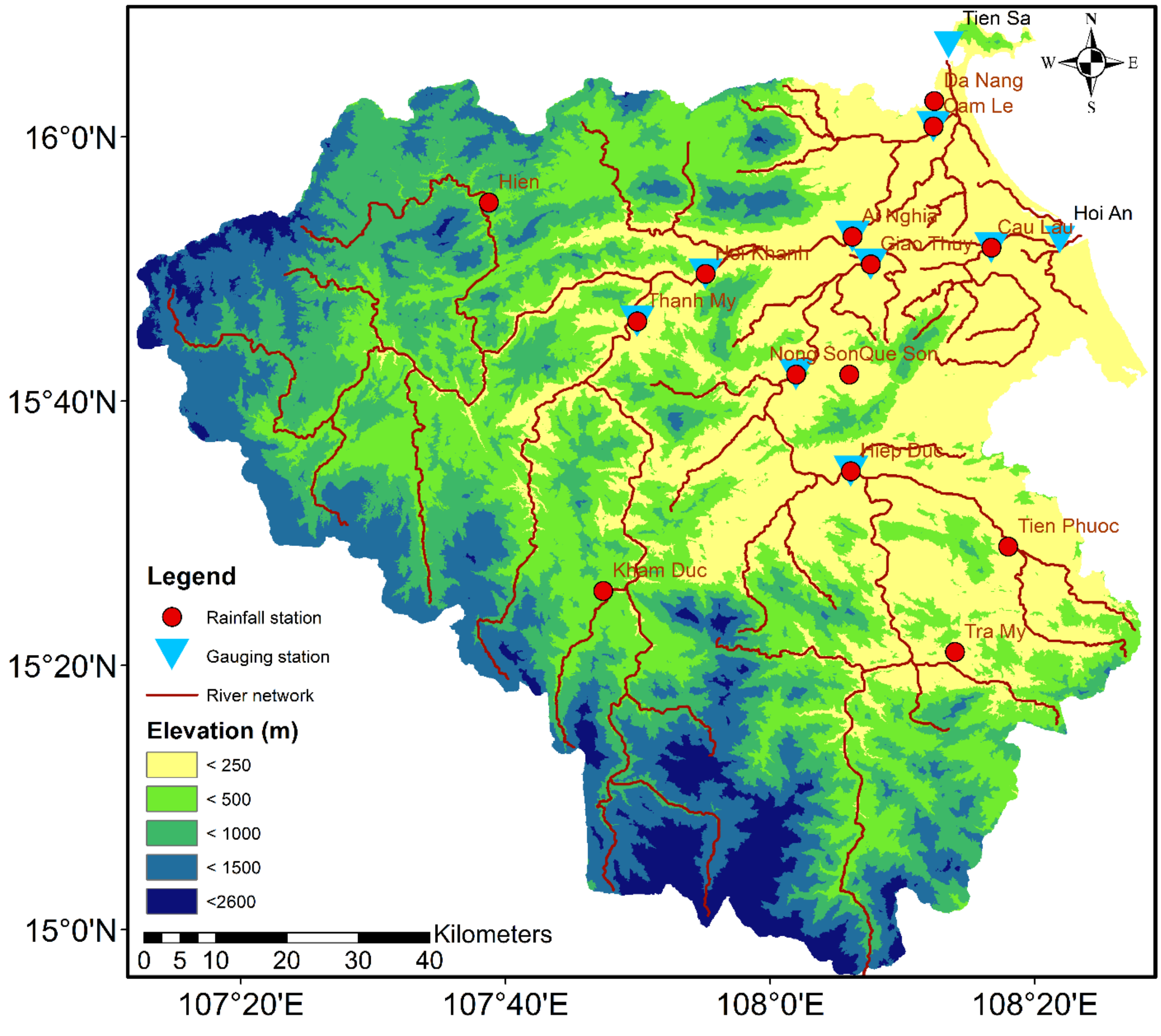


Figure 2.10: River network and hydro meteorological station at Vu Gia Thu Bon catchment.

There are 2 national rainfall stations which can measure hourly data. They are Da Nang station, representative for coastal area and Tra My station, served mountainous region. Other stations, including Tien Phuoc, Kham Duc, Hiep Duc, Hien, Thanh My, Nong Son, Que Son, Hoi Khanh, Ai Nghia, Giao Thuy, Cam Le, Cau Lau , are popular rain gauge stations which operate manually due to the volunteer of local people. Thus, the observed step is long, 12h in flood reason, daily in remaining days. Besides that, the data, measured from popular station, contains many potential uncertainties. The water level is observed at 6 stations long two main branches of river system, Vu Gia and Thu Bon. Nevertheless, in comparison with river length, the density of gauging station is quite sparse. It seems that this network is still not enough to control the water level process for Vu Gia Thu Bon catchment. Furthermore, they mostly concentrate on the downstream part. This situation creates difficulty for flood managementas well for validating the model results. Over the catchment, there are only two stations having capacity for measuring the discharge data, Nong Son and Thanh My. They locate at the middle of Thu Bon and Vu Gia branches, respectively. So their data merely express partly the flow originating from upstream of each branch. At the downstream, where having a complicating river network, there is not any flow measured station. There is a big challenge for accounting the exchanged water between branches, also for evaluating the model performance. Sea levels at two river mounts, Hoi An and Son Tra, are benefited as downstream boundary conditions.

2.7 Conclusion

The Vu Gia Thu Bon is one of the largest catchments located at central of Viet Nam, which is annually confronted to severe damages due to natural disasters such as catastrophic flood and drought events. Furthermore, according to the prediction of IPCC's scenario (Pachauri & Reisinger 2007), under the impact of global warming, sea level increase, changes in hydrological cycle, abnormal phenomena, e.g phenomena El Nino and La Nina in Vu Gia Thu Bon basin, flood and drought disasters are forecasted to happen more frequently and more extremely. This situation will generate more severe consequences to people, livelihood, and social-economic development. Hence, in order to mitigate the impact of these catastrophes on the region, an efficient tool is required to help hydrologists and authorities to have a good understanding on what is happening in stream flow regime and its potential variations within the future. However, studying the hydrological process of this catchment meets several difficulties such as large scale, complicated river system, especially the lack of data for modelling. Due to these difficulties, there has not been yet a completed study of flood risk assessment and climate change over this catchment. Determining a high performance model, which is hoped to overcome above difficulties, is the main point in this study. Model selected and constructed process are showed in the next chapter.

Chapter 3 HYDROLOGICAL MODELLING

This chapter sets out to develop an efficient model which can represent as accurately as possible the hydrological characteristics of the Vu Gia Thu Bon catchment. This model is considered as a basic tool for evaluating the variation of the catchment's hydrologic process under the impact of climate change. In order to get background for selecting the most suitable model for Vu Gia Thu Bon catchment, an overview of the concepts and some of the main issues within hydrological modelling is first provided. After that, the chapter presents the model selection process. Based on available model and catchment's real situation, deterministic distributed model – MIKE SHE is chosen for modelling purposes. Next, the chapter describes MIKE SHE model construction, sensitivity analysis, calibration and validation. Finally, the chapter presents the discussion of the model results, uncertainty and performance of MIKE SHE of model in representing the hydrological process at this catchment.

3.1 Model definition

Hydrology is a subject of great importance to human and environment, which deals with all phases of the earth's water (Chow *et al.*, 1988). There are lots of components and complex interactions with the hydrological system. Various definitions about the hydrological system were developed but in a simplified way, it can be said as a set of physical, chemical and/or biological processes acting upon an input variable or variables, to convert it (them) into an output variable (or variables) (Xu, 2002). This continuous converted process can be named hydrologic cycle what is the water transfer cycle, which occurs continuously in nature; the three important phases of the hydrologic cycle are: Evaporation and evapotranspiration, precipitation and runoff (Raghunath, 2006).

In order to reduce the negative impact of this system to human being, the people always study on this subject to understand more deeply its operation and could give relative prediction. However, with its complication, up till now, the people has just discovered a small part of this system. Nowadays, with the development of mathematics and computer science, model is seen as general and efficient tool for study what happen in hydrological processes and the impact of modern anthropogenic factors on the hydrological system (Yu, 2002). A model is an expression to show a part of natural or human created world which can be in the form of a physical, analog or mathematical model (Dingman, 2002). Brooks et al., (2013) express that Hydrologic models, simplified representations of actual hydrologic systems, predict hydrologic responses and allow one to study the function and interaction of various inputs, and in so doing gain a better understanding of hydrologic events. Generally, model of the hydrologic system may be explained as a function which transforms input variables into output results (Xu, 2002).The model result can help us to have a better understanding of the hydrological phenomena operating in a catchment and of how change in the catchment may affect these phenomena. Furthermore, they help the hydrologist to have scientific evidences for forecasting future scenarios such as climate change or land use change, also for suggesting the constructive design in the catchment. However, the model could not describe all components of hydrological system, as well as the relation between them. It only has the capacity to depict sketchily this system. Xu (2002) defined that hydrological model is simplified representation of a complex system which has a lot of variables e.g. rainfall, run off, evapo-transpiration, temperature, infiltration, soil, moisture,…etc. So this model represents an approximation of the actual system. It makes the model unable to translate well the happening in nature. Because of the limitation in calculated capacity, hydrological cycle of watershed is isolated for studying in watershed scale. This work is looked like one of basic simplifications when interrupting the spatial continuum of hydrological system.

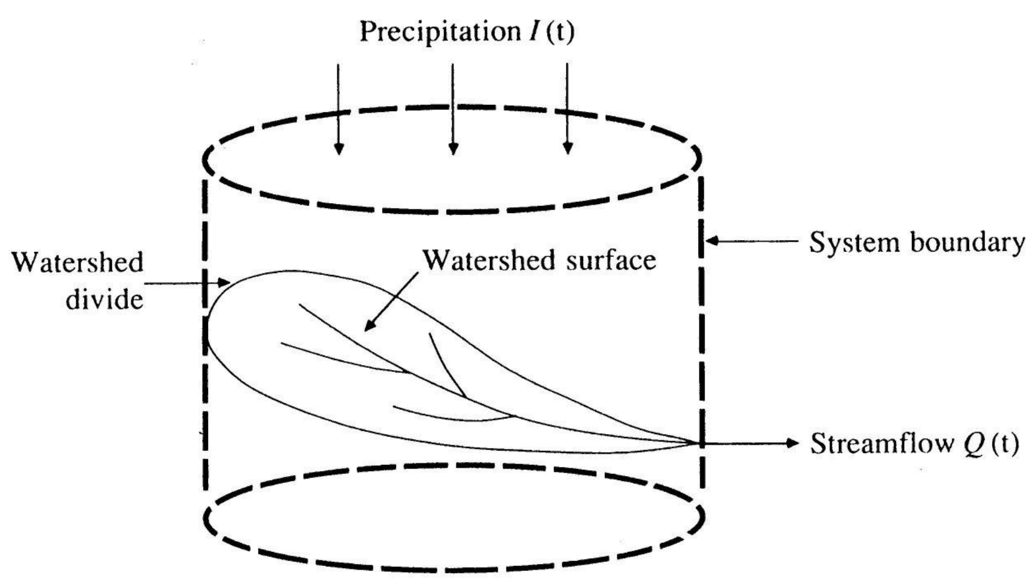


Figure 3.1. The watershed as a hydrologic system (Chow et al., 1988)

A watershed can be explained with a division by topographic or groundwater as the Figure 3.1. It is defined as the terrain area contributing surface stream flow into a river network or any point of interest (Brutsaert, 2005; Chow *et al.,* 1988; Dingman & Dingman, 1994; Linsley *et al.,* 1949). Thus, when saying about hydrological model, we imply that this model simulate hydrological process for a small area or a catchment.

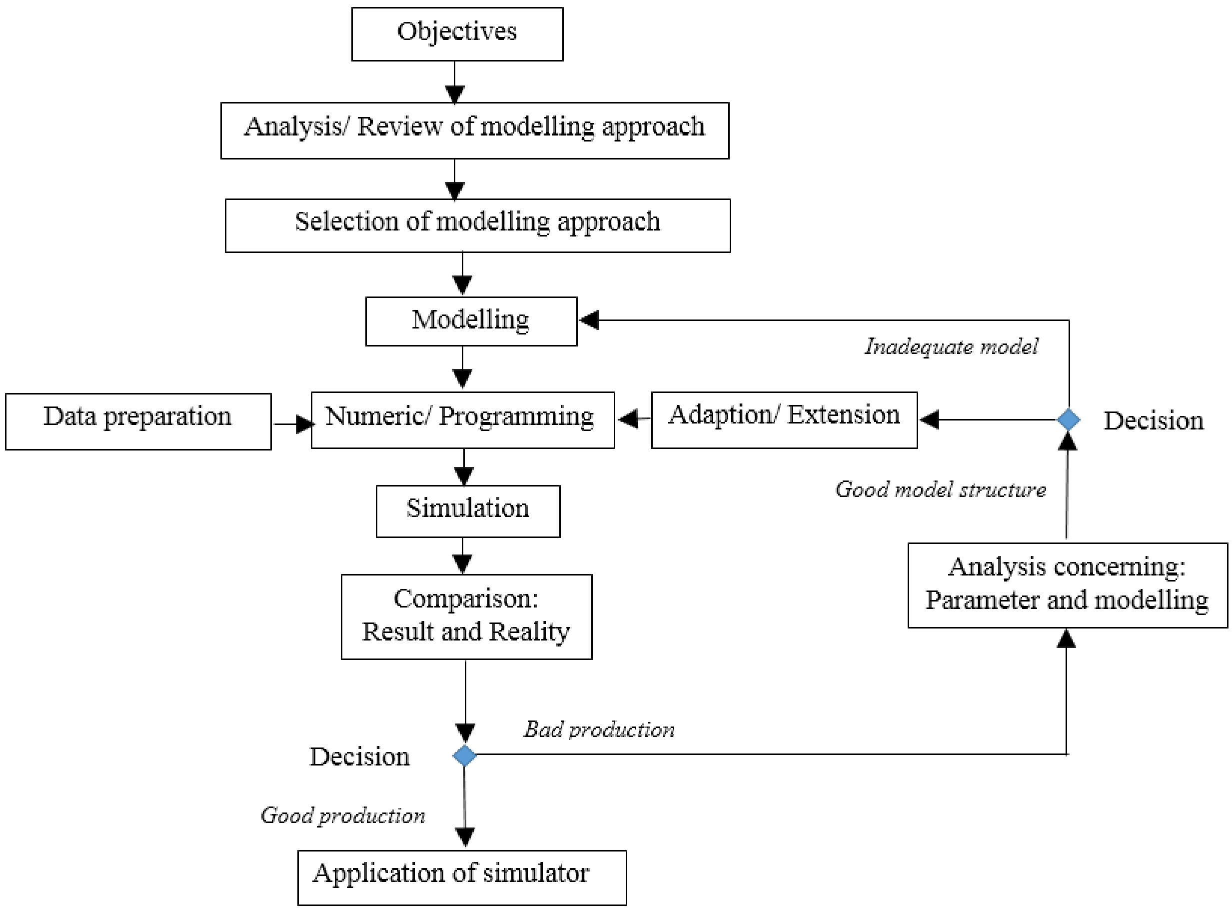


Figure 3.2. Hydrological modelling schema for the catchment.

In a watershed scale, the hydrological model is constructed on simplified equation which is simply the statement of the law of conservation of (Raghunath, 2006) and is given by

$$I = O + \Delta S$$

Where

I = inflow

O = outflow

ΔS = change in storage

The above equation shows that during a given period, at a catchment the total inflow into a given area must equal to the total outflow from the area plus the change is storage.

The methodology for applying a model to simulate the hydrological cycle in a catchment in most case is in Figure 3.2. This methodology is summarized from the study of (Rochester, 2010; Xu, 2002; Yu, 2002). Follow this schema, problem definition is the first step and plays an important role in hydrological research. This step is to outline existed problems in the catchment. From that the hydrologist will specify model objectives which are the basis for model selection and data preparation. Hence, this step affects hugely kind of selected model, also decide model structure.

The second factor influencing the model selection is data available. Regarding to Raghunath, (2006), adequate data and length of records are necessary for the analysis and design of any hydrologic project. The basic hydrological data required are:

- Climatological data;
- Hydro meteorological data like temperature, wind velocity, humidity, etc;
- Precipitation records;
- Stream-flow records;
- Seasonal fluctuation of ground water table or piezometric heads;
- Evaporation data;
- Cropping pattern, crops and their consumptive use;
- Water quality data of surface streams and ground water
- Geomorphologic studies of the basin, like area, shape and slope of the basin, mean and median elevation, mean temperature (as well as highest and lowest temperature recorded) and other physiographic characteristics of the basin; stream density and drainage density; tanks and reservoirs.

3.2 Model classification

Up to date, many hydrological models have been developed with different theories to simulate catchment's hydrological phenomenon. They have contributed significantly in getting more knowledge about hydrological phenomenon, as well forecasting the future scenario. They have provided logical proofs for strategists, authority ability to make reasonable decisions in mitigating the impact of hydrological disaster to human beings. However, the performance of hydrological models is not similar due to developing based on different theories, and serving different purposes.

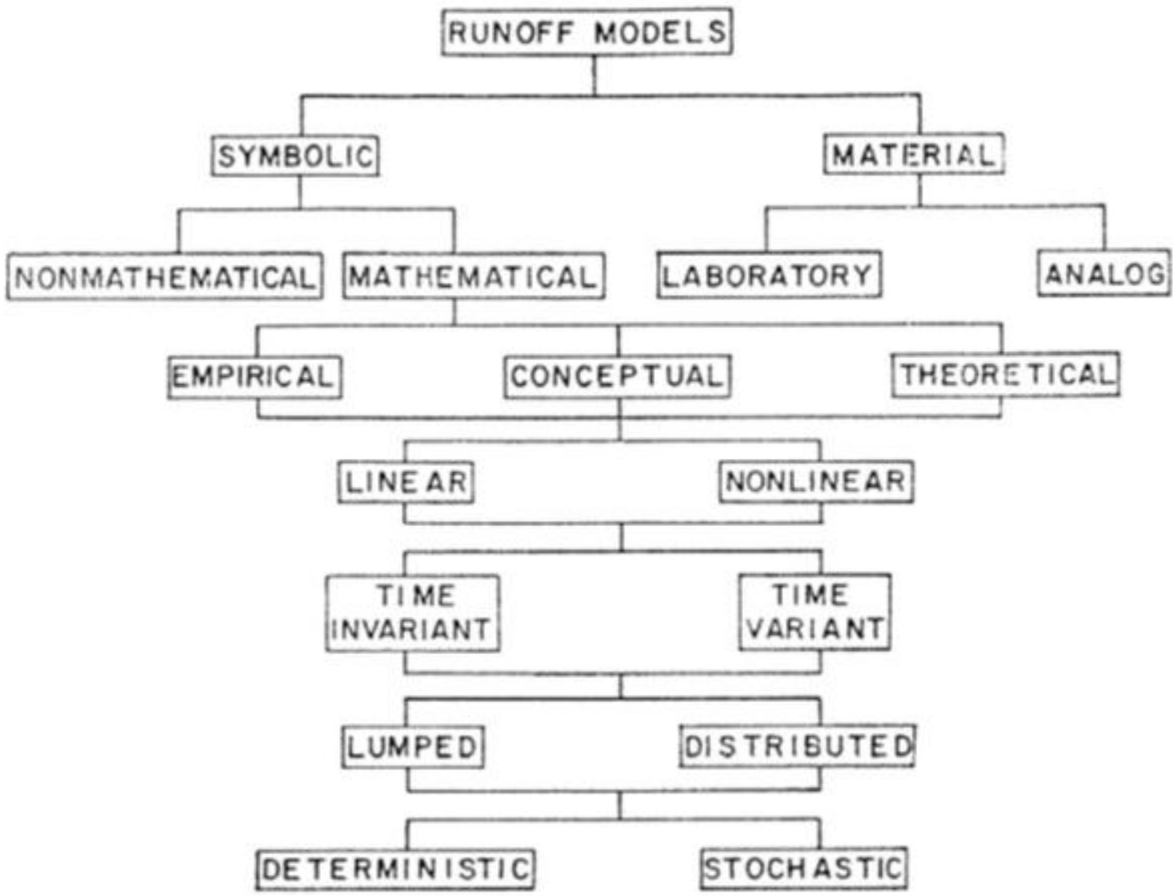


Figure 3.3. Hydrological model classification (Singh, 1988)

The capabilities and limitations of each model can be identified accurately relied on model classification. Proper classification is expected to be helpful for engineer, experts and research to understand the characteristics of model before deciding to employ them into their work (Harun *et al.*, 2012). The model may be classified according to several criteria. Singh, (1988) distinguished hydrologic model as material and symbolic as Figure 3.3. Each major category can be subdivided into more detailed subcategories.

3.2.1 Material model.

As the definition of Chow *et al*., (1988), a material model (also called a physical model) is the way which use a similar system to represent the real system. The imitative system has similar properties with reality, but it is much easier to work. This kind of model includes scale model and analog model. Scale model (laboratory) is a system which represents the real system on a reduced scale. For example, this method is generally used to verify the hydraulic regime of spillway. And the system, which uses another physical substances to introduce the characteristics of prototype, is called Analog model as flow of electric current which represent the flow of water. The material model cost is quite expensive and not convenient for construction. But it could be applied to assist the researcher in replacing a phenomenon in an unfamiliar field or to construct experiments for typical system (Xu, 2002).

3.2.2 Symbolic model, formal or abstract model.

There are many definitions related to this distinction, but Xu, (2002) stated that formal model is the way which uses a symbolic system to represent the structural properties of original system. Singh, (1988) divide this system into two major categories: nonmathematical and mathematical model. However, in literature, this kind of model has considered only on the mathematical aspect. Following this direction, Chow *et al.*, (1988) specified abstract model use an mathematical equation to describe a natural system. This model is operated based on a mathematical relation which creates the linking between input and output variables. Because of the simplicity, advantage, mobilized characteristic, accurate relatively representation, this kind of model has been developed widespread nowadays. The linking between input and output variables are represented via different kinds of mathematical function which are able to consider on different aspects due to the viewpoint of developers, such as space, time, mathematical structure…. Hence, the symbolic mode genre is quite abundant. In order to classify models, it is necessary to consider what features they have in common and the respects in which they differ. The current models are arranged as following distinctions which are often seen in the hydrological literature.

a. The distinction between theoretical, conceptual and empirical models

Relied on the presentation method of the hydrological cycle, the hydrological model can be classify into 3 subcategories. The degree of representation of the concerned physical model can stipulate hydrological model being in the below types:

Empirical model is also called the black box model which mostly is independent with physical process. It is totally built on the experimentation or observed input-output correlation (Oogathoo, 2006). Empirical model attempt to represent relationship between input and output time series using transfer function. Obviously, the model structure building depends on the measurements for the model output variables (Willems, 2000). Hence, model parameters can be estimated only by using concurrent measurements of input and output. This is assessed as the simplest hydrological and could be constructed quickly. In many situations, this kind of models can provide accurate answer and serve as a useful tool in decision making (Xu, 2002). However, this model has several weak points. The big limitation is that it is established for a specific catchment and time interval. Consequently, if the catchment characteristic change, it might not be suitable anymore. The limitation of this method also show at its efficiency when applying with other catchment or the outside events. However, it is still used for establishing general catchment characteristic or evaluating quickly the phenomena in catchment. Artificial Neural Networks (ANNs) is the later development of empirical model (Xu, 2002).

Theoretical model (physically based model or white box model) conversely are derived from physical law and assumptions and it has a logical structure similar to the real world system (Xu, 2002). In theory, most of model parameters could be measured on the reality. Hence, it is expected to reflect truly the catchment characteristic and to supply entire view of the catchment's hydrological process for hydrologist. Although, this kind of model is quite complex and requires a numerous data, it has good point in simulating hydrological cycle. In the part of ….. the outstanding of this kind of model will be disserted in more details. Many hydrological models have been developed following this direction like MIKE SHE, SHETRAN, SWAT, TOPMODE.

The intermediate type of empirical model and theoretical model is named conceptual model (grey box model). Generally speaking, conceptual model is considered by the physical law but in higher simplified form (Singh, 1988). Hence, the conceptual model does not have any true physical meaning (Rochester, 2010). The model parameters of this kind of model can not be determined directly and need calibration to get optimal value. The conceptual model have been developed and applied (e.g HYRROM, HBV,…) in reality due to its performance and simplicity.

b. The distinction between linearity and non-linearity

In the term of linearity, there are at least two meanings: linear in the system-theory sense and linear in the statistical regression sense Xu, (2002). The first definition is most widely used in hydrological modelling literature. Lewarne, (2009) stated that in linear models, there is a simple correlation between the input and output but for the nonlinear model, there is a chaos and an irreversibility that makes this model more difficult to study.

c. The distinction between time factors of model

In the term of temporal characteristic, the hydrological model may also be categorized into event based and continuous model according to the number of hydrologic events simulated (or simulated length). Event based model simulate only a specific event for a short time phase (hours to days). On the contrary, the model which can be applied to translate a series of hydrological event (long time simulation), is called continuous model (Harun *et al.*, 2012). Evidently, the continuous model with more good points has been used in reality than event based model.

The hydrological model can be divided into two types due to relationship between input and output factor with time, including time invariant and time variant model. A model is called time invariant model if its input-output relationship does not change with time. Inversely, if this relationship changes depending on time, this kind of model is time variant (Xu, 2002).

d. The distinction between lumped and distributed model.

The hydrological model can be organized in three categories due to the different concrete levels in representing spatially the catchment characteristics. In terms of spatial discretization, there are three primary spatial elements used: lumped, semi distributed and distributed models (Figure 3.4).

The model, which uses the simplest way to express the catchments characteristics in space, is called lumped model. This model assumes that all characteristics are constant across the catchment (Chow, 1972). Lumped parameter models are considered much simpler in their treatment of spatial variation. In this kind of model, each parameter is described by a value that is uniform for the whole catchment. The parameters of lumped model could not be determined directly from physical characteristics of the catchment under consideration. They are generally determined via calibration (Chow, 1972; Madsen, 2003). Consequently, this kind of model can not classify the hydrological process precisely. Moreover, the lumped model merely assess the catchment responses simply at the outlet without obviously counting for individual sub-basin responses(Cunderlik, 2003).

In contrast, distributed model is constructed in order to divide the catchment into sub units. Each unit represents of all physical characteristics for a real area. These kinds of models maintain the physical details at a given grid size and consider the distributed nature of hydrological properties such as soil type, slope and land use (Refsgaard, 1997; Vansteenkiste *et al.*, 2013). In principle, the parameters of distributed model could be gotten from the catchment data. For this reason, distributed model is evaluated to be able to translate the hydrologic process in a catchment more accurately and concretely. One more advantage of distributed model is that the outputs, such as water level, discharge, hydrological factors, could be perfectly extracted at anywhere in the catchment. These efficiencies of distributed model help to overcome difficulties in the lack of observed data, which have a great significance for simulating the hydrological process at a large catchment, especially in developing countries.

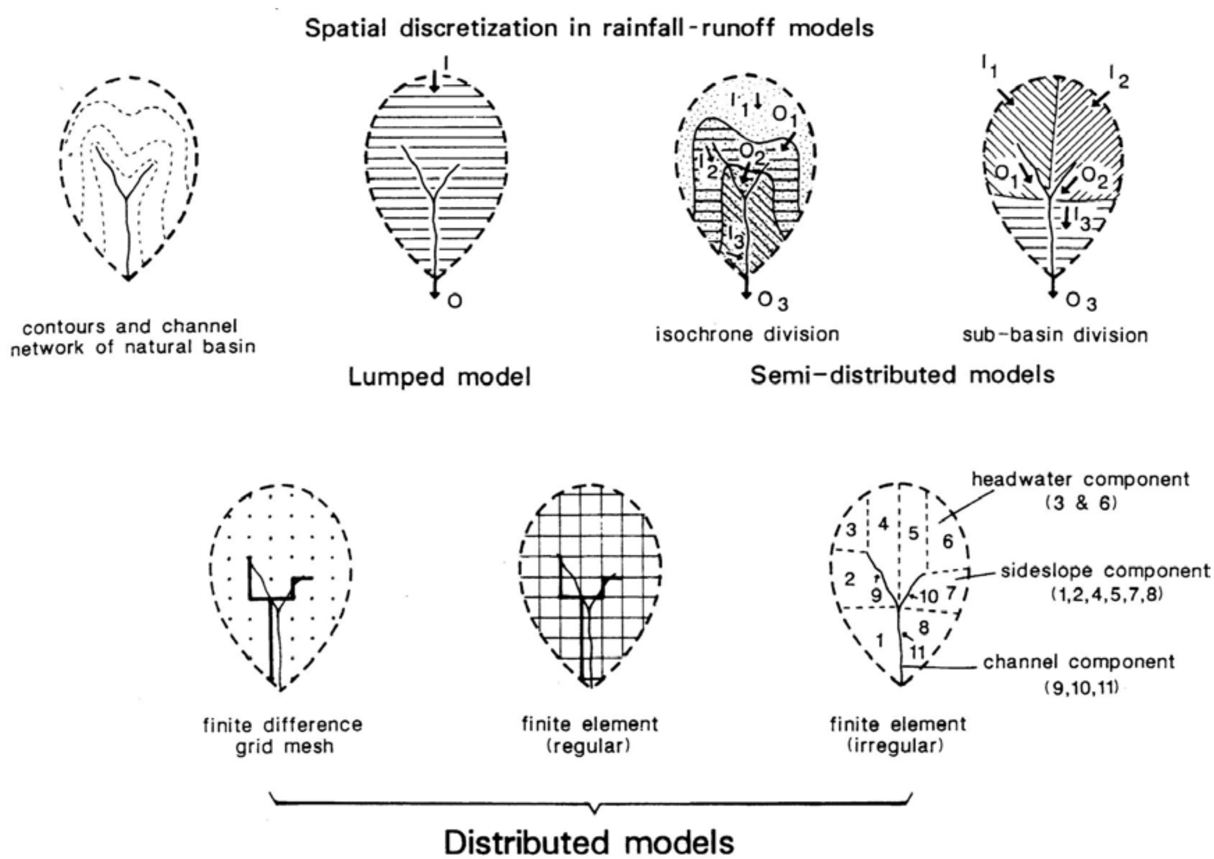


Figure 3.4. Graphic representation of geometrically – distributed and lumped models (Jones, 1997) . I is input and O is output.

Beside the superiority, distributed model still exists weak points. Although the spatial input data such as topography, soil type, land use nowadays might be available, it is not really easy to find the spatial data for calibration or validation (Beven, 1996). This leads to the quality estimation of distributed model in the whole catchment being mostly unable, so the calibration and validation are able to merely carry out against the data at several gauging stations. Additionally, this model type commonly consists of more parameters than lumped models thus the calibrated process is more complicated and difficult to achieve the acceptable values (Reed *et al*., 2004). However, Refsgaard (1997) noted that more detailed physically base and spatially distributed models are assumed to give a detailed and potentially more correct description of the hydrological process in the catchment. As a result, they might provide more accurate prediction.

For above reasons, an intermediary of two kind of model above has been developed to harmonize the conveniences together with inconveniences between simple and complicated spatial distribution. This is semi-distributed model, which is partly permitted to change in space with division of catchment into an amount of sub basin. Hence, semi-distributed is seen as a more physically-based structure in comparison with the lumped model. However, it requires lesser amount of input data in contrast with the fully distributed model (Cunderlik, 2003).

e. The distinction between deterministic and stochastic model.

Relying the relation between model variable and random, Chow *et al.*, (1988) divided hydrological model into two sub model types. The first is the deterministic model which does not include elements of randomness. Every time you run the model with the same initial conditions you will get the same results. The second is stochastic model which includes elements of randomness. Every time you run the model, you are likely to get different results, even with the same initial conditions. A probabilistic model is one which incorporates some aspect of random variation. As a result, deterministic model is estimated to be more suitable in order to make a forecast while a stochastic model is frequently used to create a prediction (Chow *et al.*, 1988; Harun *et al*., 2012).

3.3 Hydrological model comparison

3.3.1 Model overview

With above theories, in recent years, many hydrological models have been developed. Their simulations help to represent a part of hydrological cycle. They demonstrated the usefulness in many aspect of human society. Following (Table 3) are the brief summary of several models which are used widely in current. In this table, the model is classified following the content of section 3.2. Besides, the data requirement is preliminarily expressed in order to supply a point of view for fitting the most suitable model with the catchment.

The comparison in Table 3.1 is to provide an overview of available hydrological models which might be helpful for model selection process.

Table 3.1 Hydrological model availability.

Name of model	Attributed to / developped by	Spatial representation	Process representation	System representation	Data requirement	Brief description
HYRROM Hydrological Rainfall-Runoff Model	UK institute of Hydrology (UNESCO, 1997)	Lumped	Conceptual	Deterministic	Precipitation	Flow simulated with simple representations of physical processes. Easy to use. Nine parameters available for calibration.
SWM4 Stanford Watershed Model	U.S. Environmental Protection Agency (Crawford & Burges, 2004)	Lumped (can be quasi-spatially variable)	Quasi-physical but considered conceptual	Deterministic	Precipitation and potential evapotranspiration, radiation, temperature, cloud cover, wind, tide.	Uses a soil moisture accounting procedure and represents hydrological processes within the drainage basin through storage and routing functions.
HBV Hydrologiska Byråns Vattenbalansavdelning	Swedish Meteorological and Hydrology Institute	Lumped (can be modified to semi-distributed and elevation zones)	Conceptual	Deterministic	Sub-basin division, altitude and land cover distribution, time series of precipitation and temperature.	Originally a forecasting and simulation tool. Daily rainfall-runoff model with conceptual numerical descriptions of hydrological processes at catchment scale.
TOPMODEL	University of Leeds, UK	Semi-distributed - subdivision into small homogenous sub-basin units modelled separately	Physically-based	Deterministic, but can be run stochastically	Topographic data, limited soil data, other parameters from direct measurement.	Collection of concepts that can be used and adapted to specific study. Combines spatial variability of source-areas with average response of basin soil-water storage

SLURP Semi-distributed Land Usebased Runoff Processes	National Hydrology Research Institute, Canada	Semi-distributed - divides the watershed into hydrologically-consistent sub units known as aggregated simulation areas	Conceptual (quasi physical)	Deterministic	Topographic data, land cover data, climate and hydrometric data.	Continuous simulation model. Parameters related to land cover. Most important parameters in model include interception coefficients, depression storage, surface roughness, infiltration coefficient, groundwater conductivity and snowmelt rates.
SWAT Soil and Water Assessment Tool	United States Department of Agriculture – Agriculture Research Service	Semi-distributed (HRUs) – grid discretization at users choice.	Physically-based	Deterministic	Multiple inputs ranging from precipitation, temperature, solar radiation, wind speed, PET, land cover, elevation, fertilizer. Available input at varying discretization	River basin scale model developed to quantify impact of land management practices in large, complex watersheds. Daily time step. Divides catchment into HRUs where sub basins have homogenous climate, soil, management and land cover.
HEC-HMS Hydrologic Engineering Center-Hydrologic Modeling System	US Army Corps of Engineer	Lumped, semi-distributed	Physically-based	Deterministic	Various parameter data for: Topography, Precipitation, temperature, land use, evapotranspiration, overland flow, unsaturated zone flow, saturated zone flow, groundwater.	It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, small urban or natural watershed runoff.

WATFLOOD	University of Waterloo	Lumped, semi-distributed or Distributed	Physically-based	Deterministic	Radar rainfall data, LANDSAT or SPOT land use and/or land cover data. Gauged precipitation for infilling and calibration, flow, snow depth, temperature and radiation.	Flood forecasting and long-term simulation using distributed precipitation data from radar or numerical weather models. Satellite data directly incorporated into model. Multiple processes modelled including interception, infiltration, snow accumulation and ablation, recharge, base flow.
SHETRAN	Newcastle University, UK	distributed	Physically-based	Deterministic	Various parameter data for: topography data, river geometrical data, geological and land use data, hydrometric data, physical properties of the soil.	The model comprises three main components, of each for water flow, sediment transport, and solute transport. These tree components is assumed to lie in a natural hierarchy. This model can be applied to parts of basins or a group of continuous basins.
MIKE SHE	DHI Water & Environment	Lumped, semi-distributed or Distributed	Physically-based (with some components optional conceptual approach)	Deterministic but with ability to run stochastically using a Monte-Carlo autocalibration method.	Various parameter data for: Topography, Precipitation, temperature, land use, evapotranspiration, overland flow, unsaturated zone flow, saturated zone flow, groundwater.	Modular structure comprising six process orientated components representing physical processes of land phase of hydrological cycle. Data is input discretely in a horizontal orthogonal network of grid squares so that the parameters can be represented at a high spatial resolution.

3.3.2 Selection criteria

The criteria for selecting a hydrological model depends on many factors. These criteria commonly change due to the purpose of study, such as planning or operation, which basically require different kinds of hydrological models (Plate, 2009). They also depend on real condition of catchment, data availability (Ng & Marsalek, 1992). However, these criteria concentrate generally on four fundamental following requirements (Cunderlik, 2003):

- Require model outputs important to the project and therefore to be estimated by the model;
- Hydrologic process that needs to be modeled to estimate the desired outputs adequately;
- Availability of input model;
- Price.

With any studies, the first requirement for choosing a hydrological model is how to describe the most accurately the processes of catchment in certain conditions. For this purpose, an insight was proposed that the more detailed the characteristic of catchment the model is, the more detailed and potentially more correct descriptions of hydrological process the model represents (Refsgaard, 1997; Vansteenkiste *et al.*, 2013). Consequently, it could reduce the uncertainty of the model in simulating the hydrological events and forecasting for the future. Have not consider the economic problem and data availability, in order to choose a suitable hydrologic model for estimating the impact of climate change to hydrologic process of a catchment, Cunderlik, (2003) proposed that the selected model must have the capacity to answer under requirements:

- The selected model could supply:
  - Simulated low peaks (stage, discharge), volumes and hydrographs at outlets of sub basins, and in the profiles of special interest within the main basin;
  - Simulated long flow sequences for water budget and drought analyses primarily for the main basin but preferably also for the individual sub basin;
  - Simulated extend of flooded area for different precipitation events and various antecedent basin conditions.
- The main hydrologic processes that need to be captured in the structure of the hydrologic model in order to adequately estimate the required project's output are:

- Single-event precipitation runoff transformation based on various antecedent basin conditions and spatial and temporal precipitation distribution;
- Continuous precipitation run off transformation based on various antecedent basin condition and temporal precipitation distribution;
- Snow accumulation and melt;
- Interception and infiltration, soil moisture accounting;
- Eva transpiration;
- Regulated reservoir operation.

Table 3.2a Standard for model selection proposed by WMO (Wittwer, 2013)

Model type	Question 1	Catchment size?		
		Small (headwater)	medium	large
	Catchment model	lumped	semi distributed	distributed
	Routing	mostly not needed	hydraulic/hydrology	hydraulic, hydrology, gauge to gauge correlation
	Question 2	Catchment relief?		
		Flat/plain	Moderate/hilly	Pronounced/ Mountainous
	Catchment model	lumped	semi distributed	distributed
Model features	Question 3	Does soil wetness effect flood generation?		
		no	to some extent	yes
	Soil water budget feature required	not need	recommended	need
	Question 4	Is snowmelt important for flood generation?		
		no	to some extent	yes
	Snow module	not need	recommended	need
	Question 5	Is river regulation (reservoir/lake/ diversions) affecting floods?		
		no	to some extent	yes
	Storage module	not need	recommended	need

Table 3.2b Standard for model selection proposed by WMO (Wittwer, 2013)

Data requirements	Question 6	What is the predominant flood causing rainfall?		
		Seasonal	frontal/ advective	convective
	Recommended data resolution	daily	daily/hourly	hourly/ sud-hour
	Question 7	What is the required leadtime?		
		Short	Medium	Long
	Required rainfall data	Observed rainfall	Rainfall nowcast is recommended (e.g radar)	rainfall nowcast and/or forecast from NWPs is required
Constraints	Question 8	Is distributed/ gridded data available?		
		no	yes	
		Lumped model is only option	semi-distributed/ distributed model is feasible	
	Question 9	What is the level of capacity of the service?		
		low	intermediate	high
		only simple toll feasible (correlation, etc)	run lumped/ black box simple model	all option available

Furthermore, towards large catchments where hydrological components are in interactive relations, the understanding completely the hydrological mechanics in large scale is inextricable. It leads to modeler could not define which one is the main factor affecting to stream flow. So for these cases, using a distributed model is need to simulate the rainfall runoff behavior (Wittwer, 2013).

According to the report of WMO, a distributed hydrological model is expected to describe more accurate than others in where the topography varies much. This insight might rely on the catchment expression as grid scale of distributed model. Through that, these kind of model will present more truthfully the slope variation. The Table 3.2 indicate the standards which WMO recommend to choose a model for simulating the hydrological cycle at a catchment (Wittwer, 2013).

The criteria are applied to select the most suitable model for simulating the hydrological process of Vu Gia Thu Bon Catchment, also for assessing the impact of climate change to run off of this catchment. Comparing these standards with catchment situation, the deterministic distributed model is recognized as the best solution for hydrological modelling at this catchment.

3.4 MIKE SHE model

Comparing the criteria of Cunderlik, (2003) and the advantages/disadvantages at the section of 3.2 demonstrates the higher performance of fully distributed physically-based hydrological model forward other kinds of model in hydrological simulation. The structure of fully distributed physically-based hydrological model is a combination of the distributed characteristic and physical interpretation the hydrological process, hence it is expected to provide significant advantages over existing hydrological models for a wide range of application. This kind of model has the ability to apply to simulate in almost components of hydrological process. Furthermore these process are solve at the grid scale, thus it helps to overcome the data problem at large catchment, catchment with limited data as well. This advantage is highlighted as one of the most fascinating aspects of physically-based distributed model. Consequently, the main interest of a fully distributed physically-based hydrological model is to be able to provide hydrological information at any locations within the catchment. The catchment characteristics are able to input the model as detailed as possible, besides, it also helps to reflect the catchment nature truthfully, thus hoped to reduce the uncertainty in simulation and increase confidence in simulation. This possibility also allows to investigate in depth the hydrological dynamic of catchment. The model calibration can be ignorable because of describing in reality the physical hydrological components or this is able to realize with the simplest ways in comparison with any other models (Abbott *et al.*, 1986). Several tools are today available and could be used for such analysis. The typical of this kind of model is MIKE SHE developed and extended by DHI Water & Environment.

3.4.1 MIKE SHE philosophy

Aims to provide scientific information for optimizing the water resource project planning, also for estimating the impact of urbanization, land use change, infrastructural development on hydrological process and on water resource development and management in Europe at the years of decade 70s, a new generation of hydrological model, which focuses on physically based distributed catchment model, is required. The model is hoped to have the potential to overcome many of the deficiencies related with simpler approaches at these time. The European Hydrological System- Système Hydrologique Européen or SHE was born in this situation to answers this requirement. After getting the success in modelling the hydrological phenomenon in Europe, SHE has become the starting point for many physically based spatially distributed hydrological models, such as SHETRAN, SHESED, MIKE SHE (Ewen *et al*., 2000). SHE was a production of the corporation between three big European establishments in domain water modelling including the British Institute of Hydrology, UK, The Danish Hydraulic Institute and the French Consulting Company SOGREAH under the financial support of European Commission (Abbott *et al*., 1986).

The SHE model was built fundamentally on the blueprint which proposed by Freeze and Harlan in 1969 for modelling hydrological cycle (Abbott *et al.*, 1986). According to blueprint theory, the run off process is divided to many different parts and solved by corresponding equations. The using different equations focused on representing the most accurately the physical characteristics of each part in the catchment (Freeze & Harlan, 1969). The algorithm is developed independently at three organizations under the form of software module, the Institute of Hydrology, UK is responsible for snowmelt, interception and evapotranspiration, overland flow and channel flow is constructed by SOGREAH and the Danish Hydraulic Institute is in charge of the flow components in unsaturated and saturated zone, and linking the module together(Abbott *et al*., 1986).

After lots of tests to validate the quality of model with many case studies, the first version of SHE was become operational in 1982. From that time, the SHE model has been continued completing and extending by DHI Water & Environment with the new name, MIKE SHE. This model is kept developing to improve the quality simulation. Today, MIKE SHE is estimated as a high performance model for hydrological modelling. It includes a full suite of pre- and post-processing tools, plus a flexible mix of advanced and simple solution techniques for each of the hydrologic processes. MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modeling study, the availability of field data and the modeler's choices, (Butts *et al.*, 2004; Graham & Butts, 2005a).The MIKE SHE user interface allows the user to intuitively build the model description based on the user's conceptual model of the watershed. The model data is specified in a variety of formats independent of the model domain and grid, including native GIS formats. At run time, the spatial data is mapped onto the numerical grid, which makes it easy to change the spatial discretization (Graham & Butts, 2005a).

MIKE SHE uses MIKE 11 to simulate channel flow. The MIKE SHE/MIKE 11 coupling allows you to simulate large water bodies such as lakes and reservoirs, as well as flooded areas. If this option is used, MIKE SHE/MIKE 11 applies a simple flood-mapping procedure where MIKE SHE grid points, are linked to the nearest H-point in MIKE 11. Surface water stages are then calculated in MIKE SHE by comparing the water levels in the H-points with the surface topographic elevations. Conceptually, you can think of the flooded cells as "side storages", where MIKE 11 continues to route water downstream as 1D flow. But, at the same time, the water is available to the rest of MIKE SHE for evaporation and infiltration. The effect of urban drainage and sewer systems on the surface/subsurface hydrology can be simulated in MIKE SHE model via the coupling with the MOUSE model and nowadays it develops to couple MIKE URBAN and MIKE SHE (DHI, 2012f).

3.4.2 MIKE SHE architecture

The preeminence of deterministic, physics-based, distributed model code in hydrological domain has already been demonstrated via analysis in the part of 3.3. These good points have been concretized in MIKE SHE model. However, beside the capacity to translate accurately the hydrological process for catchment, the applicability of deterministic physics-based distributed model in reality confronts several difficulties. The requiring a significant amount of data or long execution time are the most important limitation when applying the physical base model. And one question, is it really necessary to simulate all hydrological components in one model? How it will improve the simulation quality when the just one or two hydrological processes dominate the watershed behavior (Graham & Butts, 2005). These two authors also give a judgment that a complete physics based flow description for all process in one model is rarely necessary. Over-parameterized description may occur for simple applications. Hence, in order to respond flexibly the simulated ways can occur in practice, MIKE SHE has been developed with many simulated methods, such as lumped, conceptual. This integration is organized in modular approach which include several solution techniques to translate the different processes in nature. It can help to optimize the function of each component when simulating for a complicate catchment. Each of hydrological processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study, the availability of field data and the modeller's choices, (Butts *et al*., 2004). The Figure 3.5 presents a schematic overview of the processes in MIKE SHE model. According to that, hydrological process is divided into eight parts in MIKE SHE model. The description of these parts is briefed as follows.

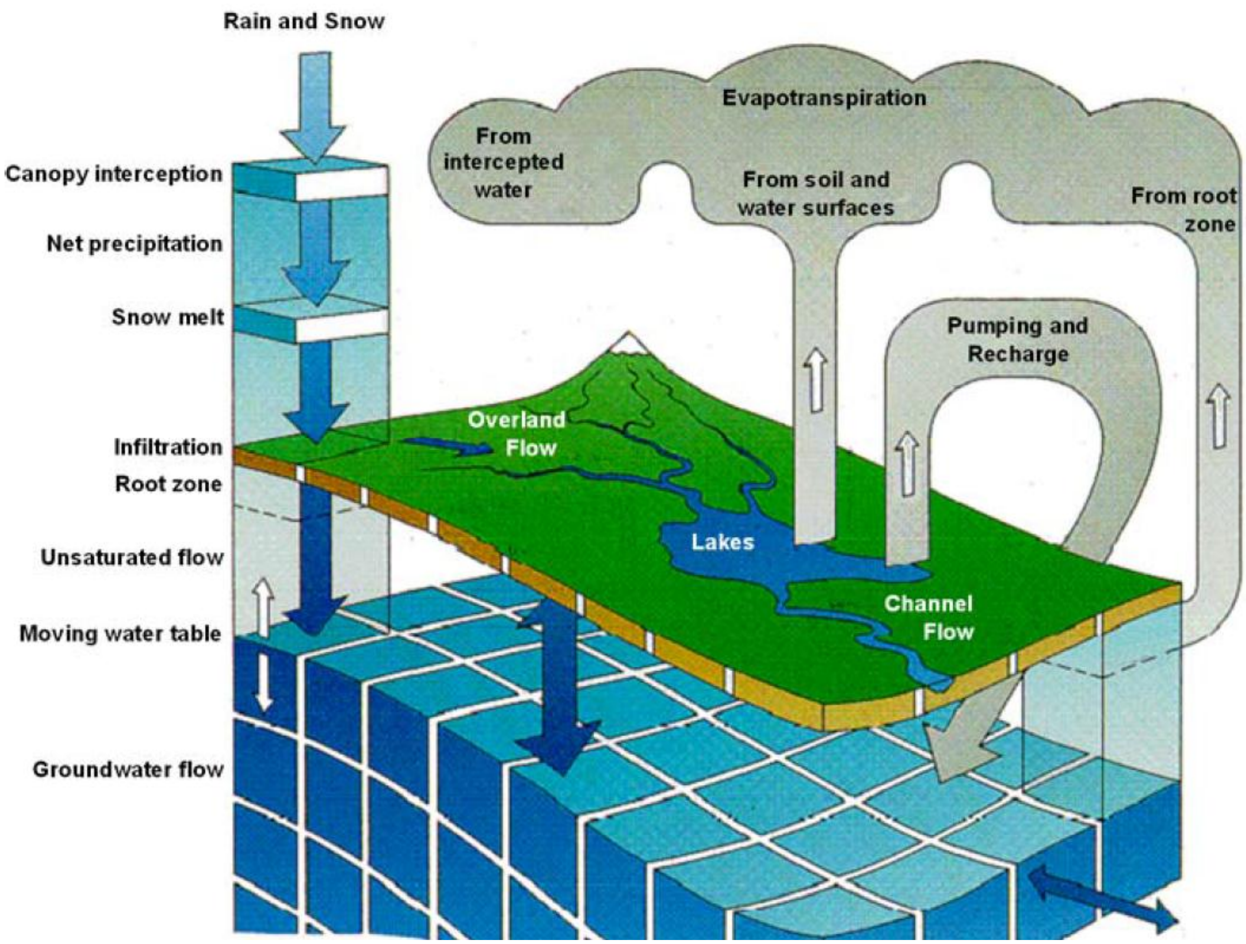


Figure 3.5. Schematic of MIKE SHE model (DHI, 2012e).

a. Precipitation

Precipitation is a key factor in hydrologic process. Hence, it is always the first data requirement with any rainfall run off model. This input data affects much on the simulation quality. In MIKE SHE, precipitation data can be input as a constant value or a time series depend on data availability and simulation objective. MIKE SHE supplies three spatial distributed format for rainfall input, such as uniform, station based or full gridded spatial distribution. The first format generally is applied for a small catchment or lack of surveyed data. The second one is suitable with locality where the density of gauging station is relatively high. The famous of this type is Thiessen Polygons. The last one is the best in representing the precipitation data. It is expected to improve the simulated quality. However, this data is quite complicated to obtain because Precipitation is typically measured at only a few locations within a watershed. In fact, this data is not available. It is generally gotten via several interpolated methods (more about the rainfall distribution will be express at section of 3.5). MIKE SHE also provides a tool to correct the rainfall variation due to the elevation via Precipitation Lapse Rate. Snow melt is an important phenomena that can dramatically affect the spring runoff timing and volume. Therefore, a realistic description of the snow melt process is important. In order to take into account the impact of snow the stream river, MIKE SHE includes a comprehensive snow melt module based on a modified degree-day method. Precipitation that occurs when the air temperature is below the freezing point accumulates as solid snow and does not infiltrate or contribute to runoff. The accumulated snow has a moisture content, and when the moisture content reaches a critical level, then additional melting contributes to runoff. For snow melt, the air temperature. The format of this data can be organized like precipitation.

b. Evapotranspiration

In water balance, the evapotranspiration is an important component. This factor is composed from evaporation and transpiration. Evaporation, which water changes from a liquid to gas or vapor. In hydrology, it is estimated as the primary pathway that water moves from the liquid state back into the water cycle as atmospheric water vapor. It occurs from free water surface including lakes, river, snow surface or from the soil. The evaporated amount might be affected by many factors such as temperature, humidity, wind, or soil wetness, soil hydraulic properties, groundwater table. In different way, the transpiration is decides by plant physiology - the depth of the roots, the ability of the roots to extract water from the soil or characteristics of leaves (Graham & Butts, 2005a). In MIKE SHE, the calculation of evapotranspiration uses meteorological and vegetative data to predict the total evapotranspiration and net rainfall due to many components: interception of rainfall by the canopy, drainage from the canopy to the soil surface, evaporation from the canopy surface, evaporation from the soil surface, and uptake of water by plant roots and its transpiration, based on soil moisture in the unsaturated root zone (DHI, 2012e). MIKE SHE 2012 supplies three methods to determine the amount of actual evapotranspiration (ET).

- Soil Vegetation Atmosphere Transfer (SVAT)

This model was developed based on a system what consist of two layer (soil and canopy) and their resistance network link (Shuttleworth & Wallace, 1985). This model includes a single, semi-transparent canopy layer located above the soil layer. In this model, actual evapotranspiration is calculated directly from standard meteorological and vegetation data. This process is not dependent on Reference evapotranspiration (Graham & Butts, 2005a).

- Kristensen and Jensen Method.

In this method, the actual ET is estimated by using empirically derived equations Kristensen and Jensen (Kristensen & Jensen, 1975). This equation was established at the Royal Veterinary and Agricultural University in Denmark. The equation is a result of summarizing the field measurement. The model uses the above equation to solve the relationship between the reference evapotranspiration rates, maximum root depth and leaf index of the plants to give the actual evapotranspiration and the actual soil moisture status. The precipitation is assumed not occur as snow because of considered temperature of model is above 0°C. The required data for this method is time series of the Reference ET, the leaf area index and the root depth, and other empirical parameters that control the distribution of ET with the system (Graham & Butts, 2005a).

The mechanism of this method can be expressed as follow: firstly, the water intercepted by the leaves is removed from total rainfall. This number will drop into ground surface where it can infiltrate or pond. Based on the ponded at reference ET and the net rainfall, the model will calculate the evapotranspiration. If amount of evapotranspiration is till smaller than Reference ET at current time step, the water loss will be continue subtracting by transpiration. The ET distribution between unsaturated zone and saturated zone relies on root's depth. The evapotranspiration is extracted from saturated zone only when the roots of vegetable are in contact with water table (DHI, 2012e). This is very important to calculate the evapotranspiration at swamps, wetlands, flood season… Kristensen and Jensen Method is required when using the Richards equation and gravity flow methods in the unsaturated zone (Graham & Butts, 2005a).

- Two Layer Water Balance Method.

Aims to reduce the complexity of simulating the transpiration process at water flow at unsaturated zone. MIKE SHE proposes a simplified water balance method. This method is Two Water Balance Model which divides the unsaturated zone in two part. The first is root zone where evapotranspiration mostly occurs. The second part is below the root zone, where does not affect much on the evapotranspiration process. This model is constructed based on the research of Yan & Smith (1994). The main objective of this model is to calculate the actual evapotranspiration and solve the relation between surface and ground water. The simulation process in Two Water Balance Method progresses as Kristensen and Jensen Method. Following that, the evapotranspiration is determined via the processes of intercepted water, then ponded water and finally transpiration from root zone. However, it does not take into account flow dynamics that is different with Kristensen and Jensen Method. The data requirement of this model is like Kristensen and Jensen Method including the time series for root depth, leaf area index and Reference Evapotranspiration (Graham & Butts, 2005a) .

This method is particularly suitable with swamps or wetlands area where the ground water table is shallow. In these cases, the actual evapotranspiration rate is closed to the reference rate. In areas with the deeper and drier unsaturated zone, the Two Layers Water Balance Method is inefficient. However model result can be acceptable via calibration (Graham & Butts, 2005a).

c. Unsaturated Flow

Naturally, in unsaturated zone, the flow can be expressed with vertical and horizontal ways. However, under the domination of gravity, the vertical way gets upper hand. Hence, MIKE SHE assumes that there is only vertical flow in unsaturated zone and it ignores the lateral movement (Figure 3.6). This assumption is applicable for most situation. However, it may limit the validity of the flow direction in several case, such as on very steep hill slopes or in small scale models with lateral flow in the unsaturated zone where the intensity of lateral and vertical flow is roughly similar. The mechanism is imitated on cyclic functions in the soil moisture. The rainfall fulfill the soil moisture. Then, the water in this part will extracted for evapotranspiration and recharge to the groundwater table. Depending on deferent engines, the UZ flow component is able to simulate with four solution options as follows:

- Richards Equation

The full Richards equation (equation 3.1) is developed based on the continuity equation and Darcy’s law. The method uses the vertical gradient of hydraulic head, which includes both a gravity and a pressure component, to represent the water movement in unsaturated zone. The pressure head as a function of saturation (moisture retention curve) and hydraulic conductivity are necessary for this method. The evapotranspiration factor is calculated as a root extraction in the upper part of the unsaturated zone. The amount of total actual evapotranspiration is equals with the integral of the root extraction over the entire root zone depth.

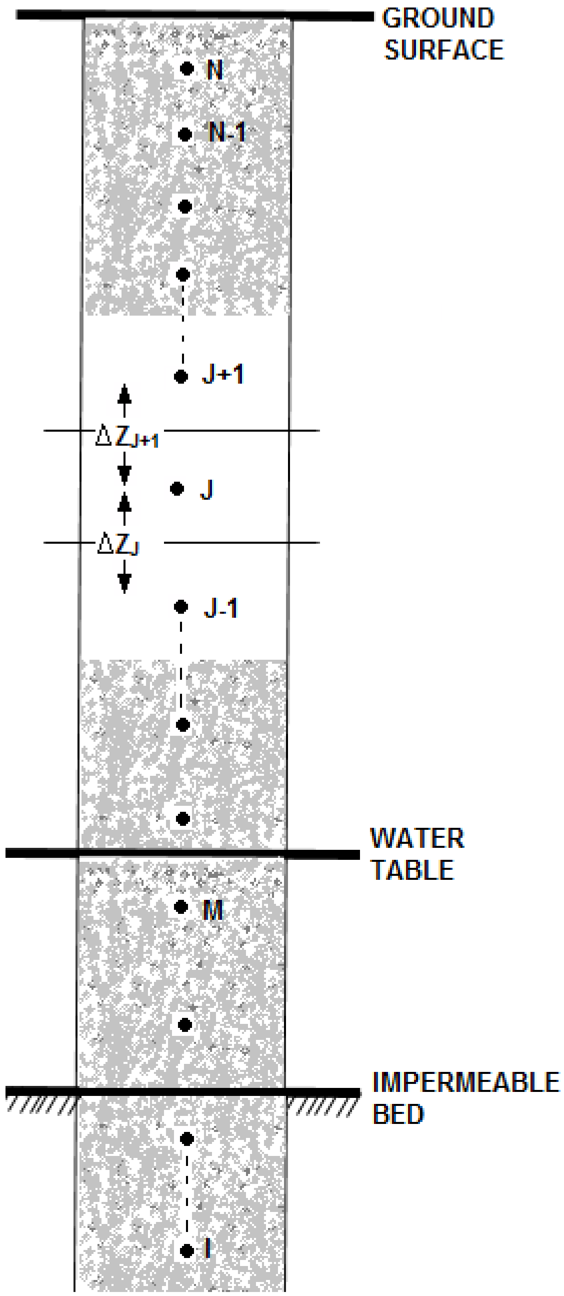


Figure 3.6. Vertical discretization in unsaturated zone. (DHI, 2012e)

Direct evaporation from the soil is considered only for the first node below the ground surface.

$$C\frac{\partial\Psi}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial\Psi}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} - S \qquad (3.1)$$

Where ψ is pressure head

θ is the volumetric soil moisture

K(θ) is the unsaturated hydraulic condictivity

Z is the gravitational component

S is the root extraction sink term

T is the time component

C is the soil water capacity

This method is the most accurate for describing the flow in unsaturated zone. However, it is limited in computational time due to its complexity. It is primarily suitable for study of unsaturated zone flow dynamic.

- Gravity Flow

The limitation about the computational time of Richards equation method is improved with Gravity Flow method. By assumption that the gravity is the main role in vertical driving force, Gravity flow ignores the effect of pressure head term to vertical flow in unsaturated zone.

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S(z) \qquad (3.2)$$

Where θ is the volumetric soil moisture

K(θ) is the unsaturated hydraulic condictivity

Z is the gravitational component

S is the root extraction sink term

T is the time component

In the Gravity Flow Module, Equation 3.2 is solved explicitly from the top of soil column downward. At the top of soil column, the depth of overland water in the ground surface is hypothesized the amount of water available for infiltration, which is used as infiltration rate in the first step and as the maximum infiltration rate for the soil column. The data requirement of this method is only the conductivity –saturation relationship.

In comparison with full Richards equation, this simplified method is faster and more computationally stable. This is applicable for coarse soil which capillary pressure is quite small and for project focus on the accuracy of evapotranspiration, of recharge to groundwater, but do not care the dynamics in unsaturated zone.

- Two-Layer Water Balance

This method was presented at evapotranspiration part. Accordingly, the two layer water balance method divide the unsaturated zone in two part, root zone and below one. This assumes the unsaturated zone storage is inconsiderable. Thus two layer water balance method does not take into account this component in infiltration and it supposes all infiltrated flow recharge immediately to saturated zone. The simple of this engine helps to reduce lot of simulation time at least with the long simulation. This method is particularly suitable with swamps or wetlands area where the ground water table is shallow.

- Lumped Unsaturated Zone Calculation (Column Classification)

Lumped Unsaturated Zone Calculation is applicable in the case of identical unsaturated flow conditions. The unsaturated flow conditions in two cell is considered as identical if they answer completely two following conditions:

- The first is identical soil and vegetation characteristics.
- And the second is boundary conditions.

In this context the flow in unsaturated zone can be calculated in one of cell which is as a representative of group. Then other cell can refer on the result of this cell. This method gives approximated accurate results for water balance simulation. It is not very accurate for local dynamics, because it does not account the influence of this procedure on the flow simulation. Applying Lumped Unsaturated Zone Calculation for unsaturated flow simulation helps to make this process shorter.

In summary, DHI (DHI, 2012e) releases comments as: The full Richards equation method is the most computationally intensive but also the most accurate when the unsaturated flow is dynamic. The simplified gravity flow procedure provides a suitable solution when you are primarily interested in the time varying recharge to the groundwater table based on actual precipitation and evapotranspiration and not dynamic in the unsaturated zone. The two simple layer water balance method is suitable when the water table is shallow and groundwater recharge is primarily influenced by evapotranspiration in the root zone. Lastly, Lumped Unsaturated Zone Calculation is suitable with long time simulation at homogeneous zone.

Besides, MIKE SHE also describes the flow through macropores in unsaturated soil which is important for many soil types. There are two selections of representing flow type in MIKE SHE, Simple bypass flow and full macropore flow.

Simple bypass flow - A simple empirical function is used to describe simple bypass flow in macropores. The infiltration water is divided into one part that flows through the soil matrix and another part, which is routed directly to the groundwater table, as bypass flow. The bypass flow is calculated as a fraction of the net rainfall for each UZ time step. The actual bypass fraction is a function of a user-specified maximum fraction and the actual water content of the unsaturated zone, assuming that macropore flow occurs primarily in wet conditions (DHI, 2012e).

Full Macropore Flow - Macropores are defined as a secondary, additional continuous pore domain in the unsaturated zone, besides the matrix pore domain representing the microporous bulk soil. Macropore flow is initiated when the capillary head in the micropore domain is higher than a threshold matrix pressure head, corresponding to the minimum pore size that is considered as belonging to the macropore domain. Water flow in the macropores is assumed to be laminar and not influenced by capillarity, thus corresponding to gravitational flow (DHI, 2012e).

In order to overcome the capacity of 2-Layer WB and the Gravity Flow UZ solution methods about the capillarity simulation, DHI provides the The Green and Ampt infiltation function which is an analytical solution to the increased infiltration experienced in dry soils due to capillarity.

The coupling the unsaturated zone to saturated zone is solved by an iterative mass balance procedure. This linking ensures a realistic description of water table fluctuations in situation with shallow soils. However, there is a difficulty in solving the linkage between the two saturated and unsaturated zone which are arisen from the fact that these two components are explicit coupled and run in parallel. This couple is not solved by a single matrix with an implicit flux coupling of the unsaturated zone and saturated zone differential equations. A great advantage of this kind of coupling is that, they are run with different time steps. It helps to optimize computational time at each other’s.

d. Overland Flow

The surface run off can be caused from ponded water which has the tendency to flow downhill towards the river system. The ponded water can be from the remaining rainfall water after the losses of infiltration and evapotranspiration, or river flow flood over their banks or groundwater flows onto the surface. The characteristics and quantity of this hydrological components are defined by the topography and flow resistance as well as the losses due to evapotranspiration and infiltration along the flow path. MIKE SHE provides two methods for representing this main kind of component of hydrology.

- Finite difference Method.

MIKE SHE handles the St. Venant equations to solve the run off in the ground surface. However, because of complexity, this equation is simplified by ignoring momentum losses due to local and convective acceleration and lateral inflows perpendicular to flow direction. After simplifying, it becomes the diffusive wave approximation. This method is suitable with simulating the free surface flow, the shallow water depth or slow velocity of surface water. The diffusive wave approximation is solved by using two dimensions difference approach to represent the relationship between the rainfall, evapotranspiration, infiltration and the surface flow. For this method, it is necessary to supply into the model three parameters:

- The Manning number which describes the friction of ground surface,
- The detention storage – the parameter to limit the amount of water that can flow over the ground surface. It means that the overland flow process only occurs if the ponded water on the surface exceed this threshold. The detention storage is accounted for infiltration or evapotranspiration. This parameter also affects the exchange between overland flow and channel flow. This is like the threshold for exchange flow.
- Initial water depth: In most cases it is the best to start your simulation with a dry surface and let the depressions fill up during a run in period. However, if you have significant wetlands or lakes this may not be feasible. So this parameters is need for the model reach quickly with balance condition.

- Semi-distributed Overland flow

An empirical relation between flow depth and surface detention, together with the Manning equation describing the discharge under turbulent flow condition is handled in MIKE SHE to describe the overland flow (Crawford & Linsley, 1966). This method is known as Semi-distributed Overland flow and is applied in many hydrological model such as SWM, HSPF, WATBAL.

e. Channel Flow

In theory, the MIKE SHE model has the ability to simulate accurately the stream and river flow as two dimension surface flow if the topography data is fine enough. However, in fact, this requirement is very difficult to respond. The high resolution topography data is a big obstacle for applying this method. In generally, this data is not available at least with large catchment. Even If this data is available, the second problem is computation issue. With this kind of simulation, it is necessary to have a strong computer system and a longer simulation. In order to overcome this issue, the river flow is assumed as one dimension flow. This component is simulated by coupling with River hydraulic program MIKE 11 which is professionally developed based on an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. Moreover, the coupling between 1D and 2D model helps the MIKE SHE model can simulate a wide range of hydraulic control structure, such as weirs, gates and culverts… which the algorithm of MIKE SHE has been not developed yet. The coupling also gives the capacity to take into account the impact of tide to floodplain via boundary condition of MIKE11.

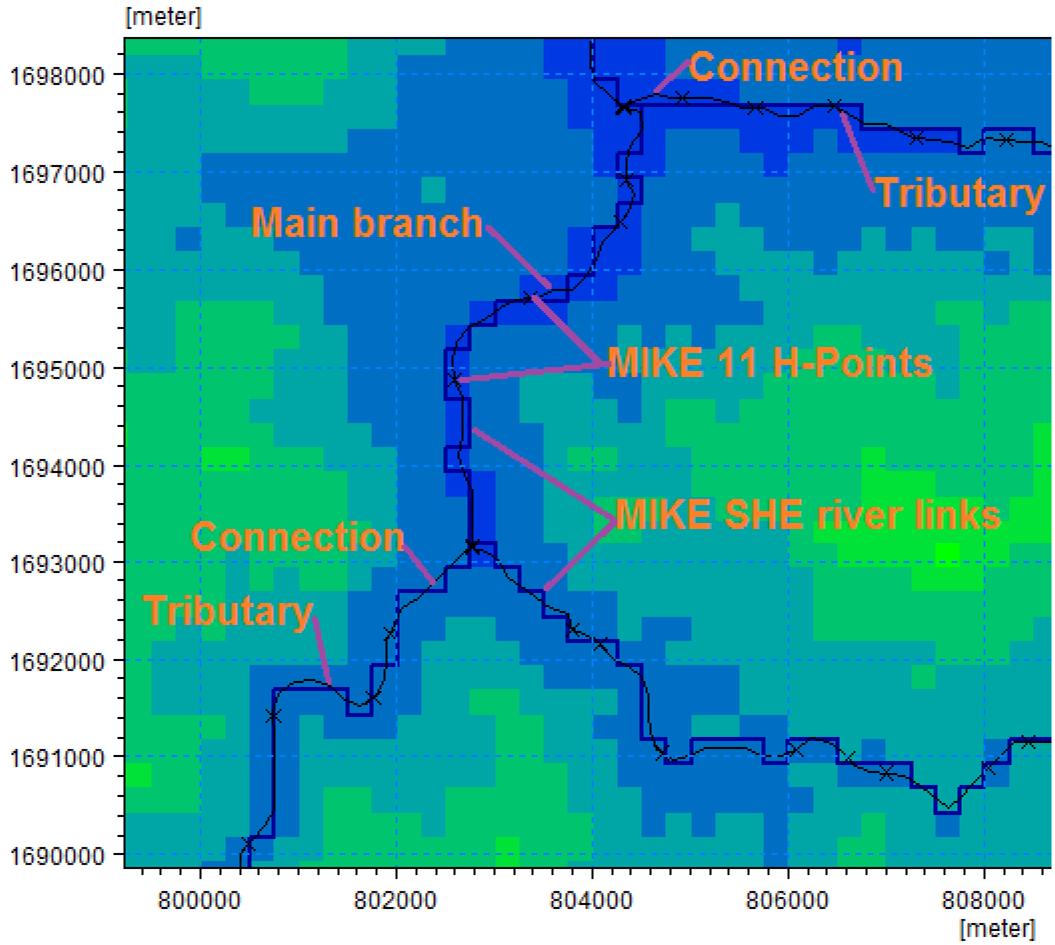


Figure 3.7. MIKE 11 Branches and H-points in a MIKE SHE Grid with River Links

The MIKE SHE/MIKE11 coupling is made via river links (Figure 3.7), which are located on the edges that separate adjacent grid cells. The river link network is created by MIKE

SHE's set-up program, based on a user-specified sub-set of the MIKE 11 river model, called the coupling reaches. The entire river system is always included in the hydraulic model, but MIKE SHE will only exchange water with the coupling reaches. Figure 3.7 shows part of a MIKE SHE model grid with the MIKE SHE river links, the corresponding MIKE 11 coupling reaches, and the MIKE 11 H-points (DHI, 2012e).

Exchange water between MIKE SHE and MIKE 11 is calculated by three principal different mechanisms (Figure 3.8): 1) Ground water exchange with MIKE 11. The river is located on the edge between two adjacent model grid cells. The river is considered a line source/sink to groundwater and the river is a one way sink for overland flow. 2) Flooding from MIKE 11 to MIKE SHE using flood codes.

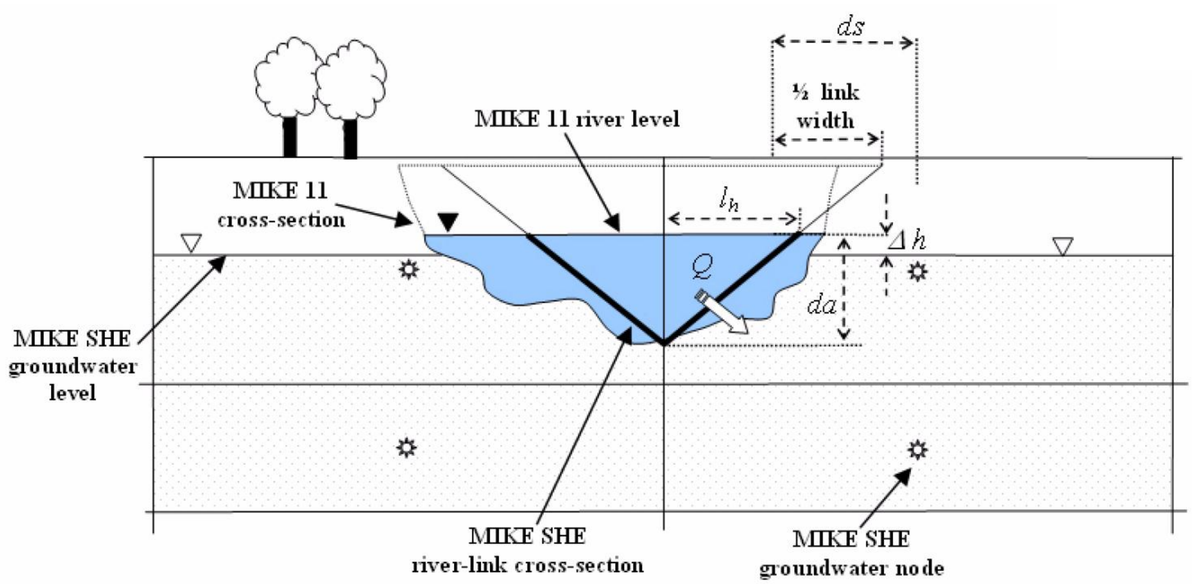


Figure 3.8. A typical simplified MIKE SHE River link cross section compared to the equivalent MIKE 11 cross section (DHI, 2012e).

The river has a wide cross section containing the flood plain and designated cell are “flooded” if the river water level is above the topography. 3) Direct Overbank spilling to and from MIKE 11. The river is line source/sink, but water above the bank elevation is allowed to flood onto the topography as overland flow.

f. Pipe and Sewer Flow

In urban area, the flow of urban drainage systems, sanitary and storm sewers have a significant effect on other component of hydrological process. They can drain both overland flow and ground water flow, and they can cause contamination of both surface water and groundwater (Graham & Butts, 2005a).

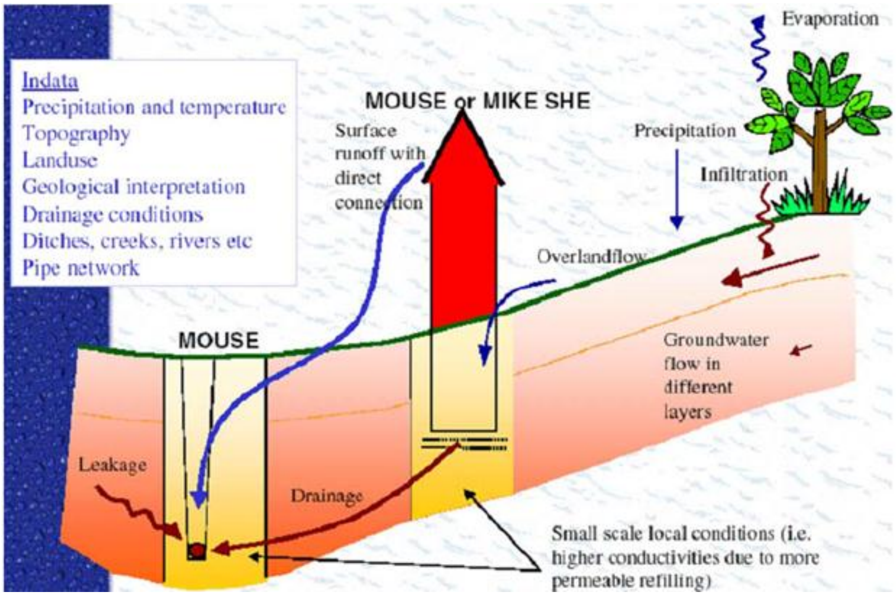


Figure 3.9. MIKE SHE to MIKE URBAN coupling linkage (DHI, 2012e).

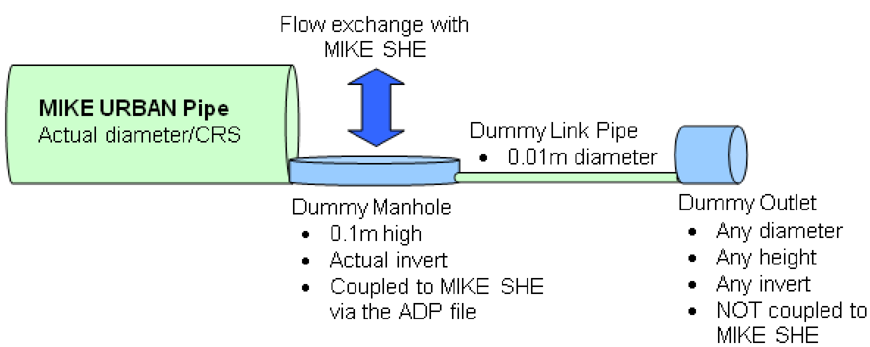


Figure 3.10. Linked mechanism between MIKE SHE and MIKE URBAN (DHI, 2012e).

In MIKE SHE this component is represented relied on the coupling with MIKE URBAN. This coupling is basically developed on the coupling between MIKE SHE and MOUSE. MOUSE (MIKE URBAN) can help to solve the flow parts in branches and looped pipe networks, with a mixture of free surface and pressurized systems. The coupling operates as two independent systems. These two systems exchange information at each time step and take it as the initial condition for next step. The water exchange is through the link (Figure 3.9) between MIKE SHE SZ and MIKE URBAN, MIKE SHE Overland flow to MIKE URBAN, MIKE SHE Overland flow to MIKE URBAN Manhole, MIKE SHE SZ drain flow to MIKE URBAN Manhole, MIKE Paver area to MIKE URBAN Manhole, and MIKE URBAN Outlet to MIKE SHE (Figure 3.10). The exchange is calculated based on the following equation (3.3)

$$Q = C.(H_{SHE} - H_{MOUSE})^K \quad (3.3)$$

Where Q is the exchange between MIKE SHE and MIKE URBAN (MOUSE), C is the exchange coefficient, K is head different component. H_{SHE} is the maximum value of the head in MIKE SHE cell, cell's elevation, manhole's elevation and H_{MOUSE} is the maximum value of the head in MIKE URBAN pipe, cell's elevation, manhole's elevation

g. Saturated zone flow

Groundwater plays a significant role in the hydrological cycle. The stream flow in dry season is mainly from the discharge of this hydrological components. Simulating this component helps to solve better the water demand problem on dry season. Furthermore, this kind of flow has many interactions with other components of hydrological process. Taking into account of this component when simulating hydrological process is to reduce the uncertainty of model. The saturated zone module also provides the function to simulate the impact of pump station to saturated zone flow. In MIKE SHE, the saturated zone is only one component of an integrated groundwater/surface water model. One of the advantage of MIKE SHE is to put the saturated zone component in the interaction with all of the other components - overland flow, unsaturated flow, channel flow, and evapotranspiration (DHI, 2012e). The operation in saturated zone is described in MIKE SHE with two method.

- Finite difference method.

The saturated zone flow is basically calculated by on the following function, 3D Darcy equation (3.4).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S\frac{\partial h}{\partial t} \tag{3.4}$$

Where Kxx, Kyy, Kzz is the hydraulic conductivity along the x,y and z of axes of the model, which are assumed to be parallel to principle axes of hydraulic conductivity tensor, h is the hydraulic head, Q present the source/ sink terms, and S_s is specific storage coefficient.

The above equation is solved by an iterative implicit finite different technique. There are two groundwater solutions/ techniques available (Butts & Overgaard, 2005): a successive over-relaxation (SOR) technique and a preconditioned conjugate gradient (PCG) technique.

In this method, the data input requirements are saturated area (Lower level, Upper level, Horizontal extent), characteristic of soil in this area (Horizontal hydraulic conductivity, Vertical hydraulic conductivity, Specific yield, Storage coefficient) Initial condition (Initial potential head), Boundary conditions (Outer boundary conditions and Inner boundary conditions), Drainage.

Finite difference method is a strong solution for estimating the groundwater flow. However, this method requires lots of data which is not always available for simulation. Furthermore, parameter estimation computational requirement is one of the biggest limitations of this method. To overcome these problems, MIKE SHE proposes Linear Reservoir Method.

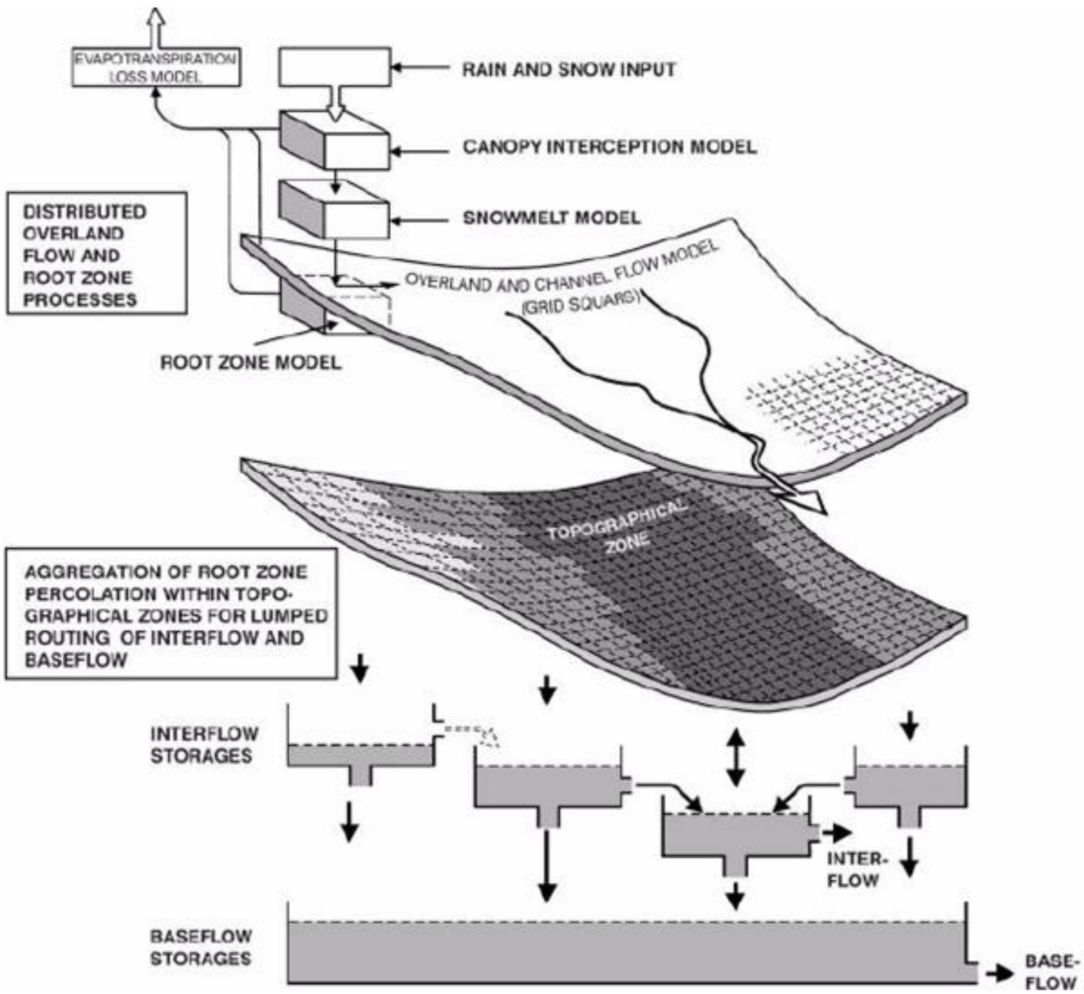


Figure 3.11. Model structure for MIKE SHE with the linear reservoir module for the saturated zone (DHI, 2012e).

- Linear Reservoir Method.

Linear Reservoir Method is a lumped conceptual approach, which is construct on the linear relation between storage and time, as follows:

$$S=k.Q \tag{3.5}$$

Where S is storage in the reservoir with dimensions length, k is the time constant, and Q is the outflow the reservoir from reservoir with dimensions length/time.

For calculating the groundwater flow, this method divides the catchment into several sub catchments as the Figure 3.11. Each such catchment is divided into a series of independent, shallow reservoir, plus one or more one, deep base flow reservoir…(DHI, 2012e). Each component is divided into many parallel sub catchments as in Figure 3.12. Hence the data requires for this method is a map with the division of the model area into sub catchment, a map of interflow reservoir and a map of base flow reservoir.

This method is primarily developed to provide a reliable, efficient instrument in the following fields of application: assessment of water balance and simulation of runoff for ungauged catchment; Prediction of hydrological effects on land use change; Flood prediction; Long term simulation like climate change assessment.

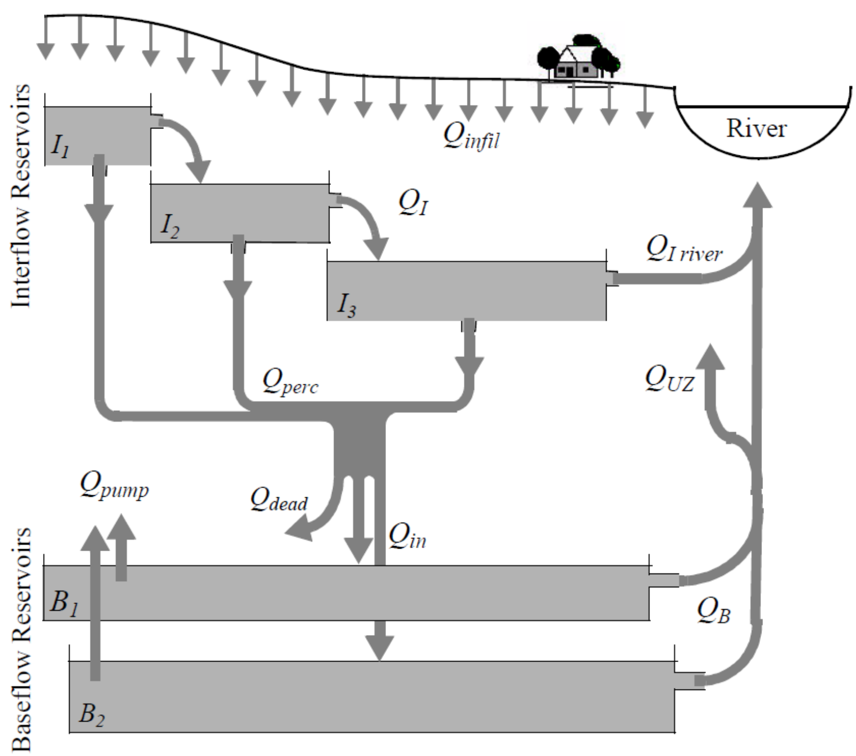


Figure 3.12. Schematic flow diagram for sub catchment – based, linear reservoir flow module (DHI, 2012e).

h. Irrigation

The Irrigation option is designed for presenting the water demand to irrigate the agriculture production in a catchment. It allows to specify a demand driven irrigation scheme with priorities. Activating the Irrigation option creates several sub-items in the data tree for the irrigation parameters such as The Irrigation Command Areas are used to describe where the water comes from and how the irrigation water is applied to the model; The Irrigation Demand is used to describe when the water will be applied in the model; Irrigation priority which define the area having to irrigate firstly if the water supply is lower than demand.

3.4.3 Performances of MIKE SHE

With its performance, MIKE SHE has been used in a broad range of applications. It is being used operationally in many countries around the world by organizations ranging from universities and research centers to consulting engineers companies (Refsgaard *et al.*, 1995). MIKE SHE has been used for the analysis, planning and management of a wide range of water resources and environmental and ecological problems related to surface water and groundwater, such as: River basin management and planning, Water supply design, management and optimization, irrigation and drainage, Soil and water management, groundwater management, interactive between water surface et ground water, ecological evaluations flood plain studies, impact of land use and climate change. Following part are several examples to prove the flexibility of MIKE SHE model in hydrological modeling. This review part will divide due to three big domains: about the applied topography, catchment modeling scale, simulated objective:

a. Morphological diversity

Throughout its history, the MIKE SHE model has validated its suitability with many topographical types. Andersen *et al.*, (2001); Graham, & Butts (2005) applied the MIKE SHE model to simulate the hydrological process of Senegal River Basin. This model was developed on an area 375,000 km^2, and included all of hydrologic components. The result was relatively preventative of the characteristic of this catchment with good obtained statistical coefficients. Thompson *et al.*, (2004) used this model to simulate the hydrological system in lowland wet grassland in southeast England. These authors used MIKE SHE coupling with MIKE 11 to present the hydrologic factors in Elmley Marshes catchment. This research gave remarkable results in simulating surface flooding, groundwater and flow in the channel. The application of the coupled MIKE SHE/MIKE 11 modelling system to the Elmley Marshes has demonstrated its potential to represent complex hydrological systems found within many wetland environments. By simulating the stream flow process at catchment (<100 km^2) in China, and at in Hawaii, USA, the works of Sahoo *et al*., (2006) and Zhang *et al*., (2008) already proved the capacity of

MIKE SHE to describe the flow in mountainous region. This model is likely to be preeminent to simulate hydrology in semi-arid area with the studies of McMichael *et al*. (2006). These demonstrations prove that MIKE SHE model have a strong ability for describing catchment hydrologic characteristics. This capacity is suitable for any topography, from lowland to mountainous or semi-arid area.

b. Catchment modeling scale

Operating on a flexible mechanism, the size of cell in MIKE SHE can be changed flexibly to adapt with real situation. Thus, the algorithm does not limit the modeling scale of study area. It leads to the advantage for using this model in watershed hydrological simulation. Indeed, the MIKE SHE model has operated well in wide range of scale from small size to great size. There are a lot of case studies smaller than 100 km^2 taking MIKE SHE for hydrological simulation. This has illustrated throughout research of Sahoo *et al.*, (2006), Zhang *et al.*, (2008). Conversely, towards large catchment, the MIKE SHE model is expected as an effective solution for overcoming the problem concerning with great size. Many studies used MIKE SHE as a way for reducing the uncertainty of catchment characteristic spatial distributions which might vary complicatedly over a big area. With its spatial distributed property, MIKE SHE has solved this problem in many catchment. It application was gotten the success for modelling the hydrological process at Senegal River Basin, which is cover a 375,000 km^2 (Andersen *et al.*, 2001), at 19,000 km^2 of Kaidu Watershed (Ma *et al.*, 2013) or 7,460 km^2 of Seim Rive (Gelfan, 2010). Moreover, this spatial characteristic of MIKE SHE help it becomes a reasonable model for surmounting the lack of data which is always big obstacle for hydrological modelling at large catchment and developing country (Hundecha *et al.*, 2002; Ma *et al.*, 2013)

c. Simulated objective:

The MIKE SHE model has been used for:

- Hydrological process.

MIKE SHE model with its advantage in taking into account most of the components in catchment's hydrology has been handled successfully to represent hydrological process for many locations all over the world. Especially, it can be used for special objectives such as snowmelt or flood simulation. Ma *et al.*, (2013) accounted the snowmelt component in the run off of 19,000 km^2 mountain area at Northwest China. Integrating as much as possible the hydrological components into model is necessary for assess the snowmelt flow, these authors said that after using MIKE SHE for their study. Extreme snowmelt floods of Seim River, which is a part of the Dnieper river basin and located in the steppeforest physiographic zone of the European Russia, was represented perfectly in the environment of MIKE SHE. This study is realized by study of Gelfan (2010).

- Flood analysis

MIKE SHE calculates the overland flow cell by cell and can link with 1D model, hence this distributed model is expected to present accurately the flood event. Furthermore, the model can give the result as 2D data, so it helps this model has the advantage in mapping the flood area. In effect, this model has already proved its remarkable characteristic in many studies. Sen & Niedzielski, (2010) applied MIKE SHE for evaluating the flood phenomenon at the second largest river of Poland. Nielsen (2006), utilized the MIKE SHE for floodplain inundation and urban drainage assessment in South East Asia.

- Impact of land use changes

The MIKE SHE model have been also used for evaluating the impact of land use change to the catchment's hydrology. Oogathoo, (2006) after comparing with others models, already selected MIKE SHE to evaluate the impact of management scenarios on the hydrological processes of the watershed by applying land-use increase/decrease percentages over Canagagigue Creek catchment, Ontario, Canada. Consequently, the study show that this model performed well in simulating runoff. Furthermore, it can be used to investigate diverse hydrological problems and watershed hydrology in a systematic way (Oogathoo, 2006). The capacity of MIKE SHE model in investigating the relation between land use change and hydrological process was confirmed in study of Wijesekara *et al.*, (2014). It was realized to assess the consequence of land use change over 1,238 km^2 of Elbow River, southern Alberta, Canada (Wijesekara *et al.*, 2014). This study demonstrated the performance of MIKE SHE in presenting the impact of land due change on hydrological process. Through the result, the authors confirmed the advantage of this deterministic distributed model.

- Ecosystem and water quality

Diversity of MIKE SHE application has been also express via its ability in the impact of ecosystem on catchment's hydrology. One evidence of this approach was showed in its application at Ecosystem Based Water Resources Management to Minimize Environmental Impacts from Agriculture Using State of the Art Modeling Tools in Strymonas Basin. This project used MIKE SHE to estimate to the impact of ecosystem to Strymonas Basin, in the south of Europe (Doulgeris *et al.*, 2012; Halkidis & Papadimos, 2007). The study over 16,747 km^2 of this Balkan basin proved the flexibility of MIKE SHE model in representing the hydrological process.

- Groundwater analysis

By accounting mostly hydrological components and especially possessing a good algorithm for ground water modelling, this model has been highlight as the best choice to simulate the ground water. In reality, many authors have been used MIKE SHE model for ground water study. Demetriou & Punthakey,(1998) used MIKE SHE to evaluate the groundwater management options for dealing with rising water table levels and land salinization problems in an Australian watershed. Based on modelling results they commented that because MIKE SHE is well suited to describe the dynamic interaction between the surface and subsurface water systems. It is the best choice for simulating the flow under the ground surface. The efficiency of this distributed hydrological model for ground water modeling was confirmed by the study of Liu *et al.*, (2007). By testing the relation between surface and ground water over 91.76 km^2 of Tarim basin in China, these authors indicated clearly the usefulness of MIKE SHE model for ground water modelling. Their successful application with MIKE SHE described an efficient method for analyzing groundwater dynamics and their response relationship to environmental factors. This judgment is important to consider groundwater pollution and ecological risk in arid areas. Moreover, certain studies also applied MIKE SHE to investigate ground water components in catchment scale (Jourde *et al.*, 2007; Sonnenborg *et al*., 2003). The preeminence of this model was benefited to assess the exploitable groundwater resources of Denmark. By simulating the different scenarios on MIKE SHE, Henriksen *et al*., (2008) proposed completely ground water resource map over Denmark. The study also outlined the exploitable capacity for each region of this country. Furthermore, the model has as well been handled for calculating discussion of argents in ground water environment, such as the research of Thorsen *et al.*, (2001). In this study, MIKE SHE was use as a basic tool for simulating the nitrate leaching to aquifer at catchment scale in Karup catchment, Denmark. Besides that, MIKE SHE has been used for determining the soil properties as well as their propagations. For example the construction of Christiaens & Feyen, (2001) realized on MIKE SHE to build the soil hydraulic properties at Ohebach catchment, Germany.

- Irrigation strategy

Starting from land use distribution and vegetation function which can introduce mostly the characteristics of vegetable due to their growth process, this distributed model has made confidence for simulating the water demand of each plant. Based on these demand, water requirement for irrigation are easily calculated. In fact, the function of MIKE SHE has been already handled to determine the need of agricultural produced zone for water (Jayatilaka *et al.*, 1998). Singh *et al.*, (1999) based on MIKE SHE result to design the irrigation plan for 694 ha tropical sub-humid area in India. After their works, they concluded that MIKE SHE is primarily proposed here as a planning tool and not as a real-time scheduling tool in irrigation planning.

- Evapotranspiration analysis

There have been lot of authors used MIKE SHE to simulate as well as determine this process in hydrological cycle. Vázquez & Feyen, (2003) evaluated the effect of potential evapotranspiration to hydrological cycle at a medium-size catchment. Vu *et al*., (2008) took MIKE SHE for determining this components over a large catchment in central Vietnam.

- Climate change impact assessment

Global warming is expected to affect mostly to catchment's hydrological factors, ex. Precipitation, evapotranspiration, ground water, ecosystem…Hence, simulating the impact of this phenomena towards the stream flow requires a model which can represent the hydrological components of catchment as much as possible. The simulation responding above requirement is hoped to increase the predicted accuracy about the future flow variation. The condition is completely able to satisfy MIKE SHE model. The algorithm presented at previous parts demonstrates that MIKE SHE can simulate entirely the hydrological factors and their interactions. This advantage gives MIKE SHE a capacity to reduce the uncertainty when applying for a climate change modelling. In truth, many studies have chosen MIKE SHE as a basic tool for evaluating the impact of climate change to hydrological system in general, especially to stream flow. Bosson *et al*., (2012) applied MIKE SHE model for simulating the terrestrial hydrology associated with different climate over 180 km^2 of Forsmark Catchment, Sweden. In this study, the change in future of temperature, rainfall, evapotranspiration were presented in MIKE SHE to count the change of flow in Swedish Forsmark catchment area. Mernild *et al*.,(2008) predicted the varied tendency of intra- and inter annual discharge from the snow and glacierized Zackenberg River drainage basin (512 km^2; 20% glacier cover) in northeast Greenland. This study realized on MIKE SHE platform. By comparing the difference in present and climate scenario of 2071 – 2100, the result indicated the increasing tendency of snow melt at this catchment also made the increase of stream flow. Relied on the difference between two model, MIKE SHE and WetSpa, in projecting the impact of climate change for medium size catchment in Belgium, Vansteenkiste *et al.*, (2013) gave a confirmation about the uncertainty concerning to modelling hydrological components in climate change simulation. In this study, MIKE SHE covered the ground water component, conversely, the WetSpa did not. This difference leads to the fact that MIKE SHE simulates a maximum decrease of 30% in the flow minima, whereas the WetSpa model projects low flow decreases up to 73%. It also indicates that the ground water has a significant role in catchment hydrological process, thus it affects much on the flow of this catchment. Via result, these authors pointed out it is a need to take into account the ground water for climate change modelling and more hydrological components presents, smaller uncertainty the prediction will get.

The complexity of groundwater flow process descriptions has a major role in low flow impact modelling and might even become larger than the uncertainty stemming from the climate modelling. Model predictions considering the groundwater flow physics encapsulate more detail and dynamics than the linear reservoir representation and seem more reliable, although it is not proven whether this is the case. Therefore, the impact predictions should be interpreted with care and only considered as being directive rather than precise in terms of future changes. With respect to high flow conditions, the models respond quite similar to the precipitation and evaporation changes. Small disagreements between the model high flow predictions were quantified and were negligible in comparison with the high uncertainty stemming from the climate scenarios. Thompson *et al.*, (2013) used MIKE SHE to project the varied trend of flow for the biggest river system at Southeast Asia, Mekong river. Over an area of 795,000 km^2 and taking into account mostly the hydrological factors in this catchment, this MIKE SHE model demonstrated its performance in modelling the impact of climate change for Mekong river. These strong points of fully deterministic distributed hydrological model – MIKE SHE model are expected to reduce a part of uncertainty when evaluating the impact of climate change to river flow and it also helps to translate better the climate scenarios in the future.

3.5 The role of rainfall spatial distribution in hydrological modelling

3.5.1 Introduction

In hydrological research, the model has a significant role. According to studies of Moon *et al.*, (2004); Strauch *et al.*, (2012) the modelling is a cheaper method and quite effective to provide a basic insight of hydrological process. Results from an accurate model will help us to be able to estimate the impact of natural phenomena to property and human, to plan, prevent, as well as find solutions to mitigate damages from these hazards on human society. However, the accuracy of hydrological model depends deeply on the accuracy of many input factors, especially the rainfall, a key factor in hydrologic process, what Arnaud *et al.*, (2002); Tao, (2009); Zhao *et al.*, (2013) have confirmed that its spatial variability affects heavily on runoff generation and also on hydrologic process in a catchment. Beven & Hornberger, (1982) studied the impact of spatial rainfall on flow and found that spatial patterns significantly affect peak flow distribution and timing, but the impact on flow volume is not so much. Chaubey *et al.*,(1999) also noted that the spatial variability in rainfall may introduce significant uncertainty in model parameter during calibration process. While the accuracy of spatial rainfall distribution is decided by a characteristic of the study area and other factors, in particular, the rain gauge density. Many researchers have a same judgment that more dense measurement network will give better results in rainfall spatial distribution but have not yet reached a clear criterion about the numerous gauges per area . Tao, 2009 show that the best method to improve the quality of spatial rainfall estimation is to increase the density of monitoring network. Obled *et al.*, (1994) recommended 5 rain gauges for 71 km^2 for a basin in the South of France. Segond *et al.*, (2007) with the study at Lee catchment, UK suggested that for largely rural catchments, a network of 16 rain gauges seems appropriate at 1,000 km^2 ; and between 4 and 7 gauges are required at 80-280 km^2. Nonetheless, this requirement is so difficult to satisfy on large catchment, not least at developing countries where the infrastructure of the rainfall observation network is sparse and still in a low quality, this causes the inaccuracy when redistribute spatially the rainfall, influence on the simulated quality. Nicótina *et al,* (2008) demonstrated with the large catchment, the impact of rainfall spatial variability is more serious, in a catchment with area more than 3,500 km^2, rainfall variability affects evidently on the output of flood modelling. From these reviews, to have an accurate hydrological model, the interpolating spatially rainfall data base on measurements is obvious.

In the past, several interpolated methods have been utilized to re-construct spatially rainfall data. Almost methods concentrate in two types: Deterministic techniques and geostatistical techniques. The first type includes Thiessen polygon, inverse distance weighting (IDW), Spline is traditional method, is often applied in practice. These methods are very simple to set up, however their accuracy is not so high. This has been demonstrated in studies of Mair & Fares, (2010); Tobin *et al*., (2011). According to Goovaerts, (2000) the inaccuracy of these methods is from their non-geostatistical that does not allow the hydrologist to consider factors, such as topography, that can affect the catch a gage. In recent years, many studies have showed that there exists a crucial relationship between rainfall and other factors, such as topography, temperature, wind, distance from the beach. Brunsdon *et al*., (2001) presented that the rainfall-altitude in Great Britain have a strong relationship, the height coefficient of rainfall varies from 1.5-4.5mm/m depending the catchment. From the database of 567 stations located in the alpine, Allamano *et al.*, (2009) also proved the dependence of precipitation in Italy due to elevation, nevertheless, contrary to expectations, maximum annual precipitations of short duration are found to significantly decrease with elevation. This tendency also appears to have a geographic drift from the western to the eastern side of the alpine chain. Previous studies, (Basist *et al.*, 1994; Gouvas *et al.*, 2009) have the same conclusion that precipitation typically increases with elevation. Other directions are to take into account the effect of atmospheric, wind when reproduce spatial rainfall like the work of Johansson & Chen, (2003); Johnson & Hanson, (1995). So some authors have used geostatistical methods which are based on the theory of regionalized variables (Goovaerts, 1999) that could help to add interactions between rainfalls with any factors to enhance the quality of spatial rainfall distribution. The most famous method among them is kriging what has affirmed its preeminent in researches as (Mair & Fares, 2010; Tao, 2009) and relatively new method that applies spatial regression for the goal of data redistribution, this method's name is geographically weighted regression (GWR), it has been used so popularly in recent years (Al-Ahmadi, 2013; Bostan & Akyürek, 2009; Lloyd, 2005). With this method, Brunsdon *et al.*, (2001) analyzed the effect of elevation with rainfall distribution and noted that in comparison with the traditional approaches, the geographical weight regression model has the advantage of being much simpler than the more complex of the multiple regression approaches and the geographical weight regression also provides a useful method for incorporating the varying relationship between rainfall and altitude. Chu, (2012) estimated that the GWR produces more desirable spatial distribution for model residuals and more accurate estimations than other methods.

However, the runoff response in hydrological model with rainfall spatial interpolation methods is difference. Past studies have not yet concluded which method is the best in hydrological simulation. With hydrologists, it makes the uncertainty to select a rainfall interpolation method for their modelling. During the simulation for Vu Gia Thu Bon river catchment- Viet Nam, we also have similar difficulties in choosing the most suitable rainfall distribution to input the model. To solve this difficult, we tested several different interpolation methods - such as Thiessen polygons, Inverse-distance weight, Spline, Ordinary Kriging methods as well as integration of attitude, distance to the sea with geographically weight regression - base on MIKE SHE, an advanced integrated hydrological modeling system from DHI. In this paper, we would like to introduce some experiences in selecting rainfall distribution method type for this catchment, also the runoff process reaction over rainfall interpolation method. The study has demonstrated the added value of each method and clearly identified the uncertainty bias introduced by the rainfall hypothesis within the hydrological modelling. The analysis demonstrates also the uncertainty of spatial distributed rainfall and their effects on runoff process simulation within the model. The analysis could be generalized and used as an operational method for large ungauged catchments.

3.5.2 Methodology for rainfall spatial distribution

The rainfall distribution methods were used in this study include Thiessen Polygon, Inverse Distance Weighting (IDW), Spline, Ordinary Kriging (OK), Geographically weighted regression (GWR). Thiessen Polygon is the method, which has been utilized by many hydrologists since its simplicity, straightforwardness. This method amounts at drawing around each gage a polygon of influence with the boundaries at a distance halfway between gage pairs so the gradient information is lost (Das & Saikia, 2009).

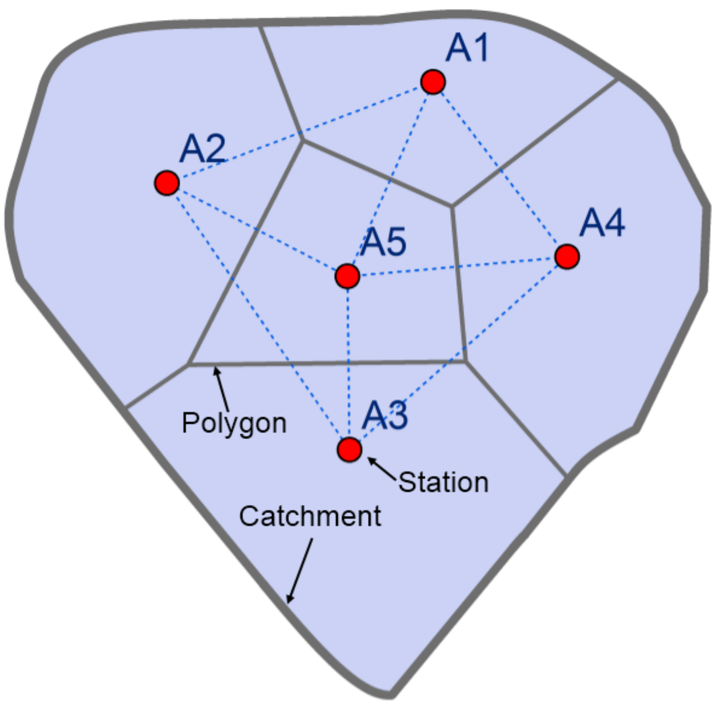


Figure 3.13 Thiessen polygon

a. The Thiessen polygon method (Figure 3.13) (equation 3.5) assumes that each precipitation gage does not get the same weight as in the arithmetic method.

$$P = \frac{\sum_i^n P_i A_i}{A} \qquad (3.5)$$

Where P_i : the rainfall at station i.

A_i: the area of polygon at station i.

A : the total area of the catchment.

n: the number of rainfall station in the catchment.

b. Inverse Distance weight method (IDW). Another common technique, the IDW was developed by the U.S National Weather Service in 1972, that interpolation method determines cell values by using a weight average of sample points in the neighborhood (Goovaerts, 2000). With IDW method (equation 3.6), the accuracy of interpolated value will decrease if the neighboring points unevenly distributed. There are many different forms of IDW interpolation, but the simplest form is proposed by Shepard (1968). The Shepard method suggests the weight function wi as follows (Azpurua & Ramos, 2010)

$$w_i = \frac{h_i^{-p}}{\sum_{j=0}^n h_j^{-p}} \qquad (3.6)$$

where p is an arbitrary positive real number called the power parameter (typically p = 2) and h_j are the distances from the dispersion points to the interpolation point, given by equation 3.7:

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \qquad (3.7)$$

where (x, y) are the coordinates of the interpolation point and (xi, yi) are the coordinates of each dispersion point. The weight function varies with a value of unity at the dispersion point to a value close to zero as the distance to the dispersion point increase. The weight functions are normalized as a sum of the weights of the unit. Then, the interpolated value of the electric field $P_{(x, y)}$ is given by equation 3.8.

$$P_{(x,y)} = \sum_{j=0}^n w_j P_{(x_j, y_j)} \qquad (3.8)$$

c. The Spline method is an interpolation method that estimates value using a mathematical function that minimize overall surface curvature, resulting in a smooth surface that passes exactly through the input points (Tao, 2009). The algorithm used for the Spline tool uses the following formula (equation 3.9) for the surface interpolation (ArcGIS, 2014).

$$P_{(x,y)} = T_{(x,y)} + \sum_{j=1}^{n} \lambda_j R(r_j) \quad (3.9)$$

Where: j = 1, 2, ..., n

n is the number of points.

λ_j are coefficients found by the solution of a system of linear equations.

r_j is the distance from the point (x,y) to the jth point.

$T_{(x,y)}$ and R(r) are defined differently, depending on the selected option.

d. The Kriging method has been known as the best interpolation method that consists of a family of least-square linear regression algorithms used to estimate random fields from which observed data are considered to be drawn as a sampling of a field realization to be (Pierre Goovaerts, 1997, 1998; Tobin et al., 2011). The equation of this method is similar to IDW. But different with IDW, where the weight wi depends solely on the distance to the prediction location, the weights of Kriging are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points. To use the spatial arrangement in the weights, the spatial autocorrelation must be quantified. Thus, in ordinary kriging, the weight, wi, depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location (ArcGIS, 2014).

e. Geographically weighted regression, a new method has been estimated to interpolate spatially rainfall, known as Geographically weighted regression (Brunsdon et al., 1998) , that is a local spatial statistical method used to examine and determine the spatial non stationary, when the relationships among variables vary from location to location (Fotheringham et al., 2003).

In this study, these above methods were applied to redistribute spatially rainfall in the environment of software ArcGIS 10.1. The effectiveness of each interpolation method was assessed by using cross-validation what temporarily removes one observation at a time from the dataset and re estimates the removed value from the remaining data by using each interpolation method (Mair & Fares, 2010). The root mean squared error (RMSE) (3.10), the correlation coefficient (R) (3.11), and Nash-Sutcliffe coefficient (E) (3.12) were utilized to evaluate the accuracy of each method. Then, the sensitivity of each rainfall interpolated technics with stream flow will be evaluated in MIKE SHE model. The smaller RMSE value is, the higher model performance will reach. The perfect value of RMSE is 0 (Moriasi et al. 2007). The performance levels of R and E are classified in

Table 3.3. The optimal values of these two factors are all 1 (Safari et al. 2012; Wang et al. 2012)

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i}-X_{model,i}\right)^2}{n}} \tag{3.10}$$

$$R=\frac{\sum_{i=1}^{n}\left(X_{obs,i}-\overline{X}_{obs}\right).\left(X_{model,i}-\overline{X}_{model}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_{obs,i}-\overline{X}_{obs}\right)^2.\sum_{i=1}^{n}\left(X_{model,i}-\overline{X}_{model}\right)^2}} \tag{3.11}$$

$$E=1-\frac{\sum_{i=1}^{n}\left(X_{obs,i}-X_{model,i}\right)^2}{\sum_{i=1}^{n}\left(X_{obs,i}-\overline{X}_{obs}\right)^2} \tag{3.12}$$

where the X_{obs} is observed value and X_{model} is modelled value at time/ place i.

Table 3.3. Performance criteria for model evaluation. (S. Wang et al., 2012)

Performance indicator	**Excellent**	**Good**	**Fair**	**Poor**
E	>0.85	0.65-0.85	0.5-0.65	<0.5
R	>0.95	0.85-0.95	0.75-0.85	<0.75

3.5.3 Results

a. Rainfall distributed method

The annual rainfall distribution is shown at Figure 3.15. The statistical results (Table 3.4) demonstrate that most coefficients of Kriging and IDW methods are better than the obtainment with other methods. The RMSE and E of Kriging and IDW methods are almost stable in all stations in the catchment. The two results have no significant differences between mountainous area and delta area. It is likely to conclude that these methods do not depend so much on the rainfall station density. Kriging and IDW methods give acceptable results not only at locations, which concentrate many stations like Hoi An, Cau Lau, Cam Le with a better interpolation quality, RMSE smallest, E>0.8 but also with Tra My, Hien station where E could reach 0.6. With other methods, these coefficients varied greatly according to location.

Table 3.4. Statistical coefficients of rainfall interpolation methods

STATION		THIESSIEN	GWR	IDW	KRIGING	SPLINE
TRAMY	RMSE	22.93	20.93	22.15	20.37	28.68
	R	0.76	0.81	0.78	0.81	0.75
	E	0.57	0.63	0.59	0.65	0.32
THANH MY	RMSE	10.114	12.465	10.425	10.593	16.962
	R	0.88	0.828	0.872	0.869	0.77
	E	0.757	0.631	0.742	0.734	0.317
NONG SON	RMSE	15.635	11.63	12.602	11.884	15.574
	R	0.803	0.891	0.869	0.885	0.801
	E	0.618	0.789	0.752	0.779	0.621
HOI AN	RMSE	9.437	40.523	9.161	9.547	15.874
	R	0.925	0.388	0.923	0.919	0.856
	E	0.841	-1.937	0.85	0.837	0.549
HIEN	RMSE	15.101	32.117	14.061	14.284	45.25
	R	0.759	0.467	0.789	0.781	0.3
	E	0.551	-1.03	0.611	0.599	-3.029
GIAO THUY	RMSE	10.062	10.121	8.464	9.427	10.153
	R	0.923	0.908	0.938	0.921	0.92
	E	0.826	0.824	0.877	0.848	0.823
CAU LAU	RMSE	9.437	21.547	7.761	7.855	11.89
	R	0.925	0.573	0.951	0.949	0.88
	E	0.853	0.235	0.901	0.898	0.767
CAM LE	RMSE	7.441	11.037	7.187	8.015	7.17
	R	0.951	0.887	0.954	0.943	0.955
	E	0.903	0.786	0.909	0.887	0.91

This analysis helps to confirm once again the effectiveness of Kriging and IDW method in re-distributing spatially rainfall. This tendency is similar to many previous studies such as (Goovaerts, 2000) while realizing rainfall interpolation for low density network in Portugal has the same conclusion about Kriging method, Goovaerts analyzed on the monthly rainfall and annual rainfall for a long period, but in this study, we used the daily rainfall, so perhaps it will supply a more real view about the change of rainfall with the small step of the Kriging, but the result of this simulation is so short, only 6 year, hence we could not affirm this trend. In his study, he also showed that the interpolated quality of Kriging method is better than Inverse Distance Weighting, it is opposite to our results, the cause may be is from the difference of catchment and station density. However, *(Tao et al.*, 2009), after comparing the effect of interpolation methods in small catchment in high density of the rainfall station in Lyon, France, made a conclusion that at the same time, results from Kriging and IDW interpolation are not much different. His judgment contributes a part to confirm our result.

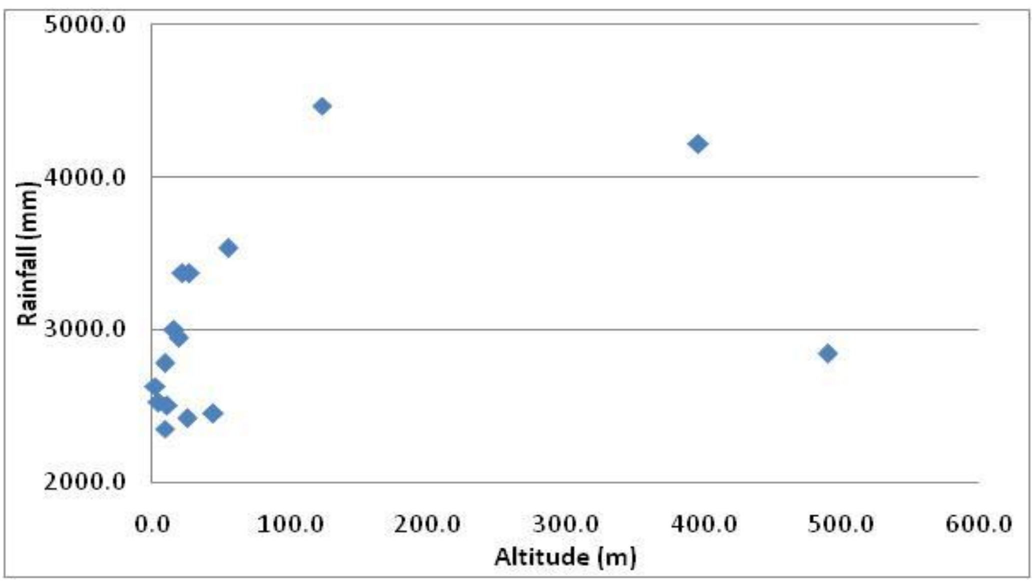


Figure 3.14. Correlation between annual rainfall and altitude at Vu Gia Thu Bon gauging stations.

Geographically weighted regression is a powerful technique and has been applied frequentlyin recent years, nevertheless in this study, it had not yet proved its preeminent. Although this method carries out and statistically analyses for each point before giving the result as well as could take into account the effect of elevation to rainfall but in fact, the achievement has not been like expectation. The statistical coefficients in the Table 3.3 have demonstrated that this method is not suitable with Vu Gia Thu Bon region. Imaging that under the geostatistical technique, the GWR method will help to mitigate the impact of density, and unequal distribution of the record network, but it is not right with our catchment. This problem is showed that not at all stations the GWR gives the bad result, concretely, at central stations, and stations are covered by others, distance between these stations is relatively equal, such as ThanhMy E=0.63, Nong Son E=079, GiaoThuy E=0.824, while E coefficient of other interpolation methods in these stations is lower, in contrast, with remote border stations are not covered by others, the E cofficient is so low, even smaller then 0.

Meanwhile, traditional techniques depend significantly on the density of rainfall station, it leads Spline method to always get the worst result. Thiessen has been able to make the good interpolation, but only at several stations, the distance of these stations with others is not so far. It is described concretely at Cam Le Station, or Ca Lau station when the distance from them to neighbours is smaller than 10 km.

The Table 3.5 as well describes that Spline's and GWR's tendency are to increase the rainfall in comparison with measurement. The average annual rainfall intensity in the intepolation period also demonstrated this tendency. Among them, the Spline gave the largest intensity with the maximum 7,313.71 mm, next is GWR 6,838 mm against 4,469.3 mm observed figure. The increase occurs mostly at upstream and mountaineous region this had been considered causing to raise the runoff in the hydrological simulated process.

Table 3.5. Average daily rainfall (mm) in period 2005-2010.

	Tra My	**Hien**	**Nong Son**	**Thanh My**	**Cam Le**	**Cau Lau**
Obs	2.24	7.78	9.23	6.63	6.44	7.21
Thiessen	9.68	6.63	8.07	6.71	6.9	6.44
GWR	9.35	13.28	7.81	8.05	7.62	7.52
IDW	9.05	7.51	7.98	7.63	6.96	7.23
Kriging	10.25	7.64	7.73	8.06	7.53	7.42
Spline	14.48	15.88	8.21	9.22	7.26	7.14

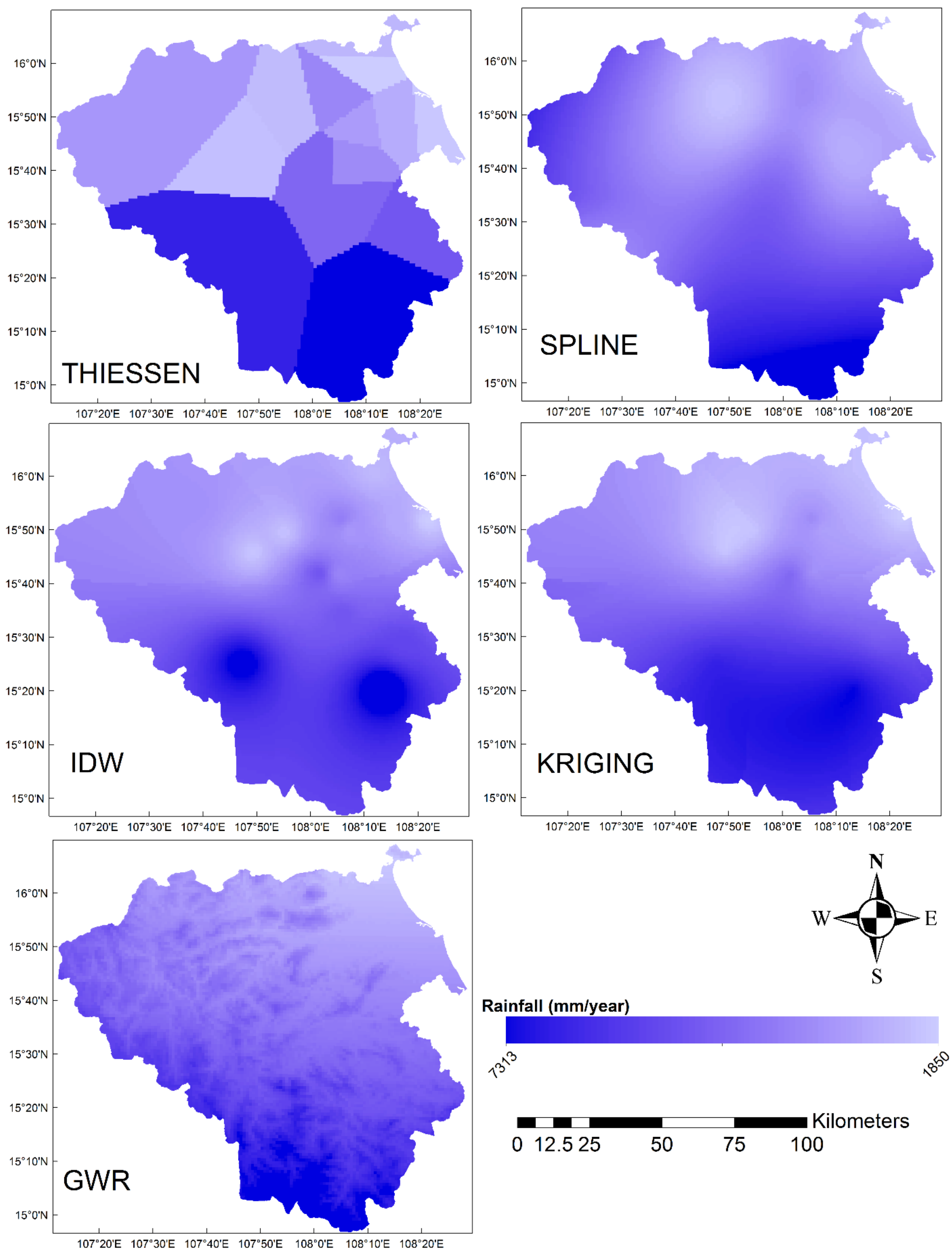


Figure 3.15. The Annual rainfall interpolation result at 15 rain gauge station correspondent with Thiessen,

b. Effects of rainfall distribution to runoff

The change in technique interpolating spatially rainfall in last step affected greatly on runoff factors in hydrological model. The techniques give a good result in establishing rainfall distribution, they show again their quality in simulating the run off. It means that the IDW and Kriging method with the best quality in rainfall distribution, also bring the better simulations in hydrological model. Conversely, the simulation using the Spline, Thiessen, GWR gives bad result.

Table 3.6. Statistical coefficients of MIKE SHE model corresponding with rainfall distribution method.

		VU GIA BRANCH					**THU BON BRANCH**				
		$Q_{Thanh My}$	$H_{Thanh My}$	$H_{Hoi Khanh}$	$H_{Ai Nghia}$	$H_{Cam Le}$	$Q_{Nong Son}$	$H_{Hiep Duc}$	$H_{Nong Son}$	$H_{Giao Thuy}$	$H_{Cau Lau}$
THIESSEN	RMSE	168.45	0.86	1.03	0.88	0.36	304.94	1.34	1.09	0.90	0.59
	R	0.87	0.77	0.71	0.67	0.83	0.89	0.83	0.80	0.77	0.82
	E	0.53	0.48	-0.01	0.30	-0.97	0.77	0.17	0.58	0.46	-0.09
SPLINE	RMSE	295.02	1.11	1.44	1.14	0.41	401.64	1.15	1.33	1.17	0.78
	R	0.80	0.73	0.65	0.63	0.84	0.87	0.79	0.77	0.73	0.80
	E	-0.43	0.13	-0.97	-0.16	-1.57	0.61	0.38	0.38	0.09	-0.95
IDW	RMSE	132.58	0.80	0.99	0.83	0.34	341.43	1.45	1.08	0.90	0.52
	R	0.88	0.78	0.72	0.68	0.81	0.87	0.83	0.81	0.76	0.81
	E	0.71	0.55	0.08	0.38	-0.75	0.72	0.01	0.59	0.46	0.15
KRIGING	RMSE	160.92	0.84	1.02	0.86	0.34	298.73	1.30	1.07	0.92	0.59
	R	0.88	0.77	0.71	0.69	0.84	0.89	0.83	0.81	0.76	0.82
	E	0.57	0.50	0.00	0.34	-0.75	0.78	0.21	0.60	0.43	-0.09
GWR	RMSE	436.53	1.24	1.36	1.11	0.47	594.67	1.19	1.26	1.16	0.85
	R	0.52	0.70	0.66	0.64	0.80	0.62	0.78	0.78	0.73	0.79
	E	-2.13	-0.09	-0.76	-0.11	-2.37	0.14	0.35	0.44	0.10	-1.31

The analysis in 3.5.3a demonstrated the Spline, GWR method lead to increase the rainfall when interpolation, it means the runoff in theory will increase. The runoff parameters in MIKE SHE result also confirm this tendency. With the Spline, the average rainfall is largest cause the increasing of runoff parameters at Thanh My and Nong Son gauging station.

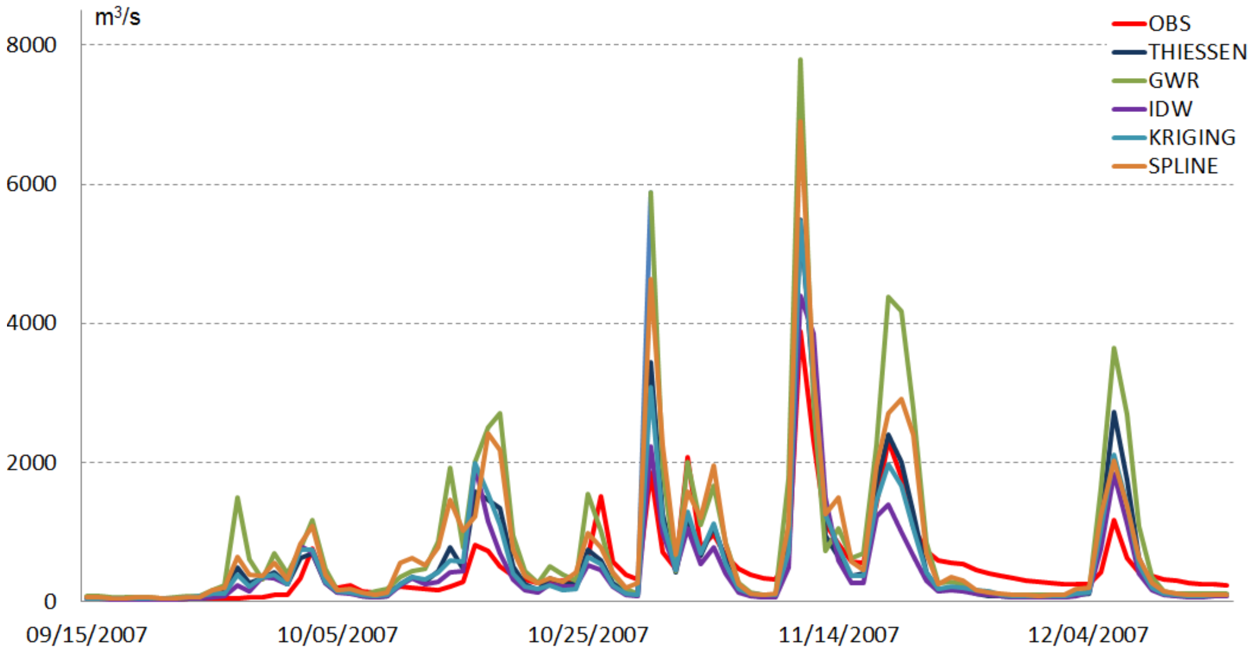


Figure 3.16. Hydrograph at Thanh My gauging station during period of 9/2007-12/2007 with different rainfall interpolation methods.

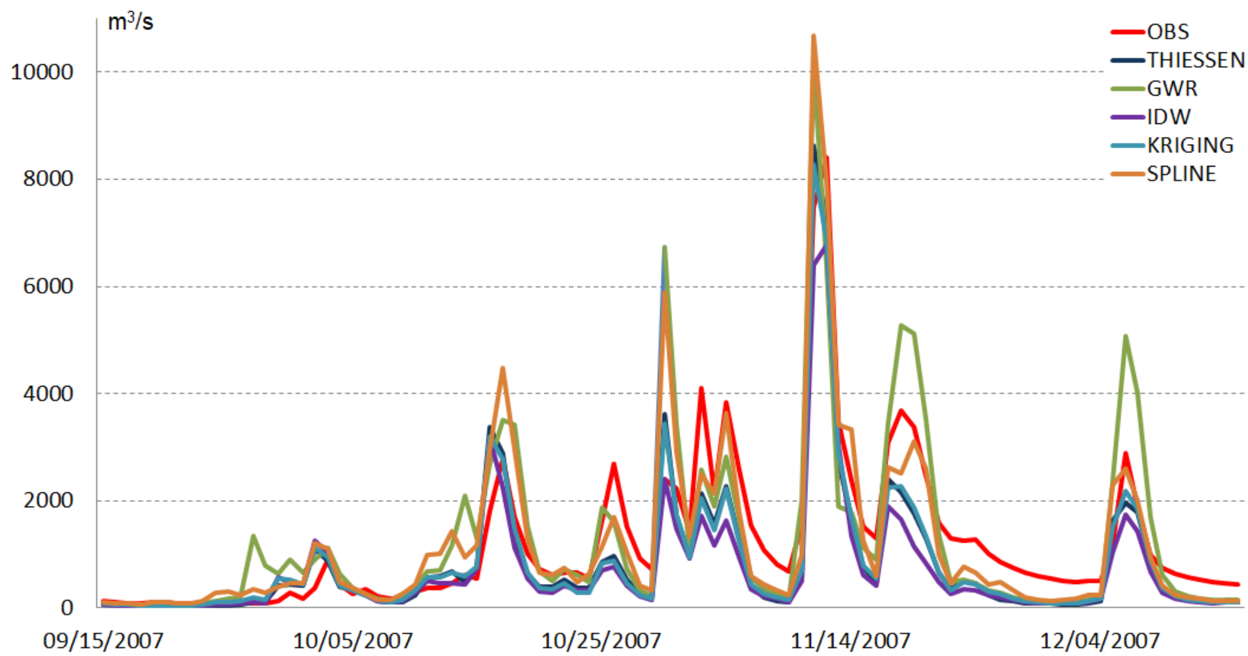


Figure 3.17. Hydrograph at Nong Son gauging station during period of 9/2007-12/2007 with different rainfall interpolation methods.

Comparing with measurement data, in period 15/9/2007 to 15/12/2007, scenario with Spline method's rainfall input give the largest peak flow reach to 10,670 m^3/s while observed data only 8,410 m^3/s, the difference is 26.9% at Nong Son, and 6,897.9 m^3/s while observed data only 3,880 m^3/s, the difference is 78% at Thanh My. Results of these differences, the statistical coefficients of this method are so small, Nash-Sutcliffe coefficient (comparing discharge) in this period at Nong Son is 0.61 and Thanh My is -0.43. The scenario taking the rainfall input from result of GWR has received the same tendency, statistical index are so bad. Meanwhile IWD and Kriging present impressionably their ability. IDW scenario gives the peak discharge at Thanh My is 4,405.99 m^3/s against the measurement is 3,880 m^3/s, the difference is only 13.6%, at Nong Son 6,784.4 m^3/s lower than observation 19% . So it is not surprised when the Nash-Sutcliffe coefficient at two stations of this method is relatively high, obtain to 0.71 and 0.72 respectively. Specially, Scenario with Kriging rainfall input could give at Nong Son station the Nash Sutcliffe coefficient lead to 0.78 and at Thanh My is 0.59 with the difference between observed and simulated discharge at Nong Son only 1.6 % and at Thanh My 15.9% . At others stations, with the water level also gives the same tendency, accordingly, all of that prove the accuracy of the IDW as well as Kriging technique in distributing rainfall, and the effectiveness on hydrological modelling (Table 3.6). Flood process as well reinforces our consideration on the accuracy of rainfall interpolation method. Hydrograph at Nong Son and Thanh My stations (Figure 3.16, 3.17) presented that rising limb of all simulations are earlier than observation but the time of peak flow exist longer. The difference occurs more seriously with the GWR and Spline methods when the time of peak flow maintains so long, and the falling limb is so slow. Thiessen, IDW, Kriging have the same trend. However, the hydrograph of model taking result of Kriging interpolation method is the closest with observation.

c. Effects of rainfall cell size to runoff

Beside the interpolation technique, we need to care another problem of rainfall input requirement when simulating the hydrological process for a catchment, it is the resolution of rainfall. This factor also affects the accuracy of model, this has been proved in many past studies, such as (Vaes *et al.*, 2001), (Berne *et al*., 2004).

To consider the impact of rainfall resolution on hydrological process on Vu Gia Thu Bon catchment, in this study, we based on the Kriging method to interpolate rainfall with the resolution varies from 1000m, 2000m, 4000m, then consider their impact on runoff factors under the MIKE SHE model. The response of river run off against varied rainfall grid size are demonstrated via hydrograph on the Vu Gia Thu Bon river system, ex Nong Son, Thanh My station at the Figure 3.18, 3.19.

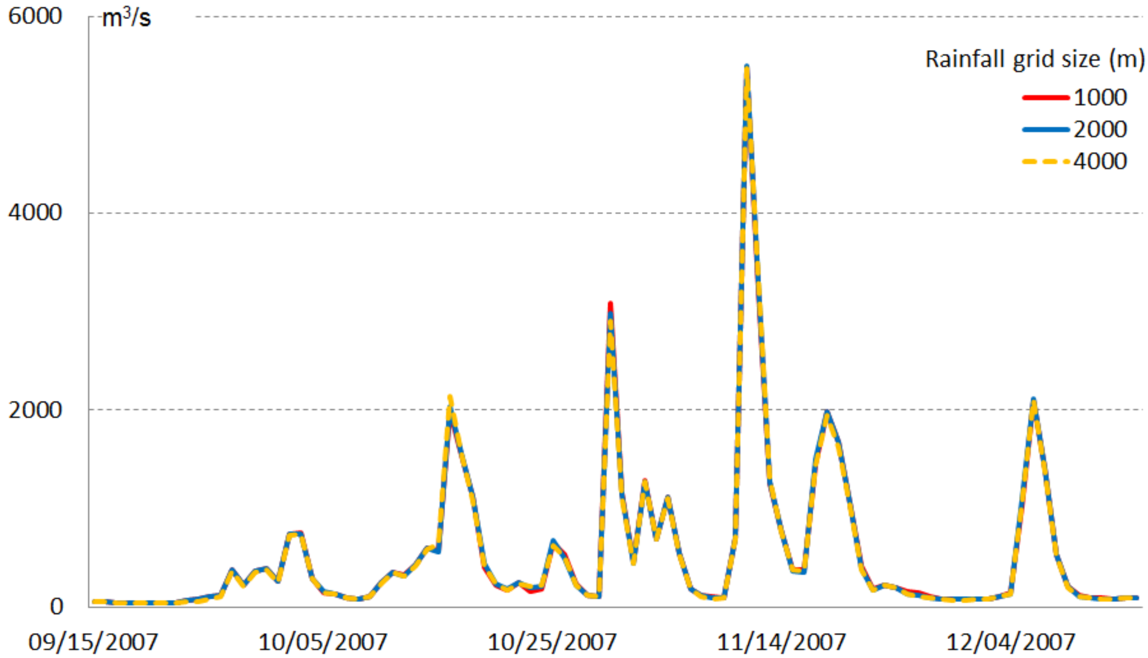


Figure 3.18. Hydrograph at Thanh My gauging station in period 9/2007-12/2007 with different rainfall resolutions.

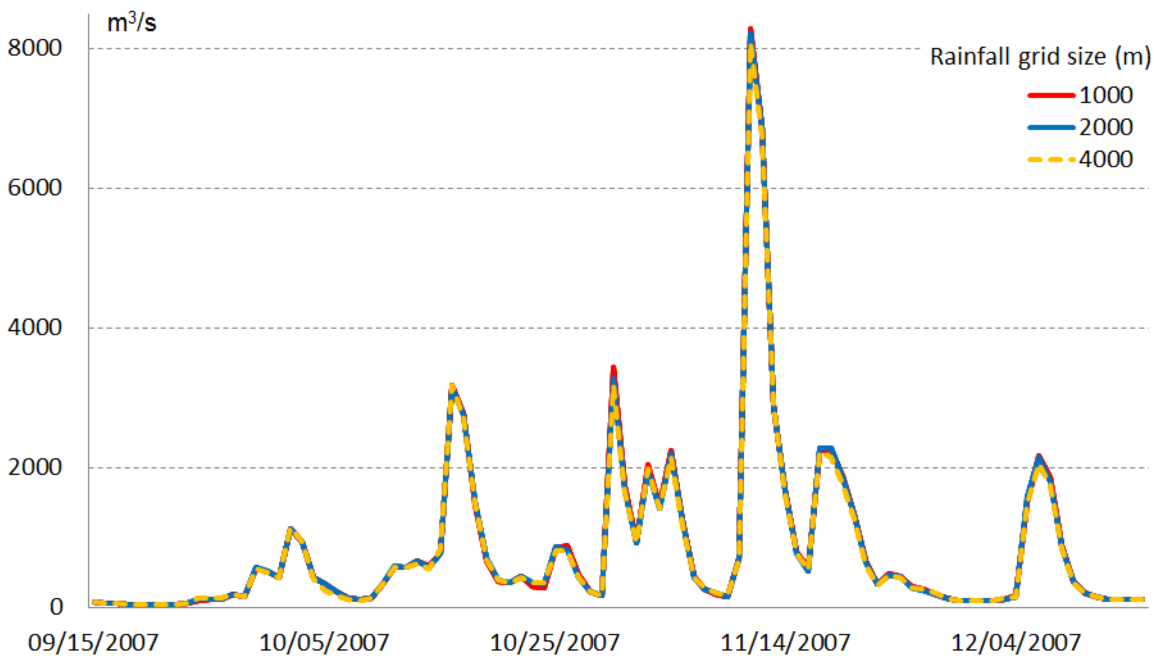


Figure 3.19. Hydrograph at Nong Son gauging station in period 9/2007-12/2007 with different rainfall resolutions.

The performance of each rainfall grid size is demonstrated at the Table 3.7. The results have shown that runoff parameters are almost similar between different input rainfall resolution scenarios. If the cell size of input rainfall is reduce, the runoff will increase. However, on Vu Gia Thu Bon catchment, this variation is very small. Simulate in period 15/9/2007 to 15/12/2007, if the resolution of rainfall changed from 1,000m to 4,000, the volume at Thanh My reduced from 4.34 $10^9 m^3$ to 4.29 $10^9 m^3$ corresponding 1.08%,and volume at Nong Son reduced from 6.65 $10^9 m^3$ to 6.49 $10^9 m^3$ corresponding 2.34%. The peak discharge also reduced only from 5,479 m^3/s to 5,465 m^3/s at Thanh My, and 8,275 m^3/s 8,078 m^3/s at Nong Son.

Table 3.7. Statistical coefficients of MIKE SHE model corresponding with rainfall resolution.

		VU GIA BRANCH					**THU BON BRANCH**				
		$Q_{Thanh My}$	$H_{Thanh My}$	$H_{Hoi Khanh}$	$H_{Ai Nghia}$	$H_{Cam Le}$	$Q_{Nong Son}$	$H_{Hiep Duc}$	$H_{Nong Son}$	$H_{Giao Thuy}$	$H_{Cau Lau}$
1000 m	RMSE	160.92	0.84	1.02	0.86	0.34	298.73	1.3	1.07	0.92	0.59
	R	0.88	0.77	0.71	0.69	0.84	0.89	0.83	0.81	0.76	0.82
	E	0.57	0.50	0.00	0.34	-0.75	0.78	0.21	0.60	0.43	-0.09
2000 m	RMSE	160.14	0.84	1.02	0.87	0.36	299.06	1.30	1.06	0.93	0.60
	R	0.88	0.77	0.71	0.68	0.83	0.89	0.83	0.81	0.76	0.82
	E	0.58	0.50	0.01	0.32	-0.97	0.78	0.22	0.61	0.42	-0.13
4000 m	RMSE	158.16	0.84	1.01	0.87	0.36	303.06	1.30	1.06	0.90	0.60
	R	0.88	0.77	0.72	0.68	0.82	0.89	0.83	0.81	0.77	0.82
	E	0.59	0.51	0.03	0.32	-0.91	0.78	0.21	0.61	0.46	-0.16

This small change in runoff factors also presents that perhaps the effects of input rainfall resolution on hydrological modelling, here is MIKE SHE model, is not very significant. Nonetheless, on this study, we simulated on scenarios which the change of input rainfall resolution varies in small amplitudes, so the result has not yet expressed exactly the tendency of runoff. Hence we could not see the important of rainfall resolution when simulating hydrological model.

3.5.4 Conclusion

The aims of this study was to estimate the accuracy of rainfall interpolation methods, and the response of hydrological model on each method, made a basis to choose the most suitable method for spatial rainfall distribution when simulating hydrological process. This study was considered based on the daily rainfall data in period 2005-2010, from 15 rainfall stations in area 10,350 km^2 of Vu Gia Thu Bon catchment, Viet Nam central. The study showed the different quality of traditional methods and geostatistical methods, and confirm again the accuracy of Kriging technique in redistributing the rainfall, accordingly, it is the most suitable method for this catchment. This method reduces mostly the impact of rainfall station density, spatial distribution of rainfall station to the interpolation results. The results also present the important of rainfall station density when interpolating spatially rainfall as well as the impact of rainfall station distribution to the quality of interpolation method. With the traditional methods, the density of rainfall station is so important. The density is higher, the accuracy is higher, and spatial factor of rainfall could be completely ignored if the density of rainfall is high enough. However, the quantity of observed station in Vu Gia Thu Bon catchment is still so small that is able to describe qualitatively the rainfall phenomena. The analysis showed that with this catchment, to get a good interpolation result, the distance between two rainfall stations should be smaller than 10 km. In addition, geostatistical methods still require equal distribution of rainfall station. The location at edge of region will get worse result in comparing with the location in central where is covered by other stations. Similar to past studies, the change of rainfall distribution have the deep impact on runoff factors, not only on the quantity, but also on the shape of hydrograph. Accordingly, The Spline and GWR methods increase highly the rainfall, hence lead to increase the runoff, simultaneously, extent the falling limb process. It leads to the inaccuracy when applying these methods for hydrological modelling and the difficulty for hydrologist to calibrate the model. Although The Thiessen and IDW methods give good result, they showed the weak point in making the process of flood. Finally, Kriging gives the smallest disparity between model and observation. So this technique is suggested for interpolating spatially rainfall to make the input data to apply in hydrological modelling. The dependence of runoff parameters on input rainfall resolution is true. If reducing the cell size of input rainfall grid, it will give larger volume, and all give higher peak flow. However this variation is not so high.

This study has confirmed again the variation of rainfall over space and the interpolation method affects deeply the rainfall distribution so they all lead to uncertainty in hydrological modelling. Hence, selecting a suitable interpolation method is so important when simulating a hydrological process. The result of this section was already published at 3rd IAHR Europe Congress in Porto, Portugal April 2014 (Vo & Gourbesville, 2014d).

3.6 Application to Vu Gia Thu Bon Catchment

3.6.1 Input data and model setup

The MIKE SHE model is built with all of the available model components, e.g overland flow, river and lake, unsaturated flow, evapotranspiration, saturated flow. As the result, the model is expected to describe accurately hydrological processes in Vu Gia Thu Bon catchment as well as to reduce the uncertainty when simulating future climate scenarios. The following data sets have been used:

- Topography: The elevation data using in the model is taken from SRTM DEM with the horizontal resolution 90 m from NASA (Figure 2.7) (http://www.cgiar-csi.org).
- Rainfall: By analyzing the effect of spatial rainfall distribution to the stream flow, the study of Vo & Gourbesville, (2014b) showed that the Kriging is the most suitable method to interpolate the rainfall distribution in this catchment. Hence, the simulations use the rainfall data that are re-distributed spatially based on daily rainfall data from 15 rain gauge stations with the Kriging method.
- Evapotranspiration: Data are inherited from the study of Vu *et al.*, (2008) .These authors calculated the potential evapotranspiration in Nong Son basin by using the Penman-Monteith equation. A monthly mean potential evapotranspiration for each vegetation type and average over the catchment were constructed.
- Land use and Soil map: The land use and soil data are simplified from the data of project Land Use and Climate Change Interaction in Central Viet Nam (LUCCI), and project Impacts of Climate Change in Mi-Central Viet Nam (P1-08 VIE). The input data are defined with five types of soil (Figure 2.9) and nine types of land use (Figure 2.8).
- Vegetation: the harvest schedule is set up for main plants such as forest, homestead, rice, sugarcane, and grass. Each kind of crop is specified by

vegetation property. The vegetation property in this simulation is taken from DHI results (DHI, 2012e).

- River and lakes: In order to simulate better the river flows, MIKE SHE model is coupled with a hydrodynamic MIKE 11 model (1D model). The model is developed over 44 major branches with a length varying from 20 km to 202 km (Figure 2.10). The geometry of each river branch is specified via cross sections. The cross sections applied in this model are from two sources: few of them at downstream are taken from the measurements, and the remaining ones are extracted from the DEM. The initial bed resistance is set up with Strickler roughness coefficient (M) varying from 15 to 25 $m^{1/3}/s$ for upstream tributaries, and the value changing from 30 $m^{1/3}/s$ to 50 $m^{1/3}/s$ for downstream branches.
- Overland flow: The overland flow appears after the net rainfall rate exceeds the infiltration capacity of the soil, water is then ponded on ground surface. The main parameter to calculate this flow is Strickler roughness coefficient (M). For Vu Gia Thu Bon, this parameter is determined depending on land use map and in 2 to 90 $m^{1/3}/s$ (DHI, 2012f; T. Nguyen, 2005; Vieux, 2001)
- Unsaturated zone: DHI suggested three methods for describing the flow in this zone: Richard's equation, Gravity flow and 2 layers UZ. However the application demonstrate that the various approaches don't provide very different results. For the current application, the simple two-layer water balance method is chosen to reduce the computational time. The physical property of each soil type is presented via the water content at saturation, water content at field capacity, water content at wilting point and saturated hydraulic conductivity.
- Saturated zone: The groundwater is supplied by Central Viet Nam Division of Water Resources Planning and Investigation (http://www.ceviwrpi.gov.vn). The characteristic of aquifer is mainly presented by horizontal hydraulic and vertical hydraulic conductivities.

3.6.2 Sensitivity analysis

In principle, the parameters of distributed hydrological model should be assessable from catchment data (Refsgaard *et al.*, 1995) but this principle is fully valid when the model is developed for a large catchment. Due to inaccurate input data as well as coarse simulated resolution, the distributed model could not represent precisely the physical property of catchment (Gurtz *et al.*, 1999). These limitations lead to the reduction on the simulated performance of the model. In order to improve the weaknesses, the calibration is required to find an optimal set of parameter values that simulates the behavior of watershed as accurately as possible (Cunge, 2003; Guinot & Gourbesville, 2003). Calibrating a fully distributed model, which consists of many components and mutually dependent parameters, is really difficult. It requests modelers to attach special importance to many parameters, even several factors influence insignificantly hydrographs. Nevertheless, it is unnecessary for MIKE SHE calibration to apply for all parameters because the number of parameters subjected to adjustment during this process should be kept as small as possible according to the approach developed by Refsgaard *et al.*, (1995). Only several parameters, which have great effects on the model, are chosen. These parameters are decided to rely on the results of sensitivity analysis process. Besides, the elasticity analysis or sensitivity ratio (SR) (3.13), which has been applied in many different models in science, engineering and economics for sensitivity analysis, is realized to exhibit more clearly the level of influence of each parameter towards river flow (EPA, 2001; Maidment & Hoogerwerf, 2002).

$$\mathrm{SR} = \frac{\left(\frac{Y_2 - Y_1}{Y_1}\right) * 100\%}{\left(\frac{X_2 - X_1}{X_1}\right) * 100\%} \qquad (3.13)$$

Where Y_1: the baseline value of the output variable using baseline values of input variables

Y_2: the value of the output variable after changing the value of one input variable

X_1: the baseline point estimate for an input variable

X_2: the value of the input variable after changing X_1

In addition, the sensitivity analysis also quantifies the dependent rate of runoff on the change of these parameters. As a result, these rates make the calibration more easy and allow obtain acceptable values quicker. It is seen to be a prior step of calibration process. For the model applied to the Vu Gia Thu Bon catchment, the sensitivity of each parameter is analyzed based on the response of discharge in Nong Son and Thanh My stations. In a complex system as hydrology, the implying the magnitude change of several model parameters due to different ones is undeniable (Muleta & Nicklow, 2005; Sivapalan *et al.*, 1987; Wang *et al.*, 2007). It is clear that accounting their interactions when estimating the sensitivity will be better (Mishra, 2009). However, with a model containing many parameters as the MIKE SHE model applied to a large catchment, the evaluation of the interaction between model parameters during analyzing the sensitivity is complicated and requires many simulations. In this analysis, the sensitivity analysis is done manually by varying individually the values of parameters one by one. This method has been applied by many authors (Andersen *et al.*, 2001; Refsgaard, 1997; Wang *et al.*, 2012). The model is set up for a long period even so the sensitivity analysis process is only based on the runoff variation during the period of two typical years, 2003 for "dry year" and 2004 for "wet/flood year". The parameter sensitivity is demonstrated via the variation tendency of base flow and peak flow at Vu Gia Thu Bon river system. Subsequently, the result of this process is expected to provide valuable information for the calibration process.

3.6.3 Results

a. Sensitivity analysis

Most of the parameters in Vu Gia Thu Bon's MIKE SHE model are analyzed in order to to estimate the runoff response. The results demonstrate the effects of the parameters on the simulated stream flows. These effects are not similar for all parameters. The results show that the difference is not only about the quantity but also about the timing of the peaks. The responses of river flow versus the variation of main parameters are showed at the Table 3.8a, 3.8b.

Parameters for precipitation-dependent time step control are put forward to reduce the numerical instabilities (DHI, 2012f). These parameters define the maximum rainfall value per time step and they are expected to have a great impact on the river flows, at least on peak flows. In fact, the sensitivity analysis results on the Table 3.8a demonstrate the role of these factors to peak flow. Accordingly, if the Max precipitation depth per time step ($P_{\text{Max depth}}$) increases, the peak flow will reduce. For the Vu Gia Thu Bon catchment, the reduced quantity is around 70 to 120 m^3/s for an increase from 10 to 200 mm for $P_{\text{Max depth}}$. This tendency happens similarly with Input precipitation rate requiring its own time step ($P_{\text{Input rate}}$). However, the impact of $P_{\text{Input rate}}$ on runoff is not as high as the $P_{\text{Max depth}}$. The increase of this factor from 0.1 to 10 mm/h leads to a reduction around 20-50 m^3/s of peak flow at the catchment. An important aspect for this factor is related on simulation time. The smaller $P_{\text{Input rate}}$ is, longer the model is running. Regarding the correlation between Nong Son and Thanh My stations in connection with precipitation parameters, the results show that change at Nong Son station is generally two times higher as compared to Thanh My station. This difference might related to catchment characteristic.

Overland flow simulates the movement of ponded surface water across the topography. It can be used for calculating flow on a flood plain or runoff to streams (DHI, 2012f). In this case, the finite differences method is selected to solve the overland flow for Vu Gia Thu Bon catchment. The Manning number (M), which is equivalent to the Strickler roughness coefficient, is estimated as the basic factor of Overland flow module. Therefore, this part considers mostly the effects of Manning number to run off. In Vu Gia Thu Bon catchment, there are many kinds of land use and soil. These lead to have many corresponded Manning values. The differences of Manning values and their distributed areas imply the impact differences towards river runoff. The difference is showed at the Table 3.8a. Nevertheless, there is one common point that the change of Manning value affects highly the peak flow, but mostly not affects the base one.

Besides, the Manning number (M) is used to represent for bed resistance in MIKE11 as well. The river flow seems quite sensible with the change of the bed resistance. It is expected to be the key factor in calibration process. Nevertheless, in Vu Gia Thu Bon Catchment, it seems that the bed resistance only affects flood flow, concretely the peak flow is significantly impacted in the interval of Manning values from 5 to 10 $m^{1/3}/s$. If M value changes in this interval, the peak discharge could raise 200 m^3/s at Thanh My and 400 m^3/s. The flow apparently do not change if the Manning value in MIKE 11 is higher than 10 $m^{1/3}/s$.

The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as water is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater table. Hence, this process plays a significant role to river run off. Correspondingly, the variation of parameters in unsaturated zone will deeply impact the runoff factor, concretely on both flows as base flow and peak flow. For simulating the unsaturated zone of Vu Gia Thu Bon catchment, the two - layer - UZ soil method is used. In this model, the physical characteristics of each soil are supplied such as water content at saturation, at field capacity, at wilting point and saturated hydraulic conductivity, yet only saturated hydraulic conductivity (K_{uz}) has a huge impact on the flow. The response of flow versus the K_{uz} variation is expressed in the Table 3.8b. According to this table, the peak flow goes down quite quickly when increasing infiltration typical parameter. This change can reach more than 1,000 m^3/s. Furthermore, the reduction of K_{uz} makes the base flow decrease. The response of base flow is small, around 10 to 20 m^3/s, but having a big value in comparison with observed base flows. With variation in soil distribution, the change in the amount of runoff against soil property variation in Thanh My and Nong Son is very different as presented in Table 3.8b.

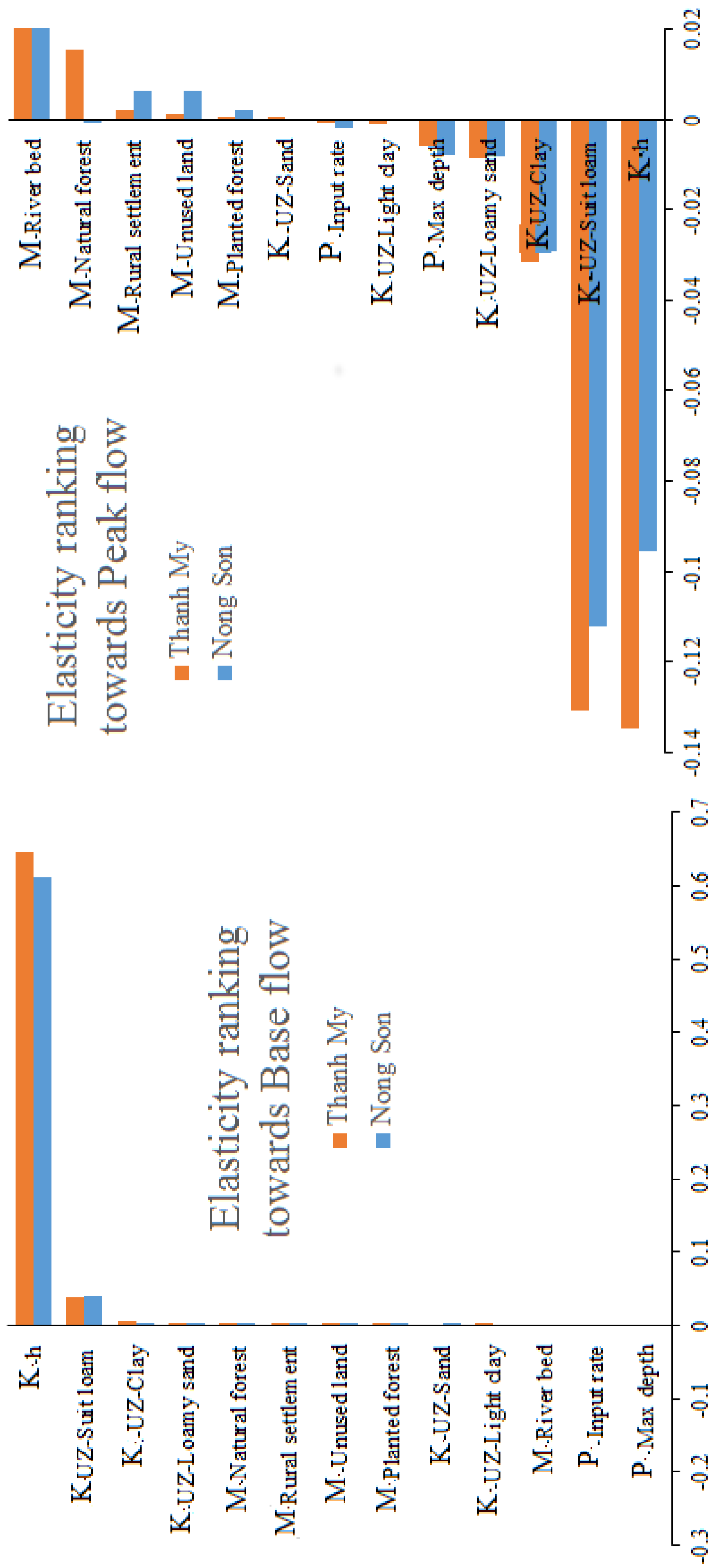


Figure 3.20. Elasticity ranking of peak and base flow due to the input parameter changes.

Table 3.8a: Response of stream flow versus the change in MIKE SHE model parameters at Vu Gia Thu Bon Catchment.

					Thanh My		Nong Son	
Module	**Type**	**Parameter**		**Unit**	**∆base flow**	**∆peak flow**	**∆base flow**	**∆peak flow**
Overland	Natural forest	M	1	$m^{(1/3)}/s$				
			5		1.83	190.16	0.98	26.4
			10		0.61	13.42	0.69	63.53
			20		0.88	32.73	0.88	-69.54
			50		0.42	11.88	0.29	-14.45
	Planted forest	M	1	$m^{(1/3)}/s$				
			5		0.22	-15.66	1.57	95.25
			10		0.14	5.58	0.5	21.18
			20		0.12	3.1	0.48	20.13
			50		0.12	2.94	0.46	13.58
	Unused land	M	1	$m^{(1/3)}/s$				
			5		0.04	3.85	0.67	49.74
			10		0.02	1.48	0.25	5.39
			20		-0.02	0.15	0.14	4.33
			50		0.01	-0.22	0.13	0.44
	Rural settlement,	M	1	$m^{(1/3)}/s$				
			5		0.47	26.57	0.43	119.79
			10		0.15	-1.9	0.18	25.34
			20		0.13	-0.93	0.14	16.28
			50		0.18	4.1	0.21	12.6
River flow	Bed	M	5	$m^{(1/3)}/s$				
			10		-0.22	236.22	-11.49	389.39
			20		0	-0.01	0.01	-9.61
			30		0	0.01	-0.01	9.61
			40		0	0	0	0
Simulation parameters	Precipitation dependent time step control	$P_{Max\ depth}$	10	mm				
			20		-0.03	-4.36	-0.14	-10.33
			50		0.18	-5.78	-0.22	-14.46
			100		0.23	-35.58	-0.21	-72.3
			200		0.17	-10.81	0.14	-28.59
		$P_{Input\ rate}$	0.1	mm per hour				
			1		0.23	-6.96	0.22	-11.9
			2		0.2	-1.24	0.18	-6.52
			5		0.08	-12.15	-0.24	-13.51
			10		0.2	2.43	0.03	-20.19

Table 3.8b: Response of stream flow versus the change in MIKE SHE model parameters at Vu Gia Thu Bon Catchment. (Continuing Table 3.8a)

					Thanh My		Nong Son	
Module	**Type**	**Parameter**		**Unit**	**∆base flow**	**∆peak flow**	**∆base flow**	**∆peak flow**
Unsaturated	Clay	K_{uz}	$1e^{-09}$	m/s				
			$1e^{-08}$		-2.18	-17.46	-3.45	-53.39
			$1e^{-07}$		-4.84	-66.43	-6.69	-166.38
			$1e^{-06}$		-3.87	-280.98	-5.7	-332.43
			$1e^{-05}$		-3.27	-476.99	-4.34	-592.19
	Light clay	K_{uz}	$1e^{-08}$	m/s				
			$1e^{-07}$		-0.42	-2.87	-0.47	-2.86
			$1e^{-06}$		-0.34	-18.35	-0.08	-6.81
			$1e^{-05}$		-0.18	-29.19	-0.26	-17.95
			$1e^{-04}$		-0.02	4.46	0.03	17.44
	Suit loam	K_{uz}	$1e^{-07}$	m/s				
			$5e^{-07}$		-3.69	-249.9	-7.22	-428.98
			$1e^{-06}$		-5.34	-317.53	-7.1	-459.5
			$5e^{-06}$		-9.8	-1321.32	-14.28	-1648.9
			$1e^{-05}$		-0.65	-132.79	-1.9	-494.44
	Loamy sand	K_{uz}	$1e^{-08}$	m/s				
			$1e^{-07}$		-0.17	-7.1	-0.92	-9.21
			$1e^{-06}$		-2.16	-89.13	-1.83	-114.61
			$5e^{-06}$		-1.12	-194.24	-1.19	-213.99
			$1e^{-05}$		-0.17	-39.17	-0.31	-65.52
	Sand	K_{uz}	$1e^{-08}$	m/s				
			$1e^{-07}$		0	0	-0.07	-0.57
			$1e^{-06}$		0	0.02	-0.24	-5.13
			$1e^{-05}$		0	-0.01	-0.13	-3.74
			$1e^{-04}$		0	0	0	0
Saturated	Aquifer	K_h	$1e^{-05}$	m/s				
			$2e^{-05}$		7.5	-169.43	12.45	-55.98
			$4e^{-05}$		11.23	-104.78	18.68	-82.65
			$6e^{-05}$		7.15	-92.3	12.46	-168.03
			$8e^{-05}$		4.7	-98.18	8.69	-99.1

The groundwater plays a crucial role in the behavior of hydrological processes with the catchment. So, the variation of this component will influence significantly on the river flow, especially the base flow when the discharge from groundwater is seen as its principal source. The groundwater is represented in the saturated zone. The flow in saturated zone is characterized by aquifer property, in these, horizontal saturated hydraulic conductivity (K_h) proves the most influence on saturated flow. For this reason, in the model, only this factor is considered. With Vu Gia Thu Bon, the results in Table 3.8b demonstrate the primary impact of this factor on peak flow. The peak flow tends to reduce quickly when increasing K_h. The reduction is so clear, when K_h rises from $1e^{-5}$ to $8e^{-5}$ m/s, the runoff goes down around 500 m^3/s at both Thanh My and Nong Son stations. On the contrary, K_h increase in the interval of $1e^{-5}$ - $8e^{-5}$ m/s makes the base flow rise approximately at 30 m^3/s at Thanh My and at 50 m^3/s at Nong Son. In spite of the insignificant variation, it is quite important for adjusting the base flow.

Eventually, the different response of flow factor due to the input parameter is compared to each other by the elasticity ranked at Figure 3.20. Following the above analysis, the saturated hydraulic conductivity of saturated zone is the first factor that modelers need to notice when playing with base flow. Besides, it is necessary to consider the role of the saturated hydraulic conductivity of clay, suit loam in unsaturated zone. The impact of these parameters to base flow discharge is not high but it is big enough for helping to get a better result. Because there are not many parameters affecting base flow, the suggestion is "try to calibrate base flow first before doing this process with peak flow". Conversely, the peak discharge is affected by most of the parameters. The change quantity of the peak is affected by the parameter and sub catchment. Importantly, the interaction between these parameters with run off might be considered for obtaining a better simulation.

b. Calibration and validation

Based on the split-sample test theory of Klemeš, (1986), he MIKE SHE model is built for a period of 11 years period from 1990 to 2000 for calibration and from 2000 to 2010 for validation. In order to stabilize the model and establish proper initial conditions, the first year of each period is used for warming up the model. Hence, in this analysis, only ten years of daily data are taken to calibrate and validate the model. The calibration is done manually. This process, of course, is based on the results of the sensitivity analysis. Only a few of sensible model parameters are used for the calibration process.

The Vu Gia-Thu Bon catchment has a complicated river system. Although the length of the two main rivers reaches to 200 km, there is only one flow measured station in the middle of each main river: Nong Son at Thu Bon branch and Thanh My at Vu Gia branch. This situation creates several difficulties for the comparison of the results between simulations and observations. Especially this is not only an inconvenient for predicting flood risk in the downstream region, but there is also a factor producing uncertainty when assessing the impact of climate change on the runoff. The lack of observation data for comparing simulation results degrades the performance of distributed model. Many hydrologists have suggested to realize calibration on multi-site, with not only the discharges but also the water levels (Wang *et al*., 2012). Accordingly, the water level at Ai Nghia station, Cam Le Station on Vu Gia branch and Hiep Duc, Giao Thuy, Cau Lau stations on Thu Bon branch as well are compared with the MIKE SHE model outputs in order to increase the confidence and simultaneously to reduce the uncertainty in projected climate scenario. The model assessment is performed with statistical measures of the root mean squared error (RMSE) (equation 3.10), the correlation coefficient (R) (Equation 3.11), and Nash-Sutcliffe coefficient (E) (Equation 3.12).

On the other hand, to evaluate the accuracy of simulation on the aspect of distributing peak flow and low flow extreme values, Willems has developed a tool to make appearance of the performance of model by using graphical goodness of fit plots: the WETSPRO method (Willems, 2009). This comparison method his expected to increase the confidence on the simulation via scatterplot and extreme value distribution of peak flow and base flow. In the analysis, this method is used to assess the capacity of MIKE SHE to reproduce properly peak flow and low flow at Nong Son and Thanh My stations.

MIKE SHE mode parameter values are varied based on the above sensitivity analysis. The optimal values reached from calibrated process are shown at Table 3.9.

- Calibration and validation with discharge.

Hydrographs in Figure 3.21, 3.22 demonstrate that the model simulates relatively accurately the runoff in Vu Gia Thu Bon catchment. Simulated base flows at two stations Nong Son and Thanh My is similar to the measurements. However, it seems that the peak of sub-main flood is not presented well. The quality of observation data may cause this limitation. In dry season, the data in these two stations is only captured once or twice per day, so it could not present precisely the time of sub-main flood appearance. It is really difficult to overcome the problem concerning to missing data, so the simulated base flow might be acceptable. Following the hydrographs, peak floods are almost the same to observation data. Occasionally, some peaks are higher than reality but the difference is not very high, it is reasonably acceptable. In theory, this problem could be completely controlled. This issue seems uncomplicated with the simulation for small area and in short time. Otherwise, for ten years simulation in a large area, and model contained many parameters like this case, gaining a perfect result is really unrealizable. It needs to take more time to analyze and adjust parameters. One question is what is more rational? An acceptable result or higher performing model with long time calibration. It must be balanced carefully during calibration process (Cunge, 2003; Sahoo *et al*., 2006). In this study, considering on the reality of data and the computer's restriction, the first one is more appreciated than the other. Furthermore, the more accurate MIKE SHE model in describing the run off in dry season than flood season might be understandable under the data aspect. The base flow is mainly composed from groundwater, so this component is not dependent so much on data factor, such as rainfall. Therefore, this component of runoff is more stable through long time and closer with the measurement if the model is set well. On the contrary, peak flow is influenced by many factors of hydrological process such as overland flow, unsaturated flow, groundwater flow, channel flow, evaporation, particularly the rainfall data. The time step of rainfall data input has a huge impact on concentration time, concretely to appearance time of peak discharge (Dendy, 1987). For this reason, the rainfall data input using large step might be the main cause of the differences of peak discharge in this MIKE SHE which uses daily rainfall input. The acceptability of this model can be explained by safe aspect. Based on this aspect, the little overestimation of model in wet season might increase the safety when simulating extreme flood events. The quality of this simulation is affirmed through validated period. The flow in ten years is regenerated approximately with the observation (Figure 3.21, 3.22).

The efficiency of MIKE SHE model is also shown through the statistical coefficients in Table 3.10. Daily and monthly discharges are compared between simulation and observation. These numbers prove the accuracy of this model in describing the hydrological process in Vu Gia Thu Bon catchment. The R and E coefficients at Nong Son and Thanh My in the calibration period are 0.92, 0.89 and 0.82, 0.78, respectively. In the validation period, these factors reduce, but not very low, R and E coefficients at Nong Son station is 0.92 and 0.82 and at Thanh My is 0.90 and 0.69. The RMSE coefficients at Nong Son and Thanh My in both periods are relatively small. In ten years, the RMSE of simulation are only 132.3 m^3/s at Thanh My versus maximum observation 4,440 m^3/s-minimum observation 12.2 m^3/s. The value at Nong Son is 288.7 m^3/s versus maximum observation 8,920 m^3/s-minimum observation 21.7 m^3/s. While the RMSE of validation at Thanh My is 123.2 m^3/s versus maximum observation 4540 m^3/s-minimum observation 20.2 m^3/s and at Nong Son is 250.5 m^3/s versus maximum observation 8,410 m^3/s-minimum observation 21.9 m^3/s.

Table 3.9. Calibrated parameter values of MIKE SHE model.

Key parameter	Unit	Optimal value
*** River bed resistance - Strickler Coefficient**		
- Tributary and upstream of Vu Gia	$m^{(1/3)}/s$	18
- Tributary and upstream of Thu Bon	$m^{(1/3)}/s$	25
- Linking branch	$m^{(1/3)}/s$	30
- Downstream	$m^{(1/3)}/s$	40
*** Overland flow - Strickler Coefficient**		
- Planted forest	$m^{(1/3)}/s$	5
- Rural settlement	$m^{(1/3)}/s$	8
- Rice	$m^{(1/3)}/s$	16
- Annual crops	$m^{(1/3)}/s$	8
- Perennial crops	$m^{(1/3)}/s$	8
- Unsed land	$m^{(1/3)}/s$	5
- Natural forest	$m^{(1/3)}/s$	2
- Urban	$m^{(1/3)}/s$	90
- Water surface	$m^{(1/3)}/s$	33
*** Unsaturated flow - soil property**		
- K_{uz}-Clay	m/s	$1.2\ 10^{-8}$
- K_{uz}-Suit loam	m/s	$2.45\ 10^{-6}$
- K_{uz}-Loamy Sand	m/s	$8.5\ 10^{-6}$
- K_{uz}-Light clay	m/s	$2.085\ 10^{-4}$
- K_{uz}-Sand	m/s	$2.89\ 10^{-4}$
*** Saturated zone**		
- K_h- Horizontal hydraulic conductivity	m/s	$6.7\ 10^{-5}$

Because of these big differences between maximum and minimum values of observed data, the values of normalized root mean square error at these stations are quite small. These are lower than 0.05. If comparing the monthly data, the efficiency of model is proved more impressively by these indications (Table 3.10).

Figure 3.23a shows the comparison plot of maximum value at Nong Son in calibrated period, which has relatively high scatter, yet almost simulated peak flows concentrate in the interval of the mean $\pm$ standard deviations and zero bias. These trends happen in the similar way with Thanh My station. But at Thanh My, the pilot (Figure 3.24a) shows a negative bias. The higher of bisector line expresses the peak discharge at Thanh My is underestimated, even so this disparity is quite small. These comparisons prove again the model performance in translating high values of run off. Furthermore, it is easy to recognize the performance of model via the frequency comparison. The Figure 3.25 shows strongly the capacity of model in simulating the peak discharge value. The simulated and observed discharge values corresponded to return period of Thanh My and Nong Son are mostly similar. These analyses demonstrate the performance of MIKE SHE model to simulate the peak discharge for this catchment.

Conversely, Figure 3.23b, 3.24b show the low flow value of simulation distribute higher dispersedly than peak flow. Even though simulated low flows are mostly in the interval of the mean $\pm$ standard deviations but they present a big negative bias. These negatives show underestimated trend of this MIKE SHE model with low flow. The trend is occurred similarly at both stations, Thanh My and Nong Son. The low flow underestimation is confirmed at the frequency comparison of Nong Son station (Figure 3.26b), but in the case of Thanh My station, the difference between observed and simulated frequencies is not so high (Figure 3.26a). However, Vansteenkiste *et al*., (2014) gave a viewpoint that the underestimation of the most extreme low flows might help to forecast better the extreme tendency of dry season, that is why using this model is able to predict the most severe drought in dry season of Vu Gia Thu Bon catchment and helps to cope more actively the drought disaster.

Throughout the results on describing the peak flows and base flows, this MIKE SHE model give an impressive capacity in representing the hydrological process in Vu Gia Thu Bon catchment. Its accuracy might contributes a significant part to forecast hydrological events occurring in this river basin.

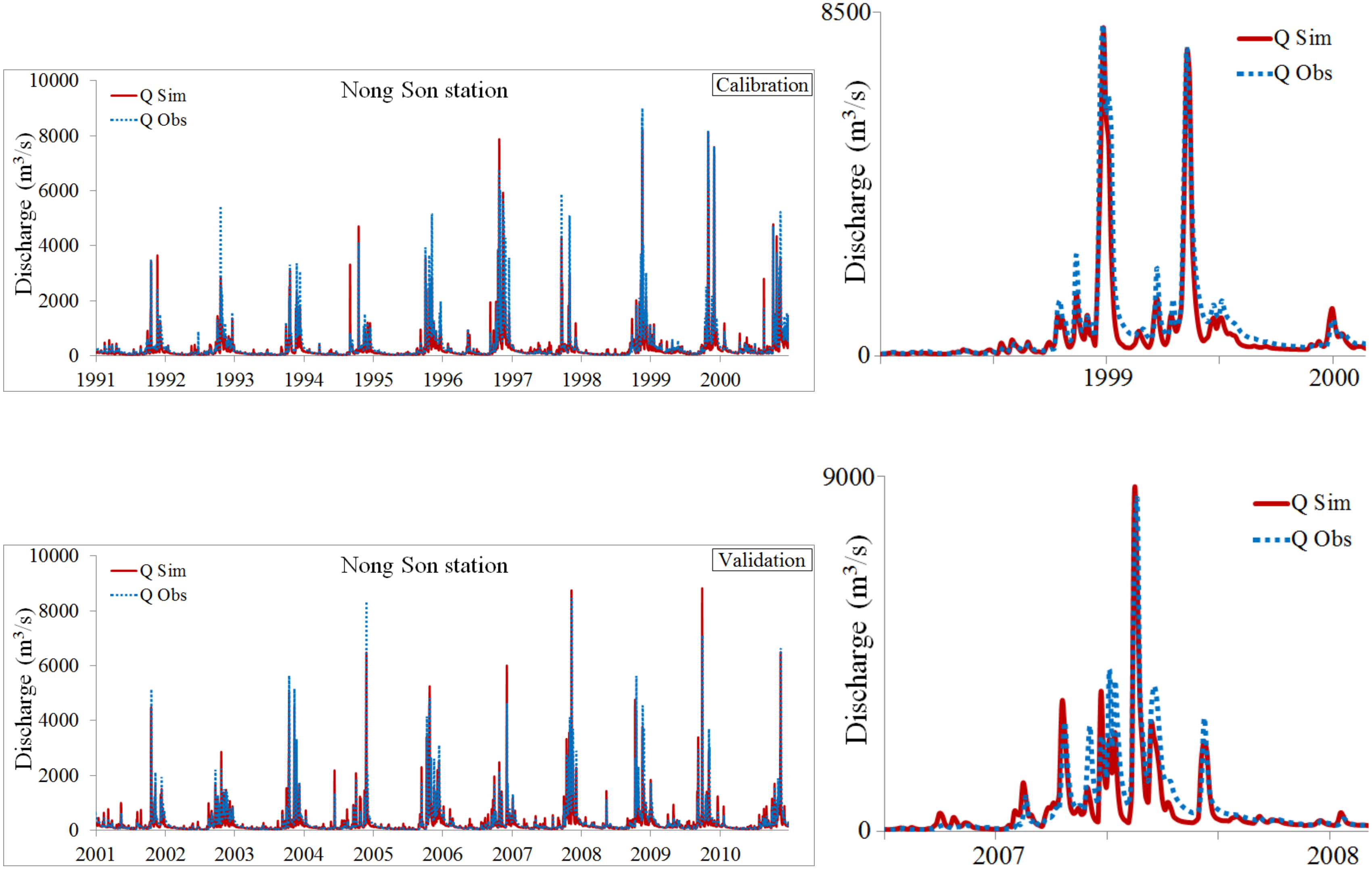


Figure 3.21. Calibrated and validated hydrographs of discharge at Nong Son station.

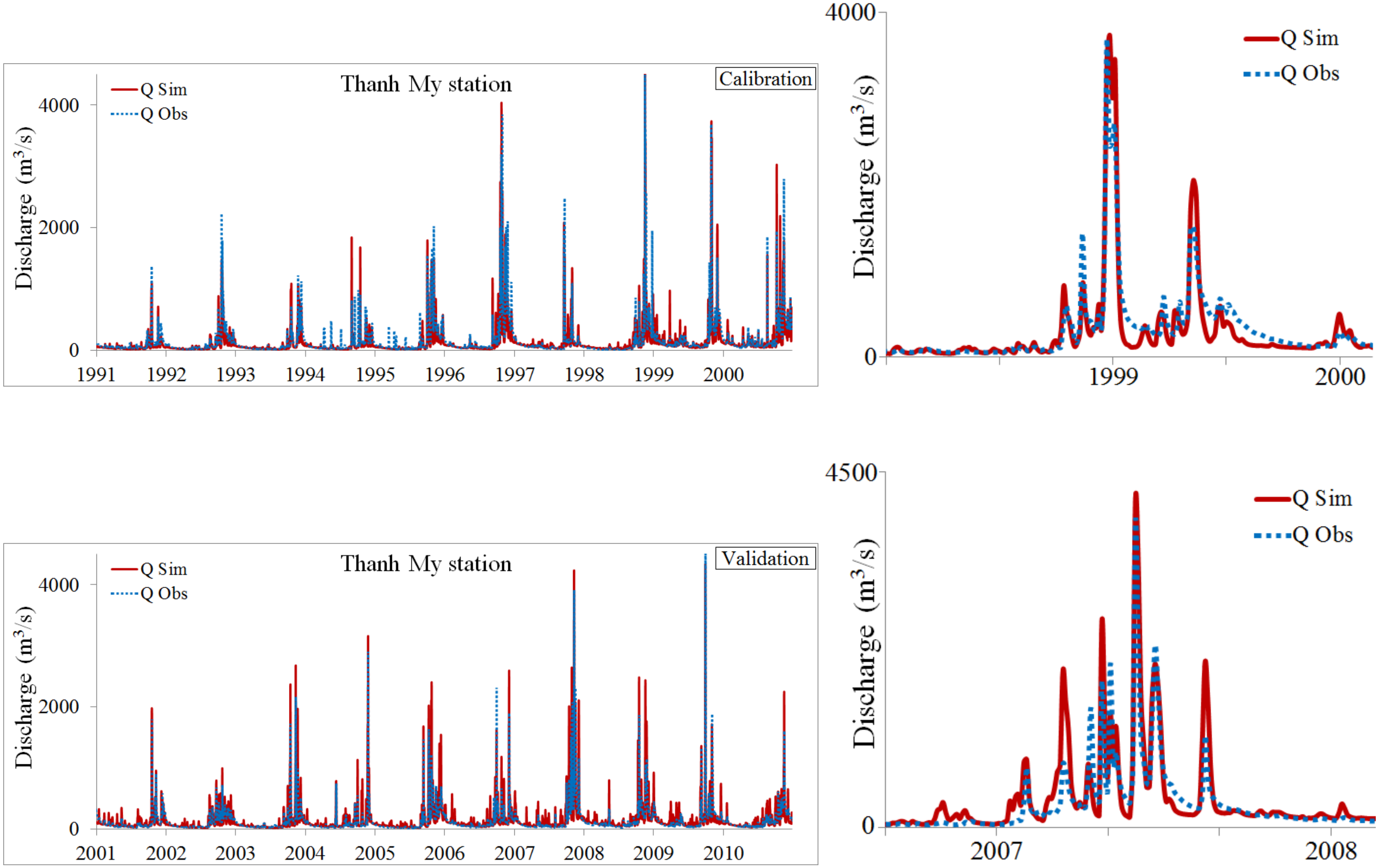


Figure 3.22. Calibrated and validated hydrographs of discharge at Nong Son station.

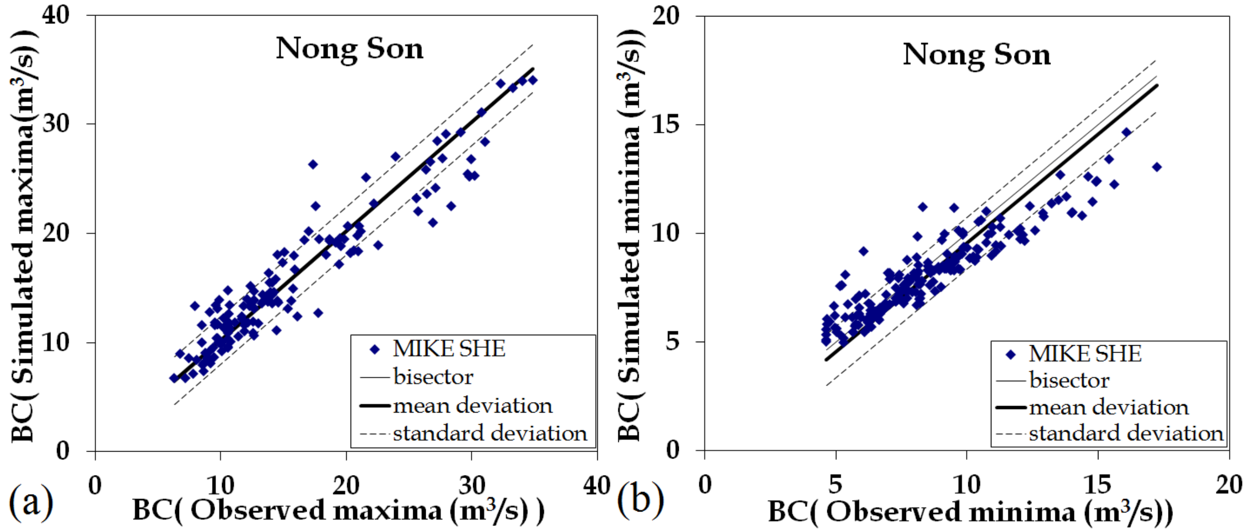


Figure 3.23. MIKE SHE calibration versus observed nearly independent daily peak flow (a) and low flow (b) at Nong Son station after Box-Cox transformation (λ = 0.25)

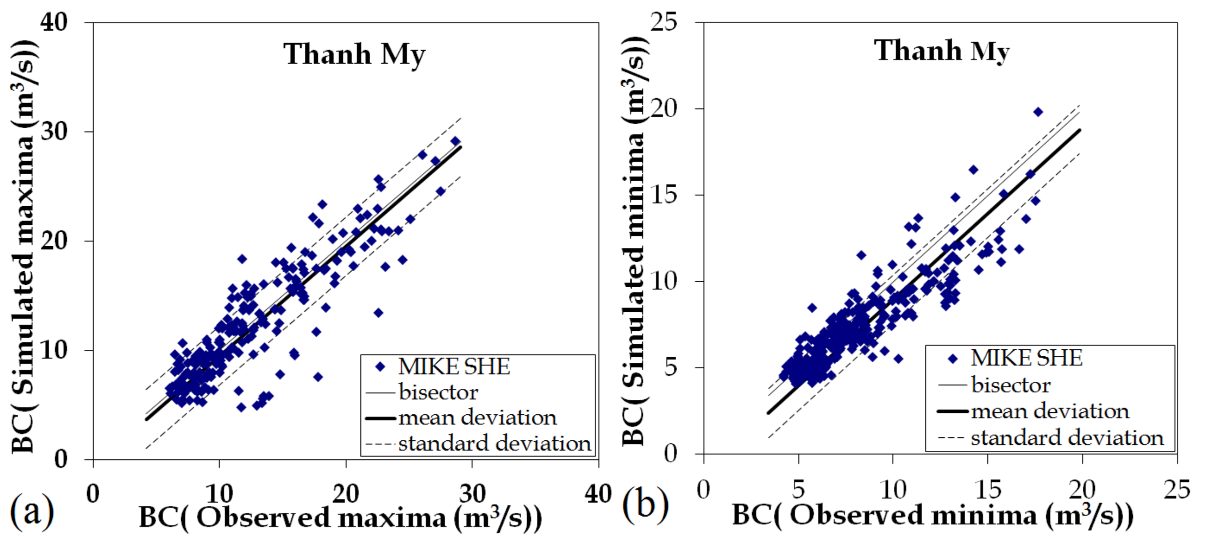


Figure 3.24. MIKE SHE calibration versus observed nearly independent daily peak flow (a) and low flow (b) at Thanh My station after Box-Cox transformation (λ = 0.25)

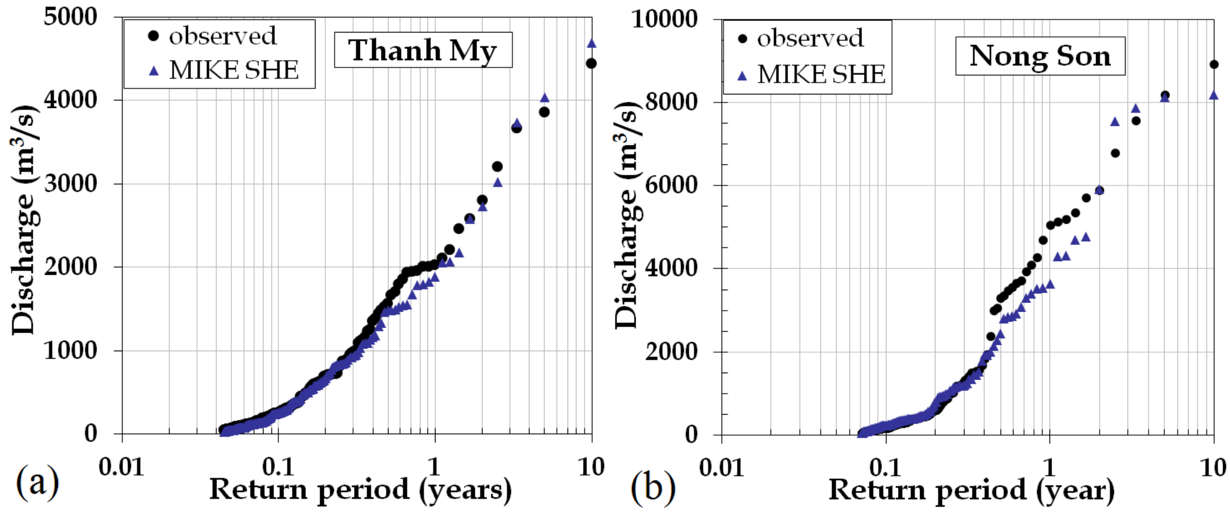


Figure 3.25. The difference of peak flow empirical extreme value distributions between calibration and observation at Thanh My(a) and Nong Son (b).

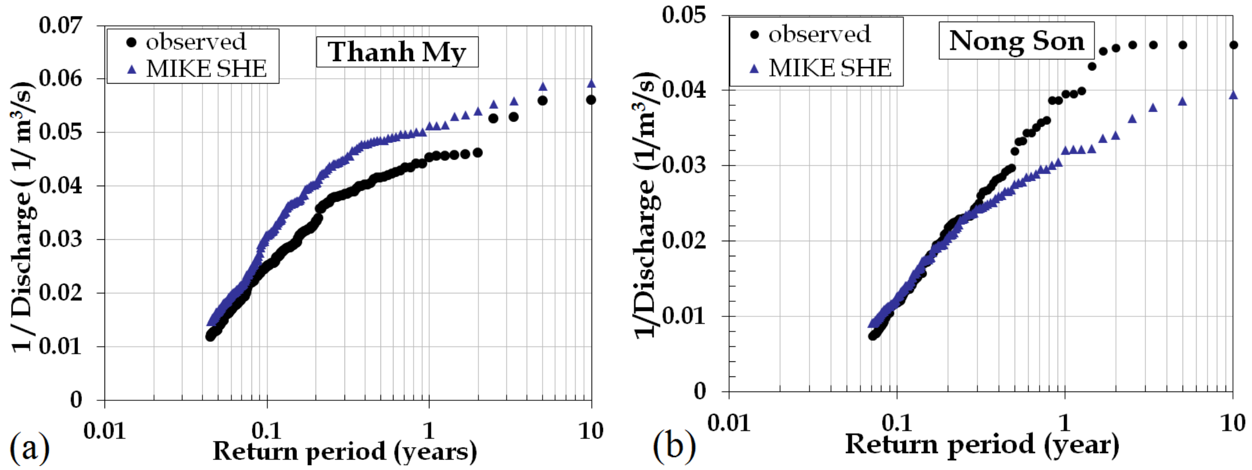


Figure 3.26. The difference of low flow empirical extreme value distributions between calibration and observation at Thanh My (a) and Nong Son (b).

Table 3.10. Statistical indices of MIKE SHE model in Vu Gia Thu Bon catchment.

	Station	Calibration (1991-2000)						Validation (2001-2010)					
		Daily			**Monthly**			**Daily**			**Monthly**		
		RMSE	R	E	RMSE	R	E	RMSE	R	E	RMSE	R	E
Water lever (m)	Thanh My	0.77	0.86	0.67	0.52	0.97	0.77	0.68	0.83	0.61	0.32	0.94	0.86
	Ai Nghia	0.70	0.81	0.63	0.41	0.96	0.81	0.66	0.78	0.56	0.35	0.94	0.83
	Cam le	0.26	0.83	0.12	0.18	0.94	0.32	0.28	0.8	-0.46	0.2	0.94	-0.13
	Hiep Duc	0.77	0.89	0.77	0.44	0.97	0.88	0.91	0.83	0.59	0.63	0.92	0.67
	Nong Son	0.89	0.88	0.76	0.49	0.97	0,89	0.84	0.86	0.72	0.42	0.96	0.89
	Giao Thuy	0.85	0.85	0.61	0.6	0.97	0.73	0.73	0.82	0.6	0.4	0.95	0.82
	Cau Lau	0.44	0.84	0.56	0.16	0.96	0.9	0.47	0.83	0.16	0.2	0.97	0.25
Discharge (m^3/s)	Thanh My	132.3	0.89	0.78	58.06	0.96	0.89	123.2	0.9	0.69	47.03	0.96	0.87
	Nong Son	288.7	0.92	0.82	160.4	0.97	0.86	250.5	0.91	0.82	131.0	0.97	0.87

- Calibration and validation with water levels:

In order to verify the efficiency of the MIKE SHE model for the Vu Gia Thu Bon catchment, the water levels recorded at several stations are compared with the results (Figure 3.27). However, the accuracy of simulated water levels is not good for discharges. Due to these differences, the statistical coefficients for water levels comparison between simulation and measurements are not as high as the ones obtained for the discharges (Table 3.10). The relation coefficient in all stations is around 0.8 to 0.9 but Nash-Sutcliffe coefficients are low and vary from 0.6 to 0.7 at the upstream station and get smaller in station under tidal effect. The source of this inaccuracy can be explained by the coarse resolution of topographic data, the lack of measured cross sections and the large distance between two computed sections (dx) in MIKE 11 (Vázquez *et al.*, 2002). Despite the fact that statistical coefficients for water levels are still low, calibrating the model relying on these factors probably adds a certain value to show the correlative level of model result with real data. By mean of analysis above, we can judge that the flow in Vu Gia Thu Bon catchment is reproduced rather impressively by MIKE SHE. The presented capacity of this kind of mode allows to simulate easily the flood event or the variability of stream flow under the impact of climate change, especially with large catchment.

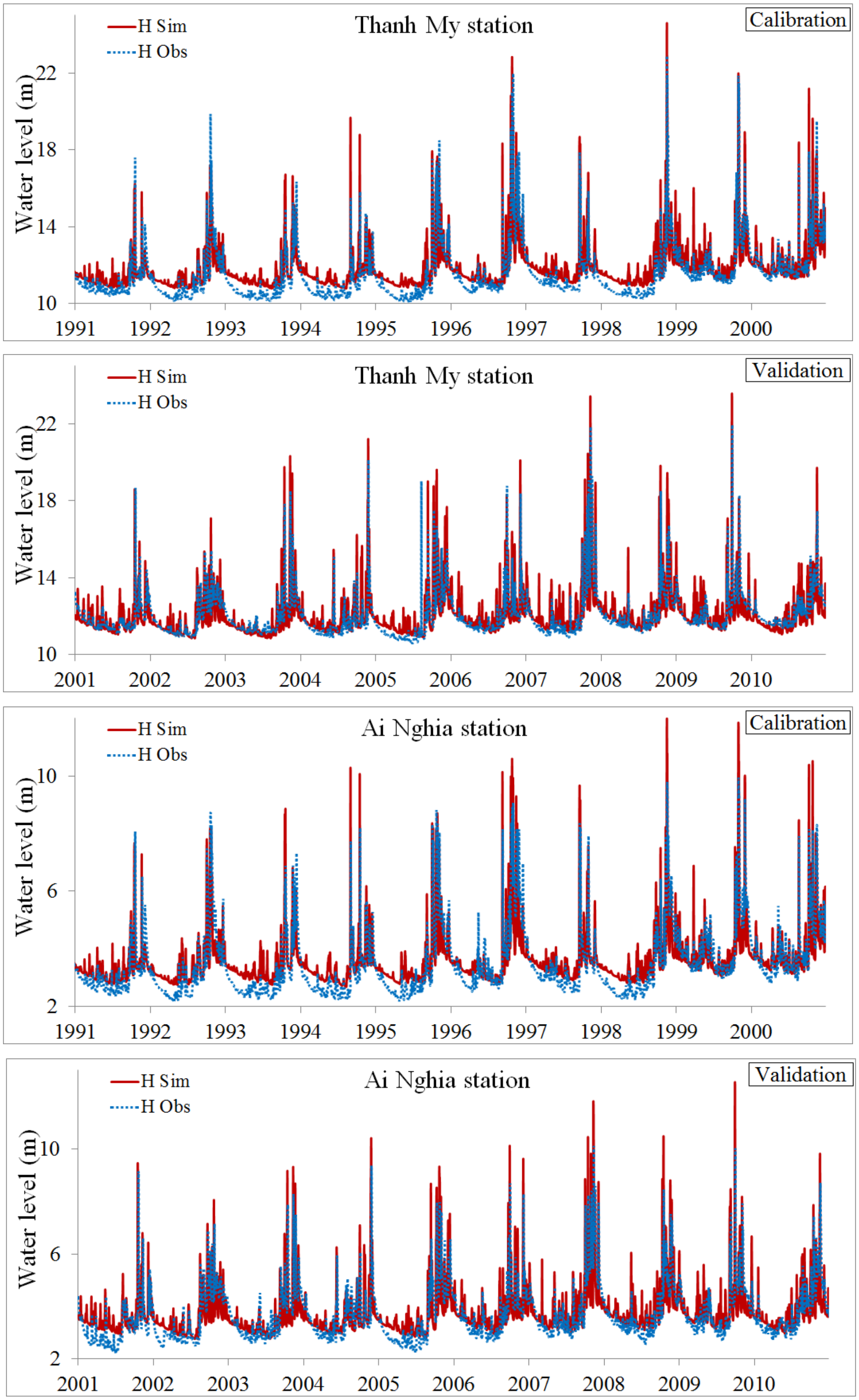


Figure 3.27a. Calibrated and validated hydrographs of water level.

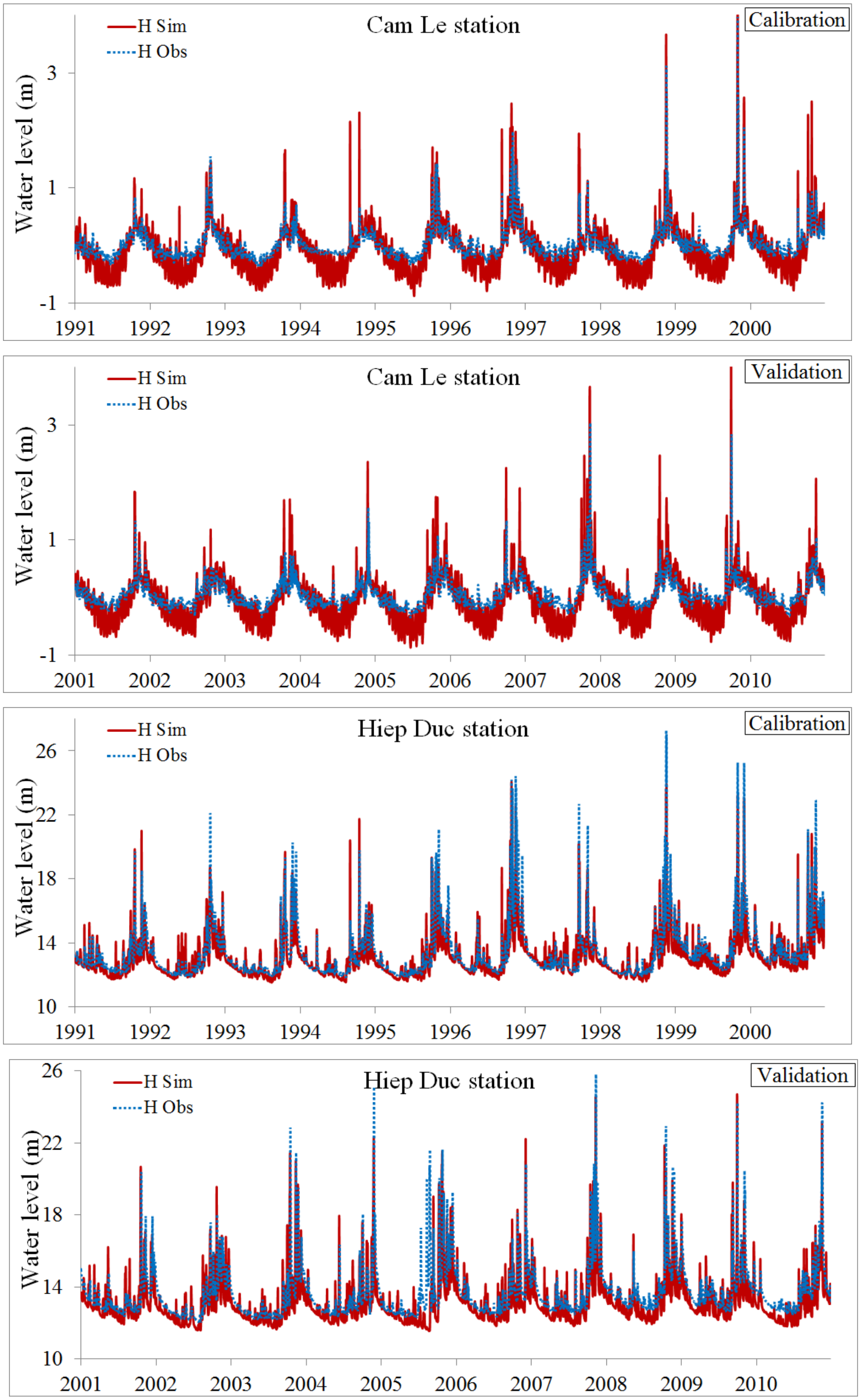


Figure 3.27b. Calibrated and validated hydrographs of water level.

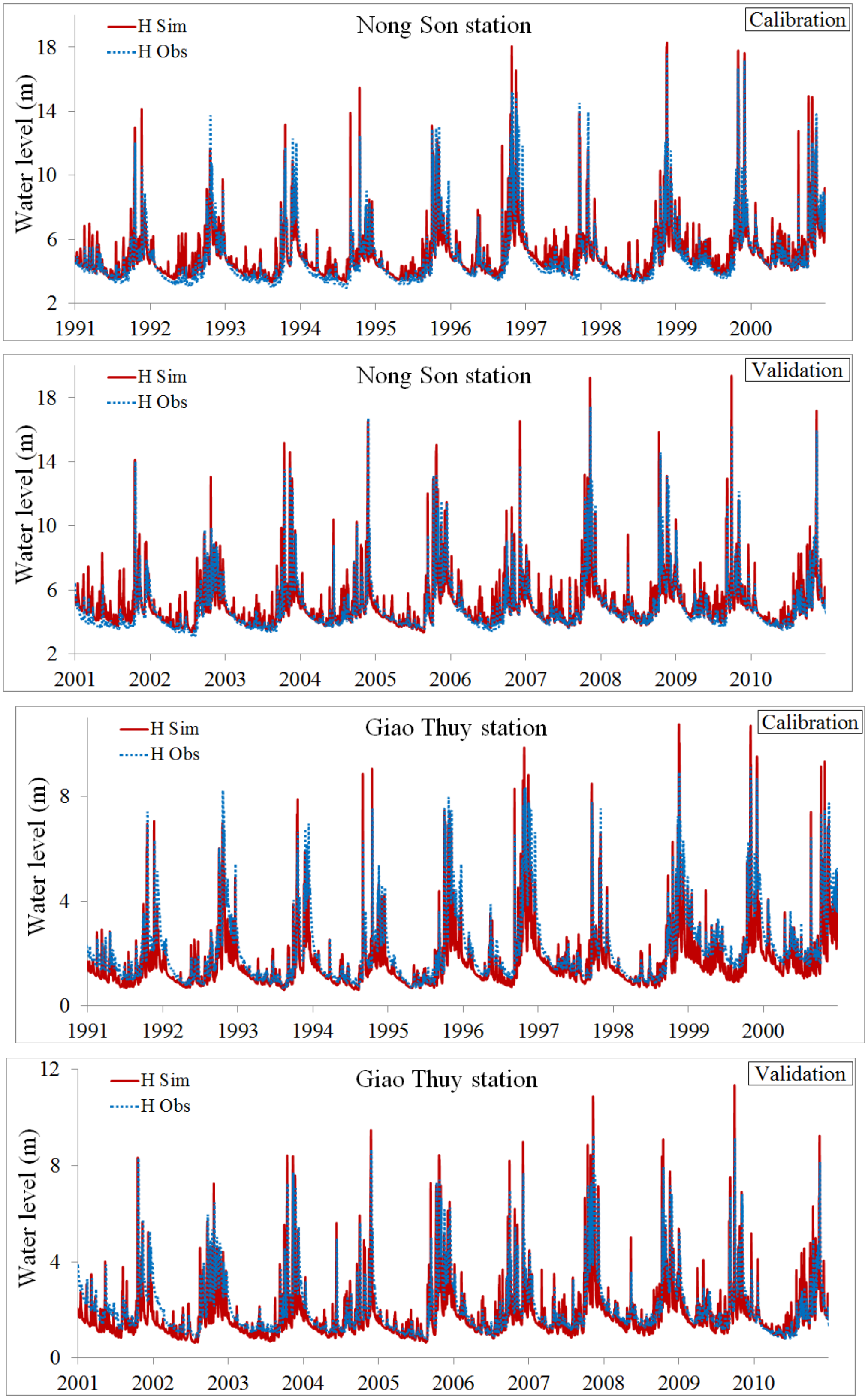


Figure 3.27c. Calibrated and validated hydrographs of water level.

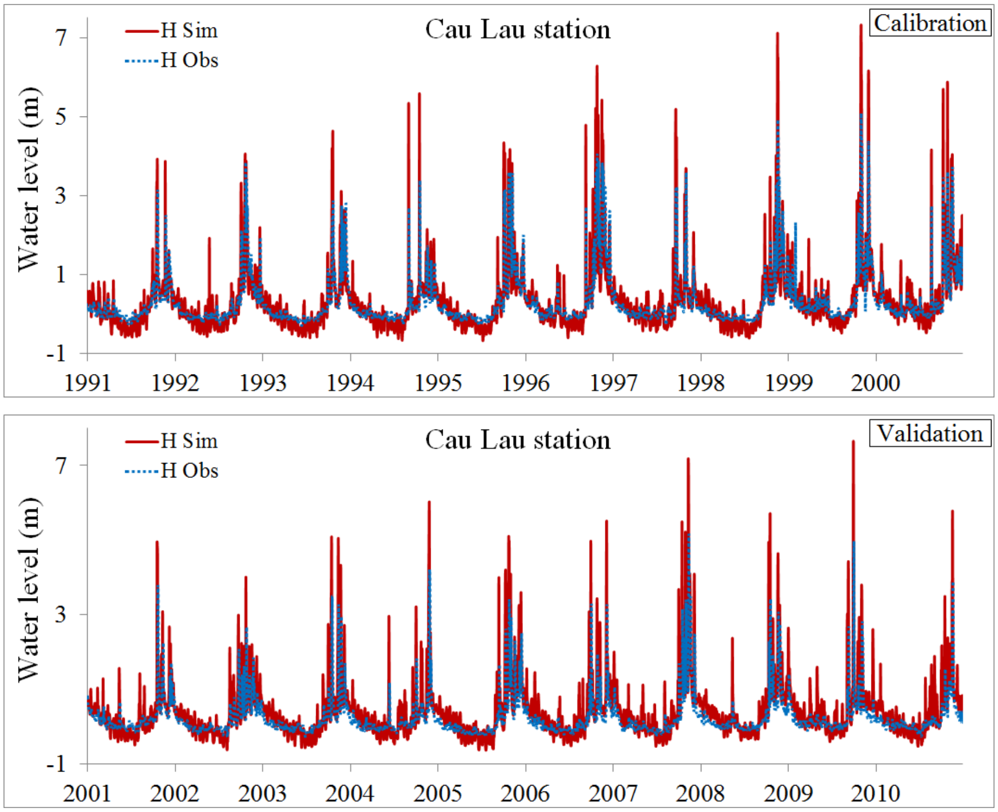


Figure 3.27d. Calibrated and validated hydrographs of water level.

c. Uncertainties

Although, trying to reflect the most truthfully the hydrological dynamic in the catchment, the model has not yet gained the optimal results when inaccuracies still remain. The statistical coefficients, such as Nash Sutcliffe and correlation coefficient (RMSE) are still weak. These coefficients could not get maximum values for many reasons. The model has many potential uncertainties for simulating hydrological processes. Uncertainty in hydrologic modelling may arise from several sources: model structure, parameters, initial conditions and observed data used to drive and evaluate the model (Liu & Gupta, 2007).

One of the most important factors regarding the model structure which may have a significant influence on the model accuracy as well as on the uncertainty of simulation, is cell size issue (Egüen *et al.*, 2012). The advantage of distributed hydrological model is to represent hydrological characteristics of catchment cell by cell. However, the resolution used in the model is still coarse due to the limitation of topographic data and computation time. The 90 m topographic grid data used may not describe precisely enough the surface of the catchment. Thus, it derives some differences of surface flows between reality and model. The land uses, the soil properties or the roughness coefficients, which are simplified in order to optimize the calibration purpose, are the large causes of underestimation or overestimation for the model.

Another issue influencing significantly the model uncertainty is the rainfall that is a key factor in the hydrological dynamic. Rainfall spatial variation affects heavily both runoff generation and hydrologic process in a catchment (Moon *et al.*, 2004). The spatial variability in rainfall mays introduce a significant uncertainty in model parameters during the calibration process (Chaubey *et al.*, 1999). The quality of spatial rainfall distribution usually depends on the characteristic of study area and other factors, in particular, the rain gauge density. Therefore, the network of rain gauge stations in Vu Gia Thu Bon is sparse, with, in average, one station for an area of 700 km^2. In the constructed model, the rainfall inputs are re-interpolated and could be considered as a great source of uncertainty. Besides the spatial distribution, the time factor is also a great potential source for uncertainty (Dendy, 1987), especially within the Vu Gia Thu Bon catchment where the concentration time is short due to the steep topography. Using daily rainfall in this simulation probably affects the rising limb and the peak flow appearance. However, these data are the unique complete rainfall data set available for long-term simulations for the Vu Gia Thu Bon catchment. The analysis about the rainfall distribution in space and in time demonstrates again the impact of lack of data on the simulation uncertainty.

The groundwater component cannot be ignored when simulating hydrological process (Winter, 1999). In terms of input data, the insufficiency of ground water data is seen as a major source of uncertainty for simulating hydrological processes. The quality of the groundwater data of Vu Gia Thu Bon catchment is not very good and the collected data do not present the groundwater properties concretely. For the whole catchment, the model integrates a unique geological layer.

Regarding the modeling methods implemented in MIKE SHE, the selection of one or another method can potentially generate several sources of uncertainty. For example, there are three functions to select for unsaturated flow such as Richards equation, Gravity flow, 2 layers UZ. The Richards equation is supposed to be the best method for simulating unsaturated flow. However, in the current application, the 2 layer UZ is chosen due to the limited available data sets and the short processing time.

The coupling between MIKE SHE and MIKE 11 contains additionally potential uncertainties. It could affect notably water exchanging between floodplain and riverbed. The number of simulating branches and intervals in MIKE 11 is considered as a main uncertainty source. In the model, the coupling between MIKE SHE and MIKE 11 is not set well due to the limited number of cross sections. Additionally, there is a difference between overland flow and river flow, but in the analysis, the river network presented in MIKE 11 is merely over 44 large branches. Understandably, the set up manner the coupling between MIKE SHE/MIKE 11 is estimated holding a big uncertainty.

An additional element affecting to the quality of hydrologic model concerns the time factor. Time step applied in the MIKE SHE model is fixed to one day. This time step is still high so it may not present thoroughly what the hydrological cycle is in the catchment. Besides, the timescale of model is limited to 10 years. The simulation time is considered not sufficient enough to bring adequately extreme events from natural phenomena. Unavoidably, simulating the stream flow at Vu Gia Thu Bon catchment will contain particular uncertainties.

3.7 Conclusion

With the aim of providing a tool able to simulate the hydrological process and estimate impacts of climate change on runoff in the Vu Gia Thu Bon river system, a deterministic distributed hydrological model based on MIKE SHE modeling system has been built. The model integrates most of the hydrological processes - from surface flow to groundwater flow, and evapotranspiration – and is expected to reproduce the hydrological cycle within the catchment. The model is hoped to produce a good assessment of the climate change impact over the region and with an estimated accuracy. One of the advantages of fully deterministic distributed model is the possibility to overcome the weakness and the lack of systematic data. The difference between actual and future runoff regime could be compared anywhere over the catchment. Hence, an overview of change in runoff regime in the whole catchment could be generated without difficulty. These points confirm the capacity of distributed models in modelling impact of climate change over the hydrological processes. The model is calibrated and validated against daily data and monthly data for the period 1991-2000 and 2001-2010, respectively. The performance of model is demonstrated via the hydrograph shapes and statistical indices comparing simulation results with data from seven gauging stations. The model efficiency is likewise confirmed by the capacity to predict extreme peak flow and base flow. However, the model still contains many uncertainties that are from many sources such as the model structure, the cell size and the input data. Eliminating these uncertain sources is likely to be impossible and that’s why it is requested to elaborate different models with various cell sizes, data accurate definition and solving algorithms in order to minimize the risk of uncertainty.

The limited data resources and the needed computer capacity reduce, in some extend, the application of deterministic distributed models and their performance. The calibration process is a compulsory and complex step in the model development. The sensitivity analysis appears as an essential step in order to support efficiently the calibration of the distributed hydrological model. The performed analysis suggests that the model comparisons should be carried out not only on the discharges but also on the water levels in all locations where measured data are available. The results of calibration confirm that it is necessary to compare the measurement and simulation at multi-sites. The multi-site calibration helps to increase the accuracy in translating what happens in the nature to model and in minimizing the global uncertainty of model as well. The analysis demonstrates likewise that the model validation versus extreme high and low values is quite important. The validation on extreme runoff value is helpful to reduce the uncertainty in simulations.

The result of sensitivity analysis demonstrates the response of runoff factors versus the variation of model parameters. Besides, the variation of runoff due to parameter changes is quite different. In Vu Gia Thu Bon catchment, the peak flow is affected significantly by most of the model parameters while the base flow is merely influenced by horizontal saturated hydraulic conductivity of saturated zone and saturated hydraulic conductivity of unsaturated zone. The analysis has demonstrated the interest of the sensitivity analysis in the calibration of distributed hydrological model. At the same time, this process helps to determine a useful impact interval of each factor on the stream flows and contribute to simplify the calibration process.

The results of sensitivity analysis, calibration and validation have been published at the 19th IAHR-APD Congress 2014, Hanoi, Vietnam (Vo & Gourbesville, 2014a) also submitted at Journal of Hydroinformatics.

Chapter 4 FLOOD MAPPING

In the previous chapter, the deterministic distributed model was used for simulating the hydrological process of Vu Gia Thu Bon catchment. Even if, this kind of model has the capacity to represent the inundation, the coarse resolution using in this hydrological model makes a big reduction in its flood area expressed efficiency. In order to present more accurately the flooding at downstream of Vu Gia Thu Bon catchment, there is a need to construct a hydraulic model with higher resolution in this area. The chapter 4 will describe the selected process, calibration, validation, also uncertainty analysis related to hydraulic model construction at the downstream of this catchment.

4.1 Introduction

As described above, climate change is predicted to occur more severely and with more complexity. Under the impact of the variation of weather factors, especially precipitation, extreme flood event is expected to increase not only in intensity but also in frequency. It is thought to have an influence on all aspects of human society in the next few years (R K Pachauri & Reisinger, 2007). Hence, responding actively with these changes is an urgent requirement today. EXCIMAP, (2007) that a prerequisite for effective and efficient flood risk management, is the in-depth knowledge of the prevailing hazards and risks throughout a river basin and areas of coastal flood risk. This includes information about the types of floods (river, coastal, lake and groundwater), the probability of a particular flood event, the flood magnitude expressed as flood extent, water depth or flow velocity, and finally, the probable magnitude of damage (life, property, economic activity). These basic information about the flood event can be gained through flood modelling and exhibited via flood map. Therefore, flood map is an effective tool in responding proactively to flood disaster in the period of preparation and planning of disaster prevention as well as in the emergency response phase (Moel *et al.*, 2009). Constructing the flood map together with taking into account the impact of climate change are seen as useful and indispensable process to respond to this natural phenomenon. It might help the local authority to have scientific evidences to suggest suitable policies and measures to reduce the impact of climate change.

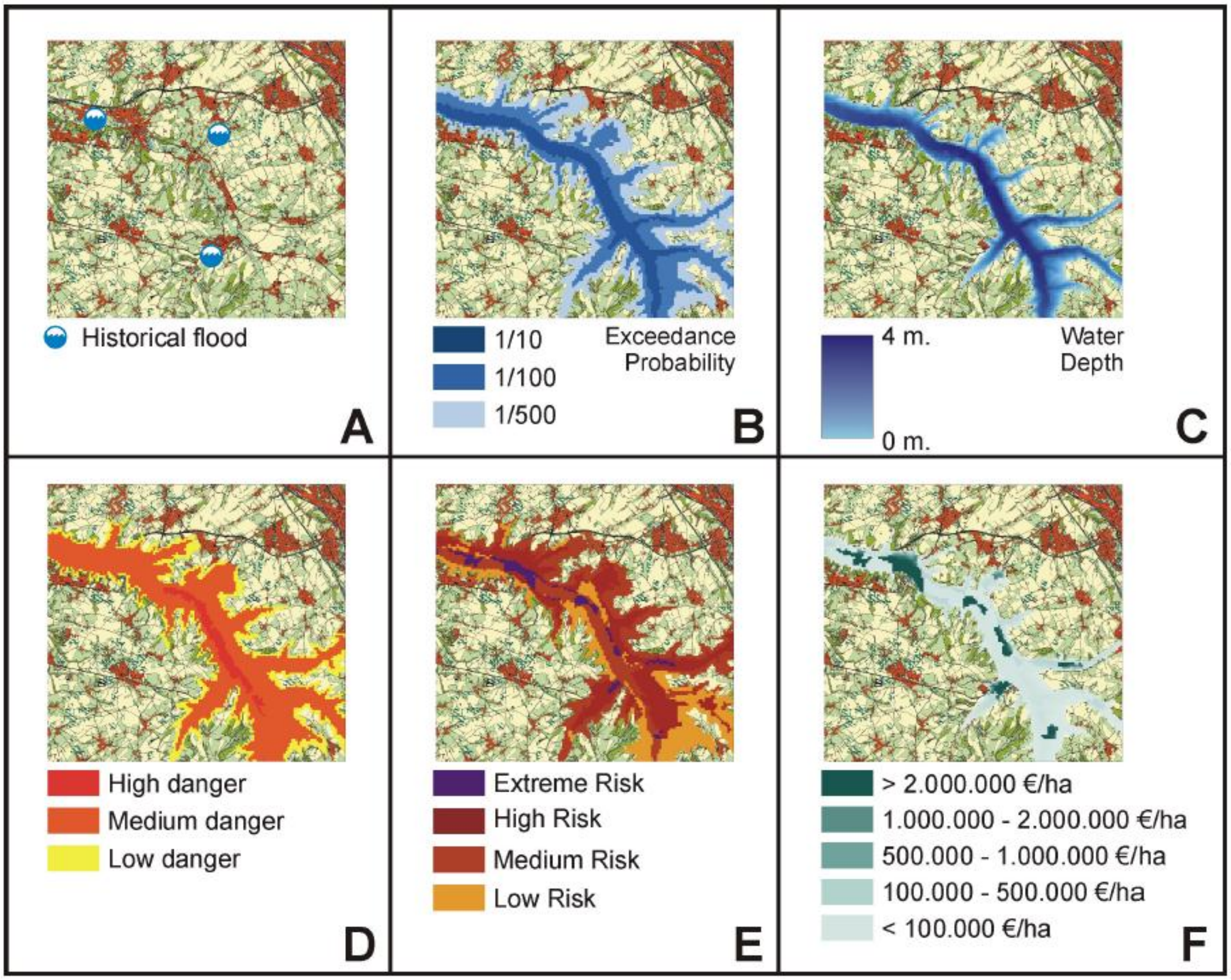


Figure 4.1. Different flood map types. (A) historical flood map; (B) flood extent map; (C) flood depth map; (D) flood danger map; (E) qualitative risk map; (F) quantitative risk (damage) map.(Moel et al., 2009)

There are many definitions of flood map (Figure 4.1), but generally they can put in two fundamental types: Flood hazard map and flood risk map. Flood hazard map shows areas which could be flooded according to three probabilities (low, medium high) complemented with: type of flood, the flood extent; water depths or water level as appropriate; where appropriate, flow velocity or the relevant water flow direction (EXCIMAP, 2007). Besides that, this map can also indicate the dangerous level of flood disaster for specific region. This kind of flood map can be constructed via historical data, statistical and modelling tool, or image processing. On the contrary, the flood risk maps indicate the potential adverse consequences associated with floods under several probabilities, expressed in terms of: the indicative number of inhabitants potentially affected; types of economic activities of the area potentially affected; installation which might cause accidental pollution in case of flooding potentially affected (EXCIMAP, 2007). The risk is generally calculated by integrating the flood hazard map with regional vulnerability (Schumann, 2011).

In this study, both of these flood maps will be generated to put a view of serious consequences due to flood disaster and climate change bring to the Vu Gia Thu Bon catchment.

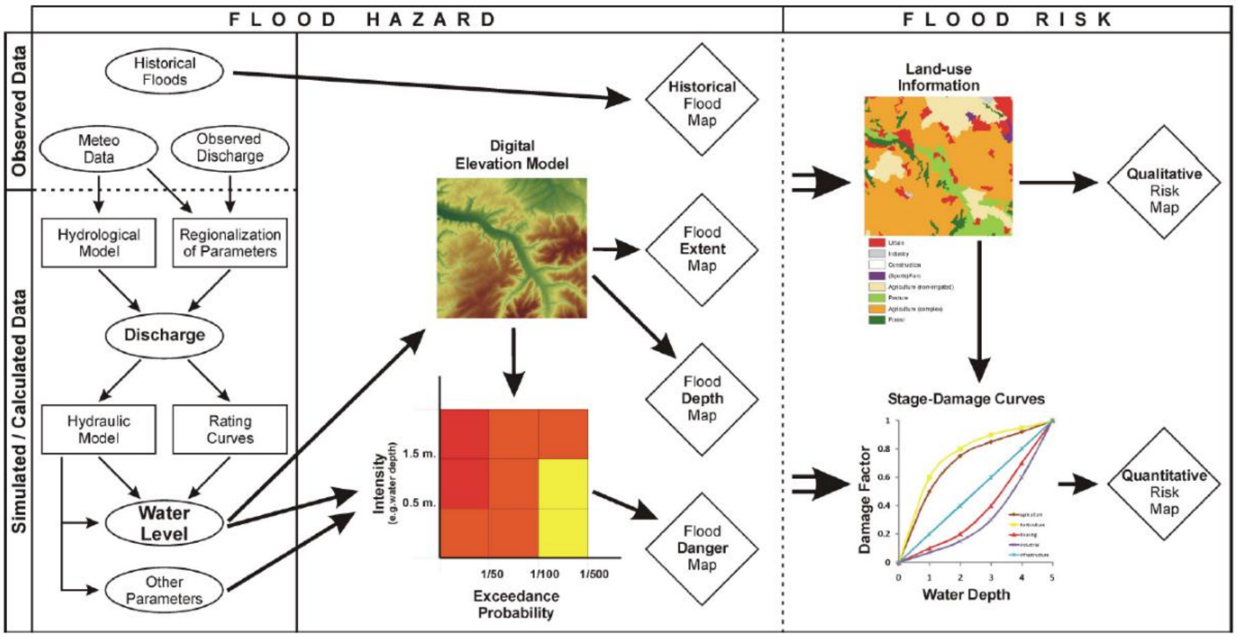


Figure 4.2. Conceptual framework for flood hazard and risk calculations (Moel et al., 2009)

4.2 Hydraulic modelling

As mentioned in the section of 4.1, the flood hazard map is an essential document for assessing the impact of a flood event to society, flood risk mitigation, flood management as well. Due to its important Up to date, many mapping methods have been developed with different theories such as hydrologic, meteorological and geomorphologic approaches representing the hazard or risk of flood in scale of a catchment (Ho *et al.*, 2010). There are many pros and cons with each method. Flood tracking is a long-standing method which relies on the traces of past events to construct the map. This method is relatively simple, and could present the real event. However, its accuracy is not so high when determining the flood traces over the catchment, especially with historic flood event. Nowadays, the development of satellite system and image processing helps to overcome the difficulty in surveying flood traces by above method. The flood map can be established by analyzing the satellite image data before and after flood events. This is known as an economical and efficient method for mapping flood hazard and dealing with the problem of inadequate data source in developing countries. The third method for flood mapping is via topography data by using GIS software. It has the limitation with the resolution of topography data. Finally, the flood map can be created by flood modelling (Figure 4.2). Although first three methods have good advantages with workload, there is a common weak point which concerns about their flexibility and their accuracy. It means that their produces do not take into account the effect of hydrological and hydraulic factors. Hence, they could not provide information related to stream flow such as speed or flood direction. These restrictions cause difficulties while forecasting the future scenario as well as assessing scale variability of inundation area under the impact of climate change. Conversely, the last method is realized by using a model which operates based on a mathematical relation between input and output hydrological variables(Moel *et al.*, 2009). The link between input and output variables are represented via different kinds of mathematical function which are able to consider on different aspects due to the viewpoint of developers, such as space, time, mathematical structure... So flood mapping using the hydraulic model is expected to translate more accurately the happening of flood event including distribution due to time and space, as well as providing hydraulic information. Especially, this method allows simulating with different scenarios which help to forecast change tendency of flood map under the impact of catchment's factor variations such as the construction, land use, or climate change.

Within hydraulic model, they are divided into several types depending on their dimensionality, capabilities and assumption in modelling water movement (Hunter *et al.*, 2007; Wurbs, 1994). The cornerstone of these models is the fundamental governing equations of fluid dynamics—the continuity, momentum and energy equations (Anderson & Wendt, 1995). This equation is in fact known as the Navier-Stokes equations, which can be applied to solve complex fluid flows in the form of three dimensional (3D) hydraulic model (Bates & De Roo, 2000). However, this model is still so complicated to use for real case at this moment, so Navier-Stokes equations have been simplified into the form of St Venant equations (Nguyen, 2012), generally known as shallow water equations (Hernández *et al.*, 2013) that have been applied to build one dimensional and two dimensional hydraulic models reliable at a simplified level. With each kind of model, they have different advantages and disadvantages. To construct flood mapping for a region, the model selection depends on many factors, not least on the actual condition of catchment.

This chapter aims to compare pros and cons of above models to choose a hydraulic model which is the most suitable for the present condition of Vu Gia Thu Bon catchment.

4.2.1 One dimensional hydraulic model

a. Model definition

One dimensional hydraulic model (1D model) has been the most widely used model for river flood modeling. This kind of model is developed on the assumption that flow in the channel and floodplain accurses with only the longitudinal direction (Bates *et al.*, 2005). For this theory, in 1D model, hydraulic variables such as velocity, depth,.. are solved predominantly in one defined direction along the channel. Because channels are rarely straight, the computational direction is generally defined along the channel centerline (Zevenbergen *et al.*, 2012). 1D model simulates the hydraulic components generally by solving the one dimensional St Venant equations that can express both continuity and the 1D section averaged Navier Stokes Equation (4.1, 4.2).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (4.1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(uQ) + gA\left(\frac{\partial h}{\partial x} - S_0\right) + gAS_f = 0 \qquad (4.2)$$

Where Q is the discharge, A is the cross sectional area, S0 is the bed slope, and Sf is the friction slope. One dimensional St Venant equations are commonly used with basic assumptions as follows: the pressure distribution is hydrostatic, the resistance relationship for unsteady flow is the same for steady flow, and the bed slope is sufficiently mild such that the cosine of the slope can be replaced by unity (Moore, 2011; Stelling & Verwey, 2005).

The necessary data to setup a 1D model normally consists of two categories that are boundary conditions and topographic data. The topographic data, which describes the geometry of river branch and floodplain, is defined by a series of cross section for example at Figure 4.3. Boundary conditions in 1D model can be defined at the upstream and downstream parts via discharge and water level data. Model results involving water level and discharge can be only obtained at each computation note, which depends on the cross section location, as well the stipulatedly calculated segment. This limitation of output result requires us need to decide the result extracted location before implementing the model.

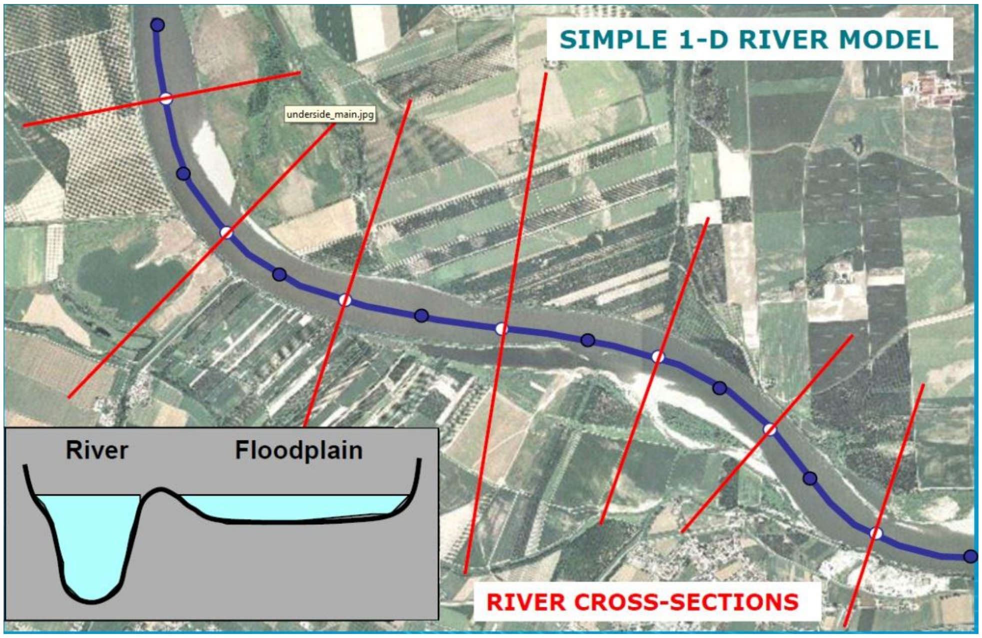


Figure 4.3. MIKE 11 Model structure (Landrein, 2011)

The 1D model nowadays has been used popularly in water flow modelling by its advantages such as short computation time, easy establishment, simple data requirement, stable operation, ability in describing the flow through hydraulic construction. However, this kind of model contains a big disadvantage that may not adequately describe lateral water diffusion. Consequently, it could not satisfactorily represent the flow part out of bank river, which is judged would no longer be 1D.

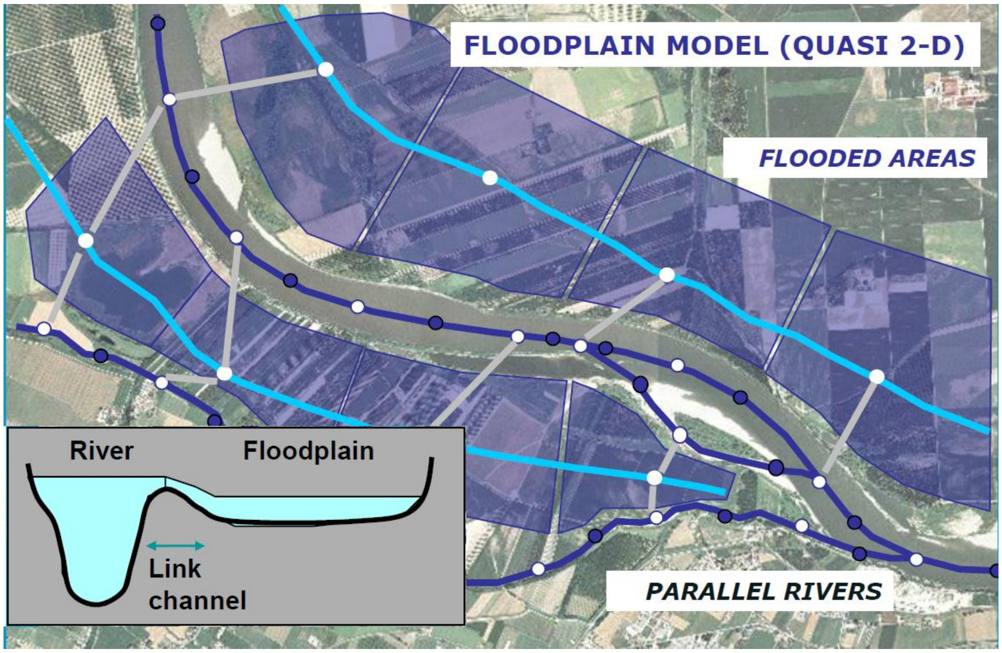


Figure 4.4. MIKE 11 Quasi model structure (Landrein, 2011).

In order to reduce a part of the inaccuracy in describing the flood flow at floodplain, the 1D model can be set up as Quasi 2D modeling. In this approach, floodplains are in parallel with main river network in 1D model, they are then connected to main river by link channels or spill units (Figure 4.4). The exchanged discharge between two parts is calculated using a weir equation.

b. Available 1D hydraulic models

- MASCARET 1-Dimensionnal free surface flow modelling

MASCARET includes 1-Dimensionnal free surface flow modelling engines (Figure 4.5). This is a product of Electricité de France (EDF), based on the Saint-Venant equations, different modules can be used to model various phenomenon over large areas and for varied geometries: meshed or branched network, subcritical or supercritical flows, steady or unsteady flows. MASCARET can represent: Flood propagation and modelling of floodplains, Submersion wave resulting from dam break, Regulation of managed rivers, Flow in torrents, Canals wetting, Sediment Transport, Water quality (temperature, passive tracers ...). MASCARET is composed of three hydrodynamic engines, which can be coupled with the module CASIER for Quasi 2D model. The main aim of a calculation is the determination of water levels and flows in various branches of the hydraulic network.

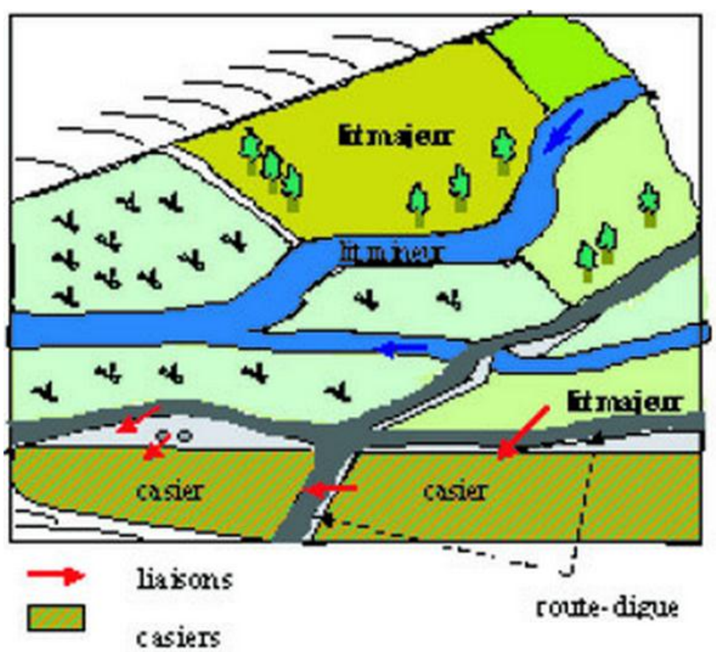


Figure 4.5. Typical example of a river and associated floodplain in MASCARET model (http://www.openTELEMAC.org/)

This model has been applied to solve many problems in reality such as modelling of floodplain of the Adour river, Modelling the Old Rhine between Breisach and Kembs during low water (30 m^3/s) for the study of issues related to the upstream travel of salmon in the Old Rhine. Breach simulation of the Bort-les-Orgues dam (France)…… (http://www.openTELEMAC.org/)

- HEC RAS

HEC RAS was developed by Hydrologic Engineering Center (Figure 4.6), which is a division of the Institute of Water Resources, U.S. Army Corps of Engineers for performing one dimensional steady and unsteady flow river hydraulics calculation based on basic equation of one dimensional model: Saint-Venant equation. This model was completed on an HEC 2 model, which was a product of the Corps' Civil works Hydrologic Engineering Research and Development Program, but has many limited points. The first version of HEC RAS model appeared in July of 1995 and has been continuously improved until now. Nowadays, HEC RAS becomes the top of free 1D model widely applying for analyzing the hydraulic problem of river flow and floodplain such as: steady flow water surface profile computations, unsteady flow simulation, movable boundary sediment transport computations and water quality analysis.

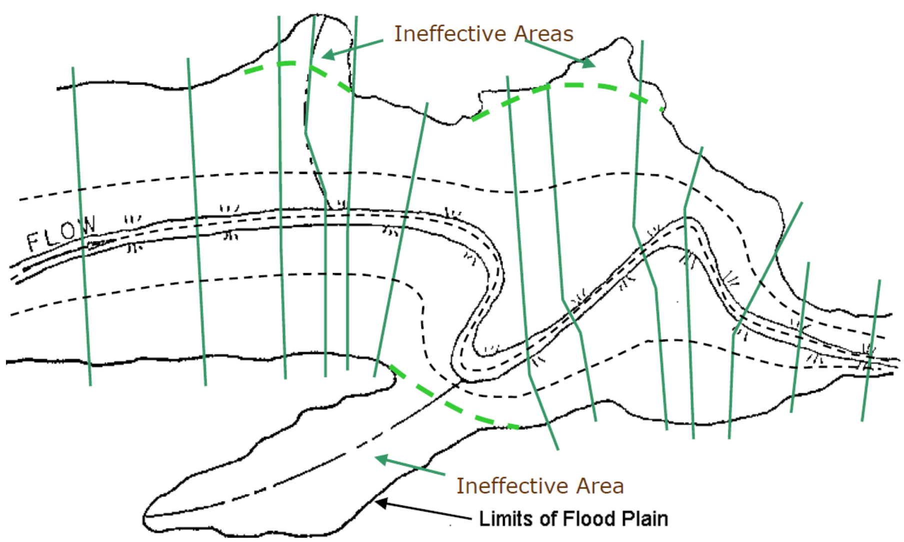


Figure 4.6. Example cross section layout of HEC RAS model (Brunner, 2010)

- ISIS-1D

ISIS-1D a module of ISIS software which is a product of cooperation between Sir William Halcrow, his Partners and Hydraulics Research Wallingford for modeling open channel and overbank flows in any network of channels. Any sensible looped or branched network can be modelled using ISIS, which incorporates a wide range of hydraulic units including a variety of conduit types, hydraulic structures, and so on. The first release of this model is 1995 (Baban, 2002) and has been continuing to complete up till now by Halcrow group. Same as others 1D hydraulic model, ISIS computes flow depths and discharges using a method relied on the equations for shallow water waves in open channels - the Saint-Venant equations. ISIS model has two versions, free version and business one which can be applied to solve systems under both steady and unsteady flow conditions. The model describes river bed and floodplain via cross section system. Hence, it transmits easily the topography at study area; gives the ability to simulate the variation of river bed as well as flexibly adds the construction on the river. The model result is given at the computation notes with discharge and water level. This model has been applied for river flow, flood modelling in England and over the world.

- SRH-1D

SRH-1D (Sedimentation and River Hydraulics - One Dimension) is a one-dimensional mobile boundary hydraulic and sediment transport computer model for rivers and manmade canals (Figure 4.7) (Huang & Greimann, 2012). Simulation capabilities include steady or unsteady flows, river control structures, looped river networks, cohesive and non-cohesive sediment transport, and lateral inflows. The model uses cross section based river information. The model simulates changes to rivers and canals caused by sediment transport. It can estimate sediment concentrations throughout a waterway given the sediment inflows, bed material, hydrology, and hydraulics of that waterway.

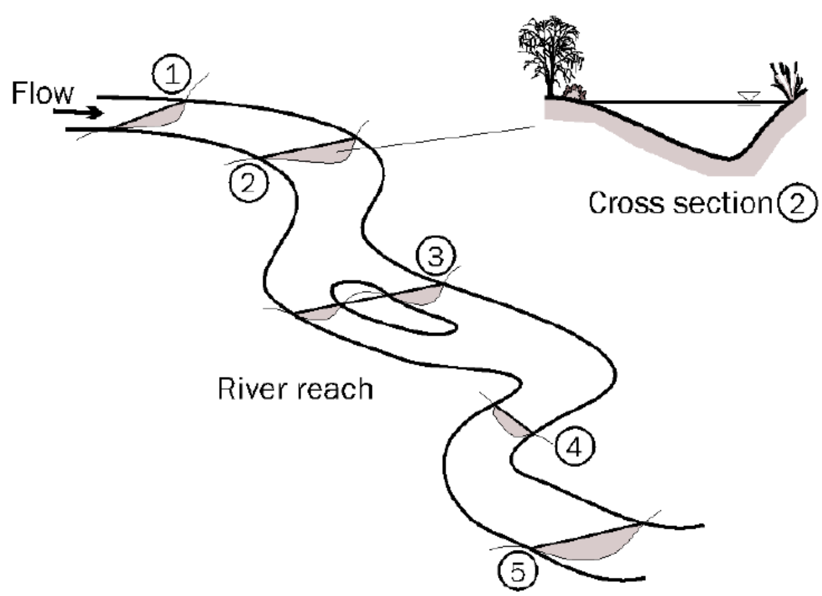


Figure 4.7. Representation of river by discrete cross section (Huang & Greimann, 2012).

The first version of this model was released at the year of 2005 under name GSTAR-1D by US Bureau of Reclamation, Technical Service Center, it was changed to name SRH-1D at 2007 and has been kept ameliorating up till now. The simulation capacity of this model has been demonstrated via lots of constructions.

- MIKE 11

MIKE 11 nowadays is known as one of the most famous of one dimensional hydraulic models for the simulation of flows, water quality and sediment transport in estuaries, rivers, irrigation systems, channels. MIKE 11 has been developed at DHI group with many main components called Hydrodynamic (HD) module besides others components such as Flood Forecasting, Advection-Dispersion, Water Quality and Non-cohesive sediment transport modules (DHI, 2012g). Constructing on the basic foundation of 1D hydraulic model, the Saint Venant equations, however with a long historic and always improved by DHI expects, MIKE 11 provides a complete and effective design environment for engineering, water resources, water quality management and planning applications. The required data for one MIKE 11 HD (Simulation editor (.sim11)) generally is input throughout 4 basic components: Network Editor (.nwk11) for river system, Cross section Editor (.xns11) for describing topography of river bed and flood plain, this file also translates the characteristic concerning each cross section or river segment, all boundary information are defined by Boundary Editor (.bnd11), Parameter Editor (.HD11) for providing river hydraulic parameters to model. Model result of Mike11 HD is similar to other 1D models, they can only give discharge and water level information at calculated points. Model result is queried in MIKE VIEW, another module of DHI software. With its exceptional flexibility, speed and user friendly environment, MIKE 11 provides a complete and effective design environment for engineering, water resources, water quality management and planning applications. The simulated capacity of this model has been tested by many case studies in worldwide.

4.2.2 Two dimensional hydraulic model

a. Model definition

Simulating the flow with one dimensional model has revealed many limitations, especially in flat floodplains where the flood wave propagation is not an one-dimensional phenomena. Due to the drawback of 1D model, in recent years with the advance in data availability, numerical methods and computational power, two dimensional hydraulic models (2D model) have increasingly been developed and applied for enhancing the accuracy of flow modelling in out of river banks (Bates *et al.*, 1998; Nicholas & Mitchell, 2003; Tayefi *et al.*, 2007). This kind of model is developed based on solving the bi-dimensional shallow water equations (2D Saint Venant equations) which simulate flow components in the form of mass and momentum conservation (Eqution 4.3, 4.4, 4.5) (Ahmad & Simonovic, 1999)

- Continuity

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=0 \tag{4.3}$$

- X_ Momentum

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{c^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}\left(h\tau_{xy}\right)\right]-\Omega q-f\nu\nu_x+\frac{h}{\rho_w}\frac{\partial}{\partial_x}(p_a)=0 \tag{4.4}$$

- Y _ Momentum

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{c^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}\left(h\tau_{yy}\right)+\frac{\partial}{\partial x}\left(h\tau_{xy}\right)\right]-\Omega q-f\nu\nu_y+\frac{h}{\rho_w}\frac{\partial}{\partial_y}(p_a)=0 \tag{4.5}$$

Where:

$h(x,y,t)$: water depth (m);

$\zeta(x,y,t)$: surface elevation (m);

$p,q(x,y,t)$: flux densities in x and y directions ($m^3/s/m$) =(uh,vh); (u,v): depth averaged velocities in x and y directions;

$c(x,y)$: Chezy resistance ($m^{1/2}/s$);

g: acceleration due to gravity (m/s^2);

$f(v)$: wind friction factor;

$\Omega(x,y)$: Coriolis parameter, latitude dependent (S^{-1});

$p_a(x,y,t)$: atmospheric pressure ($kg/m/m^2$).

ρ_w: density of water (kg/m^3);

x, y: space coordinates(m);

t: time (s);

$\tau_{xx}, \tau_{xy,} \tau_{yy}$: components of effective shear stress;

$v, v_x, v_y(x, y, t)$: wind speed and components in x and y direction (m/s).

Above system of equations can be solved through three methods which define types of two dimensional models, these are finite element methods, finite volume method and finite different method.

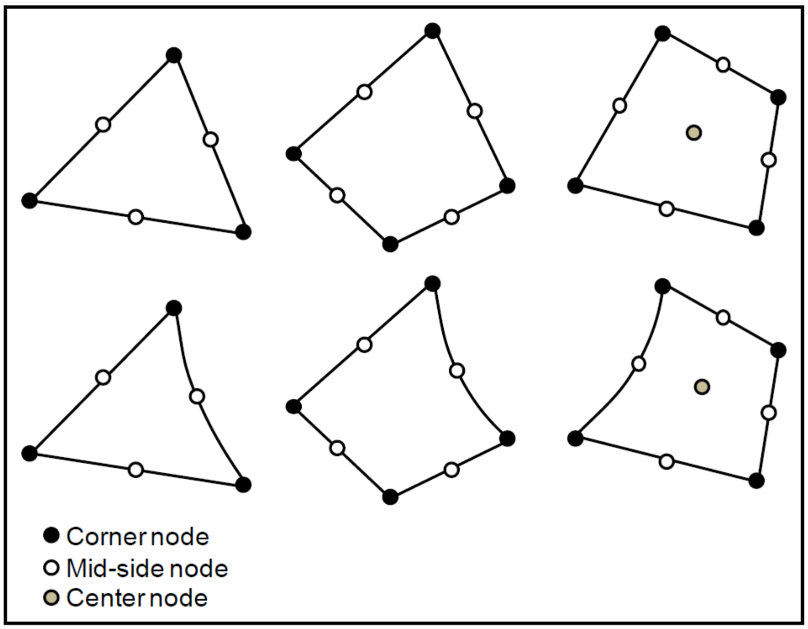


Figure 4.8. Element types and shapes (Zevenbergen *et al*., 2012).

The first one, finite element method, is well suited for solving differential equations over complex domains (Zevenbergen *et al*., 2012). In this method, input information related to study area is expressed as an unstructured mesh or grid which typically has the shape of triangular or quadrilateral (Figure 4.11). Each element involves noted located at corners, mid sides and where velocity and depth are computed (Figure 4.8). Furthermore, several modes also add computation note at the center of each element, for example FST2HD model (Zevenbergen *et al*., 2012). In each element, the unknown variables in 2D Saint Venant equations are calculated approximately by the way of a linear combination of piecewise linear functions. At each computation note, there are many such functions, and each takes the value of one at one vertex and the value of zero at all other vertices. A global function based on this approximation is substituted into the governing partial differential equations. This equation is then integrated with weighting functions and the resulting error is minimized to give coefficients for the trial functions that represent an approximate solution (Néelz & Pender, 2009; Wright, 2005). Due to use probably the unstructured mesh with different element shapes in describing the input data such as topography, roughness parameter, etc…, this method demonstrates the flexibility in simulating water flow at river bed and flood plain. Despite the reduction of computation node, this characteristic helps to increase the performance of 2D model while still keeping the accuracy of result at necessary locations. More detail that, there are a need to increase node density at the area of high velocity gradient (change in magnitude or direction, having structure), at river bed or important area. Inversely, at high altitude area where is rarely hit by flood event or at unimportant area, computation node density can be reduced. The Figure 4.9 displays the presence of model parameters by the mesh.

The second method is finite volume method. With the same solution for dividing the computation space into many unstructured element, the finite volume element method solves the system of equations 4.3, 4.4, 4.5 at discretized element as finite element method. However, the control volume of each divided part is the key for calculating unknown variables (Néelz & Pender, 2009). By the advantages in terms of conservativeness, geometric flexibility and conceptual simplicity, this method is increasingly popular and has become the most widely used in the area of Shallow Water flow modelling(Néelz & Pender, 2009).

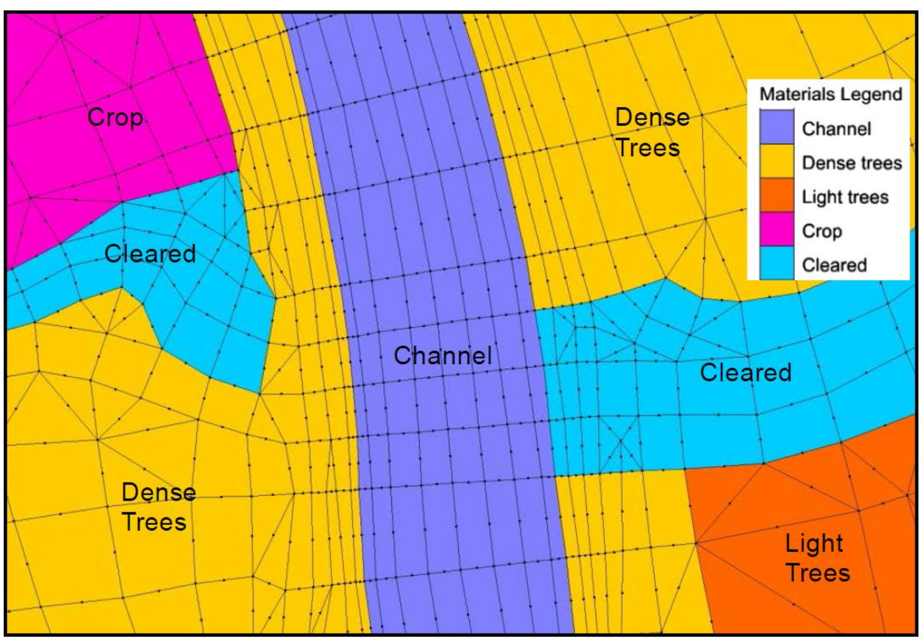


Figure 4.9. Example finite element network layout (Zevenbergen et al., 2012)

The last one to solve 2D shallow water equation is finite different method. The method uses a structured grid of Δx and Δy (Figure 4.11) increments over the domain to determine the values of velocity, depth and other variables by approximating derivatives with finite differences at each grid cell (Néelz & Pender, 2009; Zevenbergen *et al*., 2012) (Figure 4.10). The principle of this method relies on the Taylor series expansions which solve the 2D Saint Venant equations as a function of a finite number of neighboring point values. This solution is estimated to be more rapid due to using the structured grid (Néelz & Pender, 2009). However, the limit of this method is that using the fixed size of grid cell leads to the non-flexibility in expressing the simulation area. It means that the density of computed point is the same at important and unimportant areas, in river bed and flood plain, flood prone area and high altitude. It results in longer in simulation time. This problem can be seen clearly at using small cell size (fine DEM). On the contrary, if applying a bigger cell size, the important areas such as river bed, flood prone area could not be described accurately. Several software packages overcome partly the above weak point by using finer grid cell at required locations.

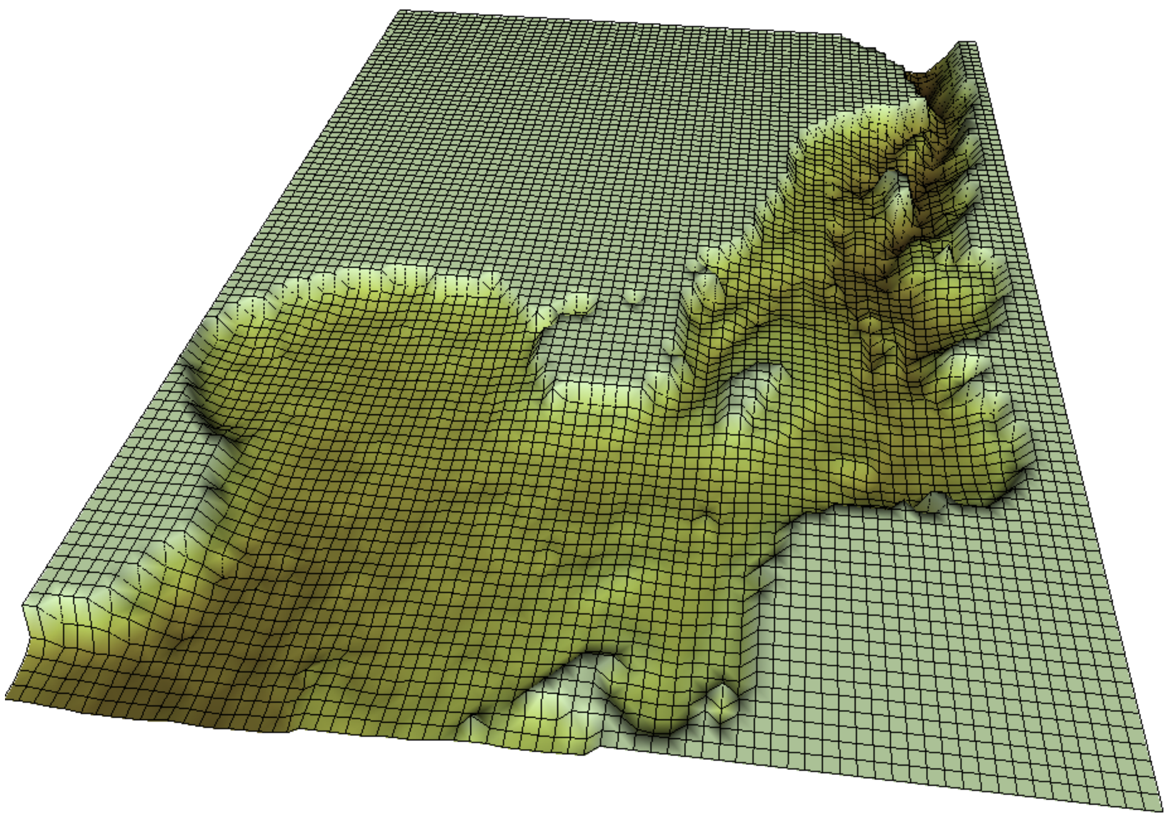


Figure 4.10. Example square grid cell for finite different method in MIKE 21 HD (Landrein, 2011)

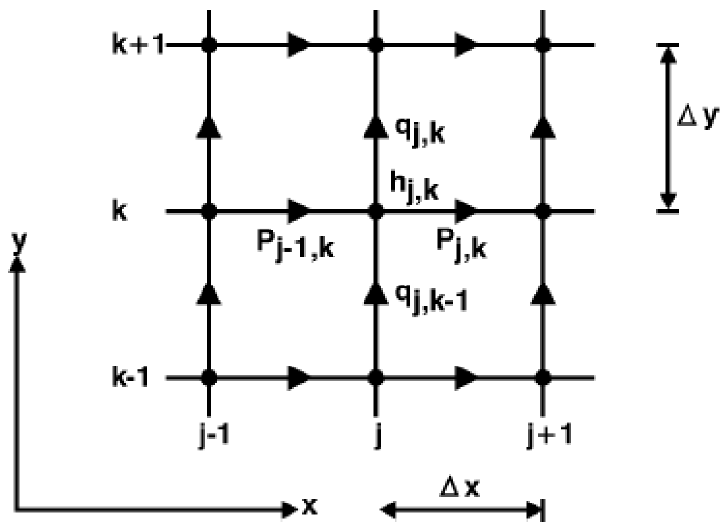


Figure 4.11. Discretization scheme of finite different models (DHI, 2012b) .

Flood modeling with 2-dimensional approach has demonstrated many strong points. The most important improvement of this kind of model is able to solve the biggest limitation of one dimensional model. That is the 2D model can represent lateral flow component. Hence, the flow on floodplain can be introduced more accurately in these models. The flexibility in introducing boundary condition is counted as another advantage of 2D model. Furthermore, on the output data aspect, 2D model might provide widely the data type than 1D model. However, 2D simulators also have disadvantages. Increasing computation time is seen as the largest limitation of 2D modelling. The 2D model is rarely applied in a large catchment with high resolution because of this drawback. The second shortcoming of 2D is concerned to data requirement. Data input quality and their resolutions are expected to influence much on the modeling result. Topography, land use, rainfall, etc … are not always available for all catchments. Moreover, the 2D model as well meets the difficulty in data for validation. It is really to find out the spatial data for calibrating 2D model in reality. Another weakness of 2D model is at present, it is very difficult to take into account the impact of construction towards the flows.

b. Available 2D hydraulic models

Almost present 2D hydraulic models are developed based on mathematical foundation of bi-dimensional Saint Venant equation. However, they exist good or not good points which depend on above different solutions. Following part will present briefly several typical models of each solution.

- TELEMAC 2D

TELEMAC-2D was developed initially by the National Hydraulics and Environment Laboratory (Laboratoire National d'Hydraulique et Environnement - LNHE) of the Research and Development Directorate of the French Electricity Board (EDF-R&D), and is now managed by a consortium of other consultants and research institutes (EDF-R&D, 2014). In this model, the system of Saint Venant equations can be solved by two methods, one is final element scheme and the other is final volume scheme (Néelz & Pender, 2009). This model can be applied in free-surface maritime or river hydraulics. The input data is prepared through Blue Knue which is an advanced data preparation, analysis, and visualization tool for hydraulic modelers (CHC, 2010). One of the good points of TELEMAC model is to allow users to program particular functions of a simulation module that are not provided for the standard version of the TELEMAC system in the environment of FORTRAN. Other strong points of this free model are able to run in both system operations, Windown and Linux. It also permits to run simulation with multi core. The parallel regime of TELEMAC model helps to save in a lot of computational time. This is very important when using two dimensions for a lager catchment, as well for high resolution mesh. Thanks to these advantages, TELEMAC model has been utilized to solve many hydraulic problems in reality.

- SRH2D model

SRH-2D, Sedimentation and River Hydraulics – Two-Dimensional model, is a two-dimensional (2D) hydraulic (Figure 4.12), sediment, temperature, and vegetation model for river systems under the development at the US Bureau of Reclamation (Lai, 2008). This model has been applied for river flow modeling since 2004. SRH-2D model algorithm is relied on solving 2D shallow water equations by finite volume method (Hogan, 2014). One of the salient features of SRH-2D is to allow the use of the most existing meshing methods available, such as the structured curvilinear mesh (pure quadrilaterals), conventional finite element mesh (purely triangles), Cartesian mesh (purely rectangular or square mesh), and the hybrid mixed element mesh (Lai, 2008). The data mesh used in SRH-2D can be prepared via SMS model or any mesh created tool which can give the quadrilaterals and triangles mesh data. This model has a wide range of application on hydraulic modeling. However, besides these good points, this model still exists limitations, such as with present version, this model is only able to install for window system and it does not have the capacity for run with many CPU in parallel.

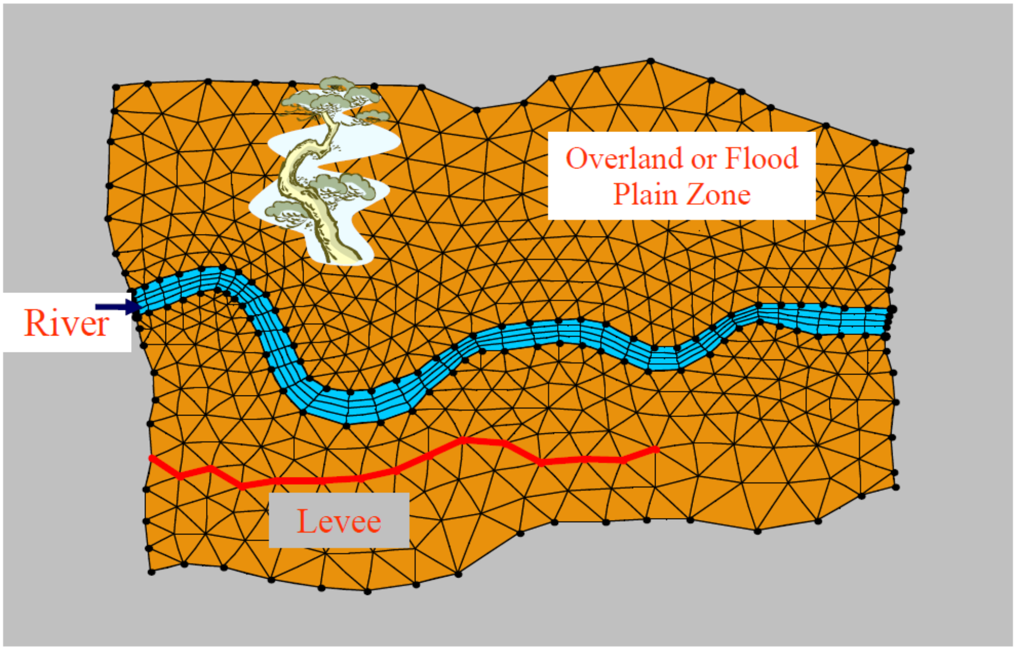


Figure 4.12. Illustration of zonal partition and mesh layout in SRH2D model. (Lai, 2008)

- TUFLOW

TUFLOW is a product of the cooperation between WBM Oceanics Australia and The University of Queensland for simulating depth-averaged, two and one-dimensional free-surface flows such as occurs from floods and tides. The first release of TUFLOW was in 1990. The solution algorithm of TUFLOW is basically written by Stelling in 1984 which solves the full two-dimensional, depth averaged, momentum and continuity equations for free-surface flow by using the finite different method (Oceanics, 2003). In parallel with TUFLOW, a TUFLOW FV, which was developed on the finite volume numerical scheme, has been released. The new generation TUFLOW FV with the flexible mesh allows for seamless boundary fitting along complex coastlines or open channels as well as accurately and efficiently representing complex bathymetries with a minimum number of computational elements. The TUFLOW FV also adds a new important function that can do simulation with multi core processing. This improvement of TUFLOW FV helps reducing a lot of computed time(WBM, 2013).

- ISIS 2D

As ISIS 1D, ISIS 2D model is as well a product of Halcrow group, but focuses on simulating the two dimensional water flow. As other 2D hydraulic models, the basic of ISIS 2D is from Saint Venant equations. In ISIS 2D model, the calculated area is discretized to regular square grid cells. The water depth and velocity of each cell are calculated approximately by using the finite different method. Hence, ISIS 2D is suitable for modelling hydraulic phenomenon in coastal, estuary and floodplain environments (CH2MHILL).

- MIKE 21

MIKE 21, is a modeling system for 2D free-surface flows, which was developed by DHI group. With two branches, MIKE 21 and MIKE 21 FM, this product of DHI is hoped to deal efficiently with the hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas and seas (DHI, 2012c). In the first one, MIKE 21 solves the 2D shallow water equations by applying the finite different method which is expected to give several limitations when modeling for a large catchment in high resolution. Understanding well this difficulty, MIKE 21 allows to simulate simultaneously two resolutions. It means that, at important locations, one more detail grid is applied to increase the simulated quality at these points. This solution helps reducing the computation time but still keep the quality at required locations. The second one, MIKE 21 FM, is a new release of DHI group for application within oceanographic, coastal and estuarine environments. This new modelling system is relied on flexible mesh approach for spatial discretization which focuses on solving Saint Venant equations with finite volume method(DHI, 2012a). The MIKE 21 is a package of complete software, so it is supported by a lot of accompanied tools for preparing input data, as well as representing the output result. DHI recently has provided a service to allow their clients to connect with the computational center of DHI to reduce the computation time of MIKE 21, unfortunately this service is not free.

4.2.3 1D/2D coupling model

a. Model definition

Considering on above analysis of one and two dimensional models, each of these kinds of model have pros and coins in flood modeling. One question is how to benefit the good points of both and overcome the limitation each other. Computation time reduction but still keeping the accuracy are a big requirement if applying these kinds of models separately. At least in present situation, it is really difficult when doing it for a large catchment. In the case of 1D model, it meets the difficulty to present accurately the flood propagation in flood plain, even though it has the advantage in simulation time and memory requirement. Conversely, using only 2D model for a large catchment will increase a significant calculated point. It surely leads to the longer in simulation and the stronger computer capacity requirement. There are several studies demonstrated that the computation time usually increases exponentially with the number of involved elements to the power of between 1.5 and 2 (Bladé *et al.*, 2012). Hence, the thorny issue has been settled by integrating two types of models in one. This solution has been realized via the coupling 1D/2D model (Figure 4.13). Following this technic, the flow is hypothesized to divide into two parts.

The first is considered as river flow that mostly runs one dimensional direction (Figure 4.14). This flow part is responsible of 1D model and defined inside of cross sections. Other parts, in floodplain, where the flow direction does not obey any definite rule, the flow is undertaken by 2D model. The approach is expected not only to reduce the computation time but also to increase the stability of modeling. This advantage might be explained as more stable of 1D model than 2D model if they is simulated for a same location (Bladé *et al*., 2012). Furthermore, using 1D/2D coupling model helps to overcome the limitation of 2D model in modelling the flow through hydraulic structure (Moore, 2011). For these advantages, this kind of simulation has become popular in recent years.

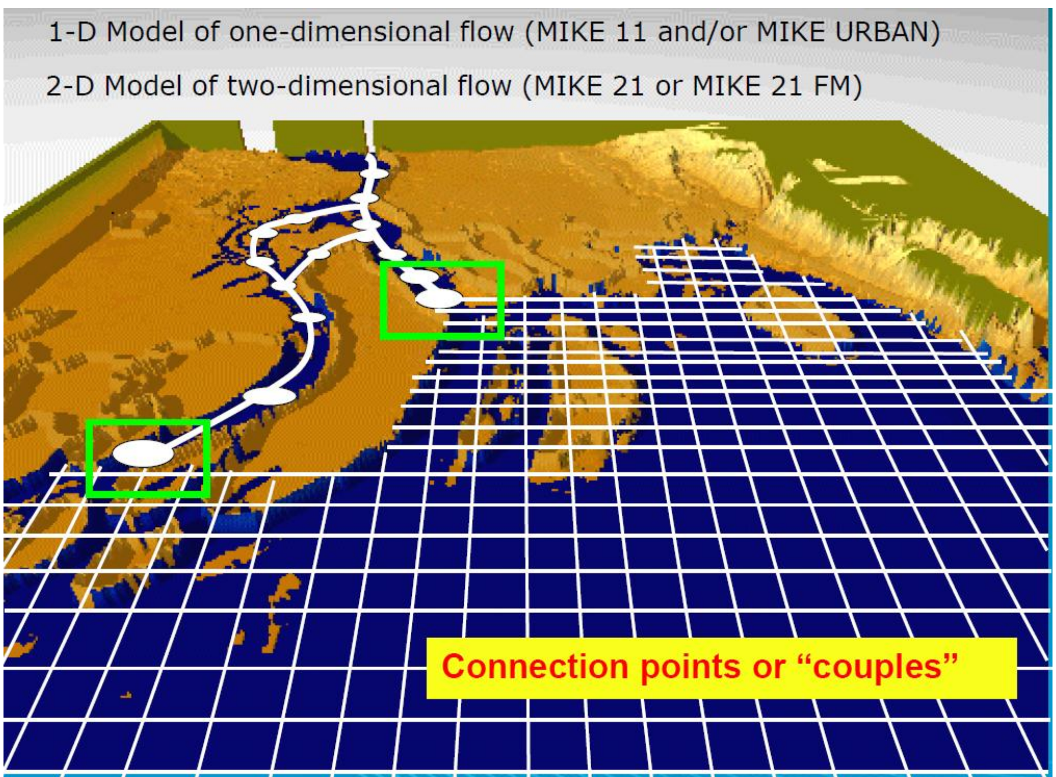


Figure 4.13. 1D/2D coupling scheme in MIKE FLOOD model. (Landrein, 2011)

The relation between two flow parts, interior and exterior of river bed, is introduced via their volume exchanges. The volume exchange generally is calculated due to the comparison of water level inside and outside of cross sections. The amount of volume exchanging between 1D and 2D model is depended on the characteristics of linkage which is stipulated by model developers (Hernández *et al.*, 2013). Several techniques have been developed to link 1D and 2D models. Therefore, almost are considered as lateral link where the 1D and 2D flows are linked by the junctions in the middle of segments (Liang *et al*., 2007). Herein, the volume exchange is determined by weir equation (Hernández *et al*., 2013; Néelz & Pender, 2009).

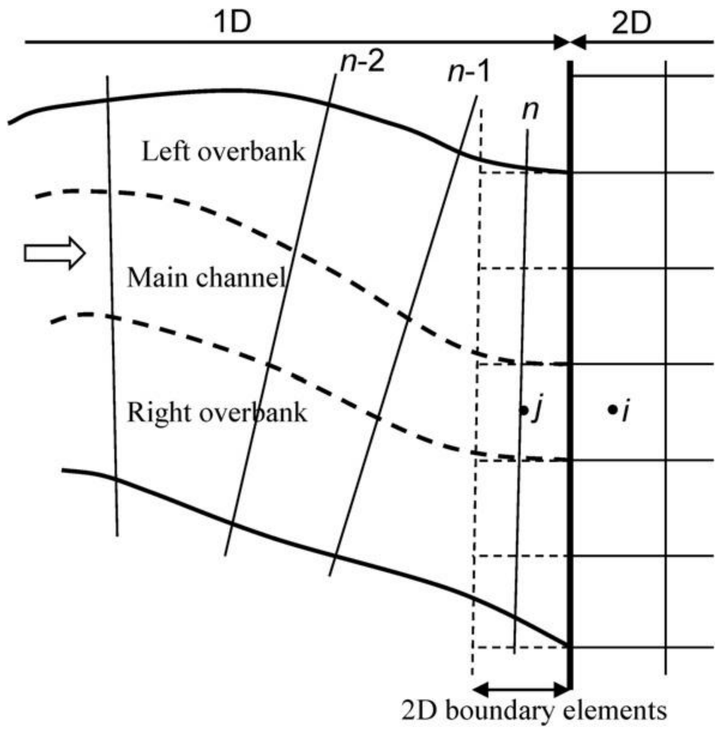


Figure 4.14. Flow direction connection at the downstream end of a 1D river reach. i is a 2D finite volume connected to boundary element j, which corresponds to section n of the 1D river reach (Bladé *et al*., 2012).

The second approach is longitudinal link (Figure 4.15). The relation between two models is considered as the form of boundary condition of each other. The form of this coupling is expressed that 2D model connects with 1D model at the end and gets the 1D mode output volume for boundary condition. On the other side, the downstream boundary condition of 1D model parts will consider from water level at junction with 2D model (Fernandez-Nieto *et al*., 2010; Liang *et al.*, 2007)

The last one might call the vertical link (Figure 4.16). Toward this coupling, the 1D domain will be set up overlappedly 2D domain and joined continuously to grid points of 2D model. Both of them will operate independently until the water in 1D model reaching river bank level. From that time 2D model will receive the information for 2D model (Bladé *et al.*, 2012) (Fernandez-Nieto *et al*., 2010).

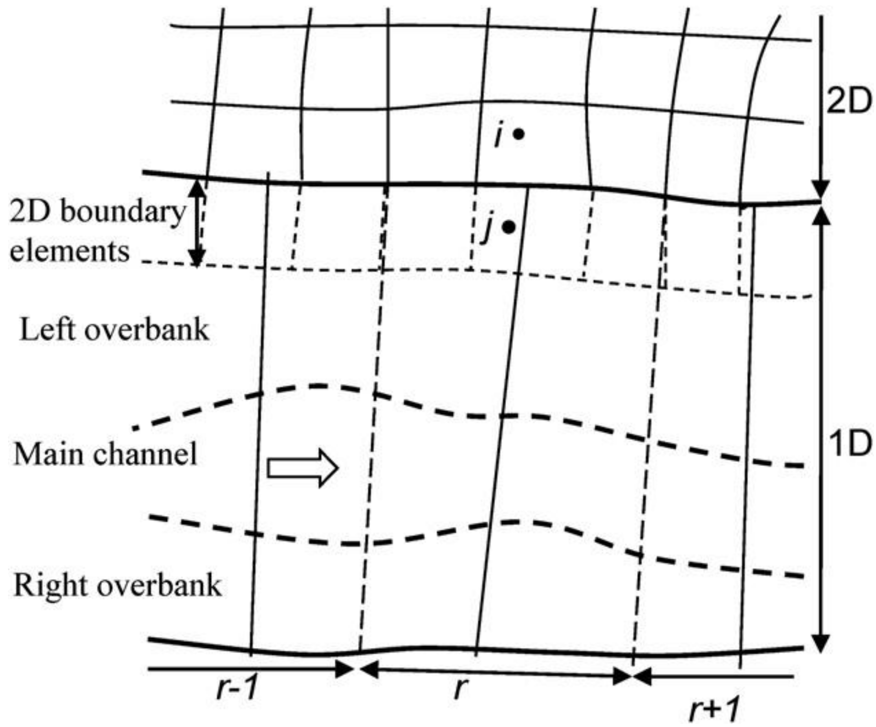


Figure 4.15. Lateral connection. i is a 2D finite volume connected to boundary element j, which corresponds to section r of the 1D river reach (Bladé *et al.*, 2012).

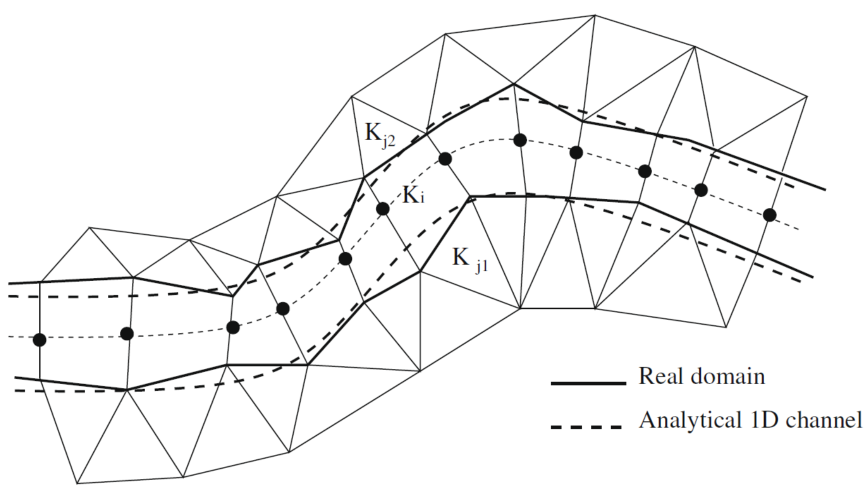


Figure 4.16. Vertical link scheme (Fernandez-Nieto et al., 2010)

b. Literature reviews

By the predominance, many coupling models have been developed and applied in reality. The MIKE FLOOD, a software of DHI which allows to couple 1D MIKE 11/ Mike urban and 2D MIKE 21/ MIKE 21 FM. Or the TELEMAC 2D model of EDF can link with MASCARET, a 1D model of its own. ISIS 1D model can be integrated with different 2D models, such as ISIS 2D (CH2MHILL), DIVAST (Lin *et al*., 2006), TUFLOW (Oceanics, 2003).

4.3 Criteria for flood model selection

Analyzing and choosing a reasonable flood model is necessary for flood mapping. It is seen as a hard work in an abundant world of hydraulic models as today. Especially, there is no existing definitive criteria which can be applied directly to yield a clear choice of method (Timbe Castro, 2007). Hereafters are several suggested criteria for this purpose which are summarized on last studies (Landrein, 2011).

- -What are the phenomena to study?
- -What are the expected results/outputs?
- -Study area, which is in upstream or downstream, urban or rural area, important or not.
- Data availability and expected accuracy.
- Work effects.

4.4 Hydraulic modelling of Vu Gia Thu Bon Catchment

4.4.1 Introduction

This step aims to provide an overall view about which model type is suitable for flood mapping in Vu Gia Thu Bon catchment. The model selection is not only based on the modelling results in this step but also on other aspects presented on the part of 4.3. However, the first consideration is relied on the efficiency of each model with flood modelling process in Vu Gia Thu Bon. The models comparing here are the products of Danish Hydraulic Institute. They consist of 1D model and quasi 2D model with MIKE 11, 2D model with MIKE 21HD, 1D/2D mode coupling with MIKE FLOOD.

Due to catchment characteristics, the inundation frequently attacks at the downstream part of Vu Gia Thu Bon river system. Besides, the population and important economic bases concentrate merely at this area. As a result, it is not need to set up flood model for whole catchment. Accordingly, above models are only compared at hollow areas which are around 1780 km^2 at downstream on 10,350 km^2 in total. They are considered on the historical flood events occurring in the period of 10 – 15 November, 2007.

The hydrological boundary conditions used in these simulations are inherited from MIKE SHE model, which was calibrated and validated for the whole catchment. The components and the efficiency of MIKE SHE model are showed at the chapter 4. Others simulation data are treated from data available at Chapter 2 for suitable with each model type.

4.4.2 Model setup

a. One dimensional modelling

The Vu Gia Thu Bon's river network is so complicated. It flows through different terrain morphologies, mountain at the western and delta coastal region at eastern. It is composed from two main rivers, Vu Gia and Thu Bon rivers, which include lots of tributaries and linking branches. This river system is represented at 1D model approach by using MIKE 11 as follows:

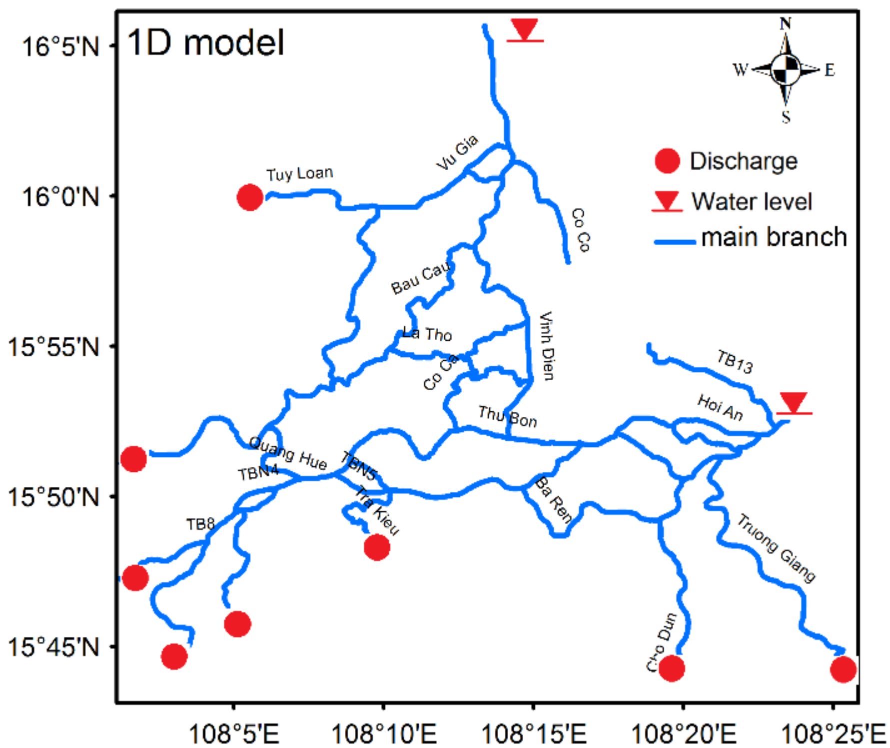


Figure 4.17. MIKE 11 (1D) model set up for Vu Gia Thu Bon river downstream.

- River network: This model is developed on 23 big rivers and linking branches at the downstream (Figure 4.17). Their lengths varied from 2 km to 55 km.

- Cross sections: The geometry of each river branch is specified via cross section. The cross section applied in this model is from two sources, few of them at the downstream are taken from the measurements, the remaining ones are extracted from the DEM.
- Boundary conditions: The upstream boundary conditions are inherited from the MIKE SHE model and set up at 8 branches. The downstream ones are defined at the estuaries of Vu Gia and Thu Bon. These data are declared by sea level at Son Tra and Hoi An stations.
- Hydrodynamic parameters: This part mainly focuses on riverbed resistance. These parameters are represented via Strickler roughness coefficient M. A common value M is set up for 23 branches and obtained via calibration process.

The model result is returned for water level along each river.

b. Quasi 2D modelling

In order to improve the simulating capacity of one dimensional model, an external system is constructed beside main river system (Figure 4.18) for increasing the storage when water is over river banks.

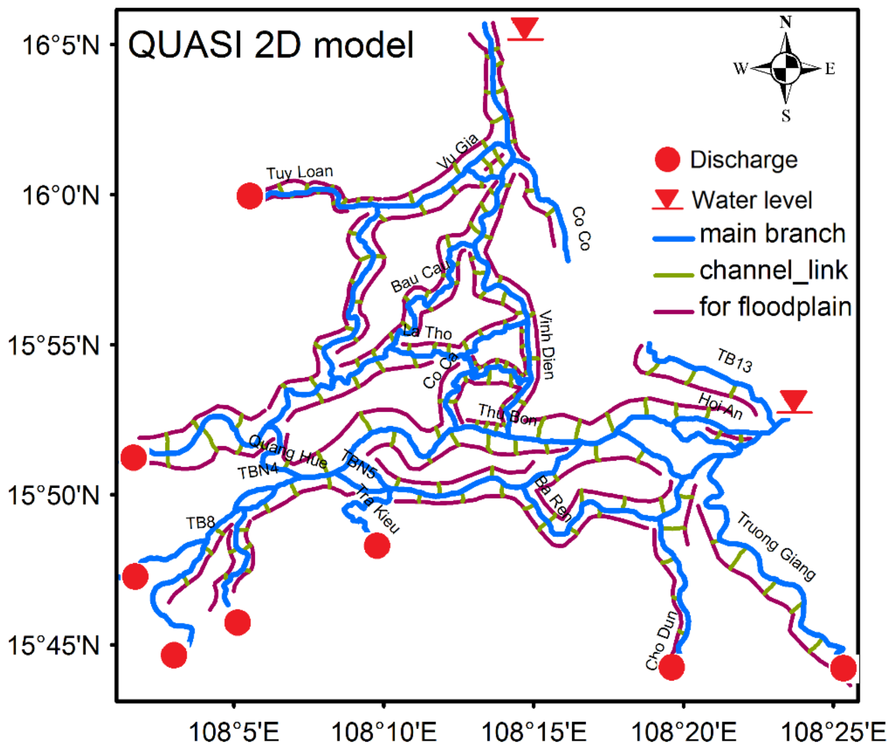


Figure 4.18. MIKE 11 Quasi (Quasi 2D) model set up for Vu Gia Thu Bon river downstream.

The new network is representative for floodplain along the river systems. The cross sections of new system are extracted from DEM 10m of P1-08 VIE project. The extracted technic is similar to the procedure applied for MIKE SHE model. The new is connected with old via links which are defined as the form of the link channel which therefore typically represents the embankment geometry between parallel rivers (e.g. main river branch and flood plain branch). Link channels do not require cross sections to be specified and are consequently simpler to use than regular channels (DHI, 2012g). The link is modelled as a single structure branch of only three computation calculation points (h-Q-h) (Figure 4.19). The exchange volumes are calculated by Q/H relations that are based on link geometry.

The boundary conditions are set up as the case of MIKE 11 in the section 4.4.2a.The bed resistances of the system are inherited from last MIKE 11 model for main river system.

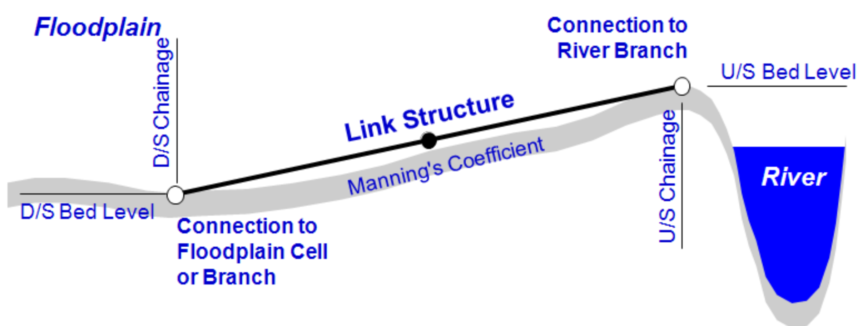


Figure 4.19. Longitudinal parameters and representation of a Link Channel (DHI, 2012g).

c. Two dimensional modelling

This approach is demonstrated by MIKE 21, 2D hydraulic model from DHI. The model is set up as the schema at the Figure 4.20

- Topography: This bathymetry is described via rectangular grid with 30 meter resolution. This data is converted for DEM 30m that was resized for DEM 15m supplied by LUCCI project. In order to increase river bed description, the DEM is continued adjusting by merging the surveyed cross sections.
- Source and sink: 17 sources are defined to transmit the flood runoff from exterior to the modelling domain. These sources are extracted at the outlet of 9 sub catchments and 8 river branches in MIKE SHE model.
- Evapotranspiration: this factor is input with November value in the result of (Vu *et al*. , 2008).

- Precipitation: This simulation uses the rainfall data which is redistributed spatially based on daily rainfall data from 15 rain gauge stations with the Kriging method (Vo & Gourbesville, 2014d).
- Resistance: This parameter is represented via Strickler roughness coefficient M. For Vu Gia Thu Bon, Strickler roughness coefficient is determined depending on Land use map and in 2 to 90 $m^{1/3}/s$ (DHI, 2012f; T. Nguyen, 2005; Vieux, 2001).

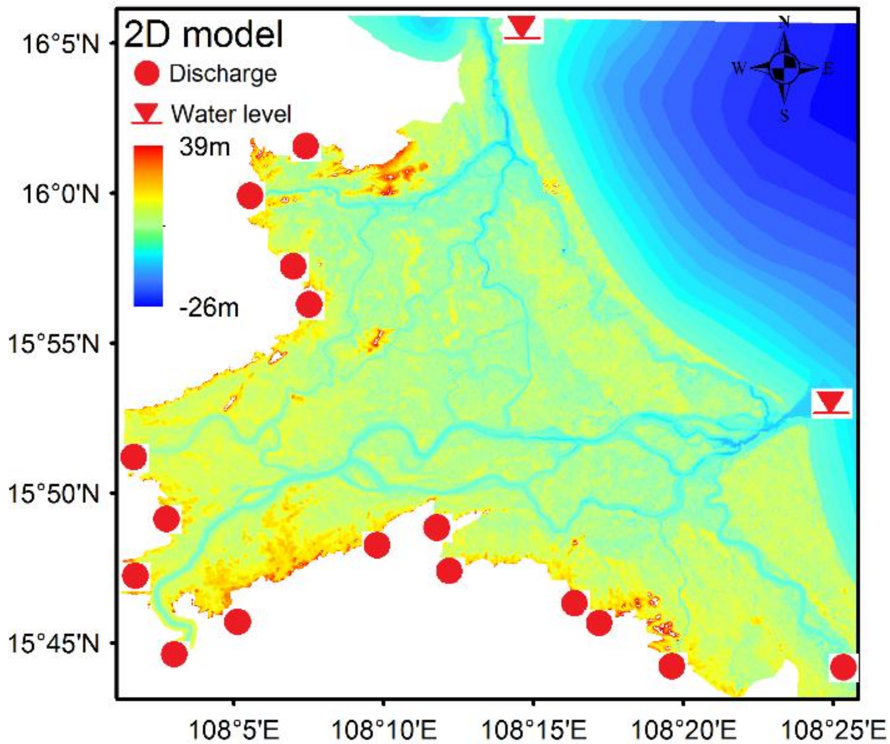


Figure 4.20. MIKE 21 (2D) model set up for Vu Gia Thu Bon river downstream.

d. 1D/2D coupling modelling

The model is handled here from DHI group as well. This model is MIKE FLOOD which is developed on the coupling between 1D model to 2D model. The model set up is shown via Figure 4.21.

- 2D model – MIKE 21: This model is set up similarly as the last MIKE 21 mode in the section of 4.4.2.c. Therefore, there are several changes in data because in this case the river flow will be responsible for MIKE 11, using of a river bed integrated topography is not necessary. It might lead to wrong result when the river flow is simulated in the same time by two models, MIKE 21 and MIKE 11. Hence, this scenario just used DEM 30 m that reclassified from DEM 15 m of LUCCI project. Second change is in the source input.

Instead, using 17 sources as the last 2D model, this model only introduces 9 sources which are representatives of 9 upstream sub catchments.

- 1D model – MIKE 11: This is benefits from the model in part of 4.4.2.a. Each river branch in MIKE 11 connects with MIKE 21 via a 2 lateral links (Figure 4.22).

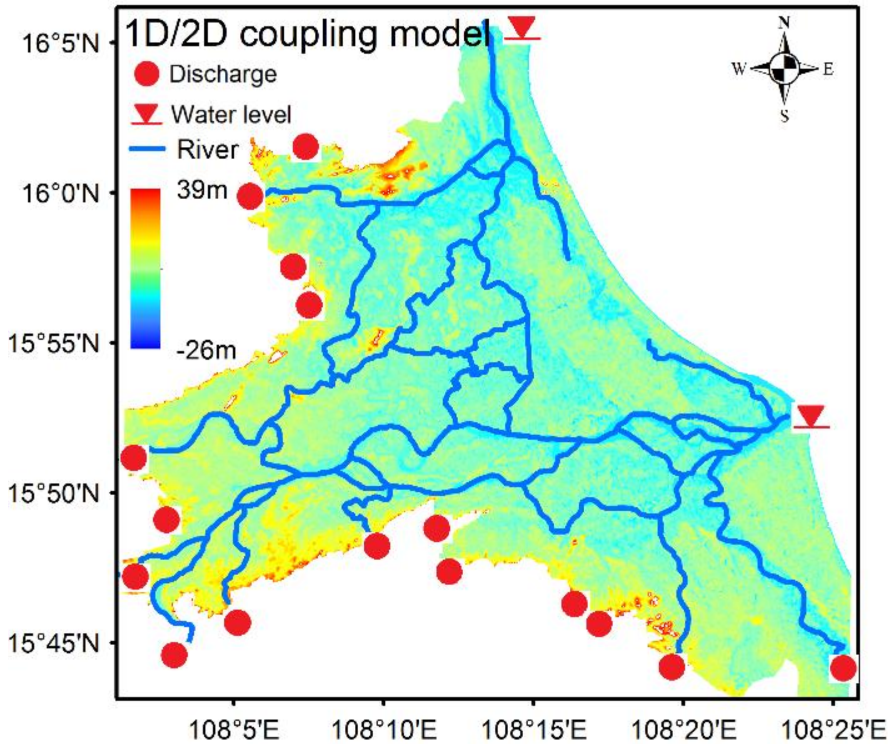


Figure 4.21. MIKE FLOOD (1D/2D coupling) model set up for Vu Gia Thu Bon river downstream.

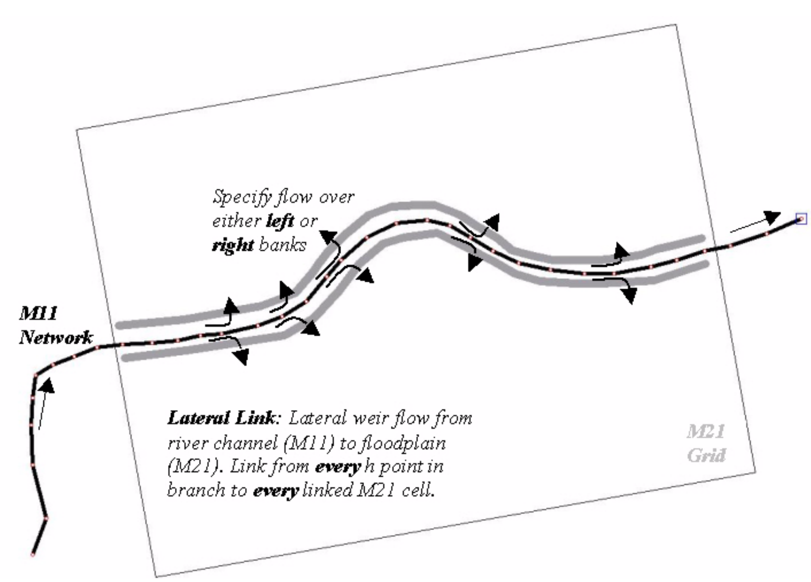


Figure 4.22. Application of Lateral Links (DHI, 2012d)

4.4.3 Results

Max water levels from MIKE 11 model (1D) and Quasi MIKE 11 (Quasi 2D) model are used to construct flood hazard maps by interpolated technic in ArcGIS. This process is taken place with the topography 30m. The results are shown at the Figure 4.24. In the case of MIKE 21 (2D) and MIKE FLOOD (1D/2D coupling, the flood hazard maps are extracted directly from model with the same cell size of input data. The result of these two models are shown at the Figure 4.24.

Relying on the hydrographs at three stations (Figure 4.23), we recognize that there is a big difference between these scenarios. The water level augments of MIKE 21 structure in comparison with the others are quite big. The hydrographs of this model are entirely separated toward MIKE 11, Quasi MIKE 11, MIKE FLOOD models at Giao Thuy and Cau Lau stations (Figure 4.23). These differences lead to a disparity in peak water level of this kind of model compared to the remaining models (Figure 4.23). The average number is that the MIKE 21 mode peak is averagely higher than others 0.75 m at Ai Nghia, 2.73 m at Giao Thuy and especially 3.57 m at Cau Lau. These analysis demonstrate the uncertainty of MIKE 21, representative of two dimensional model in simulating flood event. These limitations might be from the topography quality which will be discussed at the part of 4.4.5. Following that, in this case due to the computation time this 2D model used a 30 m topography that resized from 15 m DEM and adjusted river bed area by adding cross section. Using 30 m DEM resolution here might not be enough to represent the topography at modelling area, at least at river bed area more detail about DEM quality presented at the section 4.4.5. The coarse resolution as this situation is potentially to reduce the performance of 2D algorithm. In addition, there does not exist a surveyed DEM that includes river bed is considered as a significant factor affecting on 2D model capacity. Although integrating the cross section in DEM helps to increase the river bed description but it is still not accurate enough. It seems that the low resolution affects not only the intensity of flood event but also the time factor. This issue is proved by the late of peak water level of MIKE 21 model in comparison with others. Almost peaks of water level of MIKE 21 model are slower than the remaining from 3h to 9h. This limitation also has a significant influence on the modelling quality of hydraulic model.

The second model we note here is the MIKE 11 model. This one dimensional model is the simplest model for set up and modeling. The computation time is quite short. For run this 5 days flood event, MIKE 11 just spent less than 30 minute in comparison with more than 1 day of two dimensional models. However, beside these advantages, this kind of mode shows many weak points. These are mentioned at the last part and now are confirmed by MIKE 11 results. Similar to the previous 2D model, the water levels of MIKE 11 mode in this case are higher than Quasi 2D model and 1D/2D model coupling. Therefore, the intensity is not as big as MIKE 21 model, the higher only 1.85 m at Giao Thuy, 0.86 m at Cau Lau, and 1.89 m at Ai Nghia (Table 4.1). This point could be explained by the absence of modelling the lateral runoff factor. The river bank fix will make the water lever being higher than reality in the case of overbank of river flow. The next limitation of 1D model is that it does not supply a function to present the hydrological factors interior of study area such as rainfall or evapotranspiration. These are expected to affect significantly on the results. Particularly with a large study area as this scenario (1780 km^2), the role of interior factors is not able to neglect. Combining two above problems, we could figure out that, water lever in 1D model (MIKE 11) is higher than Quasi 2D and, 1D/2D coupling modes because it is impossible to describe the flow exchanged with flood plain. Therefore, although this model only counts exterior flooding causes via boundary conditions, the water lever is still lower than MIKE 21 what put in all inside and outside resources. The results in MIKE 11 are lower 1.49 m at Giao Thuy, 3 m at Cau Lau, higher 0.51 at Ai Nghia than MIKE 21 (Table 4.1). This distinction proves the prominence of 1D model in introducing river flow than 2D model. Additionally, the 1D model meets the difficulty in constructing flood map. Instead of providing directly the flood map as 2D model, 1D model only gives the water level along the river. Then, from level, the flood maps are established by interpolating in GIS model.

Regarding Quasi 2D model (Quasi 2D), the results at Figure 4.24 show that after taking a part of lateral river flow, the peak of water level is cutting down a lot in comparison with 1D model (MIKE 11). The reduction is so big, around 1.56 m at Giao Thuy, 0.59 at Cau Lau, and 1.49 at Ai Nghia (Table 4.1). These numbers prove that a significant water quantity was partly transformed and stored in flood plain. This scenario seems more reasonable than 1D model which merely defines the water run inside river banks. But in the other side, the recession limb of MIKE 11 quasi is higher than MIKE 11. It means that after reaching to peak flow, the water in flood plain returns to supplement for main river flow. Other characters of Quasi MIKE 11 are similar to MIKE 11 model.

Finally, MIKE FLOOD model which is coupling between 1D/2D coupling models. Let take a look at Figure 4.23, we can recognize that the hydrographs of MIKE FLOOD keep the same with the ones in MIKE 11. Yet, the measure is quite smaller than in MIKE 11. This disparity demonstrates the effect of coupling with 2D model. These couplings allow the part of overbank water to be able to exchange easily with flood plain. The Figure 4.24 also displays the difference between 1D/2D coupling and Quasi 2D model. It is pointed out here via the lower of hydrographs of MIKE FLOOD than of MIKE 11 quasi. This inequability might cause from the link methods. One joints partly with flood plain, Quasi 2D, one completely couple with flood plain. Likewise, not like the Quasi 2D model, the 2D model represents the flow part in flood plain with two directions. Hence, the flow exchange between two flow parts is better and more accurate. Besides that, the 1D/2D coupling can describe more precisely the flow sources than 1D model due to 2D model. In particular, the issue seems more impressive with distributed modes as Mike from DHI where the boundary extraction and input are very flexible. The extracted point can be defined easily, so it helps to simulate continuously the flow into 1D/2D coupling model. Furthermore, not only the outside flow sources, by coupling with 2D model, the 1D/2D coupling has the capacity to express the inside flow sources such as rainfall.

Table 4.1. Variability of max water level due to model structure (m).

Station	**Water level (m)**			
	1D model	Quasi 2D model	2D model	1D/2D coupling
Giao Thuy	11.973	10.411	13.4648	9.833
Cau Lau	6.388	5.798	9.38699	5.265
Ai Nghia	12.773	11.279	12.2609	10.489

Table 4.2. Scale variability of inundation area due to model structure (hectare).

Flood depth (m)	**<0.5**	**0.5-1.0**	**1.0-2.0**	**2.0-4.0**	**4.0-8.0**	**>=8**
1D model	3,720.51	3,909.60	7,430.31	10,330.38	3,741.93	307.17
Quasi 2D model	3,339.81	3,922.20	6,585.84	6,765.39	1,970.28	261.63
2D model	2,574	2,828.70	6,335.28	14,240.25	10,334.25	912.33
1D/2D Coupling	3,354.48	3,449.60	5,564.07	4,965.48	1,838.25	31.23

Table 4.3. Uncertainty of peak flooding event due to model structure (m).

Station	**Peak water level appearance time**			
	1D model	Quasi 2D model	2D model	1D/2D coupling
Giao Thuy	**11/11/2007 19:00**	**11/11/2007 19:00**	**11/11/2007 22:00**	**11/11/2007 19:00**
Cau Lau	11/11/2007 22:00	11/12/2007 1:00	11/12/2007 10:00	11/12/2007 4:00
Ai Nghia	**11/11/2007 19:00**	**11/11/2007 19:00**	**11/11/2007 0:00**	**11/11/2007 19:00**

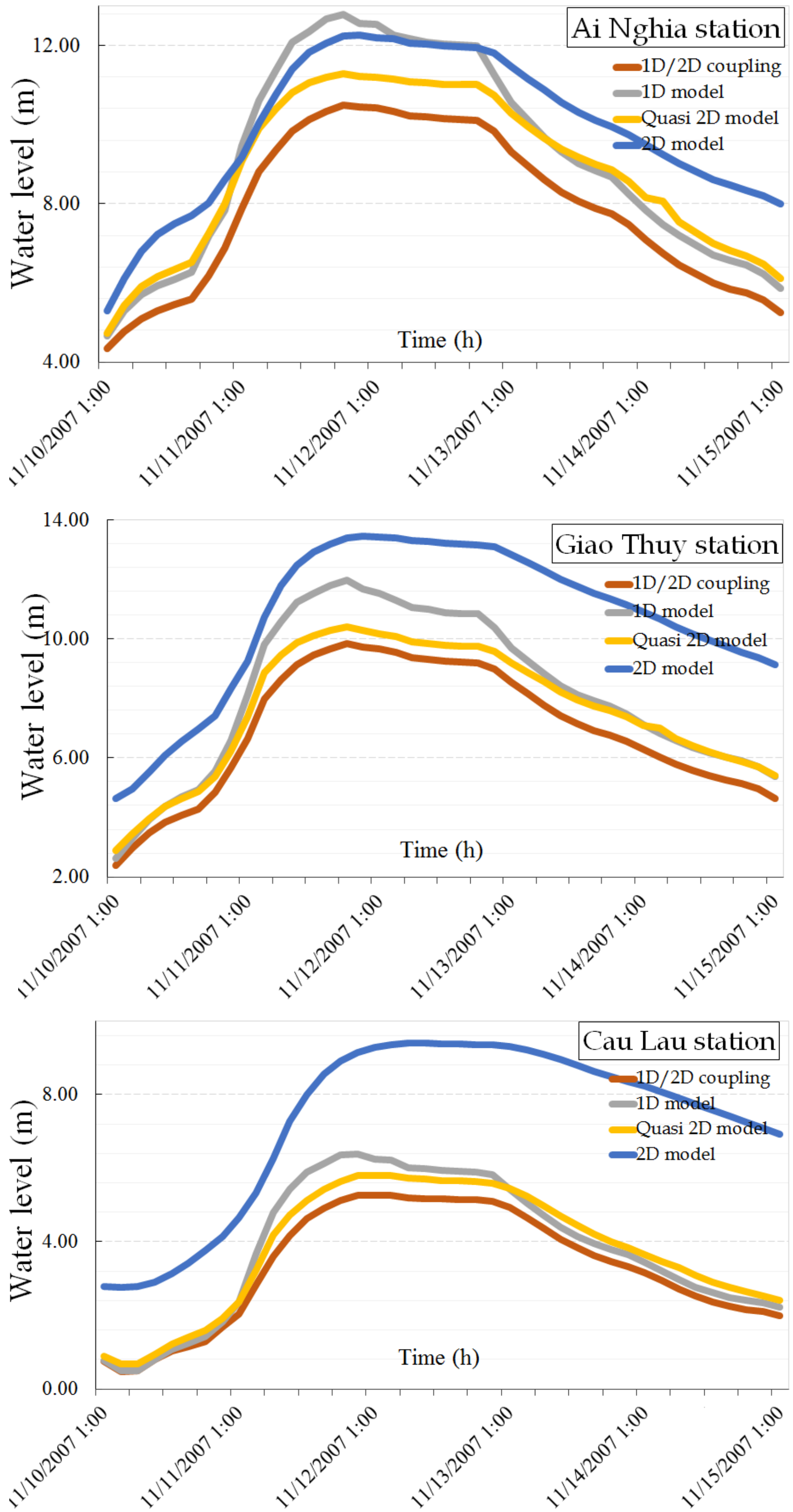


Figure 4.23. Hydrographs of water lever due to model structure.

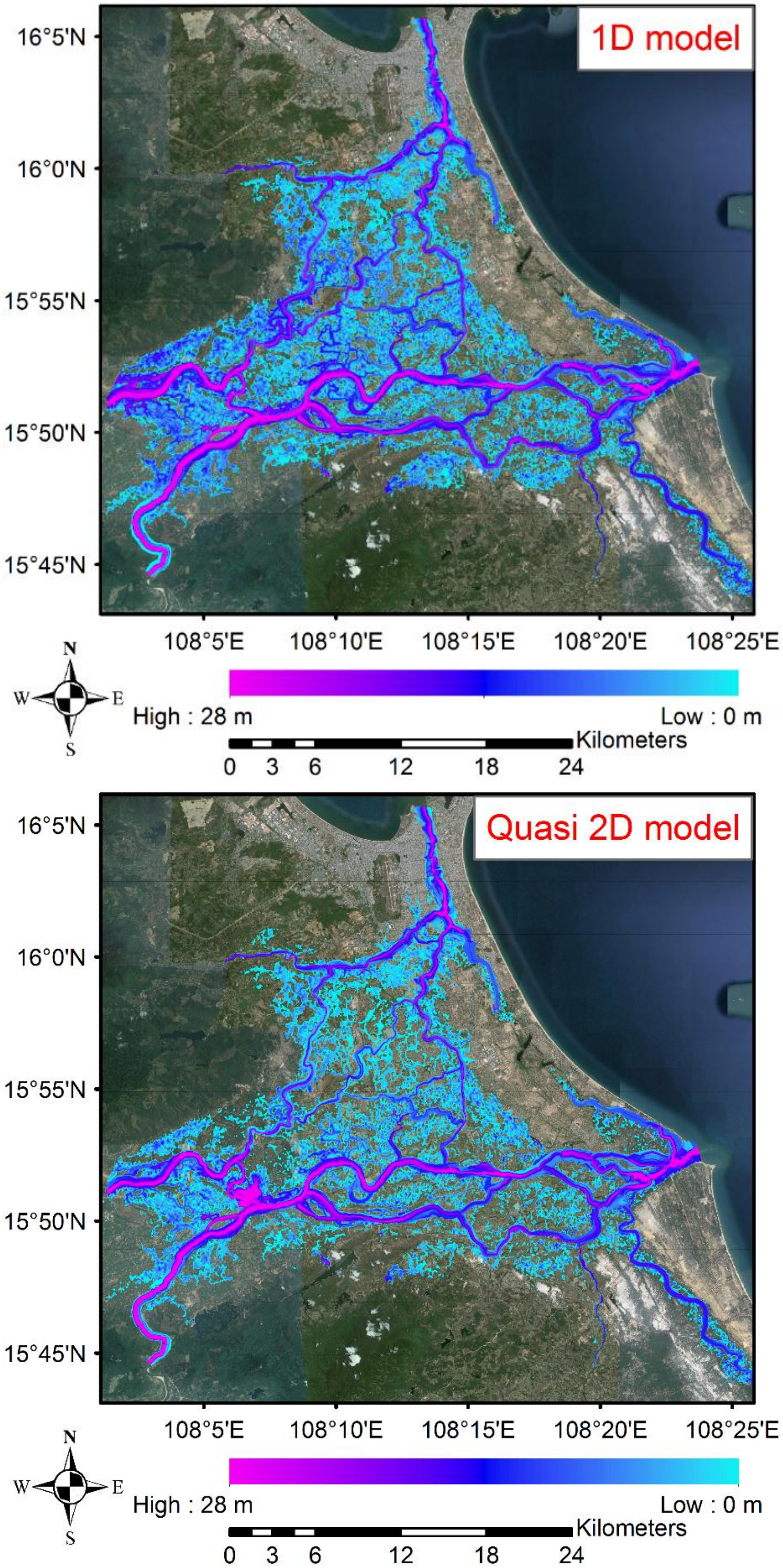


Figure 4.24a. Flooding area variation due to model structure - 1D model and Quasi 2D model.

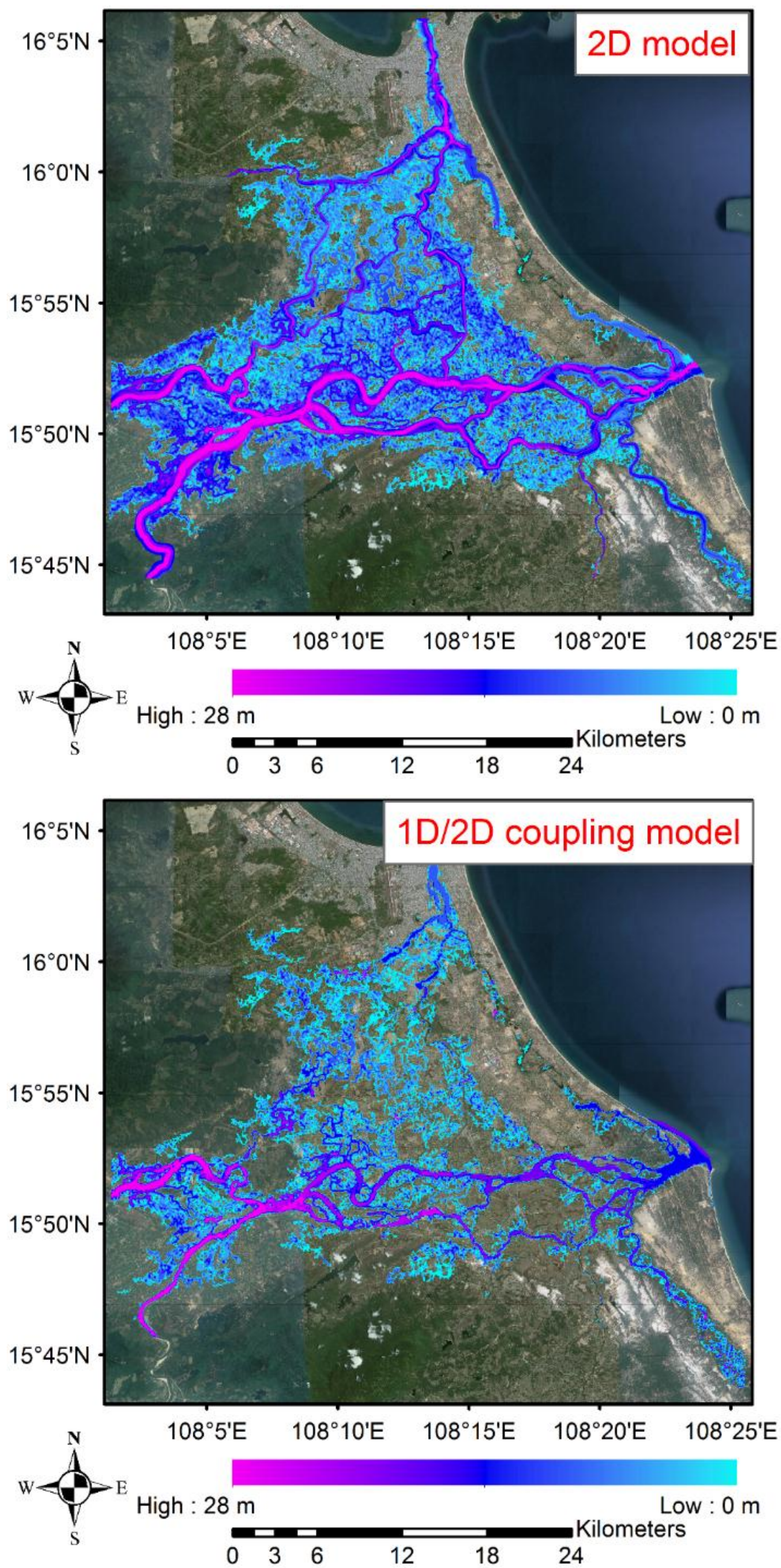


Figure 4.24b. Flooding area variation due to model structure – 2D model and 1D/2D coupling model.

The different hydrographs, peak flows appearance time lead to the uncertainties in determining the flood area. This point is shown very clear in the Figure 4.24 and Table 4.2. There is an unevenness between flood maps. With the highest flood peak, the 2D model gives large flood area (Figure 4.24). The next serious one is 1D model when the total inundation area is 25,179.39 ha and deeply inundated area is 4,049.1 ha. These numbers are 19,505.34 ha; 2,231.91 ha and 15,848.64ha; 1,869.79ha with Quasi 2D model and 1D/2D coupling model respectively (Table 4.2).

With these strong points, the flow simulated by 1D/2D coupling model is more confident than others, notably with a large catchment, complicated river networks, or lack of data areas.

4.4.4 Model selection for Vu Gia Thu Bon catchment

The previous part has demonstrated the performance of each kind of model towards flood modeling in the downstream part of Vu Gia Thu Bon river system. Therefore, in order to select a right model for this purpose, not only the model performance is considered. As shown in the section 4.3 the selected model needs to refer on several criteria. This part will concentrate to analyze more on data situation at Vu Gia Thu Bon catchment and computation time to choose a suitable model for flood mapping.

The condition at the downstream part of this river system is the first consideration. It is a flat area with complicated river network. The main branches and linkage channels mix densely at this region. This completeness makes the flow become so turbulent. Consequently, it leads to the inaccuracy when simulating the flow at this area with 1D model. Furthermore, at flat regions, the water in river frequently overflows the riverbanks to flood plain. If fixing the flow only inside two riverbanks, the inaccuracy in water level is inevitable. Thinking about Quasi 2D model, nevertheless, as above analysis this model only helps to overcome partly of 1D model. It just increases the harmonized capacity of 1D model. Other character is no changed. One more reason is that with a complex river as this case, it is impossible to pre-determine perfectly the flood plain for each branch. Many stream flows closely at a flat area lead to their effect area being not clear. In addition, how many links between main channel and lateral channel are enough to present the relation between them? It is very uncertain to set up them. Hence, applying the Quasi 2D model in this case might not very reasonable. One similar point of 1D model and Quasi 2D model is that it is not easy to introduce the interior flood cause such as rainfall. With a small area, this component can be forgotten, but with a large area as this study, this component is expected as one of principal flood causes. Hence, ignoring interior factors with a 1780 km^2 study area is not possible. At least, this region covers 6 rainfall gauging stations where having the average annual rainfall from 2000 to 4000 mm, the passing over might cause a big inexactness. Besides, there is not a surveyed cross section which is enough to present well the flood plain. The measurement data, collected in this study, describe only the river bed. The cross sections using in last simulation are extracted from the DEM 10 m with the limit quantity. It is not expected to these data to express accurately the profile of flood plain.

On the other hand, two-dimensional model meets the difficulty of computational time and memory capacity. Although, in this catchment, there are several DEMs with the resolution higher than 30m such as DEM 10 from P1-08 VIE Project and DEM 15 m from LUCCi Project. Therefore, if using this DEM for 1,780 km^2, it is predicted to conclude that the simulation time will be several weeks. Furthermore, to solve around 8 to 17 million cells of DEM 15m or 10m, it definitely requires a strong computer. But it is not feasible in this situation. One more region is that, in theory, the algorithm of MIKE 21 does not limit the size of simulation. In fact, they recommend that this model is merely able to run well if the model is lower than one million of cell. This is one big limitation of 2D model. Indeed, two MIKE 21 models were built with the cell size of 10m and 15 m, but it could not run, even if just load the data. Thus, requiring a smaller cell for 2D modeling in the case of Vu Gia Thu Bon is not realizable.

However, there are also problems with 30m selected resolution. The DEM is interpolated from DEM 15 m of LUCCi Project, so the question concerned to its quality is unavoidable. Furthermore, The DEM 15m does not present the topography at river bed. In other to improver this lack of data, the DEMs used in last MIKE 21 model are modified by taking into account the topography at river bed area. More detail, the survey cross sections, which benefit from MIKE 11, are divided into many points along the rivers. From these points, a raster is made and merged to old DEM. This technic helps us to dig the topography corresponding with observed data but the problem is that the density of cross section is so sparse. Average one cross section per km, these are not enough to express perfectly the change of river bed. Consequently, it reduces the capacity of water transportation of model. Nevertheless, the two dimensional model overcomes the limitations of one dimensional model.

Recapitulating the model efficiency and real situation at Vu Gia Thu Bon, the 1D/2D coupling model is suggested as the most reasonable selection for flood modeling at this region. This structure helps to overcome the lack of data as well as to simulate for a large catchment.

4.5 Morphological uncertainty and flood modelling

4.5.1 Introduction

The important role of topography data in flood modelling has been proved by many studies (Bates *et al.*, 2003; Cook & Merwade, 2009; Haile & Rientjes, 2005). The accuracy of this data is expected affecting significantly water surface elevation and flood propagation. Digital Elevation Model (DEM) is one of the general topographic data using nowadays in hydraulic modelling. This data allows to represent efficiently ground surface and supplies a capacity to extract automatically hydrological features of catchment, thus it has many advantages such as processing efficiency, cost effectiveness, accuracy assessment in comparison with traditional methods based on topographic maps, field surveys or photographic interpretation (Teng *et al*., 2008). However, the accurate and high resolution topography data is not always available for all catchments, especially in poor countries and large catchments. The lack of an accurate DEM data leads many uncertainties in hydraulic modelling. Hence, testing and comparing the quality of DEM is a necessary step before using them in flood modelling. The issue is similar with Vu Gia Thu Bon river catchment. The flood mapping in this catchment faces with the lack of high resolution and accurate topography data. Hence, the aim of this study is to estimate the impact of topography on water surface elevations and flood inundation extents. The study also presents the uncertainties of topography data when modelling flood events. These simulations are carried out on MIKE 21 of DHI. The results might show strong and weak points of each kind of topography data. They could help modelers to get several judgments when deciding the resolution of topography, data source to build the flood map. This study is also expected to give some usefulness for flood modeling in the coastal part of a big catchment.

4.5.2 Literature reviews.

The DEM accuracy is decided by many aspects (Cook & Merwade, 2009; Horritt & Bates, 2001; McDougall & Temple-Watts, 2012). Nevertheless, the resolution is the most important factor which has been considered. This factor is expected to affect the elevation of area, slope gradient, slope aspect and drainage gradient. Haile & Rientjes, (2005) stated that by using a rectangular grid DEM structure, the elevation area covered by a grid element becomes a lumped property and is replaced by a single value. So, in a same area, high resolution DEM contains more grid cell than lower one. Hence, it is expected to present more details on the ground surface. It helps the hydraulic model being able to reflect more accurately the flood propagation in the catchment. This judgment has been demonstrated in many previous studies. Horritt & Bates, (2001) tested the difference in flood modelling against the spatial resolution from 10, 20, 50, 100, 250, 500 and 1000 m and concluded that the change in scale of DEM might have an influence on the model performance. The coarser resolution use, the lower model performance is. In the same way, Avanzia *et al.*, (2013) simulated on different DEM grid sizes (10, 20, 40, 80m). The results show that the grid size affects not only the flood area but also the inundation time. The data with bigger grid gave a higher peak flood and maintained the inundation longer than smaller ones. Furthermore, the capacity of DEM to describe the river bed is also considered as a big source of uncertainty in river flood modeling. After constructing the flood inundation map for Strouds Creek in orange county, Texas, US, Cook & Merwade, (2009) reveals that most of the topography datasets do not include bathymetry details of river channel. They counted that the inundation area in Strouds creek decreased approximately 30% if incorporating with surveyed cross section even if they simulated with 6m DEM resolution.

Finally, the origin has been seen as one of key factors which have impacts on the DEM accuracy. There are lots of DEM generated technics, from traditional methods as cartography, ground survey, or modern as digital aerial photogrammetry, LiDAR. Each of them has different strong and weak points. Hence, they content potential uncertainties for DEM quality (Mason *et al*., 2011). Furthermore, the interpolated technics in creating or resampling the DEM also reduce significantly the accuracy of topography data (Vaze *et al.*, 2010). Comparing on DEM resampling from 3 different methods, nearest neigh, bilinear, and bicubic, the results of Haile & Rientjes, (2005) indicated that there is a huge variation between these scenarios. It proves that the interpolation methods should be considered when evaluating the quality of DEM.

4.5.3 Methodology

In order to minimize the impact of data accuracy on flood modelling results, the part will show the testing process of different DEM data on the aspect of resolution, bathymetry described capacity and origin. These tests are realized in the downstream part of Vu Gia Thu Bon catchment via MIKE 21 model.

In this study, MIKE 21 model is setup only for flood prone area instead of the whole catchment. This area (Figure 4.20) covers an area of 1,780 km^2 at the downstream of Vu Gia Thu Bon catchment, where most of flooding events of the highest magnitude occur in history.

The components to construct the MIKE 21 model are:

- Topography: This bathymetry is described in the form of rectangular grid.
- Source and sink: 17 sources are defined to input the flow of corresponding sub catchments at the upstream which is kindly small to simulate by river branches. These sources are extracted at the outlet of 17 sub catchments in MIKE SHE model (Vo & Gourbesville, 2014a).
- Boundary: Two boundaries is set up at the downstream with the sea level data of Hoi An and Son Tra gauging stations.
- Precipitation: This simulation uses the rainfall data which is redistributed spatially based on daily rainfall data from 15 rain gauge stations with Kriging method.
- Resistance: This parameter is represented via Strickler roughness coefficient M. For Vu Gia Thu Bon, Strickler roughness coefficient is determined depending on Land use map and in 2 to 90 $m^{1/3}/s$.

4.5.4 Results

a. Topography data (DEM) resolutions

In order to estimate the effect of DEM resolution on flood propagation, this study has been realized with three different grid size DEMs, 30m, 50m, 90m. These are resampled from one original Dem 15m from LUCCI project. The resampling DEM grid size is expected to change significantly the quality of DEM.

Firstly, this judgment is proved through the change of slope. The results shown in Figures 4.25, 4.26 and Table 4.4 demonstrate this tendency. According that, the average slope of DEM 30 is higher than the remaining. And the maximum slope value of DEM 30m is multiplied approximately 3 times than the one of DEM 90m. The big difference in slope value is expected to impact on the lag time of flood event, the flood drainage velocity, inundated time and then have an effect on all model qualities.

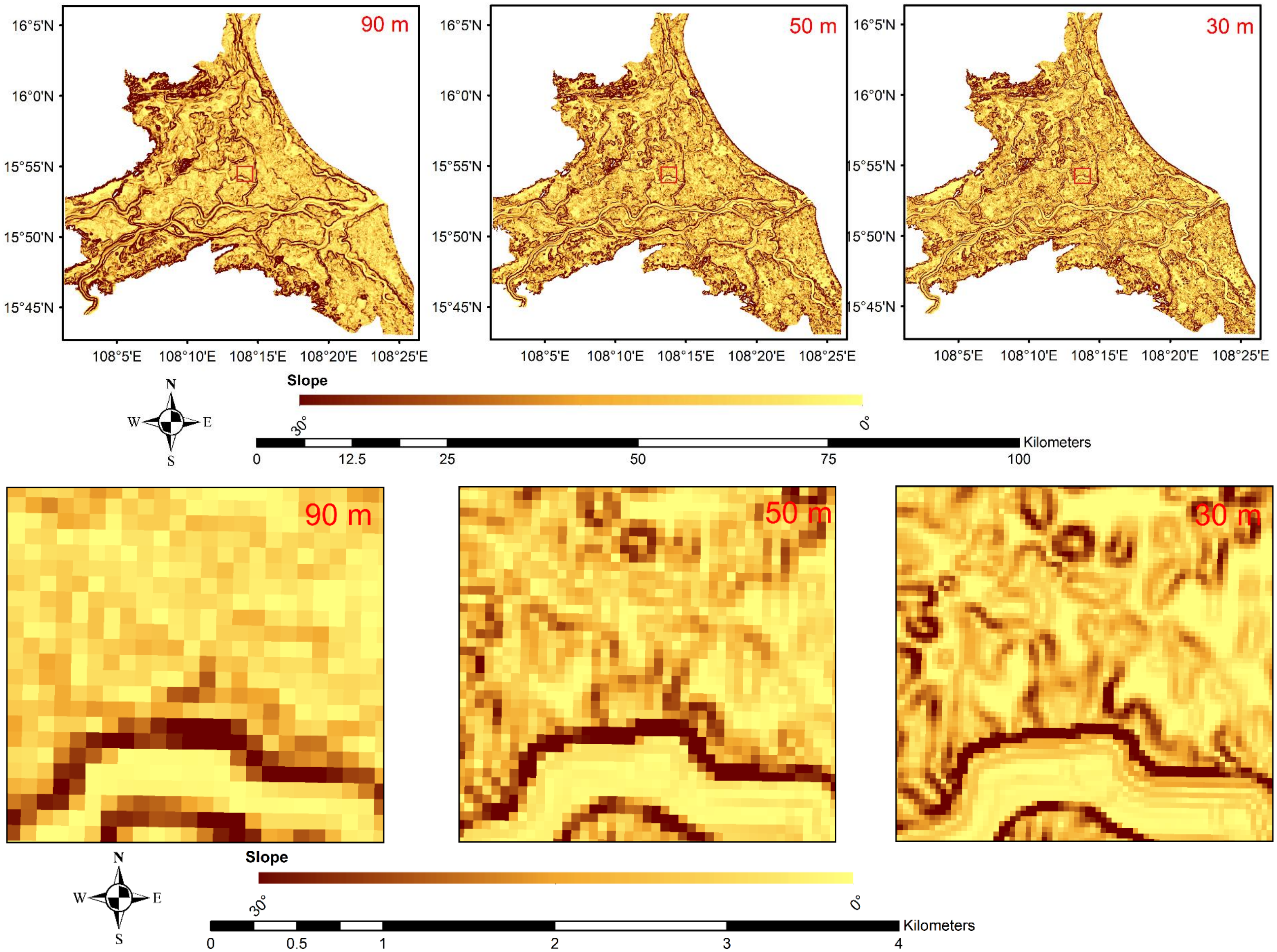


Figure 4.25. Slope distributed map against DEM resolution

The huge variation of slope value might be explained as the ground surface represented capacity of DEM because the DEM using rectangular grid structure represents the ground surface with the lumped property (Haile & Rientjes, 2005). The altitude value, expressed by the cell, is averaged of smaller cells in this area. Hence, DEM with small size can describe more concretely the surface, this principle is illustrated at the Figure 4.26.

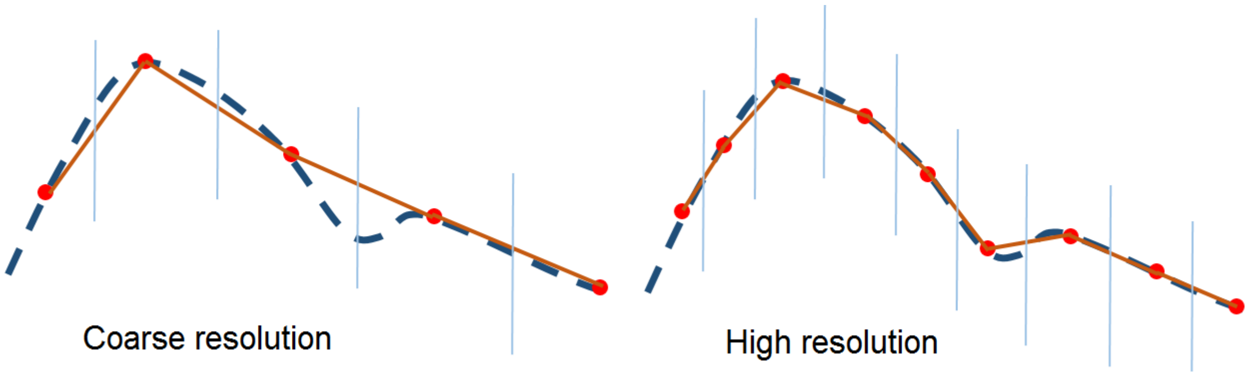


Figure 4.26. Different outlines of DEM resolution.

Table 4.4. Slope variation due to the DEM resolution.

Resolution	**30m**	**50m**	**90m**
Max	30.62	21.47	10.49
Min	0	0	0
Mean	1.46	1.26	0.95
Standard deviation	1.56	1.21	0.88

The second factor related to DEM resolution is flow direction. The water will generally run in order to follow the best advantage ways. This principle is brought similarly into model.

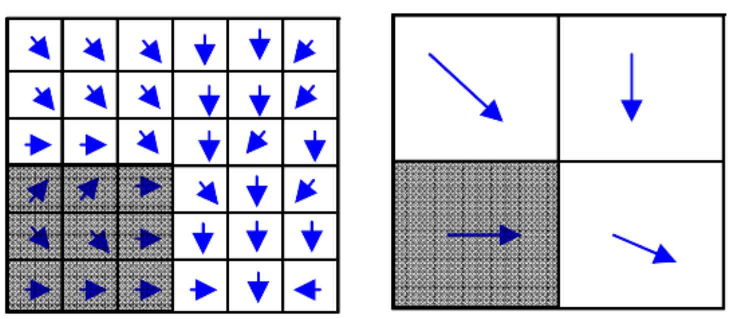


Figure 4.27. The effect of DEM resolution on flow factor.

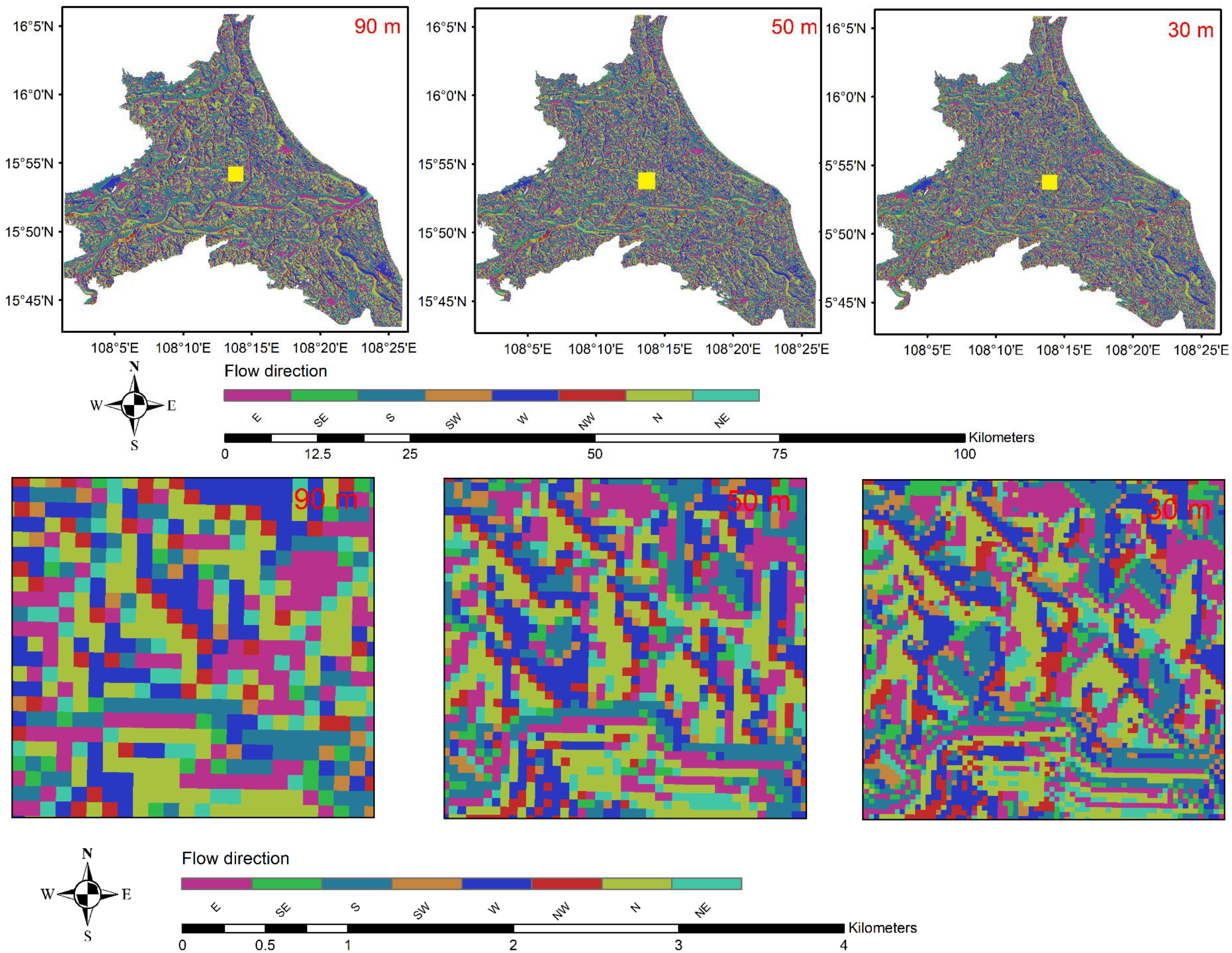


Figure 4.28. Flow direction distributed map against DEM resolution.

Table 4.5. The varied percentage of flow direction against DEM grid size.

Direction	E	SE	S	SW	W	NW	N	NE
30m	17.53	7.87	15.33	7.21	16.79	7.99	18.2	9.09
50m	17.95	7.13	16.13	6.08	17.55	7.3	19.45	8.41
90m	18.22	6.58	15.21	5.51	17.51	7.46	20.79	8.72

By comparing the cell altitude overall catchment, the model will determine the good direction for flow. As this reason, when changing the resolution, the altitude value of cell will change. Consequently, it leads to change the direction of run off. The Figure 4.27 is one example for this explanation. The variation of flow direction has a significant meaning with characteristics of flood events, especially the flood area, the magnitude, the time of event. Analyzing on three different resolutions in Vu Gia Thu Bon catchment, the result introduces that the flow direction is influenced seriously/ dramatically by the resolution of DEM (Figure 4.28, Table 4.5). It might lead to the big uncertainty when using a coarse DEM for flood modelling.

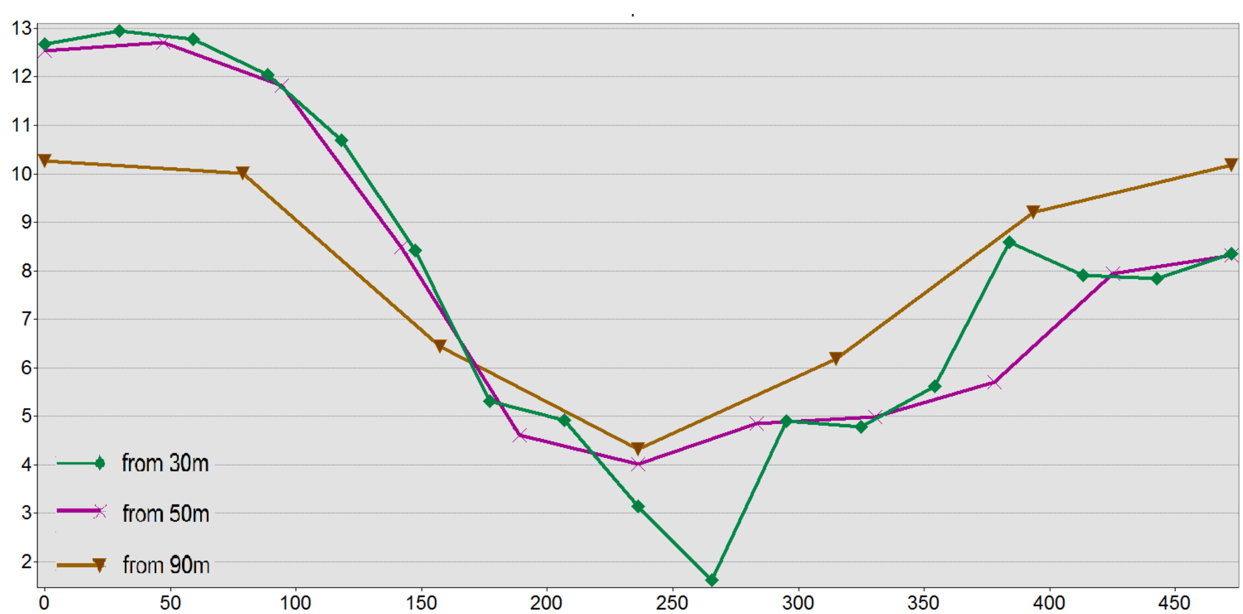


Figure 4.29. Topographic description of DEM due to resolution.

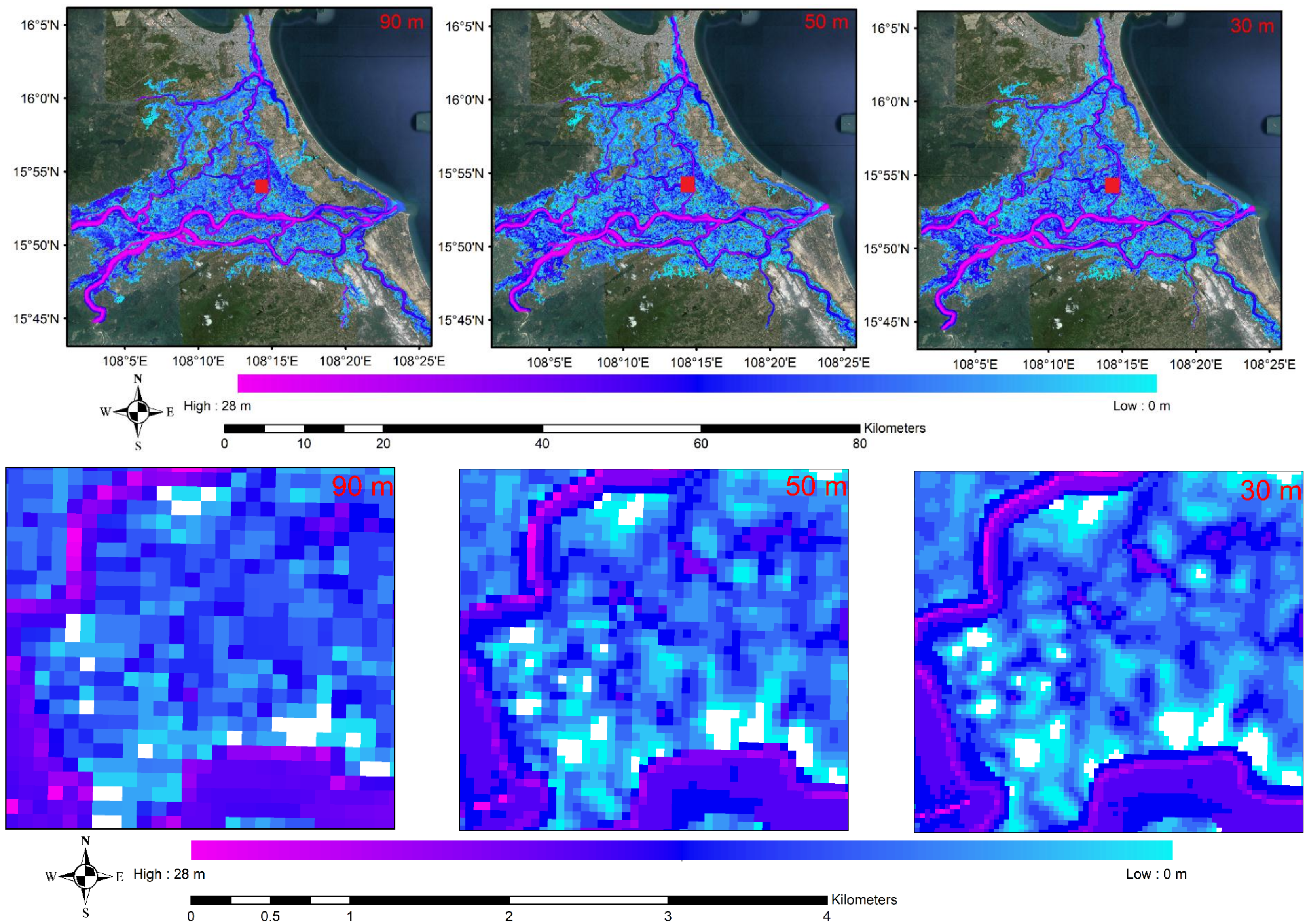


Figure 4.30. The effects of DEM resolution on flood are at downstream of Vu Gia Thu Bon area

The detail level of DEM is demonstrated by the cross section extracting from different DEM resolutions. In the Figure 4.29, it is very easy to realize that the smallest expresses the most detail the shape of topography. With 30m scenario, the lowest point is 1.62m, in comparison with 4.01m in 50m scenario, and 4.32m in 90m scenario. These big differences will impact surely on flood discharge capacity. Besides that, relied on the shape of cross section in Figure 4.29, the small cell describes more concrete the river bank. Both of these factors will result in the model capacity in simulating the flood plain.

The changes on DEM accuracy due to resolution result on the change of flood inundated area, are the peak of flood event and inundated time. The results, tested on three DEMs, have been displayed in the Figure 4.30. The results show that there is a big disparity between low and high resolution DEMs (Figure 4.30). The DEM 90m, with the no high quality, small average slope, and lowest capacity in expressing the topography, brings the largest inundated area. According to the statistical number (Table 4.6), the inundation area of DEM 30m reduces around 1,895.71 ha in comparison with two remains. But it is more important when the difference occurs concentratedly at deep flood area, deeper than 1 m. The inequality is also presented at max flood depth, the max flood depth corresponding to DEM 30 m is higher approximately 0.25 m than DEM 90 m. These differences are expected to have more influence on flood risk prediction and flood management.

Table 4.6. Scale variability of inundation area due to data resolutions (hectare).

Flood depth (m) / **Resolution (m)**	**<0.5**	**0.5-1.0**	**1.0-2.0**	**2.0-4.0**	**4.0-8.0**	**>=8**	**Total >0.5**
90	2,841.48	3,040.74	7,014.60	16,027.47	14,934.80	5,346.81	46,364.42
50	2,590	2914.25	6,688.50	16,056	15,382	5,244	46,284.78
30	2,646.99	2,914.92	6,546.51	15,424.20	14,320.50	5,183.55	44,398.68

b. River and non-river adjunct

Not similar to 1D model, flood modelling using 2D hydraulic model depends significantly on quality of topography, especially the capacity of topography in representing the river bed (Hernández *et al*., 2013). Using the DEM low quality without adjusting river bed topography for flood modelling is expected to give a big uncertainty. Previous studies suggest that combining the DEM with measured cross section is necessary for improving the quality of DEM at area lack of data (Cook & Merwade, 2009). As presented, there is not available a DEM with describing details the river bed at Vu Gia Thu Bon catchment.

In order to overcome this problem, a 30m DEM is adjusted by adding the river bed via measured cross section system. This issue is realized in ArcGIS (Figure 4.31). This improvement is hoped to increase the run out capacity of river. The results in Figure 4.32 prove that after incorporating with the measure data, the river bed can move down around 10m. It is really a significant space for flood flow.

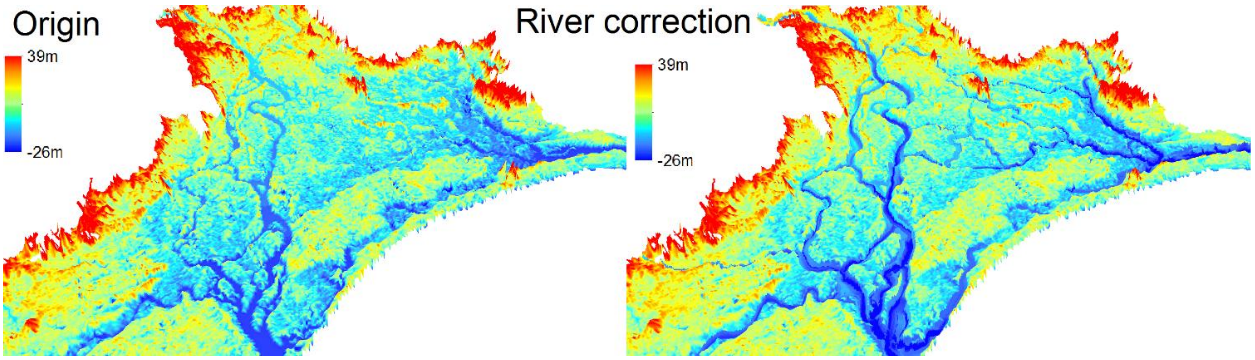


Figure 4.31. Topographic represented capacity of different DEM

Comparison result, displayed at the Figure 4.33 and Table 4.7, demonstrates the difference in inundation areas between two DEMs, one origin and one adjunct. Obviously, the flood area will be reduced with the scenario which uses the adjusted DEM. However, the reduced number is very huge, around 11,707 ha decreasing with the DEM origin. Furthermore, the max flood depth changes from 26.6m to 23.32m. These reductions provide evidence to confirm the importance of DEM modification due to measured cross section.

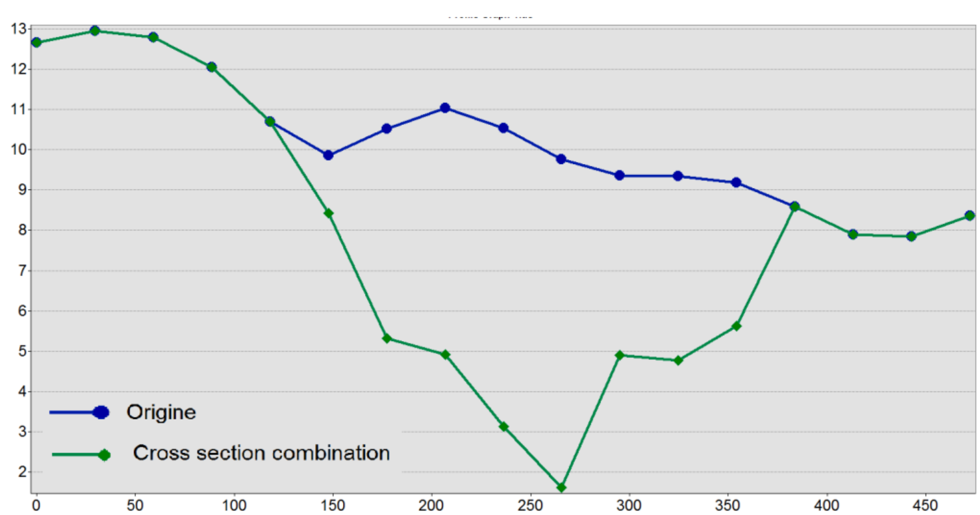


Figure 4.32. Difference in river description between origin and adjusted DEM

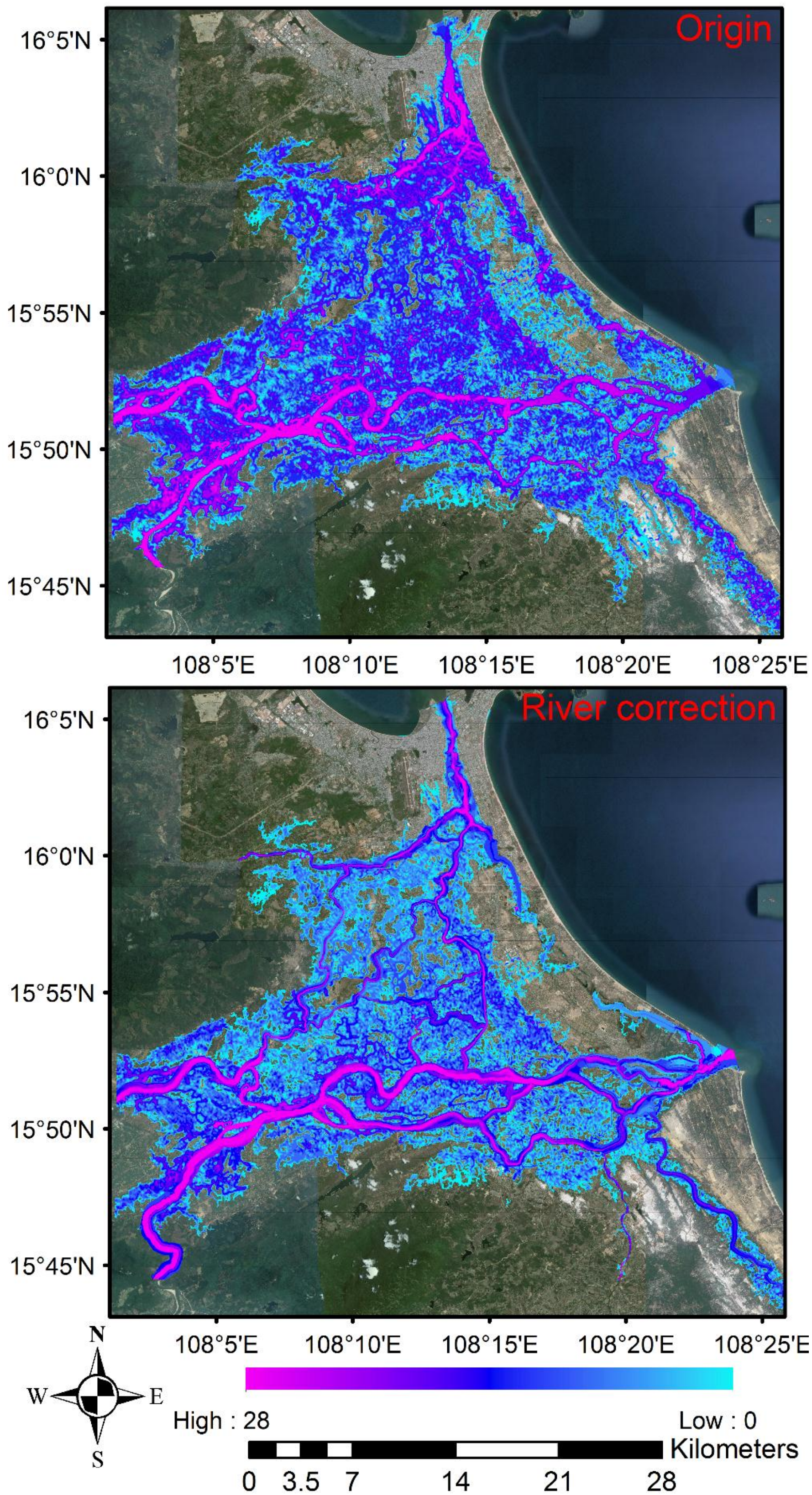


Figure 4.33. The difference of inundation area between adjusted and non-adjusted DEM

Table 4.7. Scale variability of inundation area due to DEM adjunct (hectare).

Flood depth (m)	<0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	Total>0.5
30m adjusted	2,646.99	2,914.92	6,546.51	15,424.20	14,320.53	5,183.55	44,398.68
30m original	2,706.48	3,031.29	6,399.09	15,674.04	25,843.41	5,149.44	56,097.27

c. Topography data origin

It is supposed that technic in creating DEM affects its accuracy (Vaze *et al*., 2010). It leads to impact on the flood modelling and flood propagation. In fact, there are lots of methods which have been used to create DEM. They may be from traditional or modern methods such as cartography, ground survey, digital aerial photogrammetry, interferometric SAR, airborne laser mapping technique (Mason *et al*., 2011) . However, each of them contains different pots and coins.

In order to make clearly the uncertainty of DEM origin to flood extent, this part will present the different flood plain results corresponding to the DEM created method. This study realized on one uses 90m SRTM DEM and the other simulates on 90m DEM resampling from 15m DEM. The uncertainty is demonstrated via the difference in inundation areas in Table 4.8. The disparity between two scenarios is around 1,785.24 ha and flood max depth altered more than 1.84 m. The results of this study also confirm the influence of DEM created methods on the flood simulation. These uncertainties should be considered for flood modelling.

Table 4.8. Scale variability of inundation area due to DEM origin (hectare).

Flood depth (m)	<0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	Total>0.5
90m resampling	2,841.48	3,040.74	7,014.6	16,027.5	14,934.8	5,346.81	46,364.42
90m srtm	2,903.04	3,057.75	6,977.34	14,653.7	13,858.3	6,032.07	44,579.16

4.5.5 Conclusion

The role of quality and resolution towards flood mapping has been much discussed in the literature. The importance of these factors has been confirmed again by this study. By representing an historic flood event in 2007 using 2D hydraulic model – MIKE 21 with different topography data, this study demonstrates that the flood area and flood depth vary significantly due to topography data resolution. Although the high resolution topography data might describe more concretely and more accurately flood area, the computation time related to data makes us consider to choose the reasonable resolution for our simulation. The flood propagation is also influenced by DEM accuracy, so with areas where do not have a good DEM, adding the observed cross section into DEM is necessary. The simulated result as well indicates that in order to reduce the uncertainty concerned to DEM created methods, it is necessary to simulate on many different data sources. In the case of this catchment, the 30m DEM resolution is suggested for using in hydraulic modelling. This resolution is evaluated to provide a more reasonable time consideration, as well as more acceptable results than others. Regarding to using the measured cross section incorporated DEM or not, this issue will be decided due to the kinds of used hydraulic model. Using the adjunct DEM is suggested in the case of 2D hydraulic model. Other case, if simulating with 1D/2D coupling, the DEM without river bed is more suitable. Because with 1D/2D model, the part of river flow is carried by 1D model. Hence, if applying the adjunct DEM here, it is probable that this flow part will be in charge of 1D and 2D as well. It might cause the flood peak reduction and give an inaccurate result. This analysis was published at 6th International Conference Water Resources and Sustainable Development (CIREDD2015), in Algiers, Algeria (Vo & Gourbesville, 2015a).

4.5 Flood modelling

The flood event in November 2007, which is one of the biggest damaged floods in the last decade, is selected to validate the MIKE FLOOD model. The MIKE FLOOD model is set up similar to the model in the section 4.4. The validation is implemented with water level of three stations at the downstream. Hydrographs of 3h water level at Figure 4.34 demonstrate the capacity of this MIKE FLOOD model to reconstitute flood process occurring in downstream of Vu Gia Thu Bon Catchment. It seems that the simulated peak flows arrive earlier than the reality. This tendency occurs similarly at all three stations. The cause might be from the inaccuracy of hydrological model which could not reach 100% performance while representing the hydrological process of catchment. The earlier of stream flow in MIKE SHE model results in unavoidably the faster in MIKE FLOOD model. However, the different time of peak flow between simulation and observation is not very big, just less than two time steps, hence this tendency might be acceptable in flood modelling. This earlier tendency of simulated peak flow is considered as a safety for flood prediction. The performance of model is also asserted via statistical index in Table 4.9. Accordingly, the difference between the highest simulated water level at these three stations and observations is not significant. The number varies approximately from 10 to 20 cm.

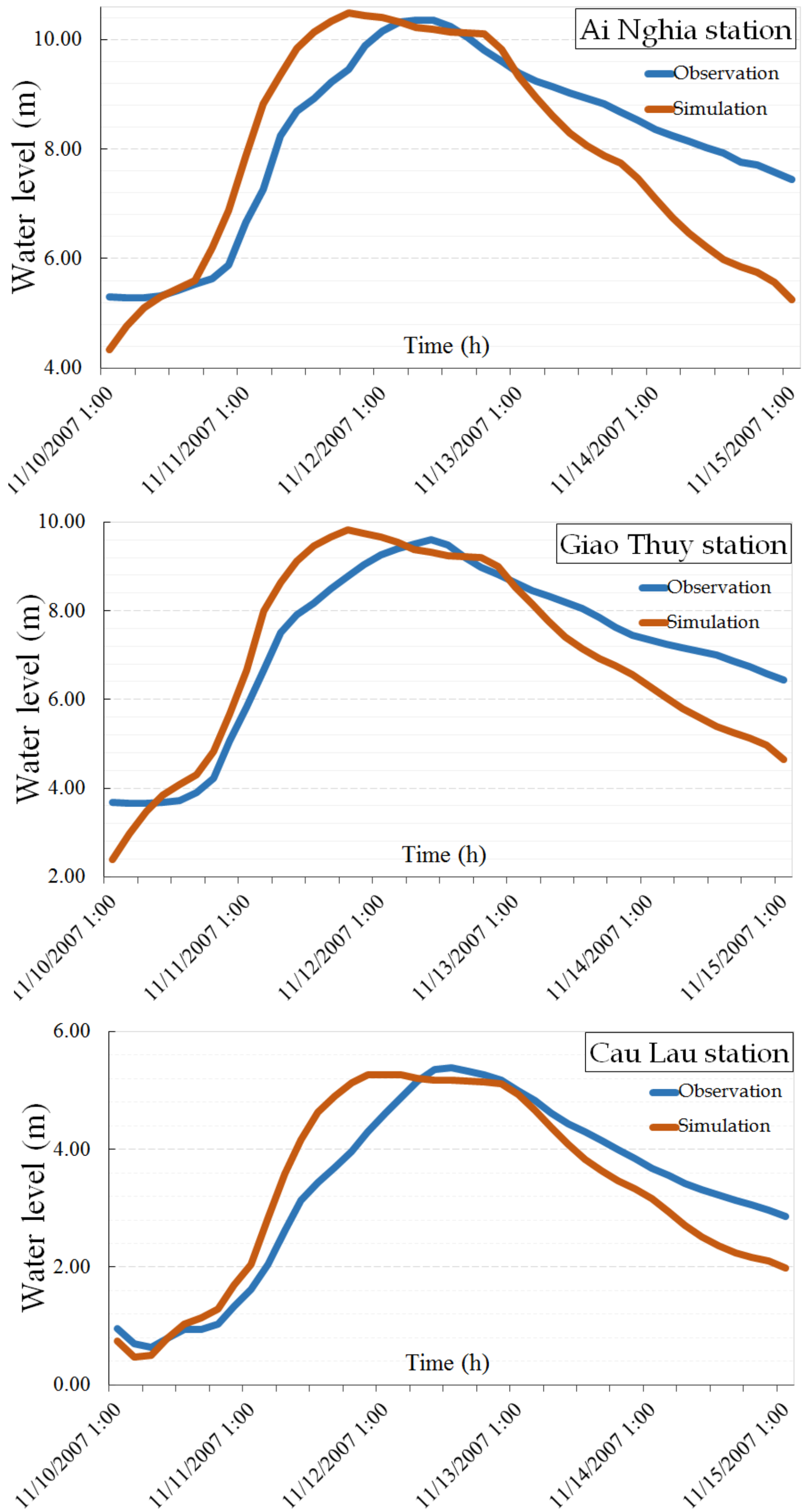


Figure 4.34. Model and observed hydrograph of water level.

Table 4.9. Statistical indices of MIKE FLOOD model at downstream area of Vu Gia Thu Bon catchment.

	Ai Nghia	**Giao Thuy**	**Cau Lau**
R	0.852	0.903	0.919
E	0.55	0.732	0.826
RMSE (m)	1.082	0.961	0.622
Delta H (m)	0.129	0.223	-0.125

The correlation coefficients between simulation and observation reach relatively high, all station R index passed 0.85. The Nash-Sutcliffe coefficient could reach to 0.83. For the above persuasive evidences, this MIKE FLOOD model is completely applicable to construct flood plain as well as forecast their variation at Vu Gia Thu Bon Catchment.

Chapter 5 CLIMATE ASSESSMENT

Relied on the climate data and validated model, this chapter will provide predictions about the flow variation at Vu Gia Thu Bon catchment in last years of this century. The flow variation will be analyzed in all aspects, such as peak flow, base flow, appearance time and frequency. These analysis will help to define the future tendency of this river system. The variation in runoff will lead to the change in inundation area. This step is undertaken by flood modelling. Finally, the chapter will demonstrate the change of flood risk map in future in comparison with present. These flood risk maps is constructed by overlapping the flood hazard maps on land use map of the catchment. Above process will be concretized in this chapter as follows.

5.1 Global Circulation Models and Regional Climate Models

The response of hydrological factors to climate change has been studied since the middle of 20th century. Most assessments have been based primarily on a coupling approach between global atmospheric general circulation models (GCMs), which are designed to simulate the past and current climates. Then, they are used to predict the future state of global climate based on specific scenarios of greenhouse gas emission, and hydrological models. However, GCMs are generally operational with very coarse spatial resolution of the order of hundreds of kilometers because of the complicated characteristics and the limitation of computational capacity(Do *et al.*, 2012). The data with a resolution of around 200-500 km, taken from GCMs, might not be suitable to estimate the variation of hydrological factors in the future for regional impact studies. Most of the river basins on the world are smaller than typical resolution of the GCM (Raghavan *et al.*, 2014), hence climate data with large cell size could not represent accurately the happening of future phenomena. Therefore, it leads to inaccuracies in hydrological models, particularly in area with complex climate conditions. In order to overcome this restriction, Regional Climate Models (RCMs) have been developed. The expectation is that RCMs with the finer resolution could represent better the characteristic of climate at regional scale. The output of RCMs, which describes more accurately the local characteristics, is used as input in the hydrological model.

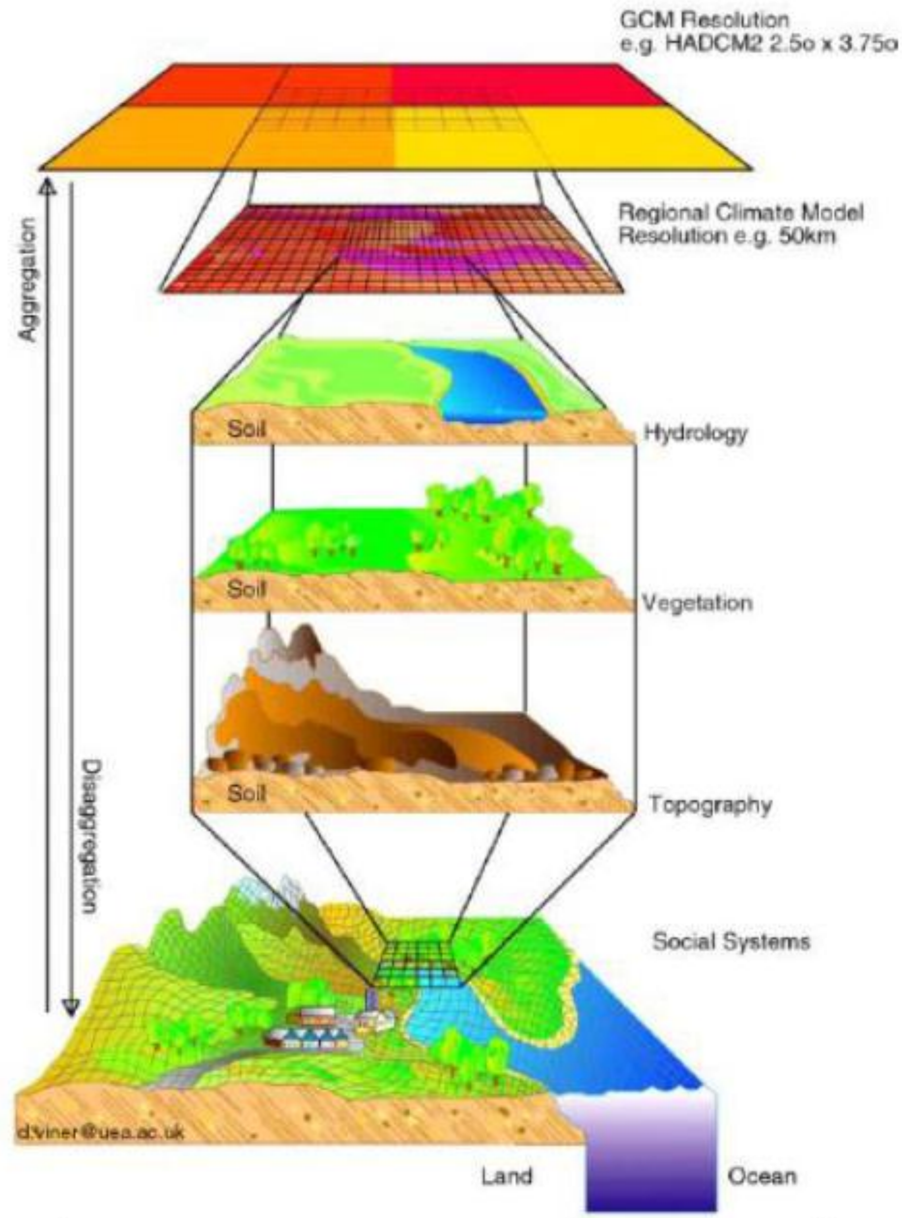


Figure 5.1. Schematic downscaling method.

Downscaling (Figure 5.1) is an important technique that applies to convert the variations of climate change factors from large to smaller scale. There are two main types of downscaling: Dynamical Downscaling (DD) and Statistical Downscaling (SD) techniques. Nevertheless, each method has advantages and disadvantages. Fowler *et al.,* (2007) showed that DD method is used to produce RCM from large scale data of GCMs. Output data are typically resolved at around 0.5° (50 km) latitude and longitude scales, some projects may be reached to 10-20 km. Thus, they have abilities to more realistically describe regional climate features such as orographic precipitation, extreme events and regional scale anomalies. On contrast, this method still remains inconveniences with concern to computational ability, limitation in number of available scenarios and strong dependence on GCM boundary forcing (Fowler *et al.,* 2007). In this study we applied the RCM Weather Research and Forecasting (WRF) Model, developed at the National Center for Atmospheric Research (NCAR) in the USA, the WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. The WRF software has a modular, hierarchical design that provides good portability and efficiency across a range of foreseeable parallel computer architectures. The model incorporates advanced numeric and data-assimilation techniques, a multiple nesting capability and numerous state-of-the-art physics options. Other than applications of weather forecasting, the model has found wide applications in climate research.

5.2 Application to Vu Gia Thu Bon catchment.

5.2.1 Global model

Based on the SRES scenario of IPCC Fourth Assessment Report, lot of GCMs were built to describe the climate scenario in future. However, on the limitation about the time of thesis, there are only three GCMs having been analyzed for Vu Gia Thu Bon catchment.

ECHAM5 is the firth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (MPIM) in is the most recent version in a series of ECHAM models evolving originally from the spectral weather prediction model of the European Centre for Medium Range Weather Forecasts (Roeckner *et al.*, 2003).

CCSM3 is the abbreviation of community climate system model version 3. It is the third general circulation model designed by National Center for Atmospheric Research, USA for climate research on high-speed supercomputers and select upper-end workstations (Yoshida *et al.*, 2008).

MIROC3.2 medre is abbreviated from Model for Interdisciplinary Research on Climate. This general circulation model is developed by Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan (Randall *et al*., 2007).

5.2.2 Regional Climate Models

In this study, the Regional climate model is developed and supplied by Tropical Marine Science Institute, National University of Singapore (NUS). RCM WRF was run over a part of the VGTB river basin (Figure 2.1) at a horizontal resolution of 30 km. The model was driven by both of ERA40 reanalysis and the GCM ECHAM5, CCSM3.0 and MIROC-medres. As for the physics options, the Kain-Fritsch scheme was used for the cumulus convection scheme, the Yonsei University scheme for the planetary boundary layer, Thomson scheme for the explicit moisture physics and RRTMG for both long and short wave radiations along with the NOAH land surface scheme for implementation of surface hydrology. The physics options were chosen from different parameterization sensitivity studies that best represented the climate of the region. Since the focus of this paper is more on the hydrology, these results are not being discussed in detail. A detailed description of the numerous physics options of the WRF model can be obtained from the documentation available at the WRF website: http://wrf-model.org/index.php

The RCM WRF model was run for the period 1961-1990 using the ERA40 analysis to assess its performance of the present-day climate. Later, the model was run using the 3 GCMs over the same period forced under the 20th century experiment to assess the model’s performance on the 30 year climatology of the present-day climate. The future climate simulation spans the period 2070-2099 driven by the above GCMs under the IPCC SRES A2 emission scenario. For simplicity in reading, the simulations of GCM ECHAM, CCSM and MIROC driven RCM WRF are being referred to as WRF/ECHAM, WRF/CCSM, WRF/MIROC. All climate simulations used the updating of sea surface temperatures, which is recommended for long term climate simulations.

In order to assess the observed rainfall data in spatial scale, the gridded observational dataset is used in this study: The Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of water resources data (APHRODITE). According to Vu *et al.,* (2012), this APHRODITE dataset is among the best match with station data over the central highland region of Vietnam, which is the neighborhood of Vu Gia Thu Bon basin. The APHRODITE data was developed by the Research Institute for Humanity and

Nature and Meteorological Research Institute of Japan. This dataset provides 0.25° resolution information on rainfall and surface temperature over the monsoon Asia on a daily time scale for long period 1961-2007. This was created primarily with data obtained from a rain gauge observation network. The basic algorithm was adopted in (Xie, 2007). More information can be found from (Yatagai *et al.*, 2012).

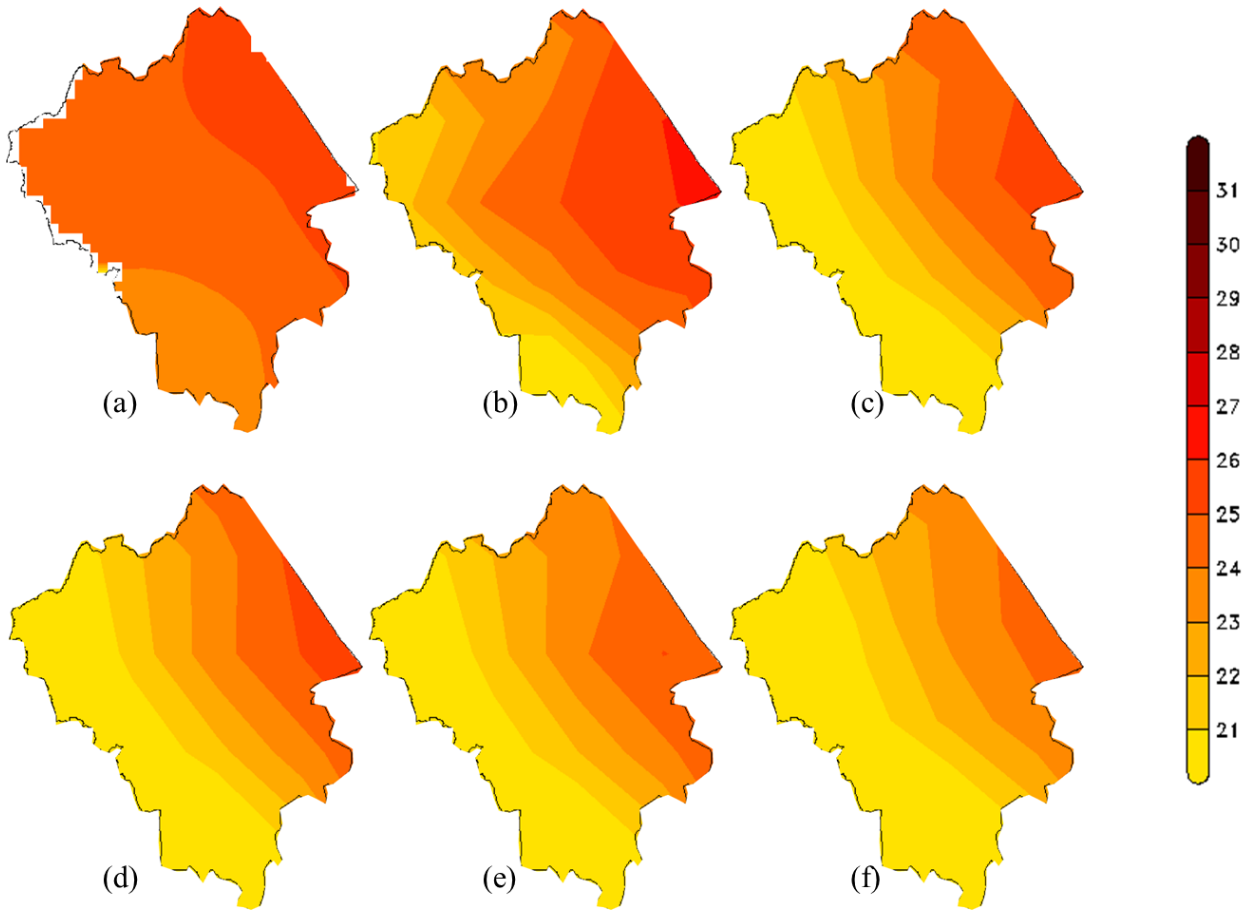


Figure 5.2. Present day climate for temperature (oC) for (a) STATION (b) APHRODITE (c) WRF/ERA (d) WRF/ECHAM (e) WRF/CCSM (f) WRF/MIROC

The present day climate variable temperature is shown in Figure 5.2. The Figure 5.2a shows the interpolation from station data in and out of the Vu Gia Thu Bon river basin using Kriging technique. The Figure 5.2b is the gridded dataset from APHRODITE and the model simulation from WRF are displayed in Figure 5.2c, d, e, f.

The temperature simulation is quite homogenous for all the datasets compared to station and gridded data with lower temperature at the southwestern side of the domain where topography is higher as seen in Figure 2.7. The advance of using high resolution model here is it can resolve well the high topography temperature. In overall, the WRF simulated data for present day climate is able to capture the temperature of the study domain.

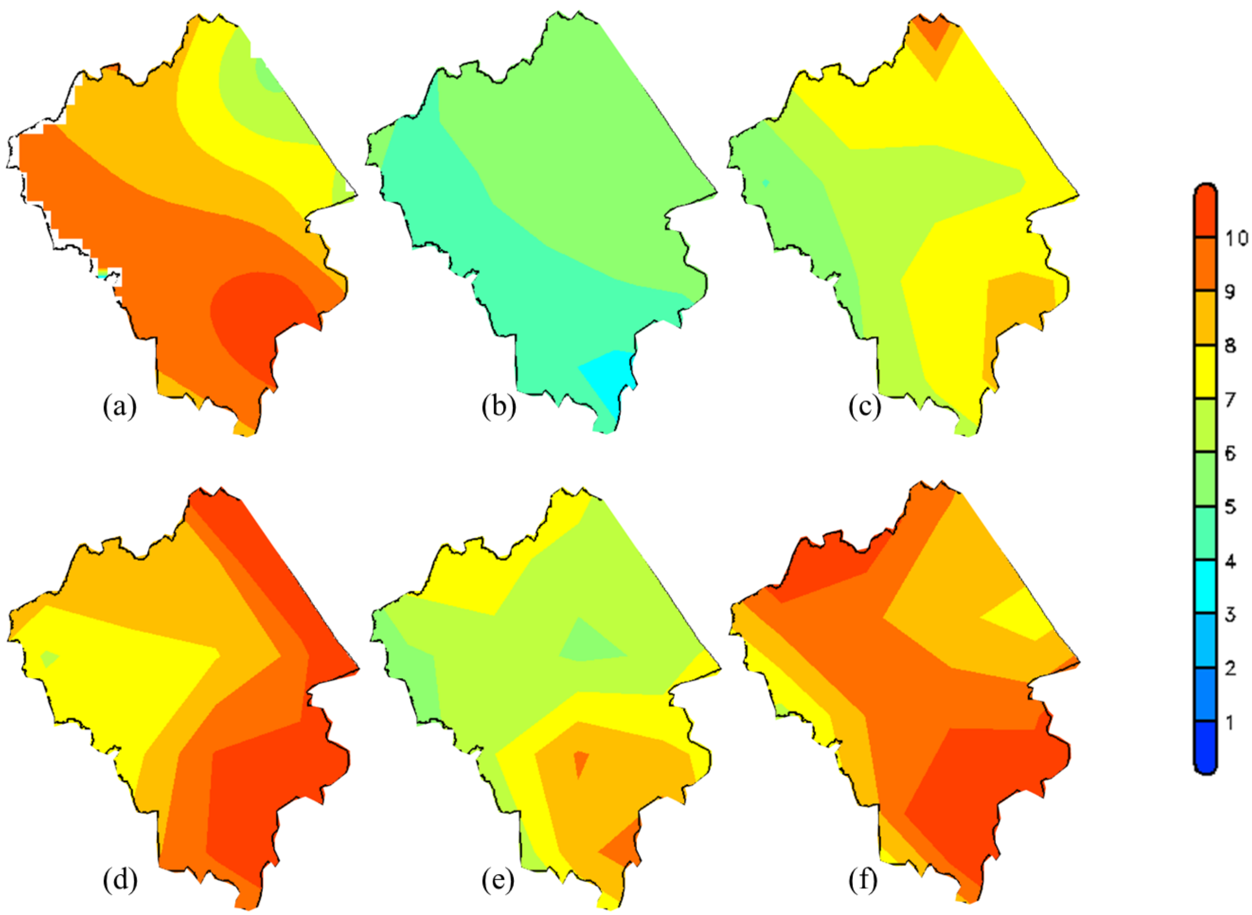


Figure 5.3. Present day climate for precipitation (mm/day) for (a) STATION (b) APHRODITE (c) WRF/ERA (d) WRF/ECHAM (e) WRF/CCSM (f) WRF/MIROC

The same measurement was applied to precipitation at Figure 5.3. Precipitation is a very difficult variable to predict. Within observation data, there is huge different between station interpolation data (Figure 5.3a) and gridded data (Figure 5.3b), the average rainfall over the study domain in APHRODITE data is lower than the station data about 2-3 mm/day. The simulated dataset WRF/ERA (Figure 5.3c) is similar to WRF/CCSM (Figure 4e) also underestimates the station data of about 1mm/day. The WRF/ECHAM and WRF/MIROC are able to capture the magnitude of station data. In addition, the higher intensity of rainfall is found at high altitude area from southeastern side of the study domain and is able to be captured by all datasets.

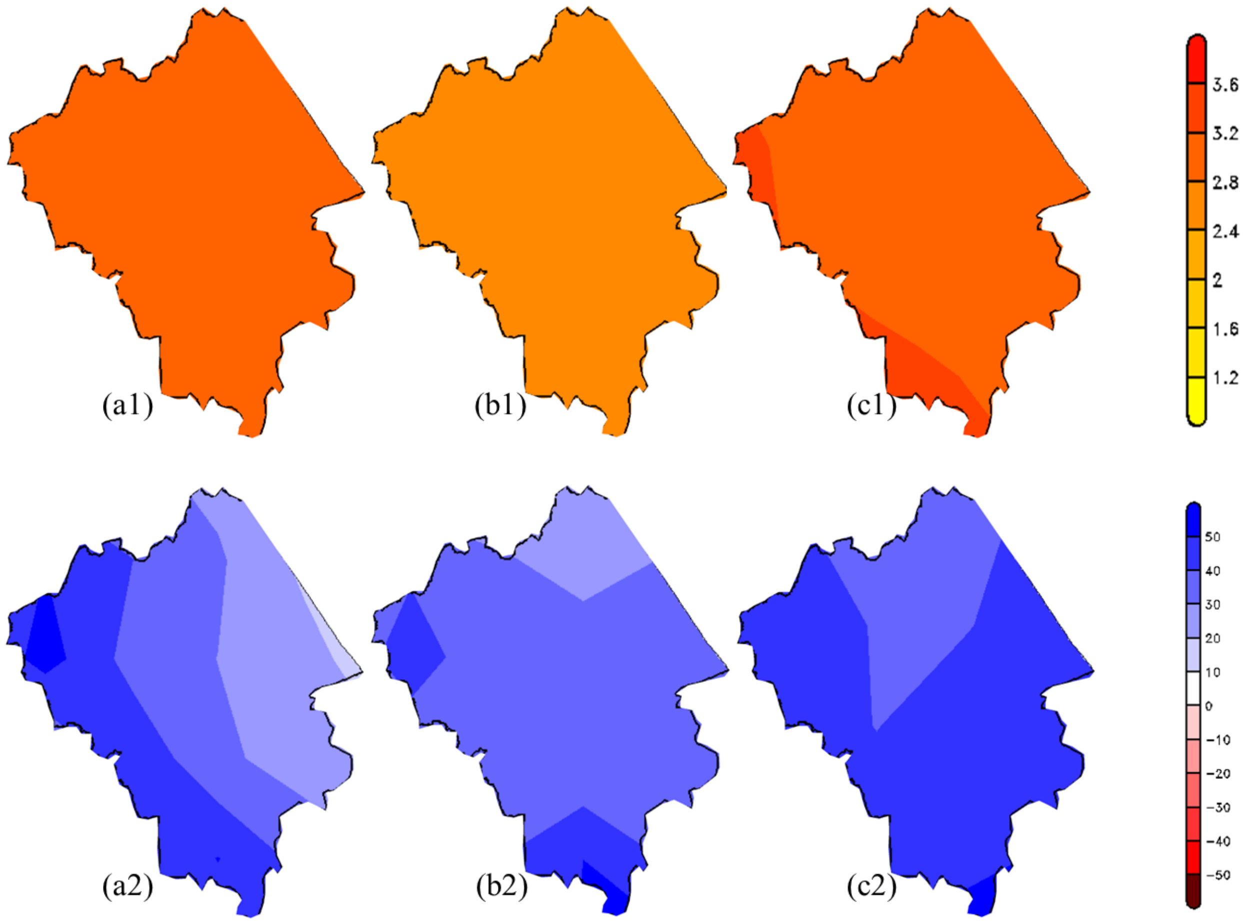


Figure 5.4. Absolute anomaly temperature (oC) (1) and precipitation (%) (2) 2070-2099 scenario A2 with respected to baseline period 1961-1990. (a) WRF/ECHAM (b) WRF/CCSM (c) WRF/MIROC.

The future climate change temperature and rainfall is assessed by downscaled GCM models under A2 scenario. Figure 5.4 shows the change in temperature (ºC) and precipitation (%) for the future period 2070-2099 with respected to baseline period 1960-1990 for 3 downscaled datasets. From Figure 5.4-1, it shows that future temperature for the Vu Gia Thu Bon region might increase about 2.0-3.2ºC for all datasets. The lowest increase is WRF/CCSM (Figure 5.4-b1) at 2ºC while the highest increase is WRF/MIROC (Figure 5.4-c1) at 3.2ºC. Figure 5.4-2 shows an agreement in increasing future rainfall for all 3 datasets of about 10-50%. The high increasing rate is about the high topography area and lower rate near the coastal area. This is an important finding and should be put under notice because when intense rainfall occurs at the upstream on the mountain side, more and more probability for the downstream to be flooded, thus making the inundation situation here worst.

5.3 Future climate change results

5.3.1 Responses of stream flow

a. Future scenario setting.

In other to assess the variation trend of river flows, the future meteorological factor is input in validated hydrological model (MIKE SHE). In this case of Vu Gia Thu Bon, two factors are accounted for this purpose. The first consideration is precipitation and the second one is evapotranspiration.

- Future climate precipitation

In order to assess the future climate precipitation, the delta factor approach is applied as in equation 5.1:

$$\Delta = \left(\frac{Pm_{FU} - Pm_{PD}}{Pm_{PD}}\right) * 100\% \tag{5.1}$$

Where Pm_{FU} and Pm_{PD} are the monthly Precipitation for future (2070-2099) and present day climate (1961-1990) respectively. The Δ is assessed by months from January to December in %. This Δ is then added to the station historical data to represent the future climate precipitation. The same Δ factor approach has been applied in our previous studies by Raghavan *et al*., (2012, 2014); Liew *et al*., (2014) . The results are show at Table 5.1.

Table 5.1. Averaged rainfall delta change factors apply during the period 2091-2100 in Vu Gia Thu Bon catchment.

GCM	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CCSM	21.81	11.07	22.59	11.18	0.07	8.17	17.31	33.79	55.56	91.04	61.5	9.49
MIROC	-2.11	-13.01	6.77	30.09	26.43	6.37	51.36	39.92	70.59	48.23	138.99	32.55
ECHAM	8.25	-18.56	5.32	33.67	-5.13	19.31	1.13	-6.05	21.47	31.03	35.36	-9.17

- Future climate evapotranspiration

This factor is calculated by the support of climate change module in Mike Zero software(DHI, 2012f)

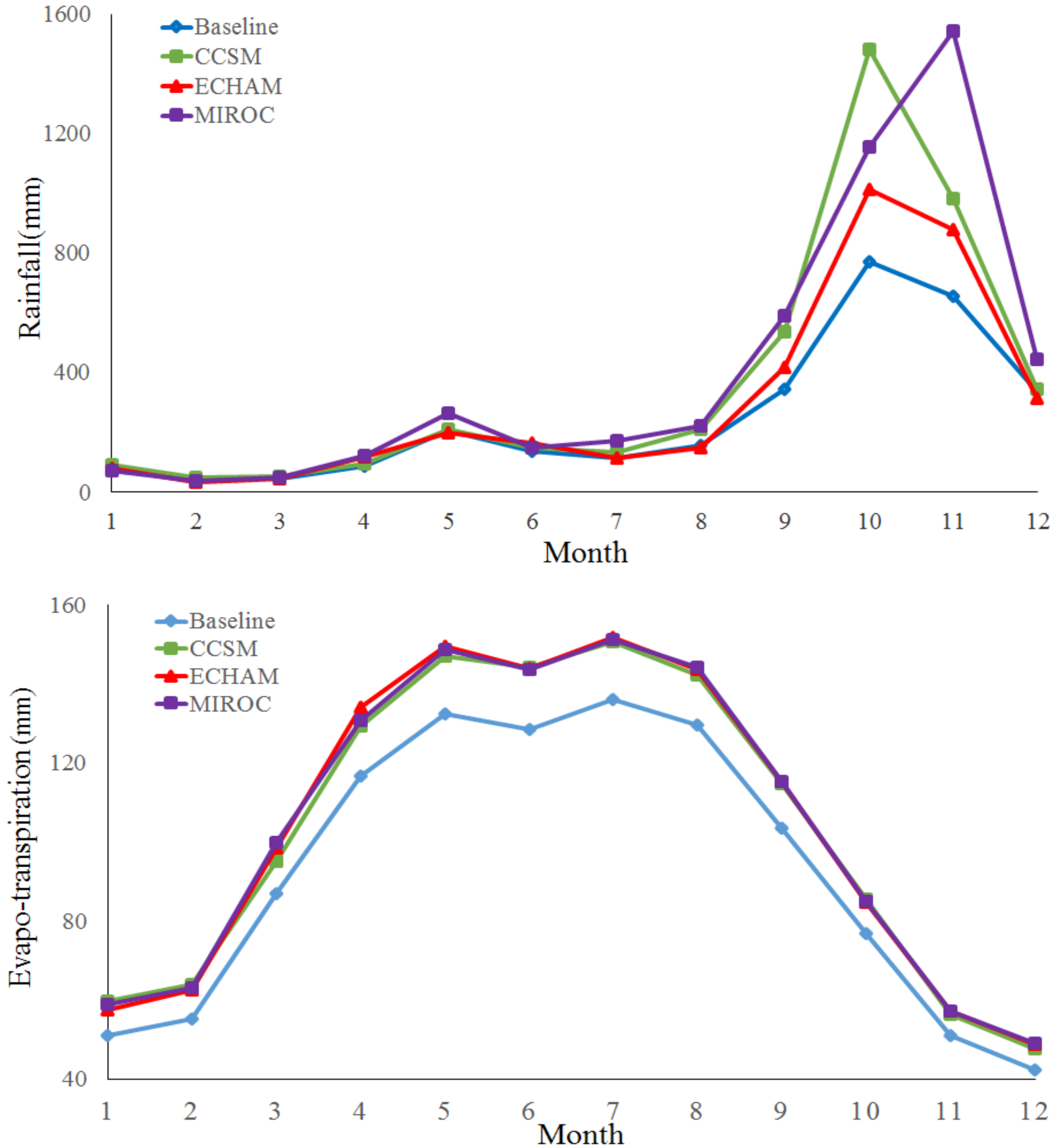


Figure 5.5. Mean monthly rainfall and evapotranspiration under actual and future climate change conditions.

These simulations take place with hypothesis that there are no changes in land use, soil map and river networks in the future or these changes have minor effect on the stream flow over this catchment.

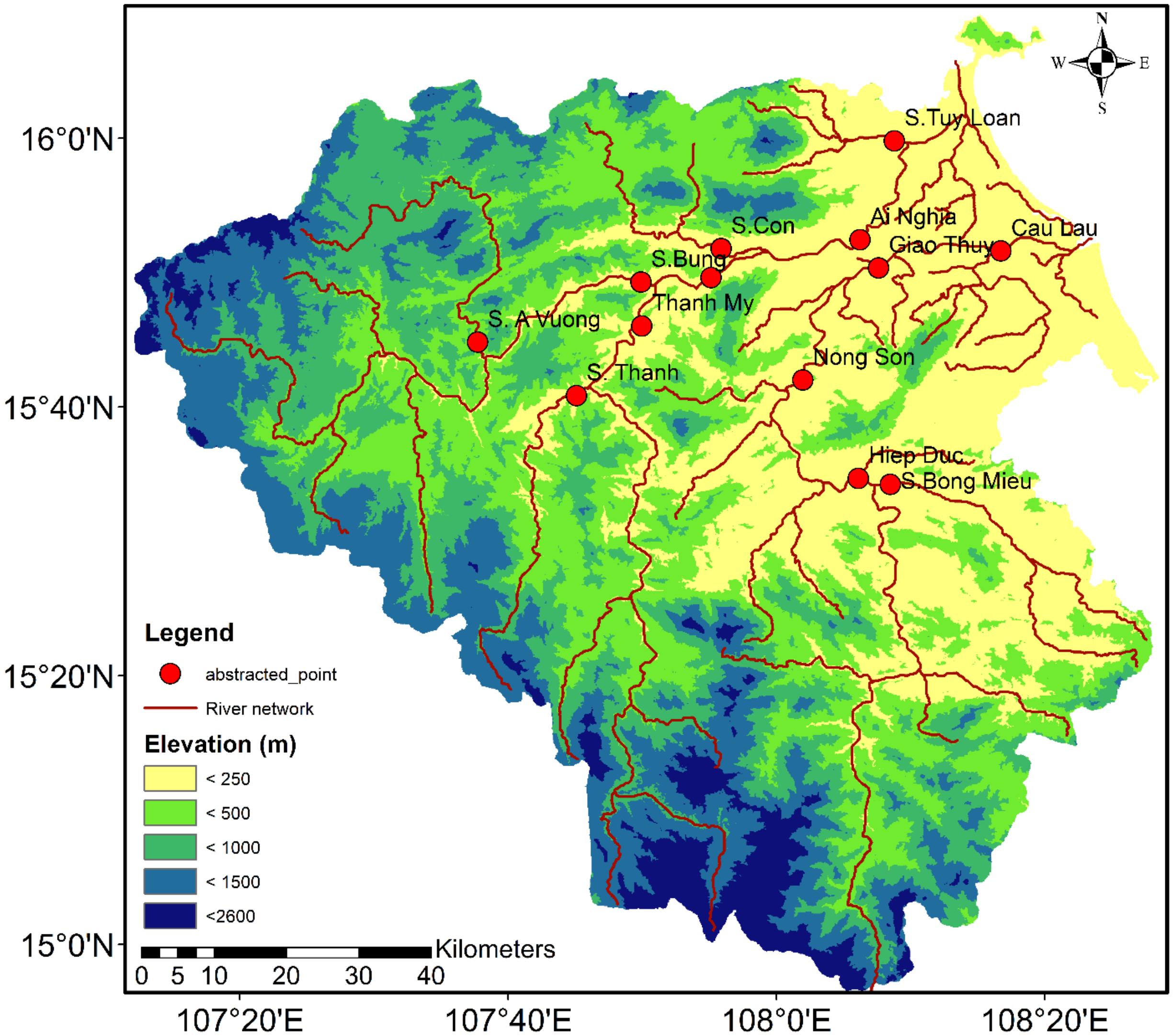


Figure 5.6. Compared locations for the change of runoff.

The global warming assumes to create the increase of precipitation and impact to evapotranspiration in Vu Gia Thu Bon catchment (ADB, 2013). Therefore, it is not surprising that the flow regime in this catchment extremely varies. The results obtained from MIKE SHE model for the end of this century indicate entirely this change. The runoff regime of rivers in Vu Gia Thu Bon system is not completely similar due to the complication of topography as well as the difference in spatial distribution of meteorological factors. In addition, the climate factors in the future is projected to vary differently at each sub catchment in this system. These drivers to different variability tendencies in stream flow in different branches and at different locations. In order to express more clearly these tendencies, in this study, the stream flow at different locations on two main rivers as well as at the outlet of large tributaries are compared (Table 5.2).

Table 5.2. Compared catchment area corresponding with Figure 5.6.

Location	River	Catchment area (Km^2)
Thanh My station	Vu Gia	1,850
Hoi Khanh station	Vu Gia	4,494
Ai Nghia station	Vu Gia	5,380
Con branch outlet	Vu Gia	640
Bung branch outlet	Vu Gia	2,420
A Vuong branch outlet	Vu Gia	762
Thanh branch outlet	Vu Gia	471
Tuy Loan branch outlet	Vu Gia	277
Hiep Duc station	Thu Bon	2,570
Nong Son station	Thu Bon	3,155
Giao Thuy station	Thu Bon	3,825
Bong Mieu branch outlet	Thu Bon	555

5.3.2 Change in flood flow

The variation of flood flow in Vu Gia Thu Bon river system is presented via the variation of flow measuring at locations in Table 5.2. According to hydrographs at these stations (Figure 5.7), it is easy to realize the considerable changes on the flow in wet season. The increase is at all months in rainy season. This tendency is similar to the conclusion of Bergstrom, et al (2001) that changes in extreme values of runoff can be more critical than mean value. This result is the consequence of precipitation rise which concentrates essentially in rainfall season (Figure 5.5). The water loss by evapotranspiration in the future is predicted to increase (Figure 5.5).

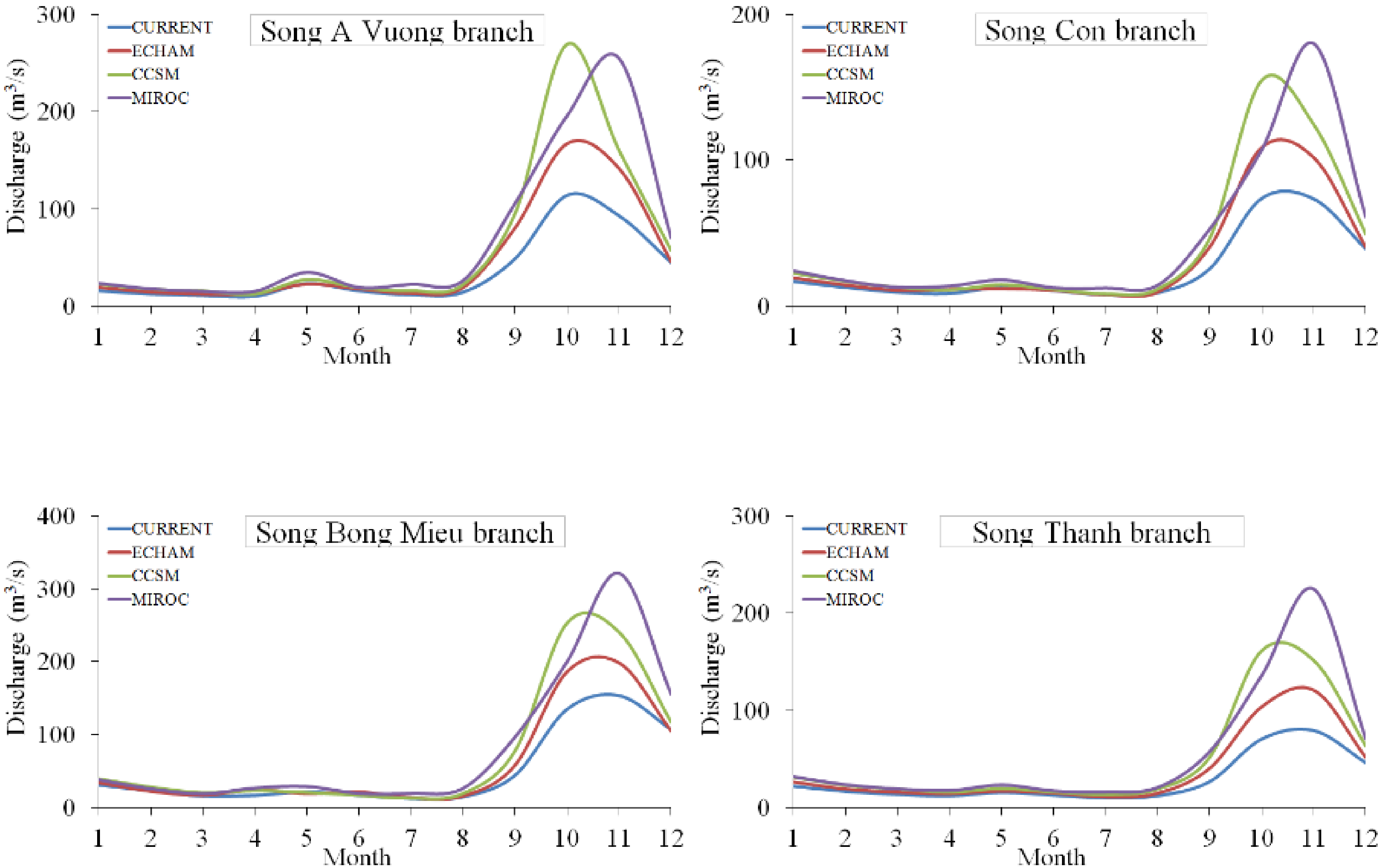


Figure 5.7a. Baseline and future stream flows at Vu Gia Thu Bon catchment.

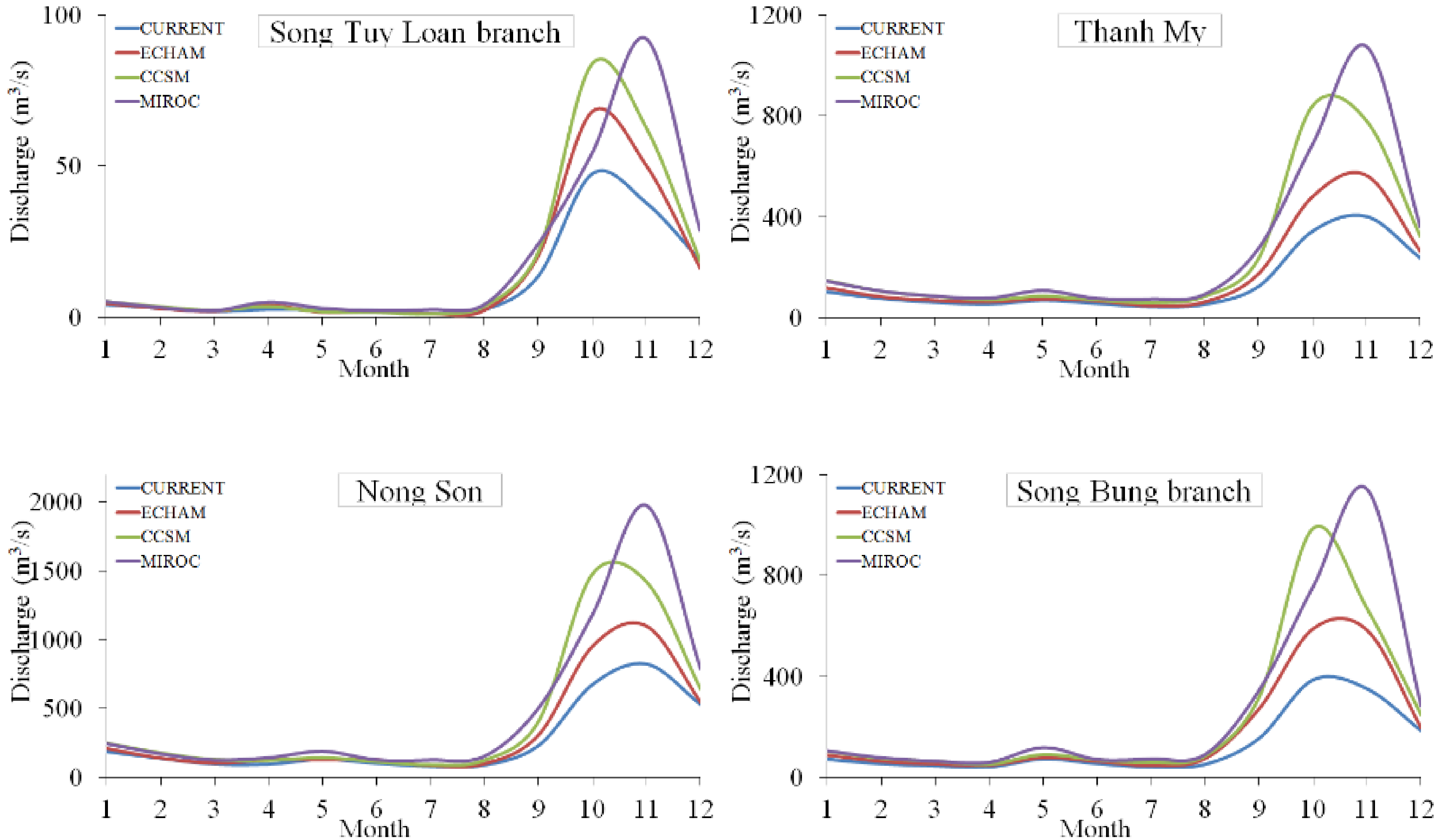


Figure 5.7b. Baseline and future stream flows at Vu Gia Thu Bon catchment.

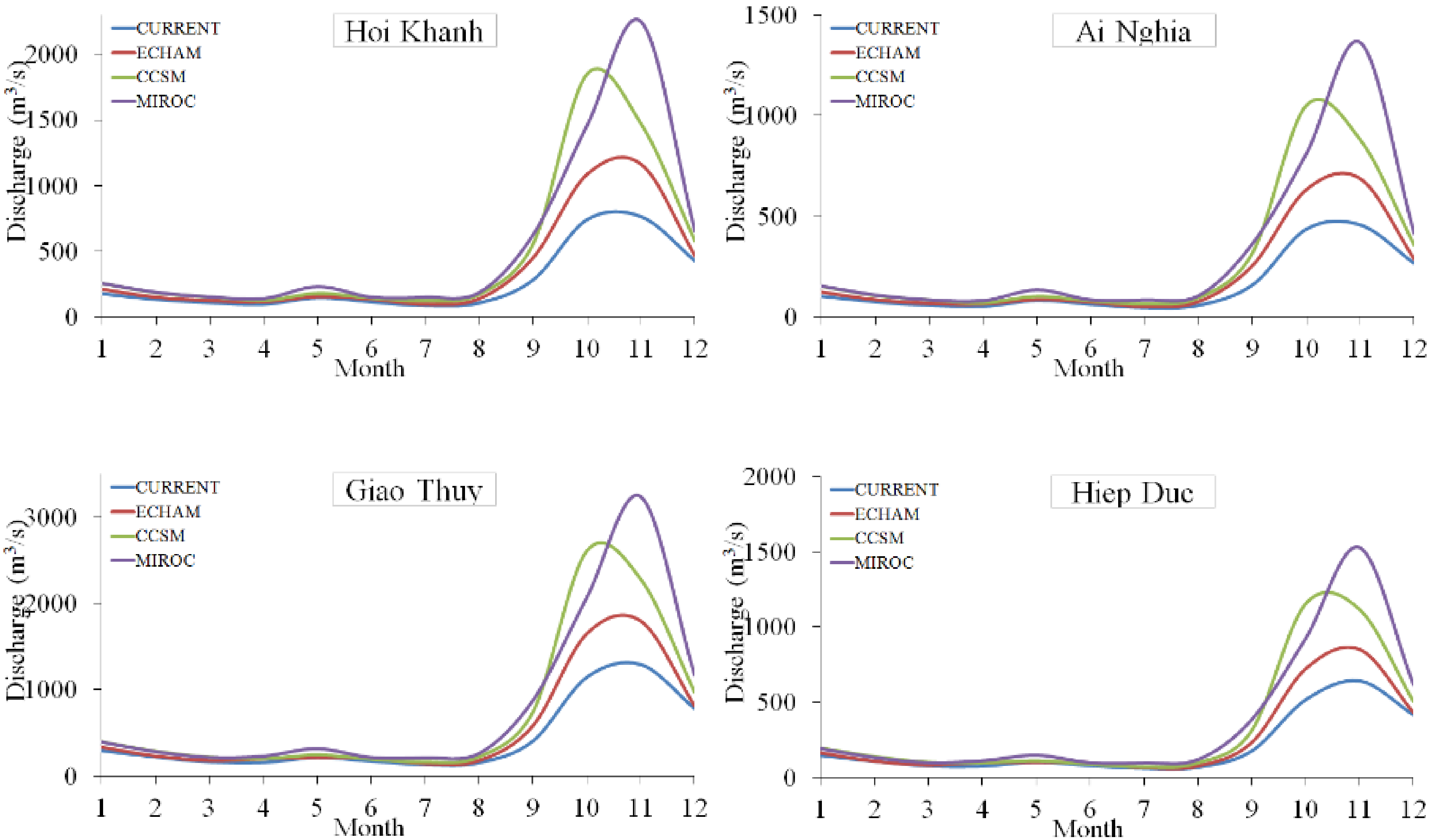


Figure 5.7c. Baseline and future stream flows at Vu Gia Thu Bon catchment.

However, the rate is smaller than rainfall and the increase of evapotranspiration also mainly occurs in dry season, so it seems that these factors do not virtually affect/have an effect on the peak flow. Those results show that in the end of 21st century flood, discharge will highly go up. The increase happens at all compared locations, from upstream to downstream, main river to tributary. This tendency is the same at all three climate scenarios. Nevertheless, monthly discharge could reach 1,076 m^3/s against the baseline 401 m^3/s at Thanh My (in November) and at Nong Son 1,976 m^3/s compared with baseline 823 m^3/s. The increase is equivalent with the rate 168 % and 140 % at Thanh My and Nong Son, respectively. At downstream, the rise might be more extreme when the flow at Ai Nghia station could reach 1364 m^3/s against with currently 457 m^3/s, the rate is approximately 200%. At Giao Thuy station, these numbers are respectively with 3238 m^3/s in future and 1,293 m^3/s in actual, the change is 151 %. The CCSM scenario also gives increasing trends. However, this trend is not as high as MIROC scenario. The maximum variation of CCSM scenario at Thanh My is only 145%, at NongSon is 119%. Whilst ECHAM scenario gives the smallest change. The maximum different percentage between the future and the baseline of this scenario is only 76% at Song Bung tributary. This difference indicates that MIROC scenario has a more extreme tendency than others. Across the variation in Figure 5.8, 5.9 one more thing is easy to recognize that the variation is unequal between locations. The trend is likely to be higher in sub catchments of Vu Gia river than the ones of Thu Bon river. The largest change could reach 225% at Song Bung branch of Vu Gia while this number is only 150% at Giao Thuy station in downstream of Thu Bon river. This inequality reveals clearly that there exists a huge difference in the variation of meteorological factors between locations in the future under the impact of climate change. Hence, estimating the variation of natural phenomenon in future needs to realize on many positions, at least with the large catchments. Moreover, the difference also helps to add more evidence to confirm the insight of previous studies that it is necessary to construct a climate model with output resolution as higher as possible or to downscale from coarse climate data to fine data corresponding with small sub catchment. (New, 2002; Hijmans, 2005)

Based on hydrographs in Figure 5.7, it is easy to recognize that the change is not only on the magnitude, but also on the time. According to that, the flow in the future obtained via MIROC output data is likely to greatly augment on November. In other months of wet season, it also increases, but not as high. There have been a similar trend on the results of ECHAM and MIROC scenarios. The results from ECHAM scenario have the similar trend with MIROC. Because of the smaller quantitative change, the shape of ECHAM looks slightly like the hydrographs in MIROC. The variation in ECHAM is quasi equal through the months of wet season. Conversely, CCSM scenario brings the increase in long time, almost at the whole season. The peak discharge in the period 2091-2100 probably shifts from November to October, earlier around one month. The change in CCSM scenario is not very extremely like results of MIROC, but it is higher than ECHAM and pretty equal over season. Analyzing the change in the time of appearance is helpful for strategist as well as local authority to prepare plans to response to these changes. Because the damage caused by flood disaster depends on both, the time and intensity of inundation, this uncertainty helps to get a global point of view to suggest the most reasonable and safe prevention against the future flood catastrophes.

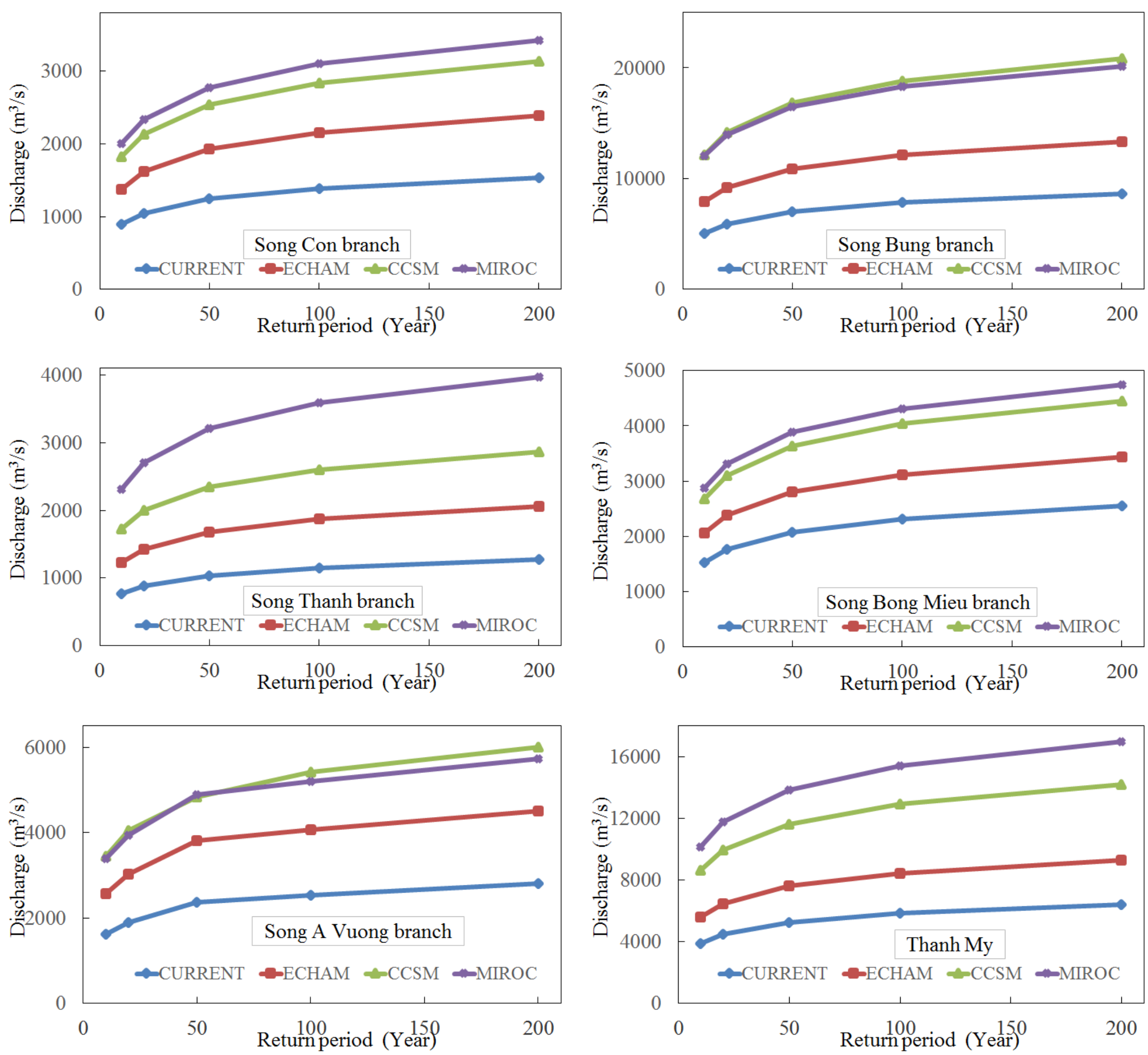


Figure 5.8a. Change in frequency of flood flow between period 1991- 2000 and 2091 and 2100.

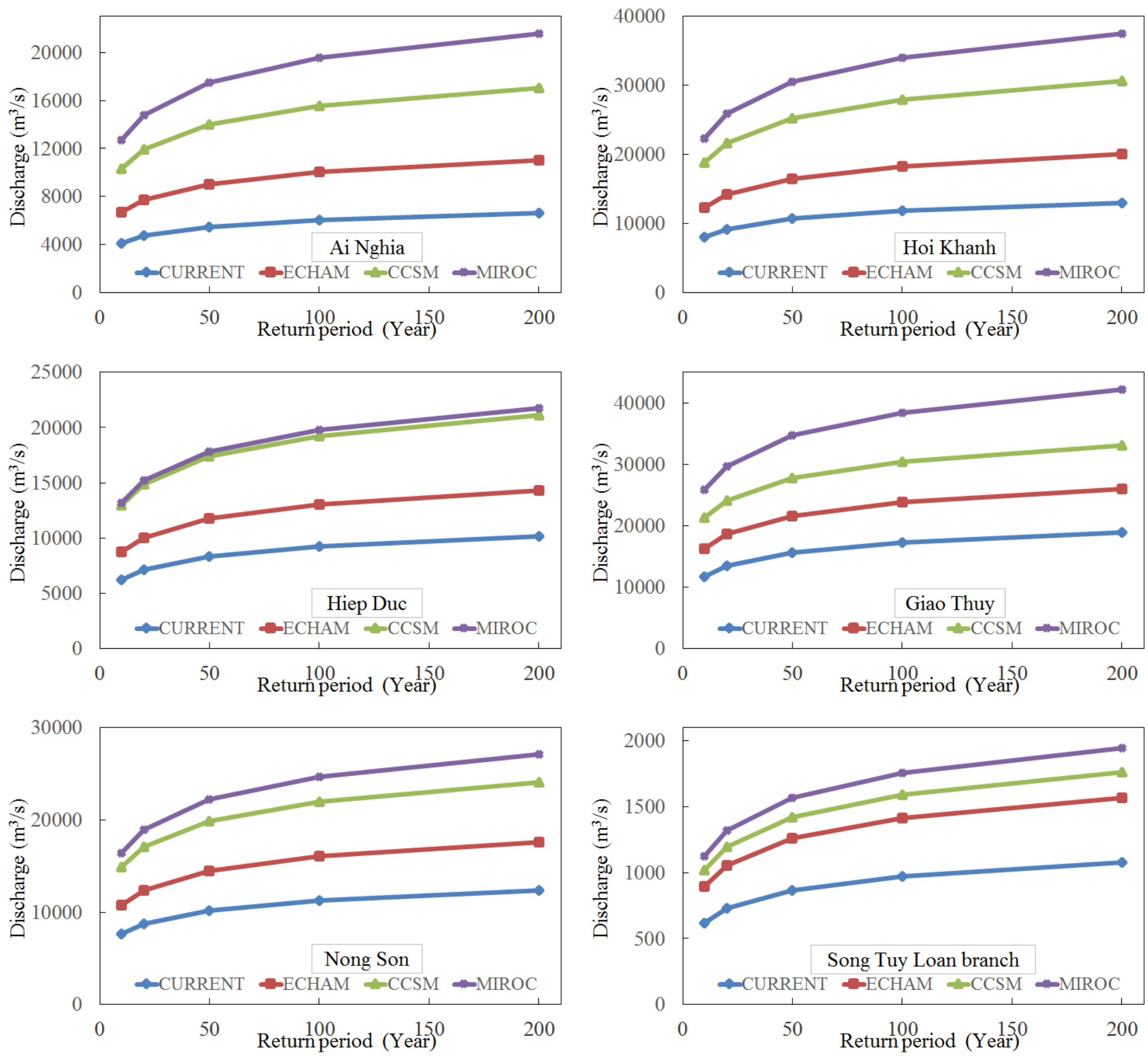


Figure 5.8b. Change in frequency of flood flow between period 1991- 2000 and 2091 and 2100.

In other to assess more accurately the frequency of flood flow, the analysis normally based on a data time series longer than 30 years (Bergstrom *et al.*, 2001; MeteoFrance, 2014). But this condition is not easy to obtain not only on observed data but also on simulated result, such as this study. The “méthode du renouvelement” is a new issue what is generated by EDF group to solve the weakness when estimating the frequency for a short data time series (MeteoFrance, 2014) This method is developed by combining the Gumbel law and Exponential law to estimate the extreme flood value. It permits to evaluate the exceptional flood event for the case having less than ten years of data. In this study, the méthode du renouvelement is utilized under the support of Hydrolab 2010 to analyze flood frequency in the future and baseline scenario. The change of frequency in Figure 5.8 indicates the violence of flood event in the end of this century. Average change magnitude of discharge corresponding to return period 100 years is from 50% to 150%, respectively with ECHAM and MIROC. The extreme change in magnitude of flood flow figure out the violence of natural catastrophe concerned on the inundation of VuGia Thu Bon catchment. In particular, the rate is huger at mountainous area, the change at several locations reaching to more 200%. It conducts to the flash flood event could happen more frequently and terribly.

5.3.3 Change in low flow

The drought and salinity situations occur essentially complicated in this region. Especially, with the pressure of high speed in social economic development and population increase, water requirement in dry season becomes more urgent. Currently, there have been several conflicts between localities concerning on this problem. So that it is necessary to estimate the runoff in dry season for the end of 21st century for this area. Fortunately, the results of this study present that under the change of climate. In comparison of low flow frequency showing in the Figure 5.9, the low flow demonstrates the increasing trend over the catchment. Even if the big increase of temperature as well as the evapotranspiration, the low flow in Vu Gia Thu Bon river system will almost increase with MIROC scenario. This is presented in Figure 5.9, 5.10. According to that, all of 8 months of dry season, the run off on both main rivers is predicted to highly rise. The variation is about from 20% to 100 % with all MIROC scenarios. It leads to the mean flow in this period changing from 64 m^3/s (baseline) to 94m^3/s (MIROC) at Thanh My station, from 66 m^3/s (baseline) to 104 m^3/s (MIROC) at Ai Nghia station and from 114 m^3/s (baseline) to 159 m^3/s (MIROC) at Nong Son station, from 188 m^3/s (baseline) to 256 m^3/s (MIROC) at Giao Thuy station. This augmentation might help to reduce the pressure for water supply, irrigation, and mitigate the salinity. In contrast, the predictions with CCSM and ECHAM scenarios are not completely advantage as MIROC scenario. In these two scenarios, the increasing trend appears at a lot of locations but the variation is not very big. Conversely, the stream flow is to reduce at some locations. The reduction likely concentrates on the months of May and June. These are commonly estimated like the most severe period of dry season. Following to the projection of CCSM and ECHAM scenarios, several areas of this catchment will face big drought risks. These risks are more serious in regions of Thu Bon river when the base flow at 3 stations of this river is on May with ECHAM scenario. The decreases approximately 1.5% at Hiep Duc, 2.8% at Nong Son and 0.4% at Giao Thuy demonstrate this tendency. The water deficit could also occur at the downstream of Vu

Gia river when the run off in May go down deeply at branches in the north such as, Song Con branch, Song Tuy Loan branch with an amount from 7% to 30%.

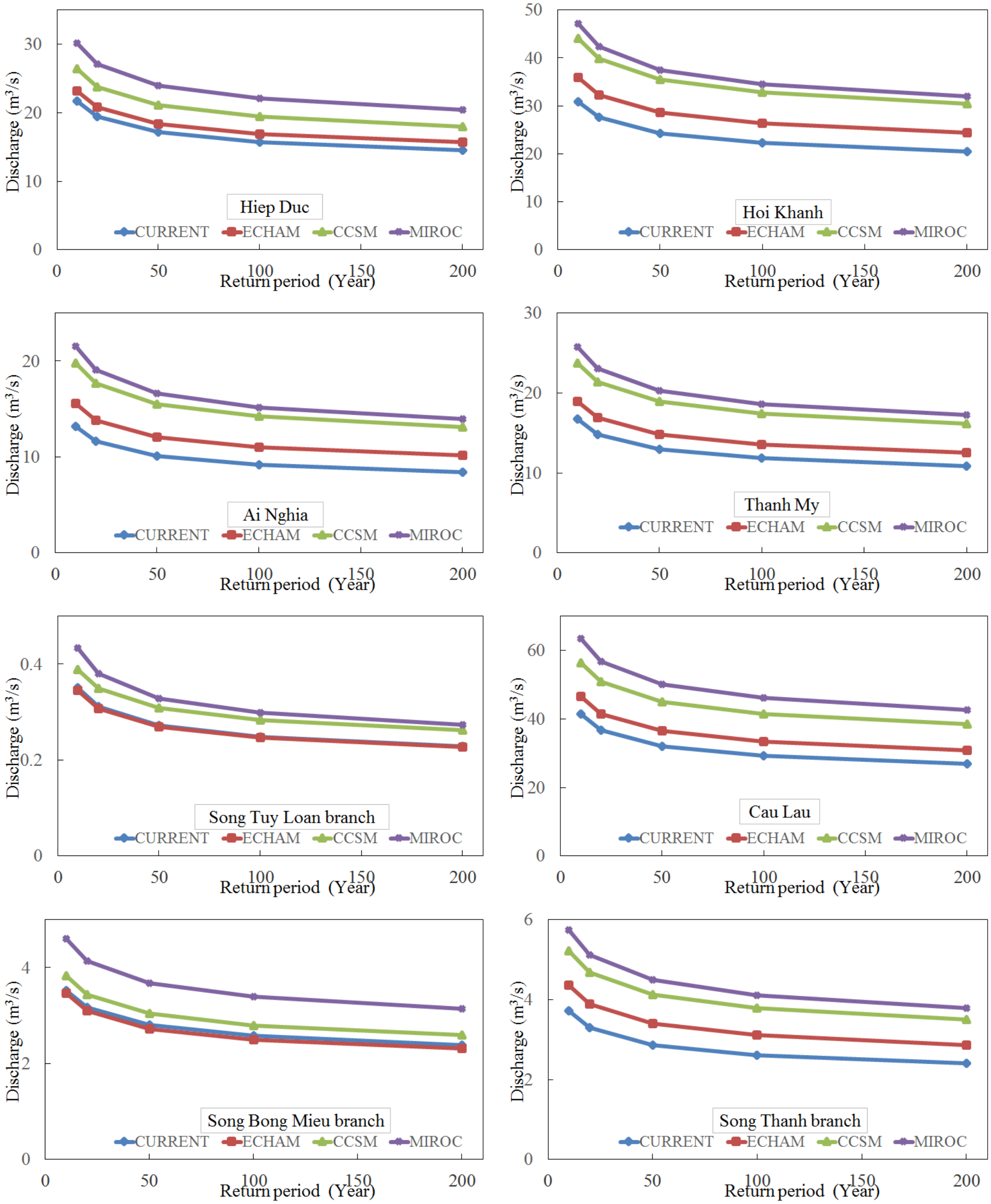


Figure 5.9a. Change in frequency of low flow between period 1991- 2000 and 2091 and 2100.

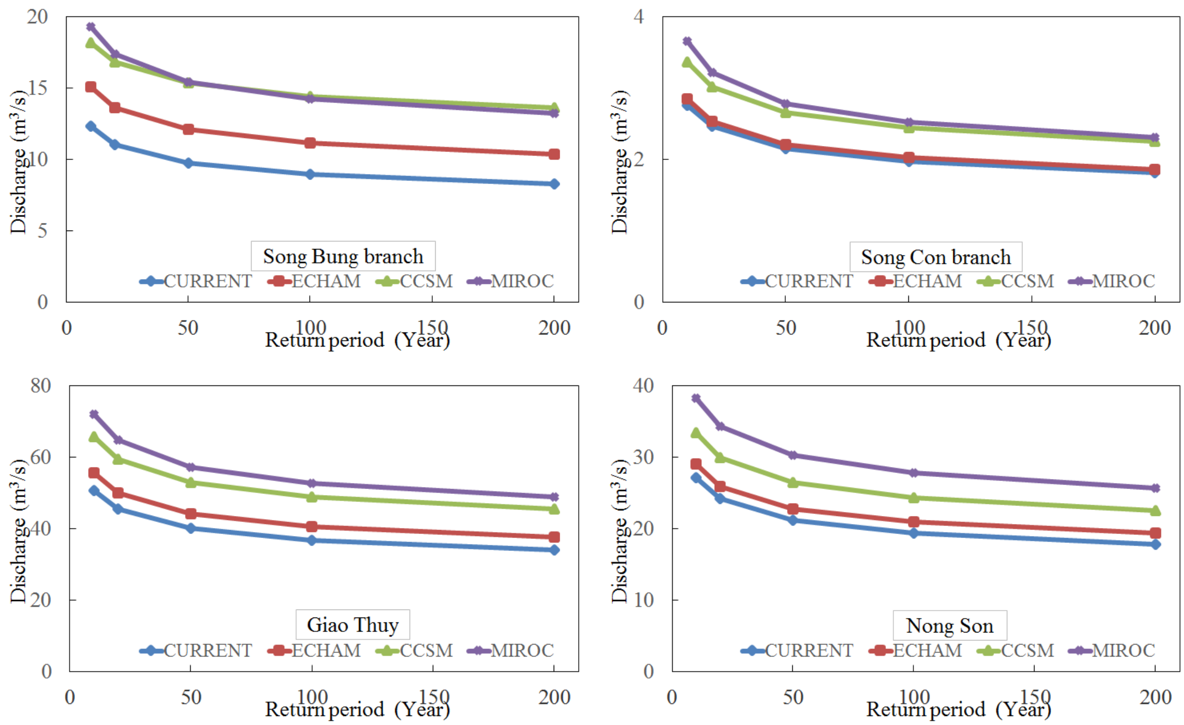


Figure 5.9b. Change in frequency of low flow between period 1991- 2000 and 2091 and 2100.

5.3.4 Hydrological shift

The variation of temporal factors in studying climate change is important. In fact, the movement of climate factors and runoff factors will have big influences on the decision to choose the harvest schedule, the types of cultivated crops, product plan and people activities. Vu Gia Thu Bon catchment is a large rice production with two main crops, Winter-Spring crop and Summer-Autumn crop, those crop seasons happen annually during period December to April and May to October (Nay-Htoon *et al.*, 2013). Unfortunately, the results of this study demonstrate that both of these main crop seasons will be impacted by earlier movement of runoff factors. Although, the earlier appearance tendency is not the same among 3 scenarios. Moreover, it describes a potentiality in the future. Figure 5.7, 5.9 show that the flood and dry seasons in the end of 21st century will come earlier than present. Lastly, the earlier movement of the seasons might bring negative impacts on harvest quantity, and product quality of this region.

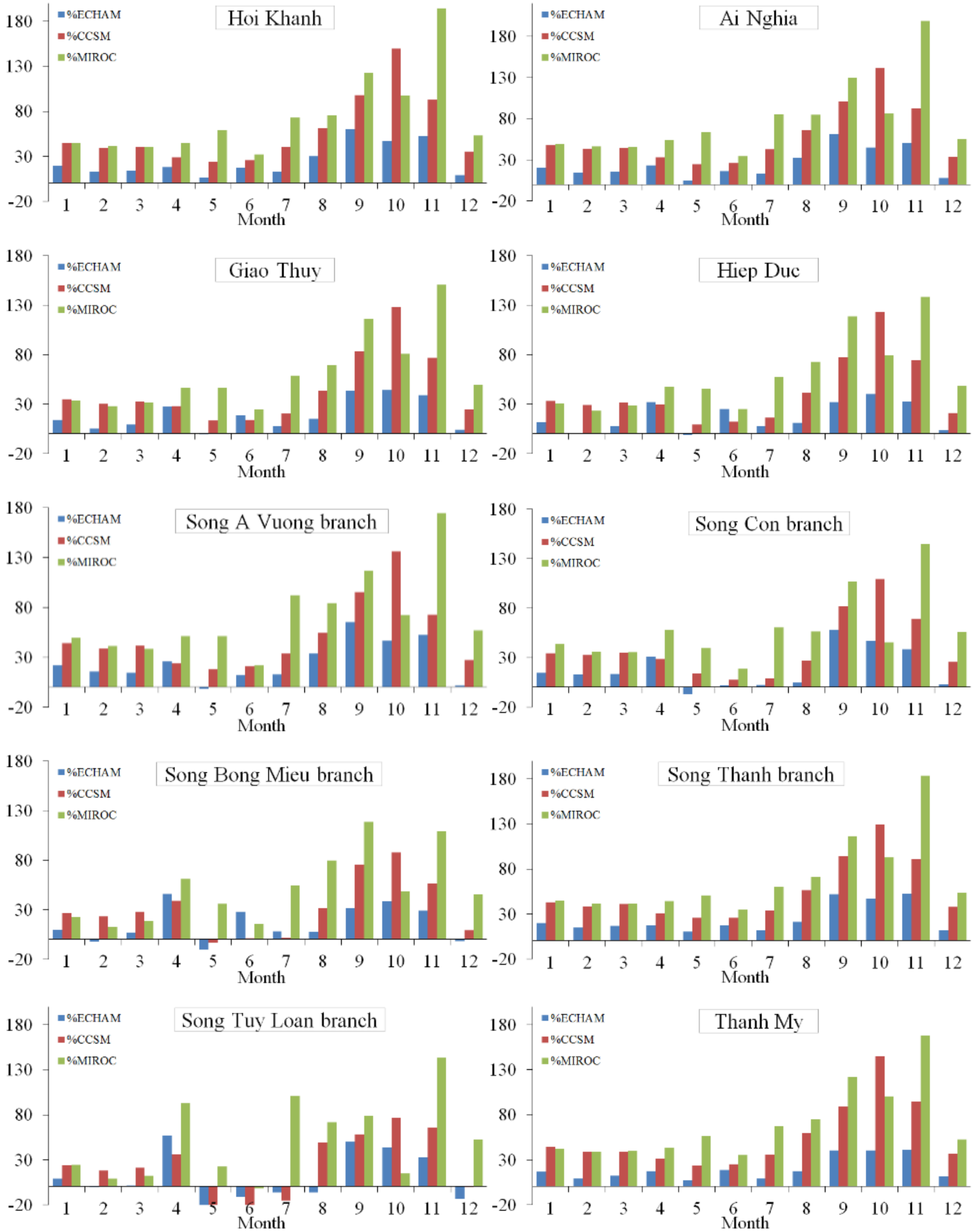


Figure 5.10a. Percentages of future monthly stream flow in comparing with present.

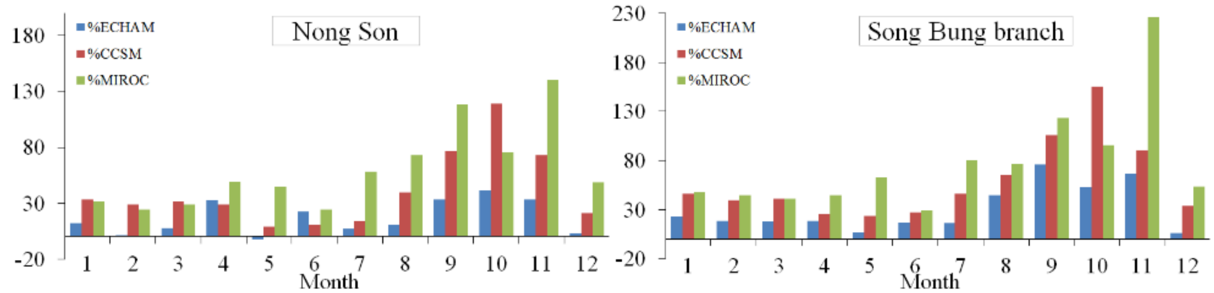


Figure 5.10b. Percentages of future monthly stream flow in comparing with present.

5.3.5 Uncertainties

The uncertainties in estimating the impact of climate change on run off have been mentioned in previous studies. Source of these uncertainties might be from the uncertainty of hydrological model, downscaling process, climate model or greenhouse gas emission scenario (Bastola *et al.*, 2011; Minville, Brissette, & Leconte, 2008; Prudhomme *et al*., 2003; Taye & Willems, 2013). Until now, there have not been yet a clear solution for solving absolutely this problem rather than realizing a lot of simulations with many scenarios to reduce a part of uncertainty. In studying the response of river run off in Vu Gia Thu Bon catchment facing the global warming, the uncertainty is considered under the following aspects:

- Hydrological model:

In spite of trying to reflect the most truthfully what happens in hydrological cycle in the catchment, this MIKE SHE model has not yet gained the optimal result when there are still lots of inaccuracies. The statistical coefficients such as Nash Sutcliffe, correlation coefficient, RMSE are still weak. Because of many reasons, these indicators could not get maximum values. Hence, this model has many potential uncertainties to simulate the hydrological process. Uncertainty in hydrologic modelling may arise from several sources: model structure, parameters, initial conditions, and observational data used to drive and evaluate the model (Liu & Gupta, 2007).

One of the most important factors of model structure, might influence significantly the accuracy of model as well as the uncertainty of simulation, is cell size issue (Egüen *et al.*, 2012). The advance of this distributed hydrological model is able to represent hydrological characteristic of catchment cell by cell. However, in fact, the resolution using in this model is still coarse due to the limitation of data and computation time. 90 m topography data using may not describe precisely the surface of the catchment. Thus, it derives some differences of surface flow between reality and model. The land use, soil property or roughness coefficients, which are simplified so much to serve the calibration purpose, are the main causes of underestimation or overestimation of this model. Another issue influencing significantly the model uncertainty is the rainfall which is a key factor in hydrologic process. Rainfall spatial variation affects heavily both runoff generation and hydrologic processes in a catchment (Moon *et al.,* 2004). The spatial variability in rainfall may introduce a significant uncertainty in model parameter during the calibration process (Chaubey *et al*., 1999). While the quality of spatial rainfall distribution usually depends on the characteristic of study area and other factors, in particular, the rain gauge density. Therefore, the network of rain gauge stations in Vu Gia Thu Bon is sparse, averagely one station observes for a large area 700 km^2. In this model, the rainfall input even if already re-interpolated, it is considered as a great source of uncertainty. The ground water is an un-ignorable component when simulating hydrological process (Winter, 1999).

In term of input data, the insufficiency of ground water data is seen as a major source of uncertainty for simulating hydrological process. Nevertheless, the quality of ground water data of Vu Gia Thu Bon catchment is not very good. The collected data do not present concretely the ground water property. For the whole catchment, the simulation has just one geological layer. Regarding to the method solving process in MIKE SHE, selecting the method for modelling components of model likewise adds several sources to uncertainty, when with one factor we can choose many methods to simulate. For example, there are three functions to select for unsaturated flow such as Richards equation, Gravity flow, 2 layer UZ. The Richards equation is estimated to be the best method for simulating unsaturated flow but for this study, the 2 layer UZ is chosen by the simple and short processing time. So, it is no surprising to say that the solved algorithm for a model component has a particular impact with model accuracy.

The coupling between MIKE SHE/MIKE 11 additionally contains potential uncertainties. It could affect notably water exchanging between flood plain and river beds. The number of simulating branches and solved intervals in MIKE 11 is considered as a primary uncertainty source. In this model, the coupling between MIKE SHE/MIKE 11 is not set well. This is a result of cross section restricted quantity. Furthermore, there is a difference between overland and river flows, but in this study, the river network presented in MIKE 11 is merely over at 44 branches. Understandably, the set up manner the coupling between MIKE SHE/MIKE 11 is estimated holding a big uncertainty. One more thing affecting to the quality of hydrologic model in reproducing hydrological process belongs to the time factors. Time step applying in this MIKE SHE model is one day. This time step is still high so it might not present thoroughly what happen in hydrological cycle of a catchment. Besides, the timescale of model is only 10 years. The simulation time is seen to be not sufficient to bring adequately extreme events from natural phenomenon to model. Unavoidably, simulating the stream flow at Vu Gia Thu Bon catchment will contain particular uncertainties.

- Downscale method:

Downscaling is definitely indispensable. Nevertheless, the issues related to this process are admitted to be similar to the leading causes of uncertainty in estimating the climate change. Firstly, the difference between statistical and dynamic methods already has showed fatal evidences for this problem. Secondly, the size of climate data output is debatable factor for the inaccuracy of the projected scenarios. The technical complication and the limitation of computed capacity limit the output resolution. Moreover, climate data applied in this project is downscaled to 30 km. As this figure, it is still big in comparison with a catchment having the wide around of 100 km like Vu Gia Thu Bon, this data could not express perfectly the variation of climate factor in this catchment.

- Climate scenario:

The climate scenario is constituted from projection based on actual data. Thus, not surprisingly, these are estimated to be the biggest source of uncertainty. In this study, the uncertainty related on this issue is presented quite clearly. Using 3 scenarios ECHAM, CCSM, MIROC, even so the variation tendency among these ones is very different. The analysis in Part 5 shows that the difference is not only about the magnitude, but also about the happening time. The negative change of run off, such as base flow decrease or flood flow increase, influences significantly natural system and local society. However, determining an accurate simulation for the future seems not to be available until now so the definition of variation amplitude of run off seems to be an acceptable solution in evaluating the climate change.

This study also has been realized on an assumption that there is no change on catchment characteristic in the end of 21st century. This assumption helps to reduce the complexity of simulation. But, in reality, it is not absolutely correct. In fact, to increase the accuracy of a climate change impact assessment, the change of land use, soil map, river networks, and harvest structures is needed to take into account.

5.4 Scale variability of inundation area

5.4.1 Methodology

The variation in river flow corresponding with climate change scenarios in the section 5.3 are abstracted and input in turn into validated MIKE FLOOD model. Results from the model are expected to show scale variability of inundation area at flood prone area at the downstream of Vu Gia Thu Bon river system.

5.4.2 Role of sea level increasing

Sea level rising due to global warming is thought to accelerate seriously in the end of 21st century. This increase will promote land loss, increasing flooding and salinization (Nicholls & Mimura, 1998). According to Fourth Assessment Report (AR4), the average sea level in period of 2080-2099 might be higher than the period of 1980-1999 from 0.18 – 0.59 m depending on the scenario. This change is projected to affect many millions more people on over the world, especially in coastal area (R K Pachauri & Reisinger, 2007). Viet Nam, with more than 3,000 km of the coast, is expected to be affected severely by sea lever rising. The report of government predicts that, the averaged sea level of Viet Nam in the last year of 21st century will be higher than present from 0.49 to 1.05m. They lead to the serious flooding overall nation, at least in coastal delta. In order to estimate the inundated variation due to sea level rising for Vu Gia Thu Bon coastal area, this part will show a comparison between two flooding simulations which take into account the effect of sea level and another doesn't.

Table 5.3. Peak water level of MIROC scenario with or without the effect of sea level rising.

Station	No sea level change	IPCC AR4 95%
Ai Nghia	14.616	14.627
Giao Thuy	14.395	14.427
Cau Lau	8.756	8.758

The comparison is realized based on MIKE FLOOD model. The sea level change is the highest scenario from IPCC AR4 for this area (IPCC AR4 95%) which projects the regional future sea level might higher 0.552 m in comparison with present.

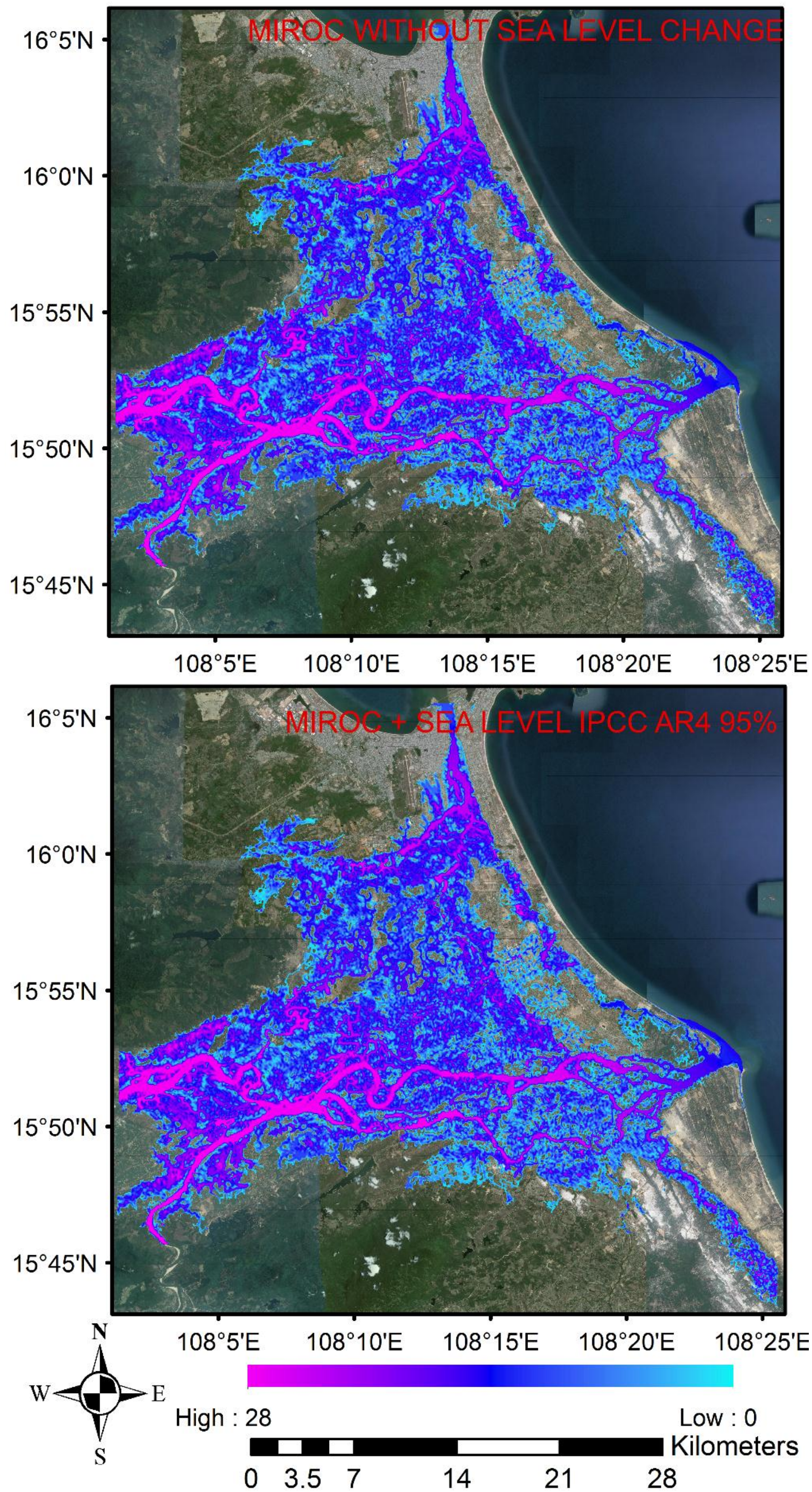


Figure 5.11. The effect of sea level rising on scale variability of inundation area (MIROC scenario)

Table 5.4. Difference of inundation area due to the effect of sea level rising.

Flood depth (m)	< 0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	Total>0.5
MIROC + No sea level change	2,849.9	3,194.6	7,170.3	17,423.2	15,961.6	2,114.2	45,863.9
MIROC + IPCC AR4 95%	2,847.5	3,192.8	7,173.5	17,356.1	16,107.6	2,116.2	45,946.3

The Figure 5.11 demonstrates the impact of sea level change to the flood area at the downstream part of Vu Gia Thu Bon Catchment. Relying to the results of two simulations in the end of 21st centuary (MIROC scenario), which take into account the variation of sea level or not, we recognize that the sea level change affects not so much the flooding increase in future at Vu Gia Thu Bon Catchment. Although, accounting the 0.552 m of absolute sea level rising, the peak of water level seemly does not change (Table 5.3). The area of potentially deep flooding (>0.5m) in consideration of the sea level rise just increases 0.26% as compared to the one without sea level change (Table 5.4). If comparising with area of flooding higher than 2m, the difference is merely 0.36%. The insignificant effect of sea level change to flooding area at the downstream of Vu Gia Thu Bon catchment might be explained by the topography characteristic. The topography over this region is relatively narrow mountainous area on the upstream and the flat coastal zone at the downstream. The flood prone area has average altitude which is higher than the sea level, even if in future scenario. These comparisons prouve that the inundation of Vu Gia Thu Bon is primarily from river flow and this judgement is mostly similar in the future. The tendency looks like the same to the prediction of Viet Nam government (Monre, 2012) due to steep topography, It is predicted that VietNam central would not be influenced significantly by the increase of sea level due to the sea level rise of 1m, only 2.5% area will be inundated.

5.4.3 Future Inundation

The increase of flood flow demonstrated at the part of 5.3 certainly implies the enlargement of flood plain. The difference between the future and today show via the change of water level at downstream and the change of inundation area. The comparison is realized on the simulated result of the extreme flood event in November 1999 and its projecting scenarios in 2099 corresponding with CCSM, ECHAM, MIROC scenarios. The second comparison is on the 100 year return period flood event in the future and present.

The peak water level variation is expressed via the number at Table 5.5 corresponding to the real flood event, and Table 5.8 is used to describe for the flood event of 100 year return period. Scale variability of inundation area under the impact of climate change at the downstream area of Vu Gia Thu Bon is explicitly showed at Figure 5.11, Figure 5.12a respectively and the figures in Table 5.6, 5.9 demonstrate the serious increase of flood area at Vu Gia Thu Bon downstream region under the impact of flood flow increase due to global warming.

Table 5.5. Peak water level comparison between future and baseline scenario (m).

Station	1999	ECHAM	CCSM	MIROC
Ai Nghia	11.773	12.94	13.61	14.616
Giao Thuy	10.967	12.433	13.326	14.935
Cau Lau	6.117	7.218	7.974	8.756

Table 5.6. Scale variability of inundation area due to climate scenario in the case of 1999 flood event base line scenario. (hectare)

Area (ha)	< 0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	total>0.5
1999	4,124.43	3,911.13	5,910.75	6,534.45	2,548.80	31.86	18,936.99
CCSM	3,679.38	4,179.96	8,898.84	13,518.45	7,083.63	617.76	34,298.64
ECHAM	3,839.22	4,198.50	7,986.78	10,207.26	5,080.95	232.56	27,706.05
MIROC	2,846.25	3,190.41	7,161.84	17,264.70	15,932.43	2114.37	45,663.75

Table 5.7. Percentage change of future inundation area in comparison with 1999 flood event (Percent)

	< 0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	total>0.5
CCSM	-10.79	6.87	50.55	106.88	177.92	1838.98	81.12
ECHAM	-6.92	7.35	35.12	56.21	99.35	629.94	46.31
MIROC	-30.99	-18.43	21.17	164.21	525.1	6536.44	141.14

The maps and numbers describe the serious impact of climate change to this area. It is predicted to have an extremely increasing trend of flood disaster in this region. The increase trend of discharge in hydrological model leads to raise almost water level at the downstream. The future water level at several cases can be roughly over 3 m than actual (Table 5.5, Table 5.8).

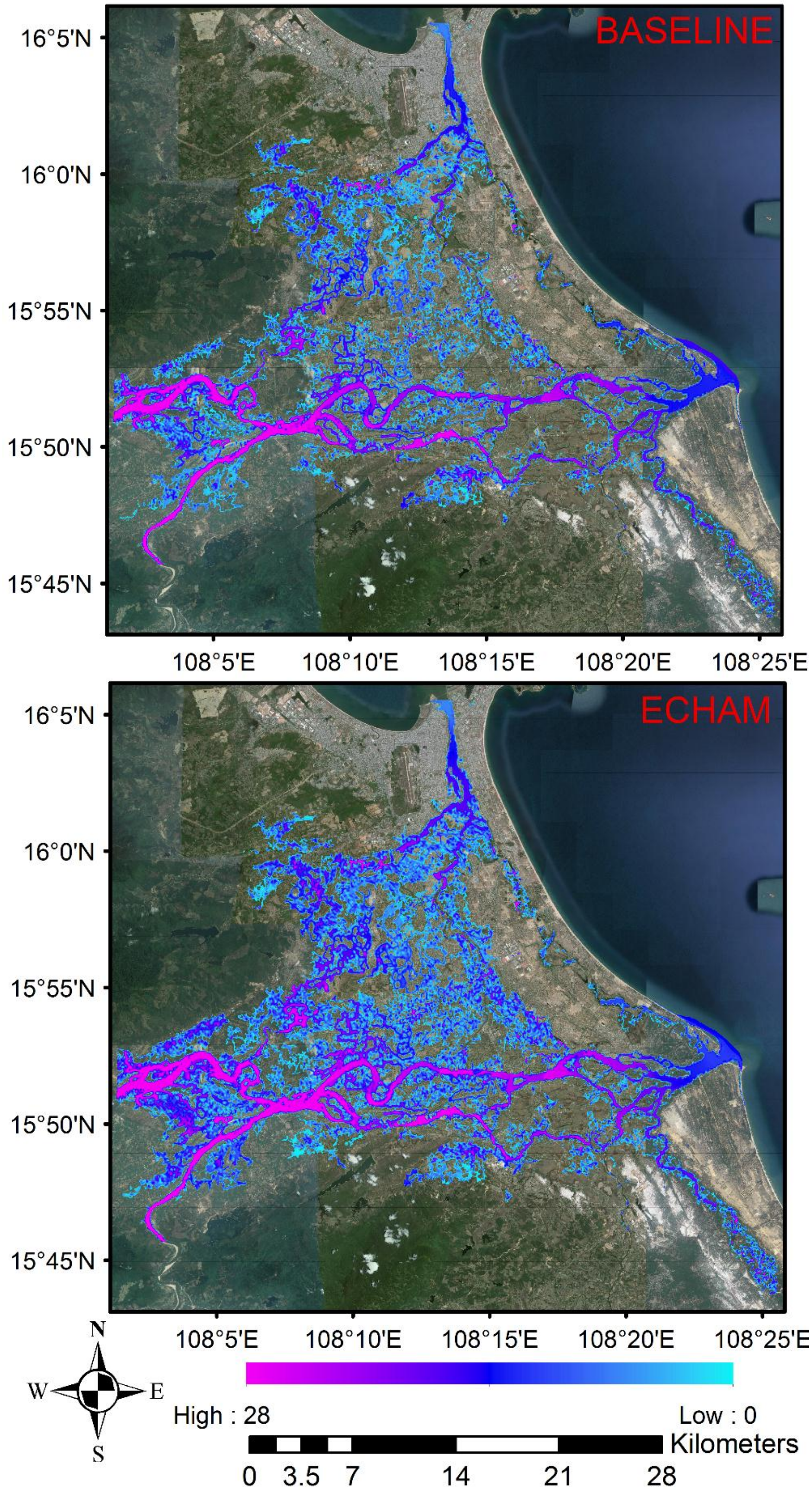


Figure 5.12a. Scale variability of inundation area under the impact of climate change in the case of 1999 flood event base line scenario.

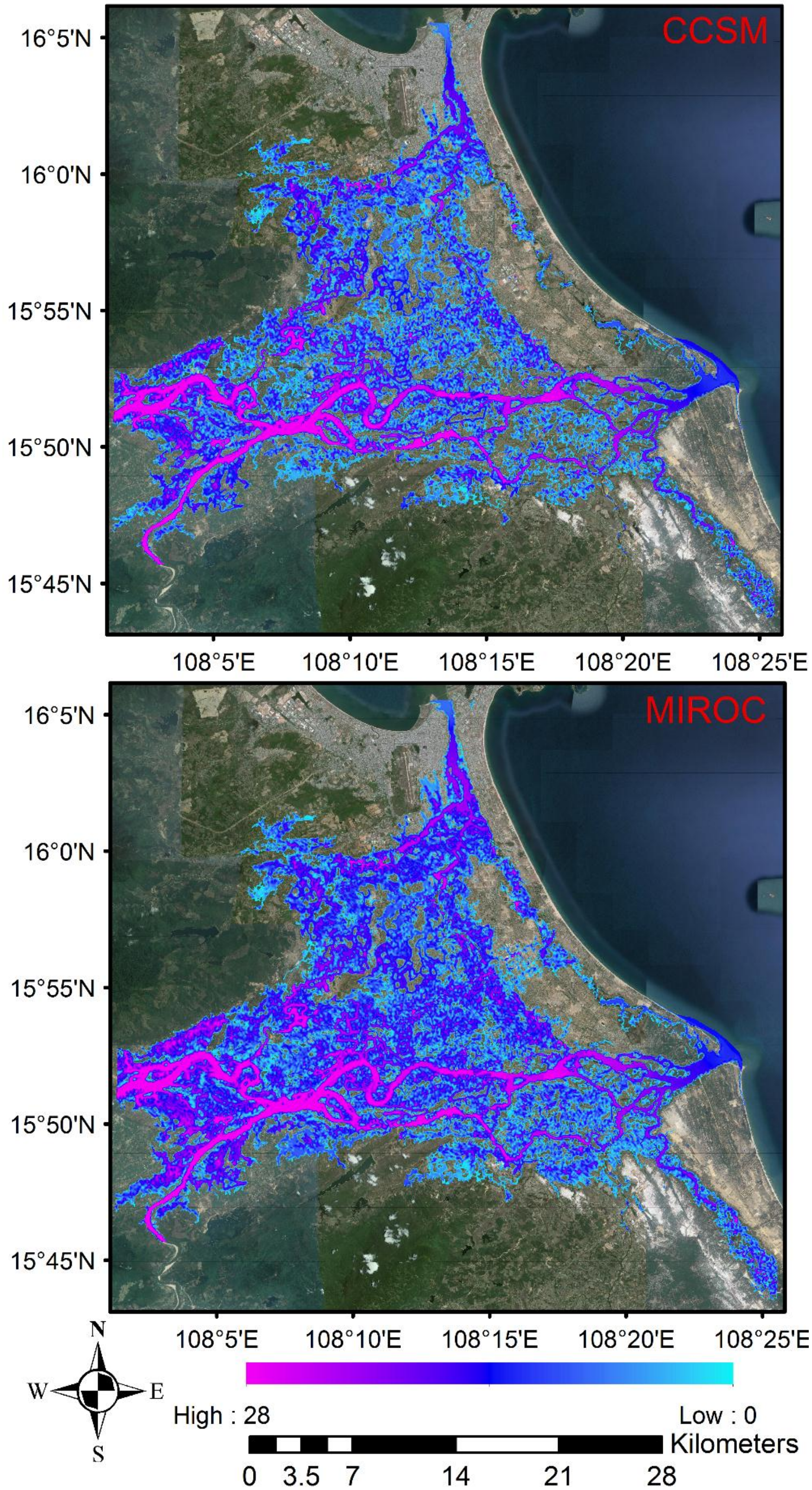


Figure 5.12b. Scale variability of inundation area under the impact of climate change in the case of 1999 flood event base line scenario.

Thus, it is not surprising when the inundation area in the end of 21st augments is greatly in comparison with current ones at Vu Gia Thu Bon catchment. Total inundation area (corresponding flood depth >=0.5m) is minimum 46.31 % higher than 1999 flood event. Especially, the difference is really catastrophic with MIROC scenario when the future inundation area might be 141% higher than the 1999 flood event (Table 5.7).

Table 5.8. Peak water level comparison between future and baseline scenario in the case of 100 years return period (m).

Station	Present	ECHAM	CCSM	MIROC
Ai Nghia	12.364	13.187	14.014	14.95
Giao Thuy	11.945	12.957	13.983	15.188
Cau Lau	6.856	7.65	8.58	9.402

Table 5.9. Scale variability of inundation area due to climate scenario in case of 100 year return periods (hectare)

Area (ha)	< 0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	total>0.5
Present	3,884.85	4,381.2	8,808.3	11,853.36	5,977.44	405.81	31,426.11
CCSM	2,974.32	3,334.68	7,450.2	17,171.82	13,752.36	1,674.54	43,383.6
ECHAM	3,412.26	3,888	8,825.67	14,985.9	8,457.03	907.02	37,063.62
MIROC	2,535.84	2,937.15	6,560.82	16,661.34	20,034.36	3,057.3	49,250.97

Table 5.10. Percentage change of future inundation area in comparison with present in case of 100 year return periods (Percent)

	< 0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	>=8.0	total>0.5
CCSM	-23.44	-23.89	-15.42	44.87	130.07	312.64	38.05
ECHAM	-12.16	-11.26	0.2	26.43	41.48	123.51	17.94
MIROC	-34.72	-32.96	-25.52	40.56	235.17	653.38	56.72

The increasing trend is similar with 100 year return period event (Figure 5.13), however, the variation is not so great with the real scenario (Table 5.10). The maximum difference between future and present is MIROC. The flood area due to 100 year return period of MIROC just increases 56.72%.

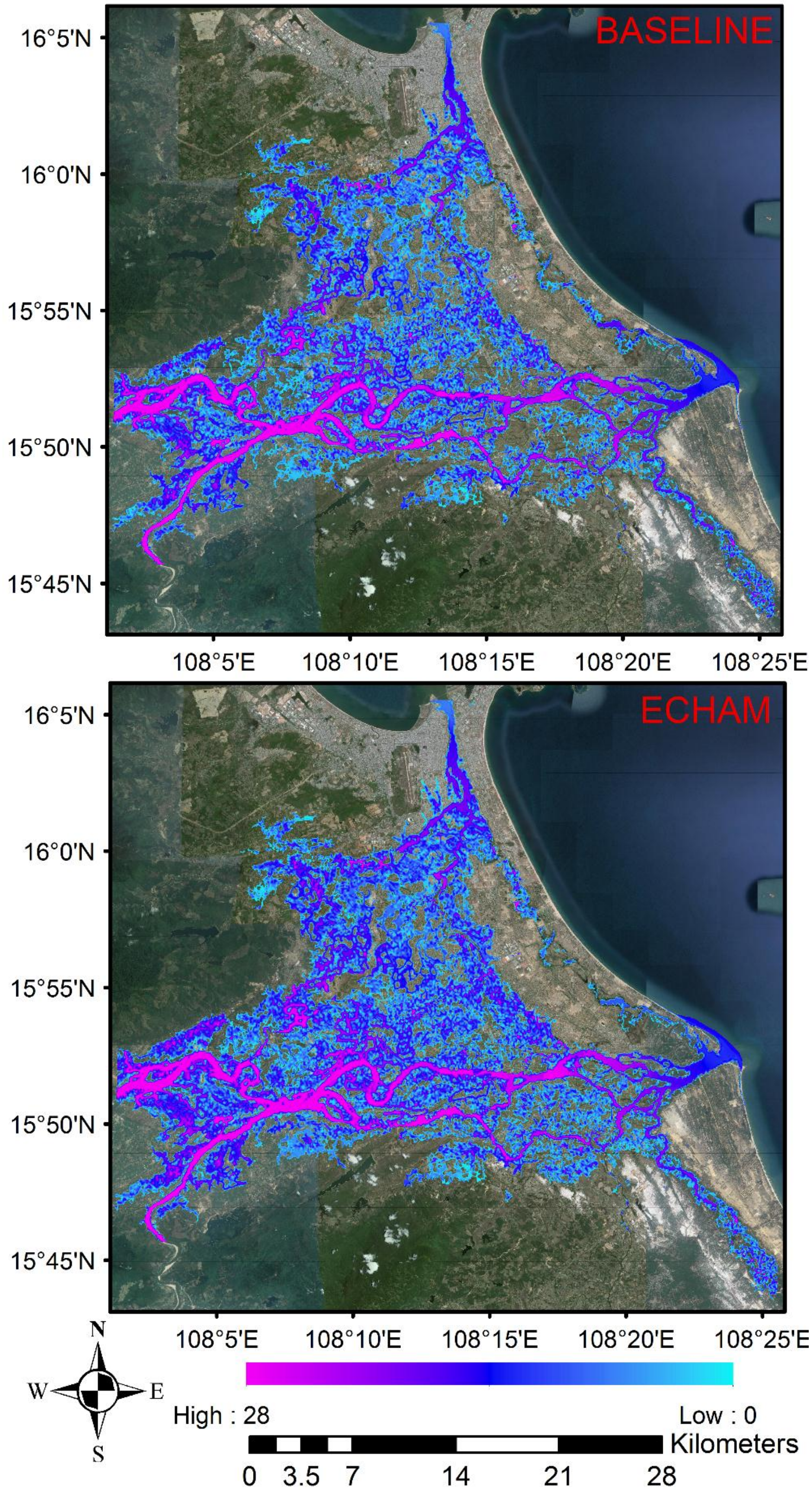


Figure 5.13a. Scale variability of inundation area under the impact of climate change in the case of 100 hundred year return period baseline scenario

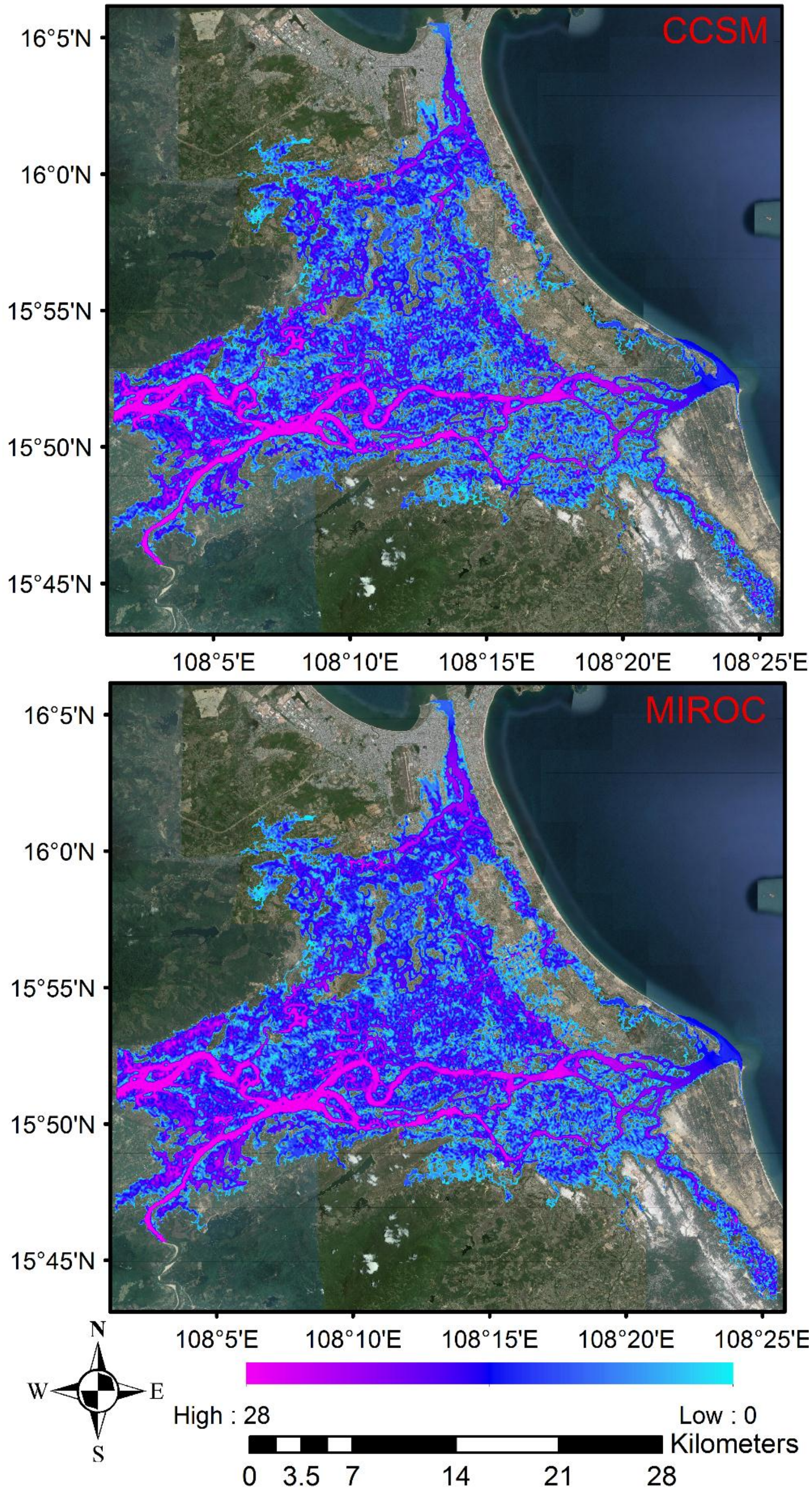


Figure 5.13b. Scale variability of inundation area under the impact of climate change in the case of 100 hundred year return period baseline scenario

More seriously, the heavy inundation area (deeper than 2m) could expand around 70% to 287% in comparison with 1999 flood event. The expansion of flood area in future is projected to make more damages for Vu Gia Thu Bon catchment. When the flood event occurring in 1999 caused catastrophic damages with 118 killed peoples, 159 injured peoples and lost more than 500 million USD of properties. If there is no changes,the damage related to flood catastrophe in future would be multiplied many times than now. Preparing a scenario to well adapt with this disaster is very necessary and urgent for the catchment.

5.4.3 Potential risk

The predicted damage due to flood disaster for the future is seem to be indispensable for mitigating the climate change impact. In this study, the flood hazard and land use map are overlapped together to evaluate the potential risk in Vu Gia Thu Bon catchment (Figure 5.14). This work realized in the resolution of 30m is hoped to provide overall view about the serious consequences of climate change for local population and authority.

The water level considered here is higher than the flood depth of 0.5m. The uncertainty in the impact of climate change is as well showed via different impacts of climate scenario. The results are described at Figure 5.15 or the risks of 1999 historical event and its projected scenarios, Figure 5.16 for the risk of 100 year return period flood event in present and in the future. Look at these figures, the largest damages are from MIROC scenario. The statistic demonstrates that if this MIROC climate scenario happens in future, this region will be devastated catastrophically.

Moreover, the damages are concreted for each type of land use at the Figure 5.15, 5.16 and by the numbers at Table 5.11, 5.12. The considered area situates at the downstream, so it is no surprise when damages from flood disaster mostly concentrate on the domain of rural settlement, annual crops, and specialized rice field. In 1999, three above land use types occupy roughly 88% of total flood area. This rate is not changed in the case of 100 year return period flood event at present and future scenarios. In the biggest varied scenario, MIROC, inundated settlement area in the end of 21^{st} century is predicted higher than three times in comparison with 1999 event. The increase of this kind of land use is around 12,193.51 hectare. With remain scenarios, the consequences for this domain are lower but the serious is not change.

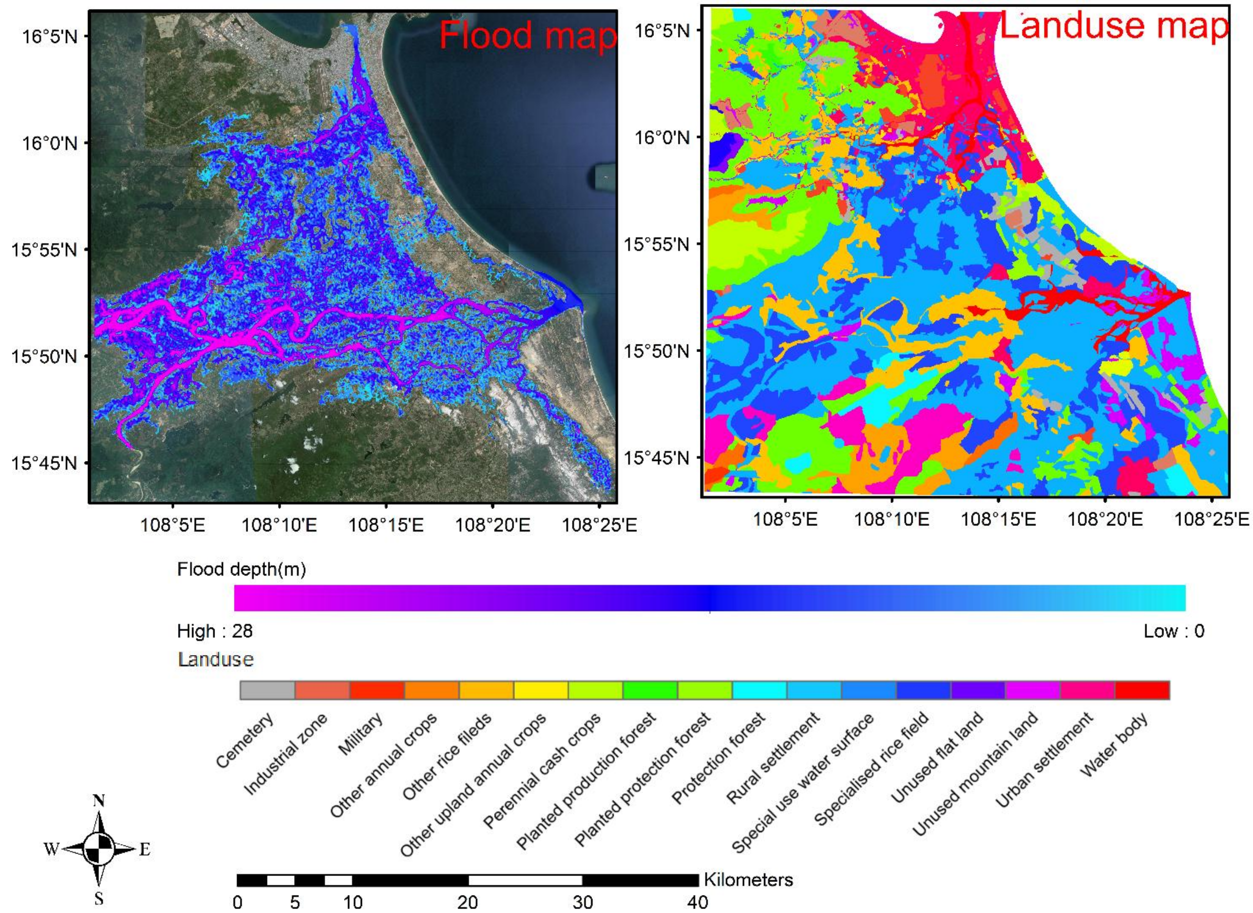


Figure 5.14. The materials for flood risk mapping.

The increasing flood area compared to 1999 flood event of ECHAM is 3,588 hectares and CCSM is 6,756 hectares. Besides that, regional primary crop plants will be affected significantly when this product area might be sunk deeply under flood flow. The statistics show that more than 34% specialized product rice will be flooded in the end of the Century with ECHAM. This area is 42% and 54% in CCSM and MIROC scenarios, respectively. The consequence of 100 year return period flood events is forecasted to be more awful. The events corresponding to this frequency are believed to damage more or less 60% rice product area (with MIROC project). The future situation is expected to risk gravely to the livelihoods of population at the downstream part of Vu Gia Thu Bon catchment. If there is no changes in awareness, these potential risks will kill more people, destroy the harvest and damage more property of catchment.

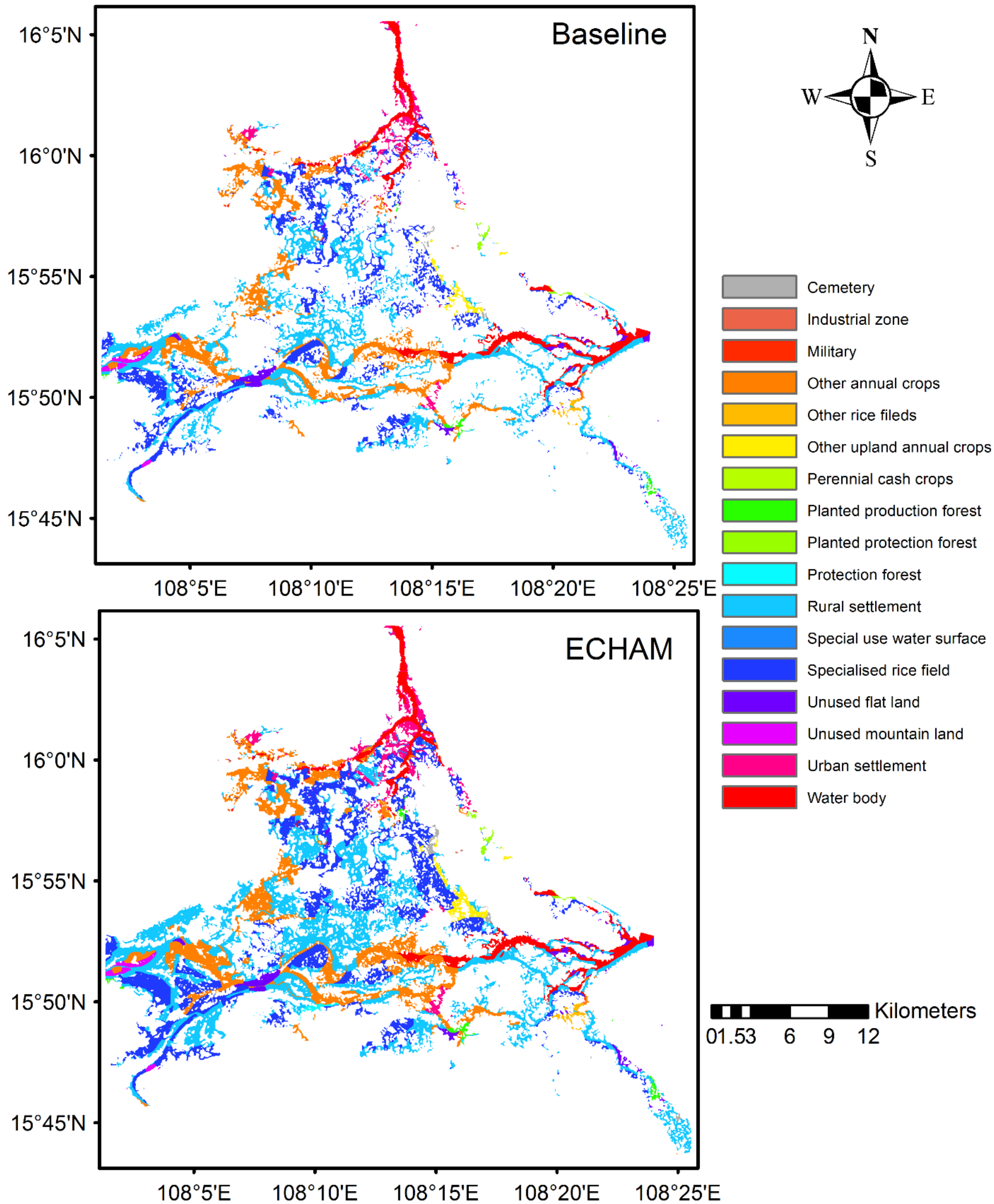


Figure 5.15a. Flood risk map for 1999 historical event and its corresponding future scenarios

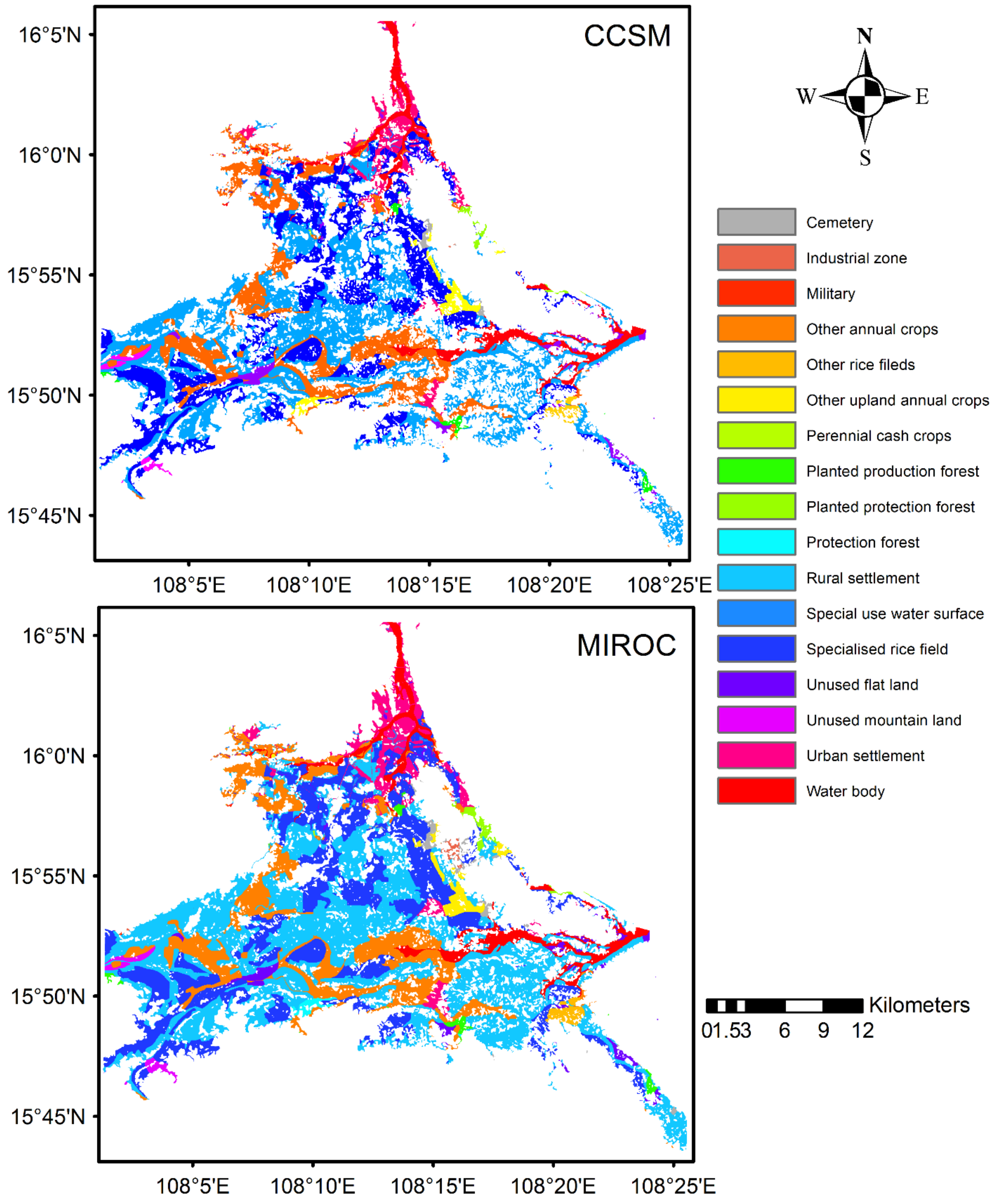


Figure 5.15b. Flood risk map for 1999 historical event and its corresponding future scenarios

Table 5.11. Potential risk area at Vu Gia Thu Bon against 0.5m flood depth of 1999 flood event and its corresponding future scenarios.

	Potential risk area (hectare)						
	1999	**CCSM**	**Change**	**ECHAM**	**Change**	**MIROC**	**Change**
Cemetery	64.44	172.89	108.45	134.01	69.57	346.05	281.61
Industrial zone	2.88	3.6	0.72	3.24	0.36	74.7	71.82
Military	4.41	6.84	2.43	5.13	0.72	17.46	13.05
Other annual crops	3,725.0	5,877.3	2,152.3	5,113.8	1,388.8	7,106.6	3,381.6
Other perennial crops	0	0.09	0.09	0	0	0.27	0.27
Other rice fields	76.86	167.49	90.63	112.86	36	299.07	222.21
Other upland annual crops	180.63	408.24	227.61	327.69	147.06	595.35	414.72
Perennial cash crops	2.07	5.13	3.06	4.14	2.07	6.57	4.5
Planted production forest	105.39	205.38	99.99	165.24	59.85	269.46	164.07
Planted protection forest	76.23	122.13	45.9	98.91	22.68	244.35	168.12
Protection forest	40.32	122.4	82.08	72.9	32.58	169.11	128.79
Religion	0	0.09	0.09	0	0	0.18	0.18
Rural settlement	6,848.2	13,604.7	6,756.5	10,437.1	3,588.9	19,041.7	12,193.5
Special use water surface	66.6	103.5	36.9	88.74	22.14	129.24	62.64
Specialized rice field	4,425.5	8,766.6	4,341.6	7,070.0	2,644.6	11,269.6	6,844.1
Unused flat land	523.26	697.41	174.15	622.98	99.72	866.7	343.44
Unused mountain land	171.09	253.89	82.8	186.21	15.12	310.23	139.14
Urban settlement	663.57	1,472.0	808.5	1,089.1	425.52	2,300.67	1,637.1

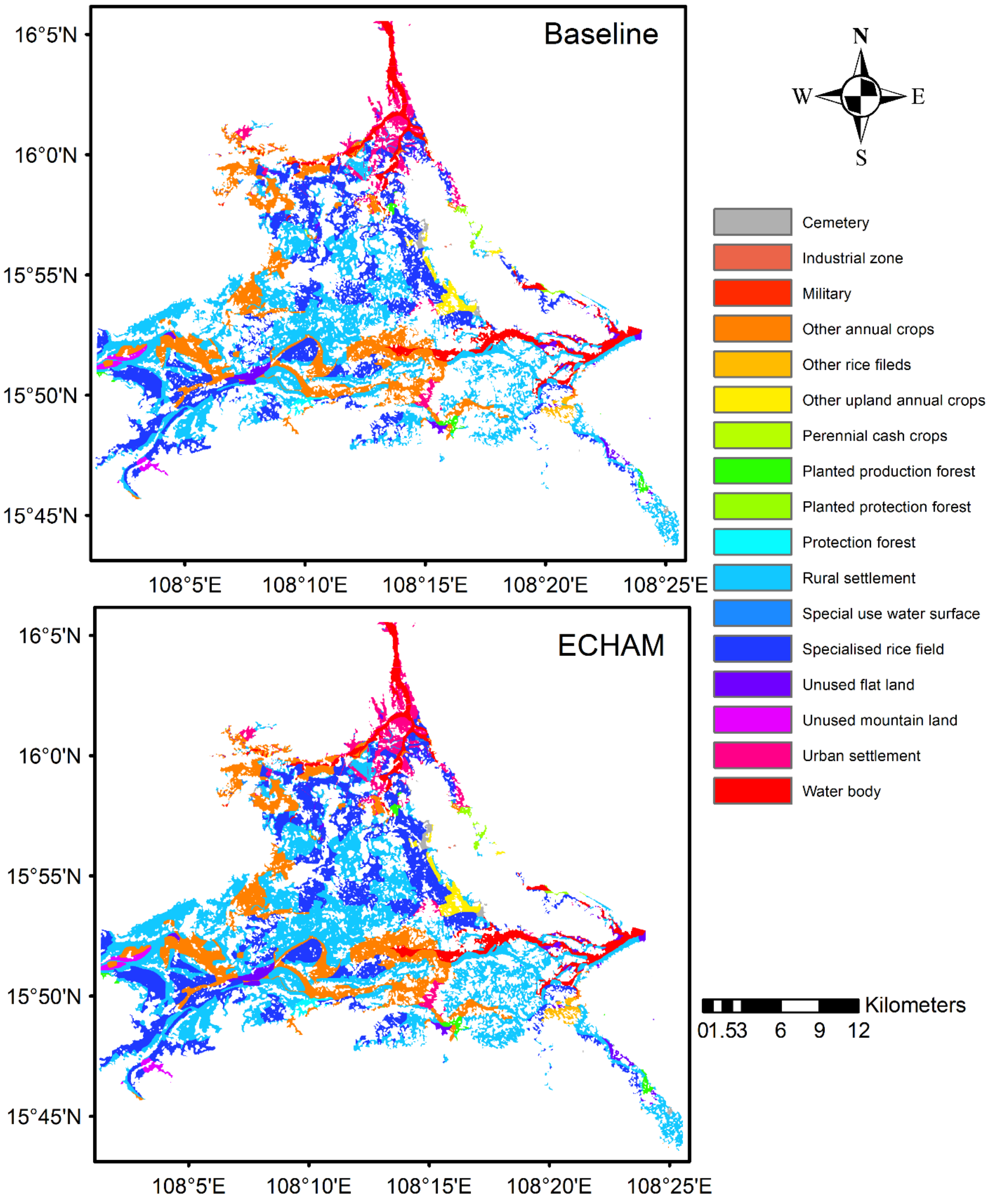


Figure 5.16a. Potential risk area at Vu Gia Thu Bon against 0.5m flood depth of 100 return period flood event and its corresponding future scenarios.

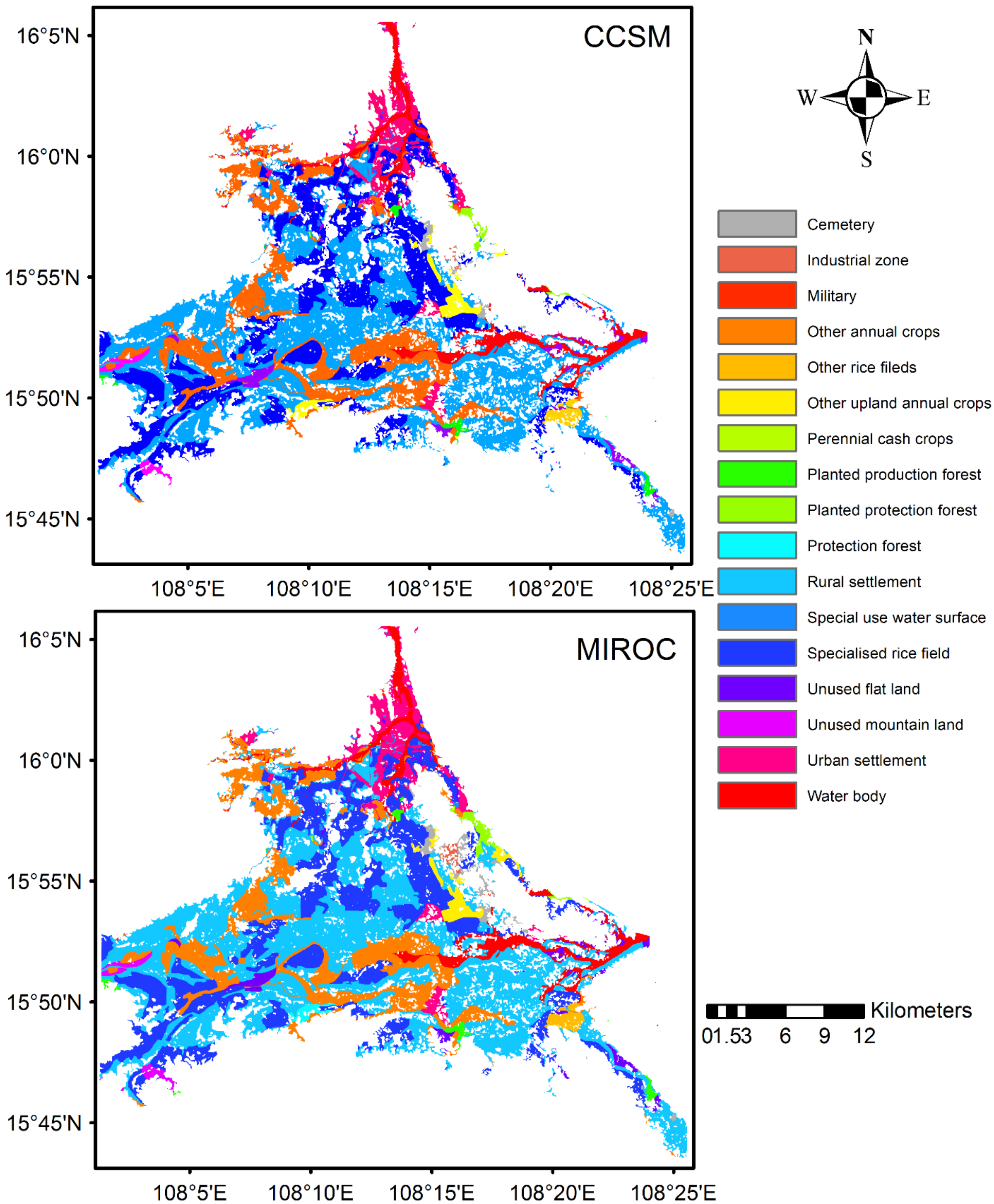


Figure 5.16b. Potential risk area at Vu Gia Thu Bon against 0.5m flood depth of 100 return period flood event and its corresponding future scenarios.

Table 5.12. Potential risk area at Vu Gia Thu Bon against 0.5m flood depth of 100 year return flood event and its corresponding future scenarios.

	Potential risk area (hectare)						
	Present	**CCSM**	**Change**	**ECHAM**	**Change**	**MIROC**	**Change**
Cemetery	162.18	283.95	121.77	192.15	29.97	532.53	370.35
Industrial zone	3.33	25.11	21.78	4.14	0.81	106.56	103.23
Military	5.94	11.61	5.67	7.11	1.17	25.2	19.26
Other annual crops	5,468.4	6,861.1	1,392.7	6,179.2	710.82	7,401.2	1,932.8
Other perennial crops	0	0.27	0.27	0.18	0.18	0.45	0.45
Other rice fields	144.72	285.12	140.4	204.3	59.58	336.06	191.34
Other upland annual crops	394.38	527.22	132.84	436.86	42.48	665.73	271.35
Perennial cash crops	4.5	6.57	2.07	5.94	1.44	6.57	2.07
Planted production forest	192.15	257.49	65.34	221.31	29.16	292.14	99.99
Planted protection forest	112.5	174.87	62.37	123.12	10.62	298.08	185.58
Protection forest	111.51	162.9	51.39	137.61	26.1	184.41	72.9
Religion	0	0.18	0.18	0.09	0.09	0.18	0.18
Rural settlement	12,108.8	18,058.0	5,949.2	14,997.3	2,888.5	20,713.2	8,604.4
Special use water surface	94.77	122.49	27.72	108.54	13.77	132.84	38.07
Specialized rice field	8,110.1	10,809.4	2,699.3	9,444.2	1,334.2	12,033.5	3,923.4
Unused flat land	669.78	821.16	151.38	730.8	61.02	937.08	267.3
Unused mountain land	251.73	301.32	49.59	271.53	19.8	334.98	83.25
Urban settlement	1,323.7	2,114.9	791.19	1,623.3	299.61	2,526.1	1,202.4

5.5 Conclusion

Extreme climatic and hydrological events are predicted to happen more frequently in recent years because of man induced global warming (Pachauri *et al.*, 2014). Despite that, these changes mostly bring the negative consequences to people lives. Thus, there is a need to rely on scientific evidences, so as to predict the future trend as well as to have accordingly mitigation plan. In order to evaluate the impacts of climate change on runoff of Vu Gia - Thu Bon river system, a deterministic hydrological model MIKE SHE model has been built. This model accounted mostly the runoff factors, from surface flow to groundwater flow, from infiltration to evapotranspiration. It is hoped to reduce a part of uncertainties when assessing the impact of climate change for the region. This model is calibrated and validated against daily data and monthly data in the period of 1990-2000 and 2001-2010, respectively. The performance of model is showed via the shapes of hydrograph, and via goodness of fits with seven gauging stations in this catchment. These robust performances confirm the high efficiency of deterministic distributed hydrological models in simulating the hydrological process as well as in assessing the impact of climate change to the run off for a large catchment.

The variation trend of run off factors in Vu Gia Thu Bon catchment under the impact of climate change is forecasted to become significantly. Results of modelling based on the change in precipitation, evapotranspiration with ECHAM, CCSM and MIROC models under A2 emission scenario in the period 2091-2100 demonstrate the increasing trend of climate variables. The great variability between baseline and future shows the serious impacts of climate change with this region. According to the analysis, the stream flow will change significantly in the whole catchment. The flow in the months of flood season could be increased averagely from 25% to 125% in comparison with present in all analyzed locations. In particular, the change could obtain up to 225 % at mountainous regions. On the contrary, at the locations of Thu Bon river, the drought in this period might happen more violent. The analysis gives the capacity that the base flow at several months in this catchment will decrease. Simultaneously, the change in temporal factors is presented clearly in this region. The above results indicate that the dry season is likely to be earlier in this catchment. Meanwhile the flood season extends and maintains longer.

The consequence of river flow change is expected to damage significantly local socio economic development and people at Vu Gia Thu Bon Catchment. In face of the context, this study is aiming to provide realistically scientific evidences about the impact of global warming to the catchment, especially the scale variability of inundation area and potential risk of this catchment faced to the climate change. The variation of flood flow is utilized in hydraulic modelling to project the change of future inundation area. The methodology by combining distributed hydrological and hydraulic models is hoped to reduce the uncertainty and save the time to reflect the most accurately the change in stream flow and flood area in Vu Gia Thu Bon catchment. The inundated area results are overlapped with land use map to demonstrate the flood potential risks of this river system. This study also considers the role of sea level rising in the future by considering this factor in simulation or not.

The study makes evidence that with a mountainous topography on the West, the steep river system and the average altitude of flood prone area higher than sea level, the main cause of inundation rising in future comes mostly from river flow which originate significantly from precipitation increase. This finding is very meaningful for the flood inundation simulation in future as well for the social economic development plan in this catchment.

The simulated result demonstrates the significant impact of climate change to the downstream part of Vu Gia Thu Bon catchment. Accordingly, the flows corresponding with three GCMs scenarios take an increasing trend. This increase of stream flow makes the inundated situation at downstream parts occurring catastrophically.

Total inundation area is roughly 46.31 % higher than 1999 flood event. More seriously, the inundation area deeper than 2m could expand around 70% in comparison with present scenario. The destruction of 100 year return period flood event at present is really awful for the catchment. Therefore, in future the destroyable characteristic of flood event having this frequency will be more violent. The peak water level of these events can be higher than present event from 2m to 4 m. It might make the inundation over catchment. The flood area corresponding with these floods can be more than now from 17% to 56%. Around 35% regional area is forecasted under the flood level in the end of this century. These figures confirm the violence of natural disaster in future, which is inherently fierce at the moment.

In order to account the impact of future flood disaster due to climate change, also figure out which domain will be affect much by their impact, the flood risks are established by overlapping flood hazard into land use maps. The risk maps demonstrate the serious consequences due to natural catastrophes towards agricultural productions, especially rice production and rural settlement sin Vu Gia Thu Bon. Counting with flood level higher 0.5 m, rural settlement, annual crops, and specialized rice field are three domains which will be influenced greatly by the consequence of global warming. In the last years of 21st century, flood rural settlement area might be 19,041 hectare increasing 178% versus 1999 flood event. This trend is similar to annual crops and specialized rice field, when their flood area are 7106 hectare, 91% and 11269 hectare, 156% respectively. Moreover, the destroyable magnitude of 100 year flood event is definitely so furious for the catchment.

The above results are considered as a basis for local authorities to make strategies in order to mitigate the effect of climate change to this area and to help the population in Vu Gia Thu Bon Catchment prevent actively and adapt better with natural disasters in the end of this century. It is also useful to water resource agencies, irrigated management, and agricultural departments to get an insight on this phenomenon. From that they will reorganize the product scheme, harvest plan, as well as suitable structure of crop plans.

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Chapter 6 CONCLUSIONS AND PERSPECTIVES

6.1 Conclusions

There is a perception that extreme climatic and hydrological events have become more frequent in recent years. This phenomenon may be caused by man-induced global warming (Robson, 2002). Their impacts have been damaged significantly in many aspects of human society as life and property on a global scale. Many areas are expected to face risk of temperature, precipitation and sea level rising. The customs and life space will change greatly in future under these changes. Particularly at poor and developing countries, the impacts of climate change are thought to be more serious due to the vulnerability of these regions where the infrastructure and people awareness are still not enough to adapt with catastrophic natural disasters. Despite that, these changes mostly bring the negative consequences to people lives, completely eliminating this natural phenomenon is likely impossible. Thus, there is a need to rely on scientific evidences, so as to predict the future trend as well as to have accordingly mitigation plan.

Vietnam is located in the region of the south East Asia monsoon. Most of the population work in agriculture and inhabitants essentially concentrate at the coastal plain, Vietnam is among the countries most heavily affected by the consequences of climate change. According to the assessment of Vietnam government, in late 21st century, Vietnam's yearly mean temperature will increase 2-3°C, the total yearly and seasonal rainfall will increase while the rainfall in dry seasons will decrease, the sea level could rise from 0.75 to 1m as compared to the 1980-1999 period. About 10-12% of Vietnam's population would be directly impacted and country could lose around 10% of GDP. These challenges urge Vietnam to have a plan, suitable policies and measures to improve public awareness, as well as capacity to respond to climate change. Efforts to aid the local population to strengthen its adaptive competence against natural disasters, also increase the capacity in responding the climate change, this thesis is proposed to expectedly provide confident assessments of variation in hydrological regime within a river basin scale. The study is carried out at Vu Gia Thu Bon catchment, one of the large river systems at Viet nam central where the economy lose annually around 6.26% of the GDP caused by natural disaster and in future this figure can reach 10% of the GDP under the climate change.

6.1.1 Modelling

The first part of this study concentrates on constructing a hydrological model which would be an efficient tool for assessing the variation of stream flow in the future. By the advantage of a deterministic distributed model, the MIKE SHE from DHI software is selected for the aim of representing the hydrological process of Vu Gia Thu Bon Catchment. This selection is hoped to overcome the difficulty concerning to the lack of data, as well as the large scale in simulating for a catchment as Vu Gia Thu Bon. The model is built over 10,350 Km^2 of catchment and it considers mostly the runoff factors, from surface flow to groundwater flow, from infiltration to evapotranspiration.

In deterministic hydrological modelling, rainfall can be defined as a major input data. Unfortunately, in this region, rainfall records are incomplete and not dense enough to accurately represent the reality of rainfall spatial distribution over large catchments. Hence, redistributing spatially the rainfall is required for hydrological modelling. In order to reduce the uncertainty related to the interpolated technics, the rainfall of 15 local meteorological stations over an area 10,350 km^2 has been redistributed spatially with several different interpolation methods such as Thiessen polygons, Inverse-distance weight, Spline, Natural neighbor, Ordinary Kriging, Geographically weighted regression. The result demonstrates that the Kriging is the most suitable method for rainfall distribution at Vu Gia Thu Bon catchment. With only one station observed for average area of 700 km^2, this density is quite sparse. Therefore, the grid size of rainfall interpolated data mostly does seemly not influence on run off simulation. Comparing in three grid sizes, eg 1000m, 2000m, 4000m, the difference between these three scenarios is not very significant, even if the 1000m scenario gives the best result.

In order to make advantage for calibrating a complex distributed hydrological model, there is a need to estimate sensitivity analysis of parameters including in the model. Relied on the response of each parameter to river flow, as well their elasticity analysis, only several parameters, which have great effects on the model, are chosen for the purpose of calibration model. Following that, the variation of runoff due to parameter changes is quite different. In Vu Gia Thu Bon catchment, the peak flow is affected significantly by most of the model parameters while the base flow is merely influenced by horizontal saturated hydraulic conductivity of saturated and saturated hydraulic conductivity of unsaturated zones. The analysis has demonstrated the interest of the sensitivity analysis in the calibration of distributed hydrological model. At the same time, this process helps to determine a useful impact interval of each factor on the stream flows and contribute to simplify the calibration process. Based on these results, the MIKE SHE model is calibrated and validated against the daily and monthly data recorded at seven stations and for the periods of 1991-2000 and 2001-2010, respectively. The quality of the results is demonstrated with Nash Sutcliffe and correlation coefficients that reach 0.82 and 0.92 respectively in discharge comparison. With the water levels, the obtained coefficients are lower but the quality of the results remains high: Nash Sutcliffe and correlation coefficients reach 0.77 and 0.89, respectively in the upstream part of the catchment. This analysis indicates again the performance of the deterministic distributed modeling approach in simulating hydrological processes and confirms the usefulness of this model with ungauged catchment or large catchment. Additionally, this analysis proves the role of multi calibration in increasing the accuracy of hydrological model for large catchment. Moreover, factors affecting potentially the model uncertainty are also analyzed. The model uncertainty might be from many sources, however, in this study, it is judged to not come from mode algorithm but caused from the lack of data, the large catchment scale and the limitation of computer. Using online topographical data, low rainfall observed station density, coarse rainfall measured time step, the lack of soil property, land cover, and ground water data potentializes the uncertainty for modelling the hydrology at a large catchment. An overview of above risks has been used to explain the uncertainty of this MIKE SHE model. Nevertheless, these limitations need to be considered and overcome in the future, at this moment, the constructed model has been proved its capacity for translating the hydrological process in Vu Gia Thu Bon catchment.

Beside the purpose of assessing accurately the flood hazard for the catchment, the second part of the thesis is to establish a hydraulic model which can map the stream flow variation. Considering on flood prone area, topographic characteristic, historical flooding of the catchment, the hydraulic model is proposed to set up for only downstream area instead of the whole catchment. Throughout pros and cons of the present hydraulic models including 1D, Quasi 1D, 2D, and 1D/2D coupling models and testing results, it is seen that the last one is the most reasonable for flood modelling at this catchment. The MIKE FLOOD is one model in the form of coupling between 1D (MIKE 11) and 2D (MIKE 21) is built over 1,780 Km^2 of catchment. The model is validated with the historical flood event in the year of 2007. The model shows its performance via high statistical index at three gauging stations, Ai Nghia, Giao Thuy, Cau Lau. Accordingly, the difference between the highest simulated water level at these three stations and observations is not significant. The number varies approximately from 10 to 20 cm. Comparing 3h data, the correlation coefficients between simulation and observation reach relatively high, all stations R index passed 0.85. The Nash-Sutcliffe coefficient could reach to 0.83. For the above persuasive evidences, this MIKE FLOOD model is completely applicable to construct flood plain as well as forecast their variation at Vu Gia Thu Bon Catchment. In developing the MIKE FLOOD model, there are several uncertainties which have been demonstrated. With the most important role, the topographical data is considered as the big source of uncertainty towards flood mapping process of Vu Gia Thu Bon catchment. This judgment is based on the big variability after comparing with the flood map which is constructed from different resolutions, quality, and their origins. This analysis is hoped to add more evidence for the effect of topography to flood modelling.

6.1.2 Climate change tendency and potential risk.

The impact of climate change is evaluated by combining two above models. The first is to consider the variation of river flow due to the change in future. To assess the most negative consequences of climate change towards the region, the variation of climate factors using in this study is constructed on GCMs with extreme emission scenarios. Concretely, they are built under A2 scenario which assumes that a very heterogeneous world with continuously increasing global population and generally oriented economic growth that is more fragmented and slower than it other storyline. The rainfall and evapotranspiration in the period of 2091-2100 is calculated based on present observation of the period of 1991-2000 for three basic scenarios, e.g CCSM3.0, MIROC- 3.2, ECHAM 5. The impacts of these factors, which change towards the stream flow of Vu Gia Thu Bon catchment, are counted via validated MIKE SHE model. Relied on the advantage of distributed model, the difference between present and future run off is able to compare at almost outlets of sub catchments and important points of two main branches of the system, Vu Gia and Thanh My. The comparison demonstrates that there exists a big change in the river flow due to the global warming in the end of 21st century. This change is not only on the flow quality but also on time appearance. According to the analysis, the stream flow will change significantly in the whole catchment. The flow in the months of flood season could be increased averagely from 25% to 125% in comparison with present in all analyzed locations. In particular, the change could obtain to 225 % at mountainous regions. The variation of run off leads the flood to happen more frequently and extremely.

The flow increase is predicted to occur in the whole catchment, but this tendency is more severe at mountainous region, especially at sub catchments of Vu Gia river when the results show that the future river flow at these areas is higher than present from two to three times. Due to the typical topography short and slope, it is forecasted that the catastrophes from flashflood obviously rise in area. There has been an increasing trend in the runoff of dry season in the end of 21st century. On the contrary, at the locations of Thu Bon river, the drought in this period might happen more violent. The analysis gives the capacity that the base flow at several months in this catchment will decrease. The decrease is showed the most clearly at the months of January – February and May – June. This phenomenon predictably makes the drought hazard in this region become more intricate and more imperative. Simultaneously, the change in temporal factors is presented clearly in this region. The above results indicate that the dry season is likely to be earlier in this catchment. Meanwhile the flood season extends and maintains longer.

The significant flood increase is predicted to result definitely in the great enlargement of inundation area at Vu Gia Thu Bon catchment. It seems to exceed the imagination. The main cause of the flow increase in the future is determined not from sea level rise, it is from the inland flow. The increasing trend of discharge in hydrological model leads to raise almost water level at the downstream. The future water level at several cases can be roughly over 3 m than actual. Thus, it is not surprising when the inundation area in the end of 21st augments is greatly in comparison with current ones at Vu Gia Thu Bon catchment. Total inundation area (corresponding to flood depth >=0.5m) is minimum 46.31 % higher than 1999 flood event. Especially, the difference is really catastrophic with MIROC scenario when the future inundation area might be 141% higher than the 1999 flood event. The increasing trend is similar with 100 year return period event, however, the variation is not so great with real scenario. The maximum difference between future and present is MIROC. The flood area due to 100 year return period of MIROC just increases 56.72%. More seriously, the heavy inundation area (deeper than 2m) could expand around 70% to 287% in comparison with 1999 flood event. The expansion of flood area in future is projected to make more damages for Vu Gia Thu Bon catchment. The increase of flood area is expected to ruin more gravely the catchment than actual. This study only considers on downstream area so it is not surprising when damages from flood disaster mostly concentrate on the domain of rural settlement, annual crops, and specialized rice field. In 1999, three above land use types occupy roughly 88% of total flood area. This rate is not changed in the case of 100 year return period flood event at present and future scenarios. The consequence due to flood disaster in the end of century might be more critical than the one of historical flood event in 1999 many times. When the biggest varied scenario, MIROC, inundated settlement area in the end of 21st century is predicted higher than three times in comparison with 1999 event. The increasing of this kind of land use is around 12,193.51 hectare. With remain scenarios, the consequences for this domain are lower but the serious is not change. The increasing flood area compared to 1999 flood event of ECHAM is 3,588 hectares and CCSM is 6,756 hectares. Besides that, regional primary crop plants will be affected significantly when this product area might be sunk deeply under flood flow. The statistic show that more than 34% specialized product rice will be flooded in the end of century with ECHAM. This area is 42% and 54% in CCSM and MIROC scenarios, respectively. The consequence of 100 year return period flood events is forecasted more awful. The event corresponding with this frequency are believed to damage more or less 60% rice product area (with MIROC project). The future situation is expected to risk gravely to the livelihood of population at downstream part of Vu Gia Thu Bon catchment. If there is no changes in awareness, these potential risks will kill more peoples, destroy the harvest and damage more property of catchment.

The happening of climate change keeps going to complicated and severe. Determining exactly run off variation in the future is so difficult, at least with the limitation of computed capacity and data simulation at the moment. Hence, in this study, the result is only the prediction. It is merely hoped to provide one more scientific evidences for enhancing the population awareness to respond the climate change. It is also expected to be useful for local authority to plan the residential, produced area, as well propose the strategy to mitigate the consequence of this natural disaster.

6.2 Recommendations and perspectives

Natural environment plays a vital role towards the existence and development of human society. Hence, understanding about the climate change and its related problems has been considered as decided issue for our survival in the future. Nevertheless, the nature is a complex system. Completely assessing this system for predicting the future happening requires a long time simulation, necessary data, and great computation system. These capacities seem to be not available in present day. As these reasons, although this study has accomplished the proposal study objectives, outlined the variation trend of climate and hydrological factors in the end of 21st, also predicted the potential risks possibly caused by climate change for Vu Gia Thu Bon Catchment, there are still a lot of uncertainties and problems needed to improve. Several issues will be suggested in following part to solve the remaining things.

6.2.1 Hydrological modelling.

As above discussions, because of the lack of simulated data, the model performance is still not perfect. It might result in the inaccurate prediction for future scenario. Therefore, trying to increase the model performance is one of priority for enhancing the confidence in climate change simulation. Actual topographic data using in this study is from online source. The quality of this data is not so high. With 90m of resolution, 16m of probable vertical error, it is not expected to describe truthfully the catchment topography. Simulating with better DEM quality is seen as one of solutions to augment the model efficiency. Srtm DEM 30m from NASA releasing in 2014 or 15 m from LUCCi project creating for this region is hoped to give better simulated result. Furthermore, the detail of other input data, such as land use, soil, vegetable growth, ground water, is low. These data were simplified in order to save the time calibration. In fact, they are able to express the fundamental characteristic of catchment, however to model reaching better efficient, their concreteness is more required. The density of cross section in 1D model decides its capacity in representing the river geometry. Increasing its density is also the objective in next time to enhance the reality of model. Besides that, the number of simulated branch now is limited at 44, it is really not the real branch quantify in this catchment, adding more branch for simulation is another solution to make this model become more accurate. At this moment, this MIKE SHE model has been validated merely against surface flows. In spite of taking into account the ground water, the MIKE SHE has not yet been compared with the measurement of this component. Thus, finding out the observed data served to confirm the quality of model on the aspect of describing the ground water has a great meaning for the catchment in developing socio economy.

6.2.2 Hydraulic model.

Like hydrological model, the resolution of topographic data has a significant role towards the accuracy of hydraulic model. Therefore, by low performance of computer, the present study just stays in simulating with the 30m data. Consequently, the flood propagation has not been expressed detail enough. Continuing to modelling with smaller cell size, such as 15m, 10m, 5m is always targeted to make the flood map more accurate. The data input at MIKE FLOOD now ignore the effect of infrastructure factors such as weir, bridge, street, and building. This makes the model not reflect well the reality. Taking into account the influence of infrastructure for hydraulic modelling plays an important role to improve the model quality.

6.2.3 Flood hazard mapping and flood risk estimation

In the scope of the thesis, there are only two flood maps corresponding with 1999 flood historical event and 100 year return period event being established. Constructing more flood event, as well with more frequency is necessary. This work helps to provide to local authority the diversity in responding actively with natural disaster. Moreover, the actual map merely supply the flood depth, flood area, other information will be presented in the next time. Regarding to the potential risks, the current calculation only introduces flood damage as the form of inundation area due to land use map. The more detail consequence of flood catastrophe will be assessed in the next period with a wide range of damage when having enough data, such as accommodation, property, productivity of vegetation. Based on these statistics, the damage curve will also be built as the basic tool for evaluating the impact of flood disaster in the catchment. Inversely, the drought disaster will likewise be distributed spatially overall the catchment to count the future water requirement and damage due to this natural phenomenon in this study area.

6.2.4 Climate change

The limitation of measured data implies that the simulation is carried out only in the period of ten years. As a result, predicted varied tendency contains a lot of uncertainties. Extending the simulated period is required to make clearer the future trend. As presenting about the uncertainty in climate scenario, hence modelling more than three GCMs and more Greenhouse gas emission scenarios as well as trying with other downscaling methods are necessary for reducing the uncertainty in climate modelling. In addition, the thesis results need to update with the new climate scenario IPCC's AR 5 which has just been released in 2013. The simulating with new data will help to validate the last prediction about the climate change impact on Vu Gia Thu Bon catchment. The study at present only accounts the variation of factors related to meteorology, other factors are supposed to be not change. It is not reasonable, so accounting in modelling other factors change such as land cover are considered to increase the reliability of climate change projection.

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APPENDIX

Appendix A: Rainfall and evapotranspiration data input.

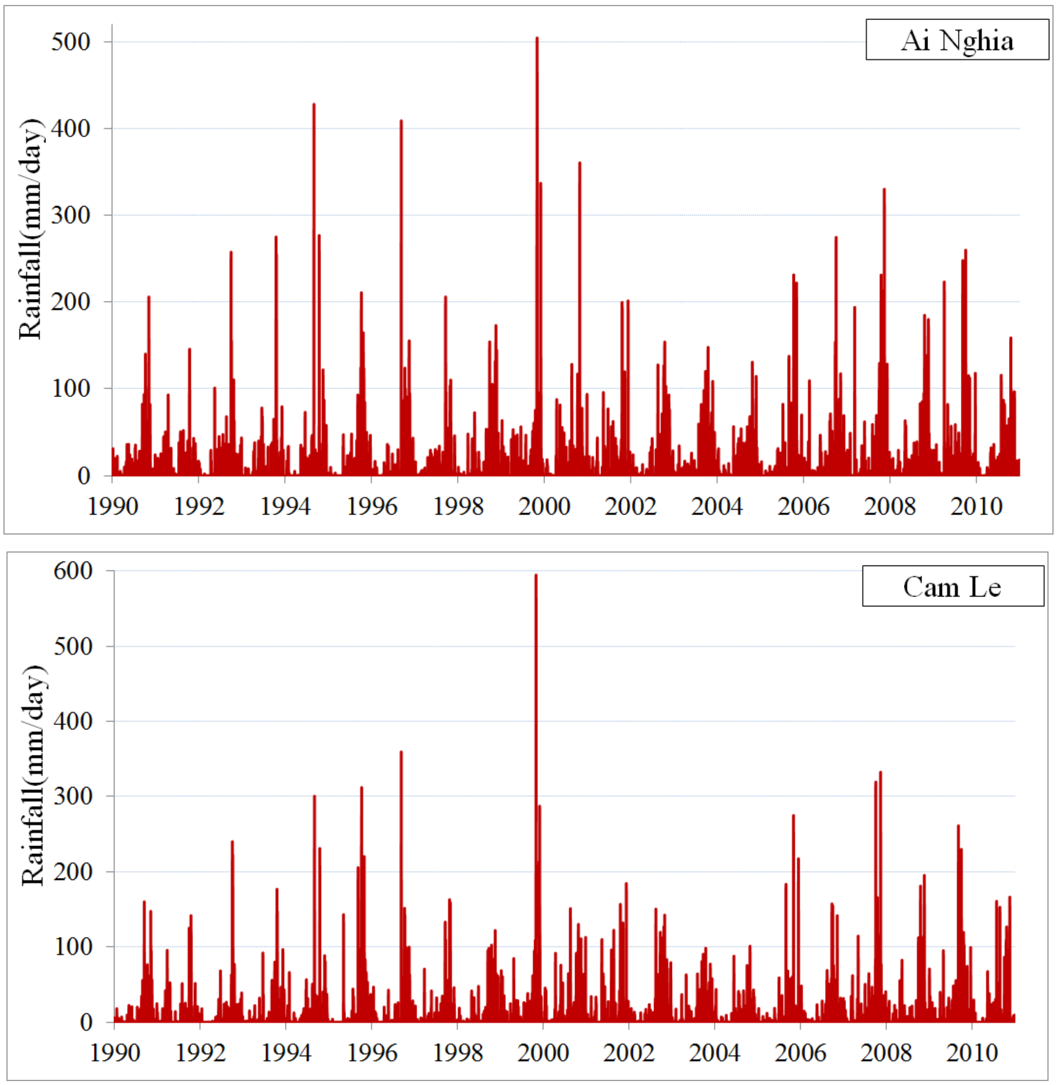


Figure A1a. Rainfall data in Vu Gia Thu Bon catchment in period of 1990 – 2010.

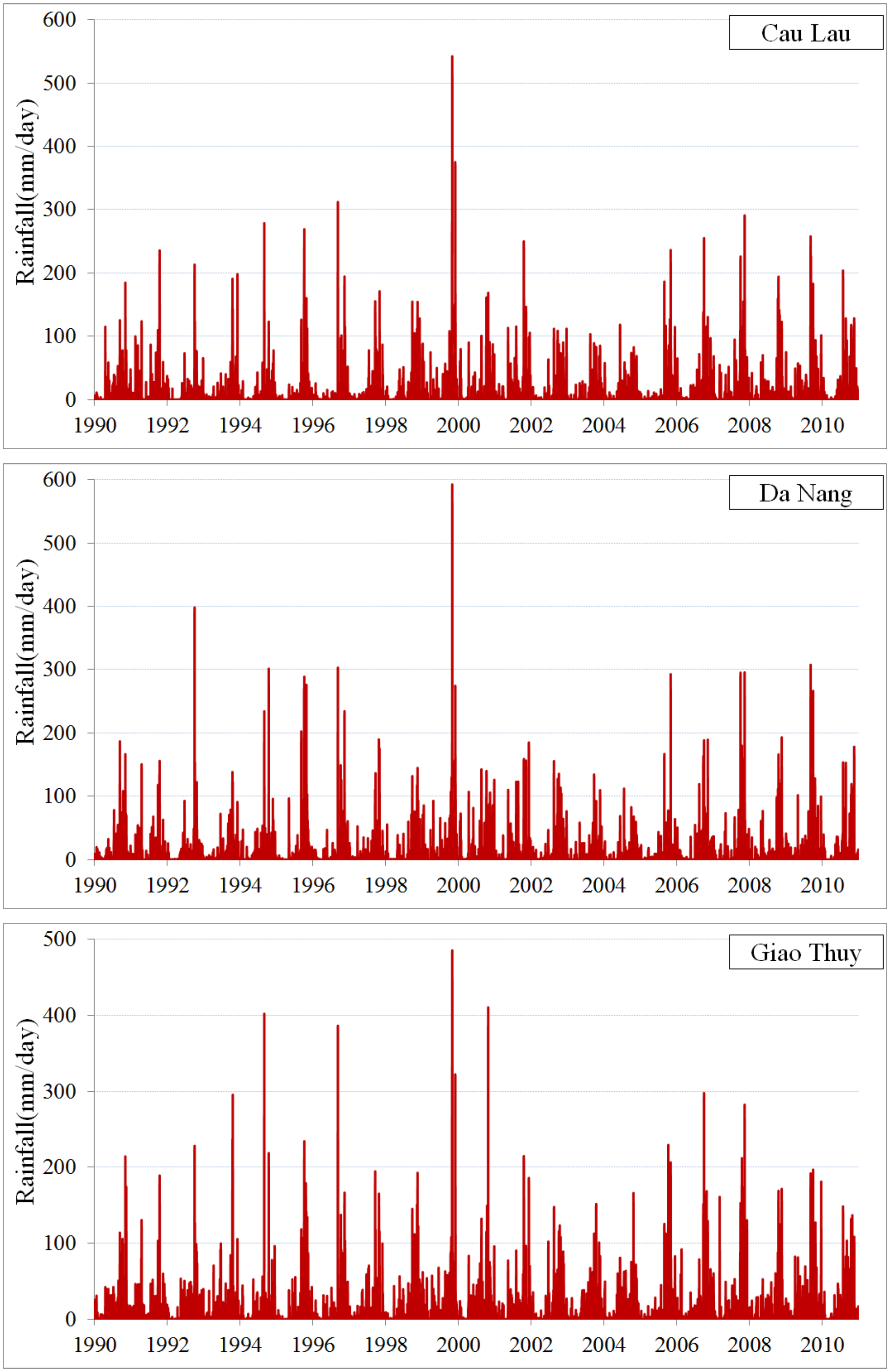


Figure A1b. Rainfall data in Vu Gia Thu Bon catchment in period of 1990 – 2010.

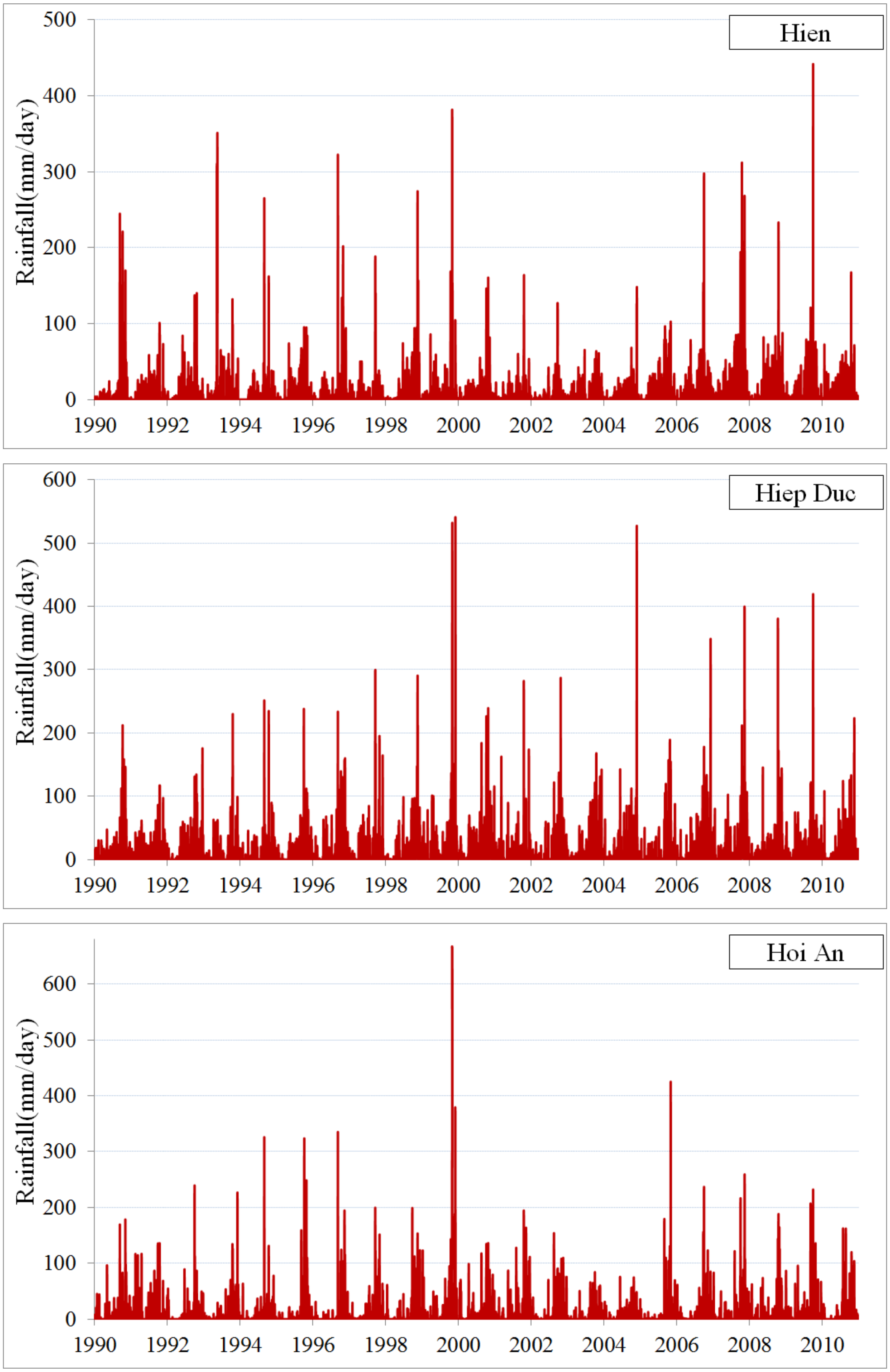


Figure A1c. Rainfall data in Vu Gia Thu Bon catchment in period of 1990 – 2010.

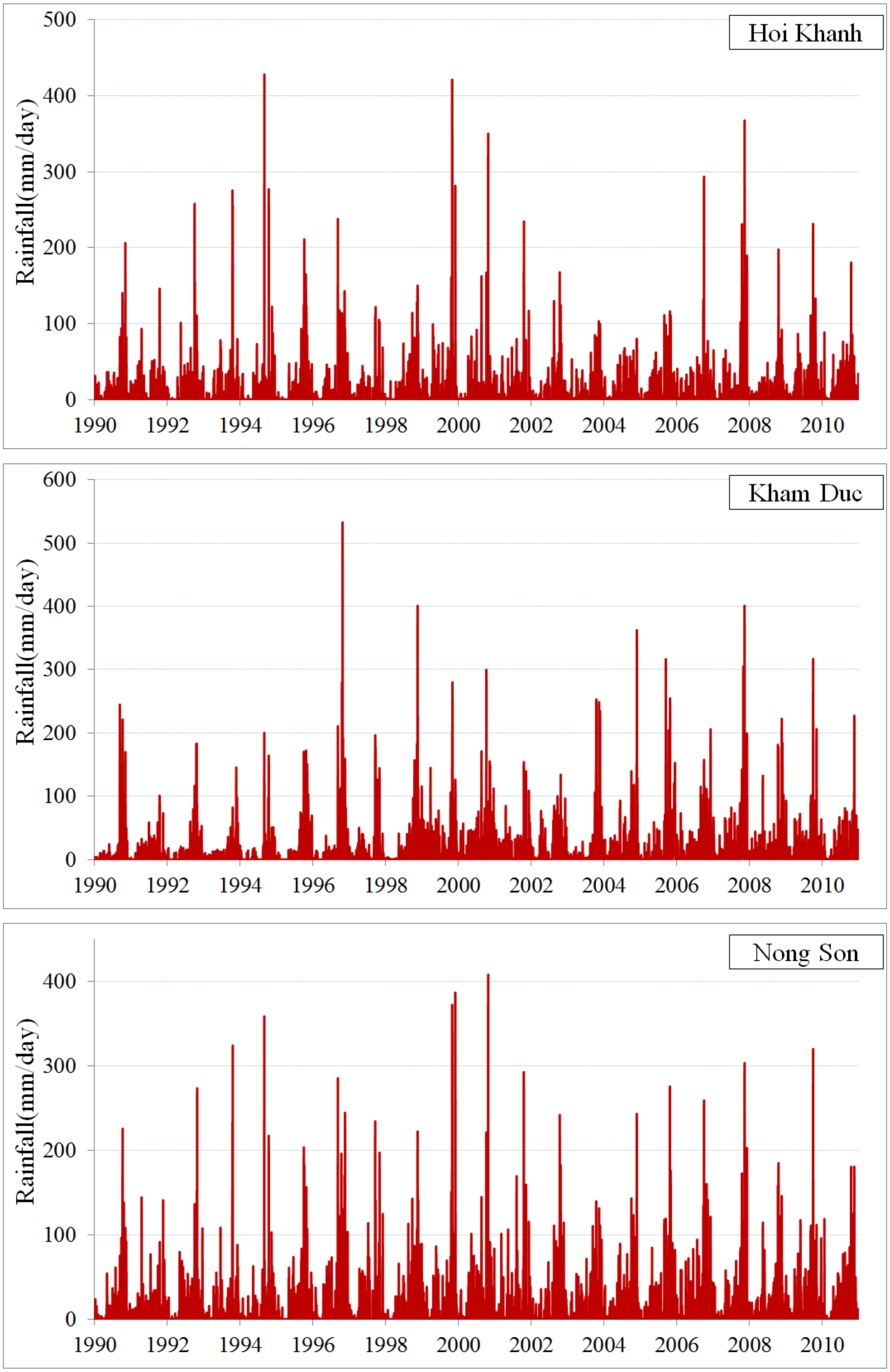


Figure A1d. Rainfall data in Vu Gia Thu Bon catchment in period of 1990 – 2010.

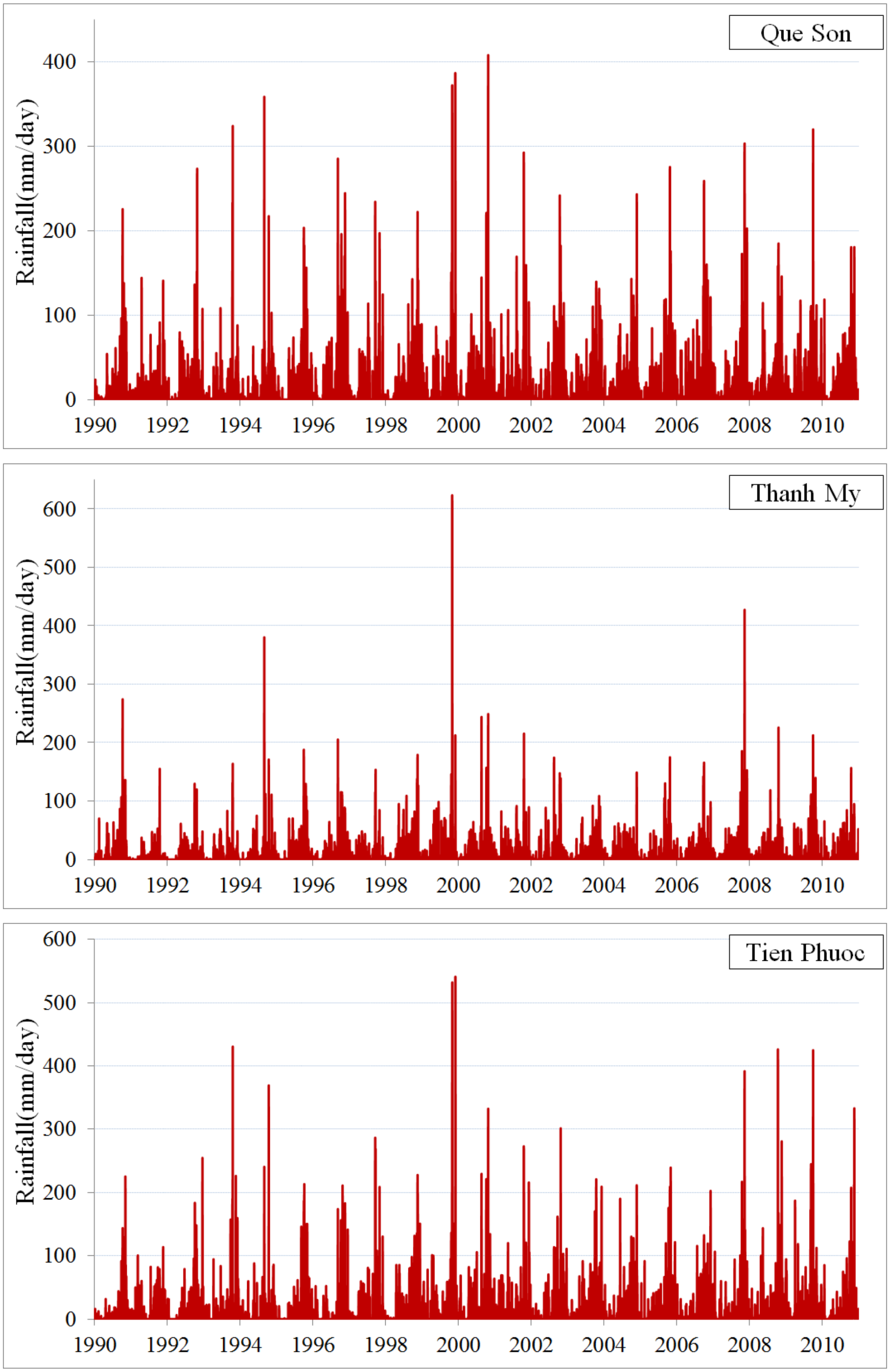


Figure A1e. Rainfall data in Vu Gia Thu Bon catchment in period of 1990 – 2010.

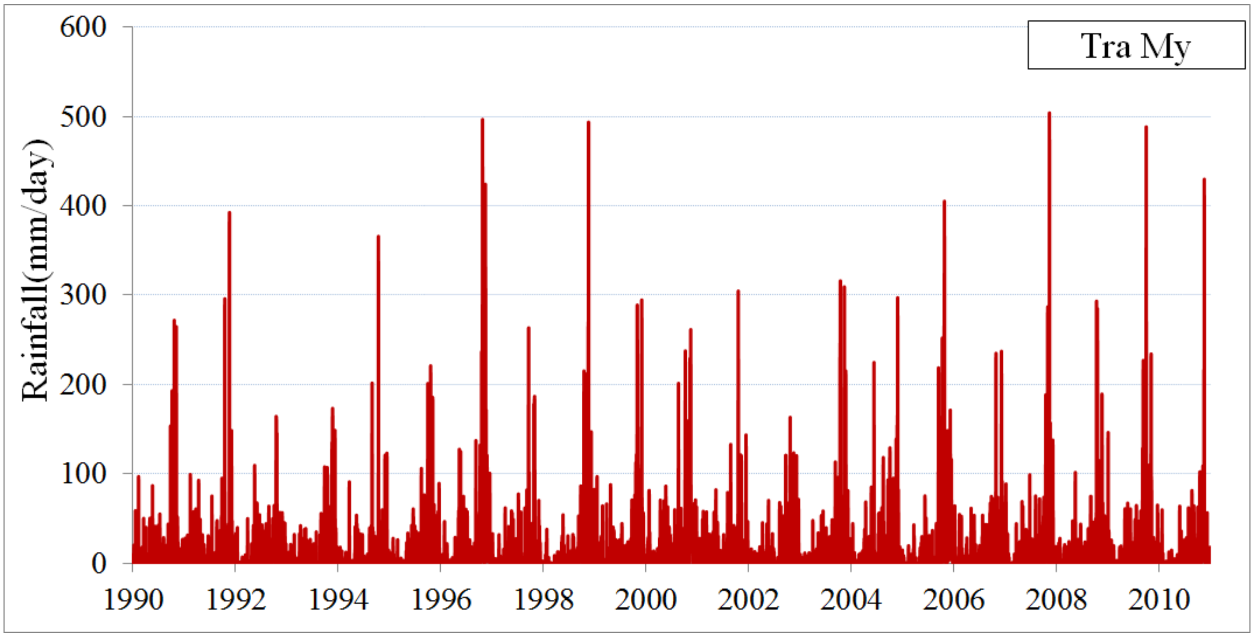


Figure A1f. Rainfall data in Vu Gia Thu Bon catchment in period of 1990 – 2010.

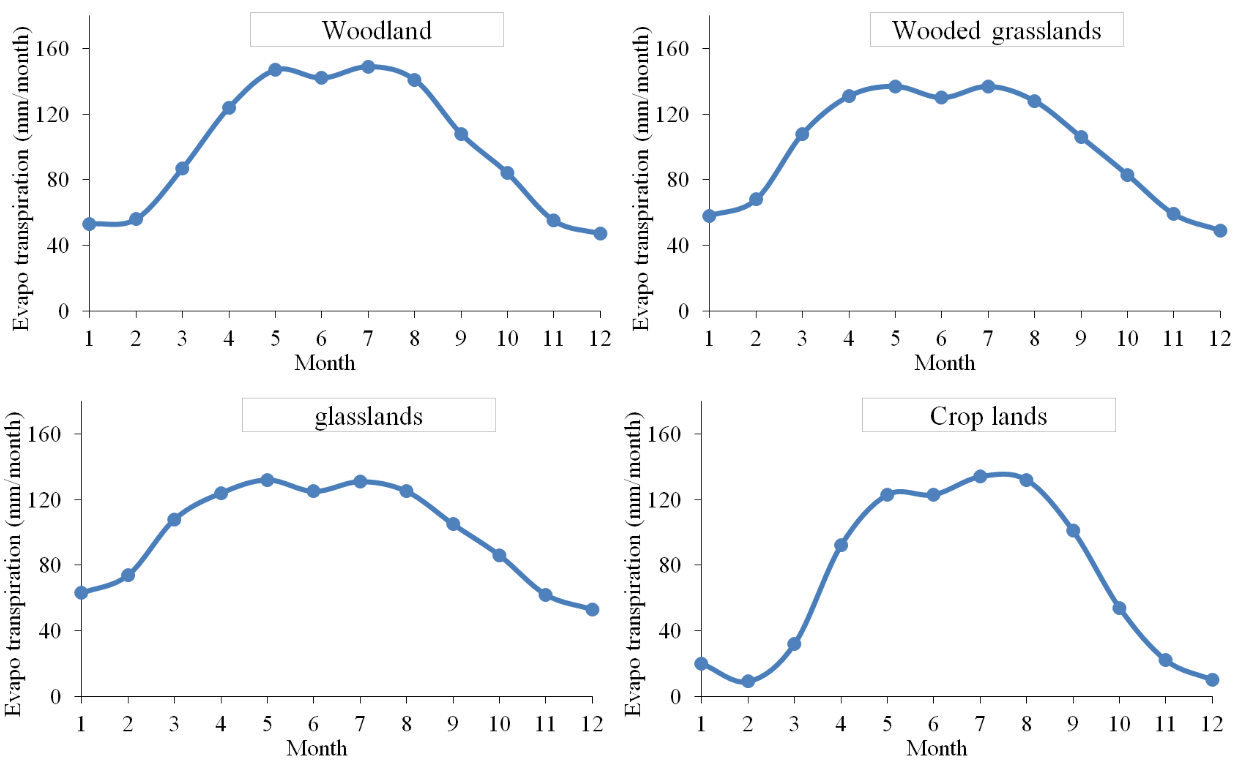


Figure A2a. Avapo transpiration using for MIKE SHE model.

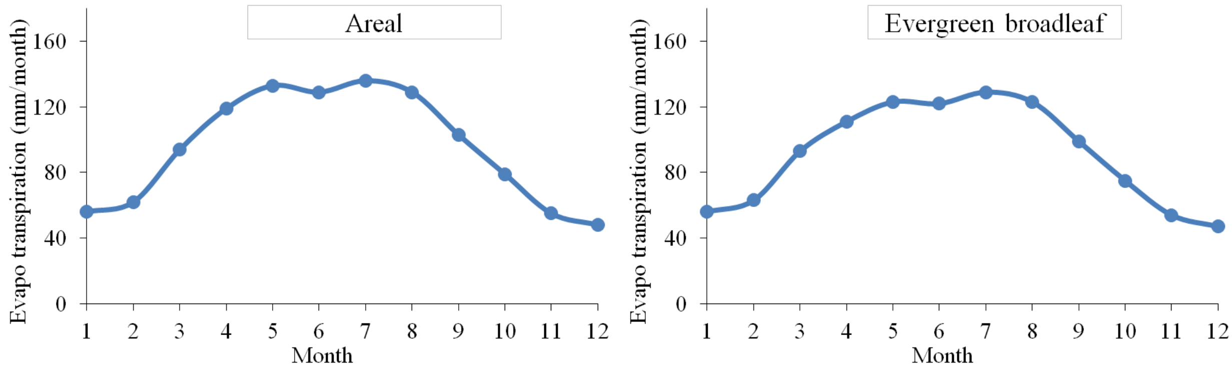


Figure A2b. Avapo transpiration using for MIKE SHE model.

Appendix B: Program for spatially re-distributing rainfall (working in ArcGIS environment)

B1. Inverse distance weighted method.

```
import arcpy
import os
arcpy.CheckOutExtension("spatial")
for k in range(1,n):
    z=str(k)
    bg=(k-1)*250
    en=k*250
    n = r"e:\\SIG\\n"+z
    if not os.path.exists(n): os.makedirs(n)
    t = r"e:\\SIG\\t"+z
    if not os.path.exists(t): os.makedirs(t)
    point = "C:\\Users\\Vongo0\\Desktop\\dailyrain1\\"+z+".shp"
    for i in range(bg,en):
        arcpy.env.extent=arcpy.Extent(0,0,165000,145000)
        name=str(i)
        field="P"+name
```

```
        raster= "e:\\SIG\\n"+z+"\\"+name
        TXT= "e:\\SIG\\t"+z+"\\"+name.zfill(4)+".TXT"
        arcpy.gp.Idw_sa(point, field, raster, "10000", "2", "VARIABLE 12", "")
        arcpy.RasterToASCII_conversion(name, TXT)
        mxd = arcpy.mapping.MapDocument("CURRENT")
        df = arcpy.mapping.ListDataFrames(mxd)[0]
        for lyr in arcpy.mapping.ListLayers(mxd, "", df):
            if lyr.name.lower() == name:
                arcpy.mapping.RemoveLayer(df, lyr)
            arcpy.RefreshActiveView()
```

B2. Kriging method.

```
import arcpy
import os
arcpy.CheckOutExtension("spatial")
for k in range(1,n):
    z=str(k)
    bg=(k-1)*250
    en=k*250
    n = r"e:\\SIG\\n"+z
    if not os.path.exists(n): os.makedirs(n)
    t = r"e:\\SIG\\t"+z
    if not os.path.exists(t): os.makedirs(t)
    point = "C:\\Users\\Vongo0\\Desktop\\dailyrain2\\"+z+".shp"
    for i in range(bg,en):
         arcpy.env.extent=arcpy.Extent(0,0,165000,145000)
        name=str(i)
```

```
        field="P"+name
        raster= "e:\\SIG\\n"+z+"\\"+name
        variance= "e:\\SIG\\v"+z+"\\"+name
        TXT= "e:\\SIG\\t"+z+"\\"+name.zfill(4)+".TXT"
        arcpy.gp.Kriging_sa(point, field, raster, "Spherical 1000", "1000", "VARIABLE
    12", "")
        arcpy.RasterToASCII_conversion(name, TXT)
        mxd = arcpy.mapping.MapDocument("CURRENT")
        df = arcpy.mapping.ListDataFrames(mxd)[0]
        for lyr in arcpy.mapping.ListLayers(mxd, "", df):
          if lyr.name.lower() == name:
            arcpy.mapping.RemoveLayer(df, lyr)
          arcpy.RefreshActiveView()
```

B3. Spline method.

```
import arcpy
import os
arcpy.CheckOutExtension("spatial")
for k in range(1,n):
  z=str(k)
  bg=(k-1)*250
  en=k*250
  n = r"e:\\SIG\\n"+z
  if not os.path.exists(n): os.makedirs(n)
  t = r"e:\\SIG\\t"+z
  if not os.path.exists(t): os.makedirs(t)
  point = "C:\\Users\\Vongo0\\Desktop\\rain\\rain"+z+".shp"
```

```
for i in range(bg,en):
    arcpy.env.extent=arcpy.Extent(0,0,165000,145000)
    name=str(i)
    field="P"+name
    raster= "e:\\SIG\\n"+z+"\\"+name
    TXT= "e:\\SIG\\t"+z+"\\"+name.zfill(4)+".TXT"
    arcpy.gp.Spline_sa(point, field, raster, "1000", "REGULARIZED", "0.1", "12")
    arcpy.RasterToASCII_conversion(name, TXT)
    mxd = arcpy.mapping.MapDocument("CURRENT")
    df = arcpy.mapping.ListDataFrames(mxd)[0]
    for lyr in arcpy.mapping.ListLayers(mxd, "", df):
        if lyr.name.lower() == name:
            arcpy.mapping.RemoveLayer(df, lyr)
        arcpy.RefreshActiveView()
```

B4. Geographically weighted regression method.

```
import arcpy
import os
arcpy.CheckOutExtension("GeoStats")
Point = "e:\\SIG\\point\\point.shp"
for i in range(1,n):
    z=str(i)
    start=(i-1)*250
    end=i*250
     t = r"e:\\SIG\\txt\\t"+z
    if not os.path.exists(t): os.makedirs(t)
    Data = "e:\\SIG\\data\\"+z+".shp"
```

```
for k in range(start,end):
    n = r"e:\\SIG\\output\\n"+str(k)
    if not os.path.exists(n): os.makedirs(n)
    n1=n
    Parameter = "e:\\SIG\\output\\n"+str(k)+"\\out.shp"
    Pre = "e:\\SIG\\output\\n"+str(k)+"\\result.shp"
    rain="P"+str(k)
    arcpy.GeographicallyWeightedRegression_stats(Data, rain, "Z1000", Parameter, "ADAPTIVE", "BANDWIDTH PARAMETER", "", "50", "", n1, "1000", Point, "Z", Pre)
    shapefile = "result"
    raster="e:\\SIG\\output\\n"+str(k)+"\\raster"
    arcpy.PointToRaster_conversion(shapefile, "Predicted", raster, "MOST_FREQUENT", "NONE", "4000")
    TXT= "e:\\SIG\\txt\\t"+z+"\\"+str(k).zfill(4)+".TXT"
    arcpy.RasterToASCII_conversion(raster, TXT)
    mxd = arcpy.mapping.MapDocument("CURRENT")
    df = arcpy.mapping.ListDataFrames(mxd)[0]
    for lyr in arcpy.mapping.ListLayers(mxd, "", df):
        if lyr.name.lower() == "z1000" or lyr.name.lower() == "out" or lyr.name.lower() == "intercept" or lyr.name.lower() == "result" or lyr.name.lower() == "raster":
            arcpy.mapping.RemoveLayer(df, lyr)
        arcpy.RefreshActiveView()
```

Appendix C: Make grid series .dfs2 for Mike model from ArcGIS output files.

The performance of distributed model in simulating the hydrological process is undeniable. However, there are still several existing problems when building these kinds of models. One of them is distributed data following the time and the space. Spatial distributed data at a time might be completely constructed by the support of ArcGIS. Therefore, the tool, which could merge all these data files into one grid series file, has not appeared seemingly yet. It makes difficulties when representing the variation of spatial factors due to the time such as the topography, land use, soil map, precipitation.... etc. For example, Mike by DHI is one of distributed models. It supplies the function to input grid series ‘fully distributed or dfs2 file’, but how to build these kinds of data? This is really a big question, at least with a long project. It is to be hoped that this simple manual would take a small part to solve this limitation.

C1. Define the difference between 2 format txts.

ArcGIS could export data under txt file or ascii file. However, the format of these files could not input directly by Mike model. DHI produced a module in Mike Zero to convert txt file/ ascii file to dfs2, but it just apply for one step data. The mission is looking for a method to reform and combine txt files which Mike model can read.

a) ARCGIS output format (Data for one step):

ncols 6

nrows 6

xllcorner 842126.66487

yllcorner 1776128.65037

cellsize 50.00000

NODATA_value -9999

18.5770 18.5652 18.5550 18.5467 18.5403 18.5358

18.5502 18.5376 18.5267 18.5177 18.5107 18.5060

18.5241 18.5105 18.4988 18.4891 18.4816 18.4764

18.4987 18.4841 18.4715 18.4609 18.4527 18.4470

18.4742 18.4585 18.4447 18.4332 18.4242 18.4179

18.4508 18.4338 18.4188 18.4061 18.3960 18.3891

b) Txt file/ ascii file format requiring by Mike family (merged for many time steps)

"VU GIA THU BON – VIET NAM" ""

"Dim" 2

"Geo" "PROJCS["WGS_1984_UTM_Zone_48N",GEOGCS["GCS_WGS_1984",DATUM["D_WGS_1984",SPHEROID["WGS_1984",6378137,298.257223563]],PRIMEM["Greenwich",0],UNIT["Degree",0.0174532925199433295]],PROJECTION["Transverse_Mercator"],PARAMETER["False_Easting",500000],PARAMETER["False_Northing",0],PARAMETER["Central_Meridian",105],PARAMETER["Scale_Factor",0.9996],PARAMETER["Latitude_Of_Origin",0],UNIT["Meter",1]]" 108.197 16.0414 0.884237

"Time" "EqudistantTimeAxis" "2007-11-10" "19:00:00" 5 86400

"NoGridPoints" 6 6

"Spacing" 50 50

"NoStaticItems" 0

"NoDynamicItems" 1

"Item" "ArcView Grid Data" "Precipitation Rate" "mm/day"

NoCustomBlocks 1

"M21_Misc" 1 7 0.798237 0 -900 0 0 0 0

"Delete" -1E-035

"DataType" 0

"tstep" 0 "item" 1 "layer" 0

18.577 18.5652 18.555 18.5467 18.5403 18.5358

18.5502 18.5376 18.5267 18.5177 18.5107 18.506

18.5241 18.5105 18.4988 18.4891 18.4816 18.4764

18.4987 18.4841 18.4715 18.4609 18.4527 18.447

18.4742 18.4585 18.4447 18.4332 18.4242 18.4179

18.4508 18.4338 18.4188 18.4061 18.396 18.3891

"tstep" 1 "item" 1 "layer" 0

65.6212 65.5434 65.4755 65.4183 65.3727 65.3392

65.5318 65.4491 65.3768 65.3159 65.2673 65.232

65.4457 65.3576 65.2802 65.2149 65.163 65.1254

65.3638 65.2694 65.1861 65.1157 65.0597 65.0194

65.2868 65.1854 65.0953 65.0187 64.9577 64.9142

65.2162 65.1067 65.0086 64.9246 64.8575 64.8098

"tstep" 2 "item" 1 "layer" 0

302.812 302.802 302.792 302.783 302.774 302.766

302.836 302.826 302.816 302.807 302.798 302.789

302.861 302.851 302.841 302.831 302.821 302.812

302.887 302.875 302.865 302.854 302.845 302.835

302.912 302.901 302.889 302.878 302.868 302.858

302.938 302.926 302.914 302.902 302.892 302.882

"tstep" 3 "item" 1 "layer" 0

149.476 149.529 149.574 149.611 149.638 149.654

149.158 149.217 149.268 149.309 149.34 149.359

148.835 148.901 148.959 149.006 149.042 149.063

148.506 148.581 148.646 148.701 148.742 148.766

148.17 148.254 148.329 148.392 148.44 148.469

147.825 147.92 148.006 148.079 148.136 148.171

"tstep" 4 "item" 1 "layer" 0

7.93192 7.93278 7.93358 7.93434 7.93508 7.93582

7.94639 7.94717 7.9479 7.94861 7.9493 7.95001

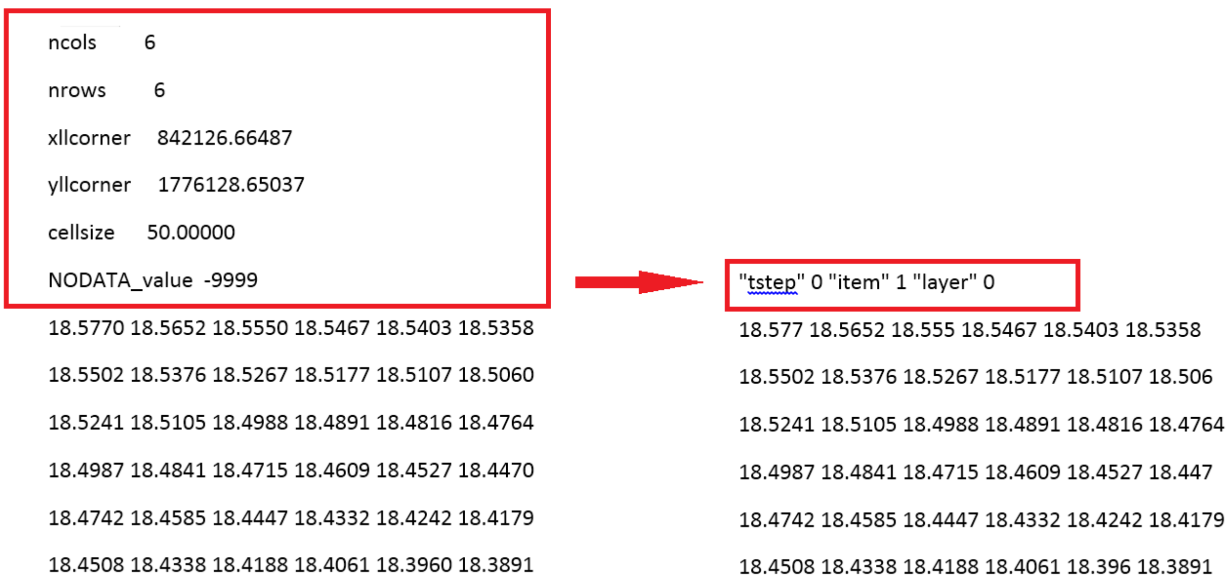
7.96091 7.9616 7.96224 7.96287 7.96352 7.9642

7.97549 7.97608 7.97662 7.97716 7.97773 7.97837

7.99017 7.99062 7.99104 7.99147 7.99195 7.99253

8.00495 8.00527 8.00553 8.00582 8.00618 8.00669

C2. Reform the format.



Change the format of each txt/ascii file by the Python code as follow (put all files txt/ascii in same folder, change corresponding information and run the code).

```
for i in range(start step ,end step):
name="C:\\Users\\TEMP.AQUACLOUD.002\\Desktop\\Ma2\\"+str(i)+".txt"
s="tstep "
f=open(name,"r+")
```

```
data=f.read()

k=data.replace("ncols 6\nnrows 6\nxllcorner 842126.66487\nyllcorner 1776128.65037\ncellsize 50\nNODATA_value -9999","*tstep* "+str(i)+" *item* 1 *layer* 0")

s=str(k)

a=open(name,"r+")

a.write(s)

a.close()
```

C3. Merge all to one file.

For this step, after converting, need to establish the part for the first txt file that could provide general informationse.x coordinate system, time step, amount of step, type of data, unit… as below:

"VU GIA THU BON – VIET NAM" ""

"Dim" 2

"Geo" "PROJCS["WGS_1984_UTM_Zone_48N",GEOGCS["GCS_WGS_1984",DATUM["D_WGS_1984",SPHEROID["WGS_1984",6378137,298.257223563]],PRIMEM["Greenwich",0],UNIT["Degree",0.0174532925199433295]],PROJECTION["Transverse_Mercator"],PARAMETER["False_Easting",500000],PARAMETER["False_Northing",0],PARAMETER["Central_Meridian",105],PARAMETER["Scale_Factor",0.9996],PARAMETER["Latitude_Of_Origin",0],UNIT["Meter",1]]" 108.197 16.0414 0.884237

"Time" "EqudistantTimeAxis" "2007-11-10" "19:00:00" 5 86400

"NoGridPoints" 6 6

"Spacing" 50 50

"NoStaticItems" 0

"NoDynamicItems" 1

"Item" "ArcView Grid Data" "Precipitation Rate" "mm/day"

NoCustomBlocks 1

"M21_Misc" 1 7 0.798237 0 -900 0 0 0 0

"Delete" -1E-035

"DataType" 0

"tstep" 0 "item" 1 "layer" 0

18.577 18.5652 18.555 18.5467 18.5403 18.5358

18.5502 18.5376 18.5267 18.5177 18.5107 18.506

18.5241 18.5105 18.4988 18.4891 18.4816 18.4764

18.4987 18.4841 18.4715 18.4609 18.4527 18.447

18.4742 18.4585 18.4447 18.4332 18.4242 18.4179

18.4508 18.4338 18.4188 18.4061 18.396 18.3891

Then go to Command Prompt, introduce the contained folder, call the command ‘copy/a*.txt output.txt’

C4. Make the dfs2 file.

Open Mike Zero model => Open a new file => choose new grid series => choose ‘from AscII file” => introduce the file.

Appendix D: Simulation specification and model processing of MIKE SHE

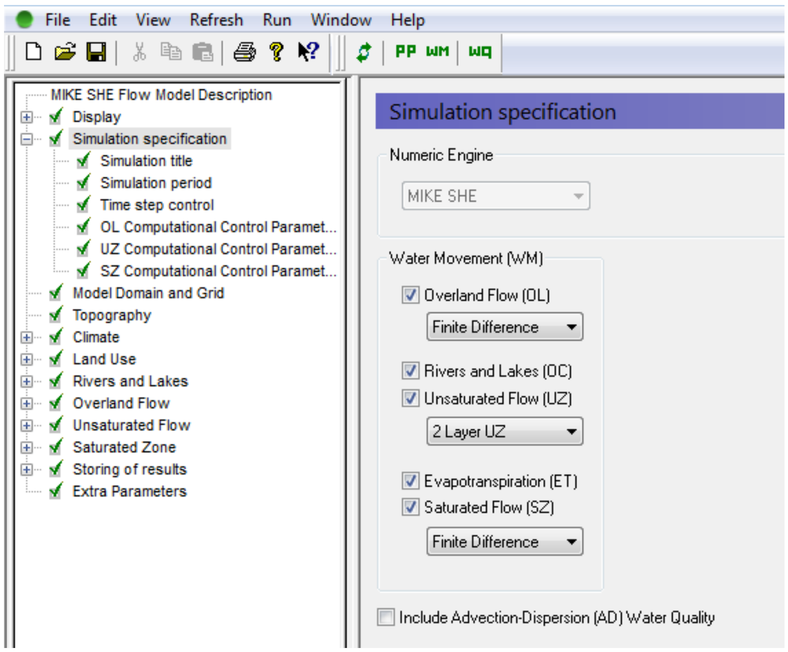


Figure D1. MIKE SHE model specification for Vu Gia Thu Bon simulation.

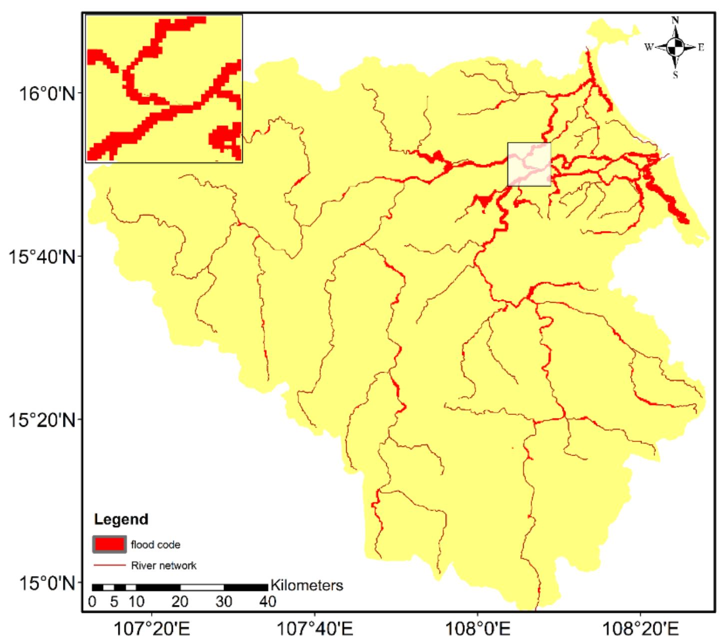


Figure D2. Flood code map automatically created in MIKE SHE.

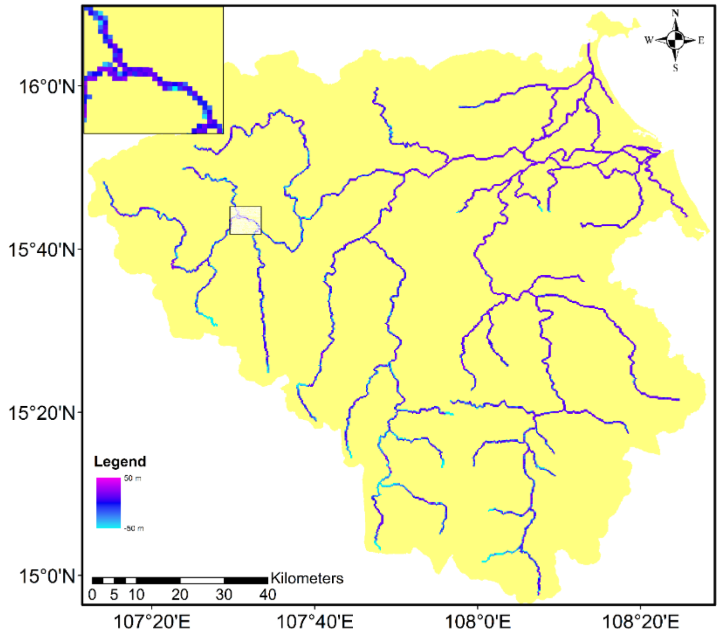


Figure D3. Difference between river bank and cross section in MIKE SHE.

Appendix E: Flood model data input.

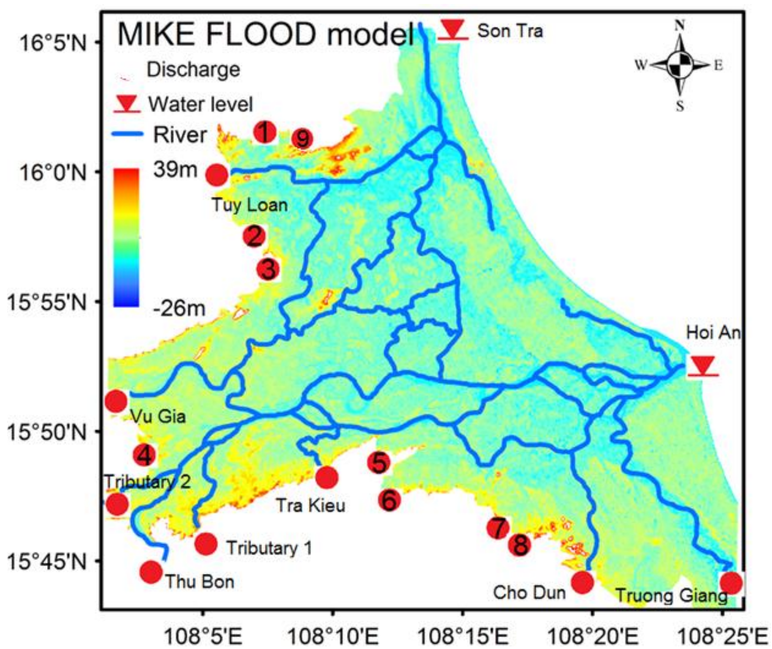


Figure E1. Boundary condition setting in MIKE FLOOD.

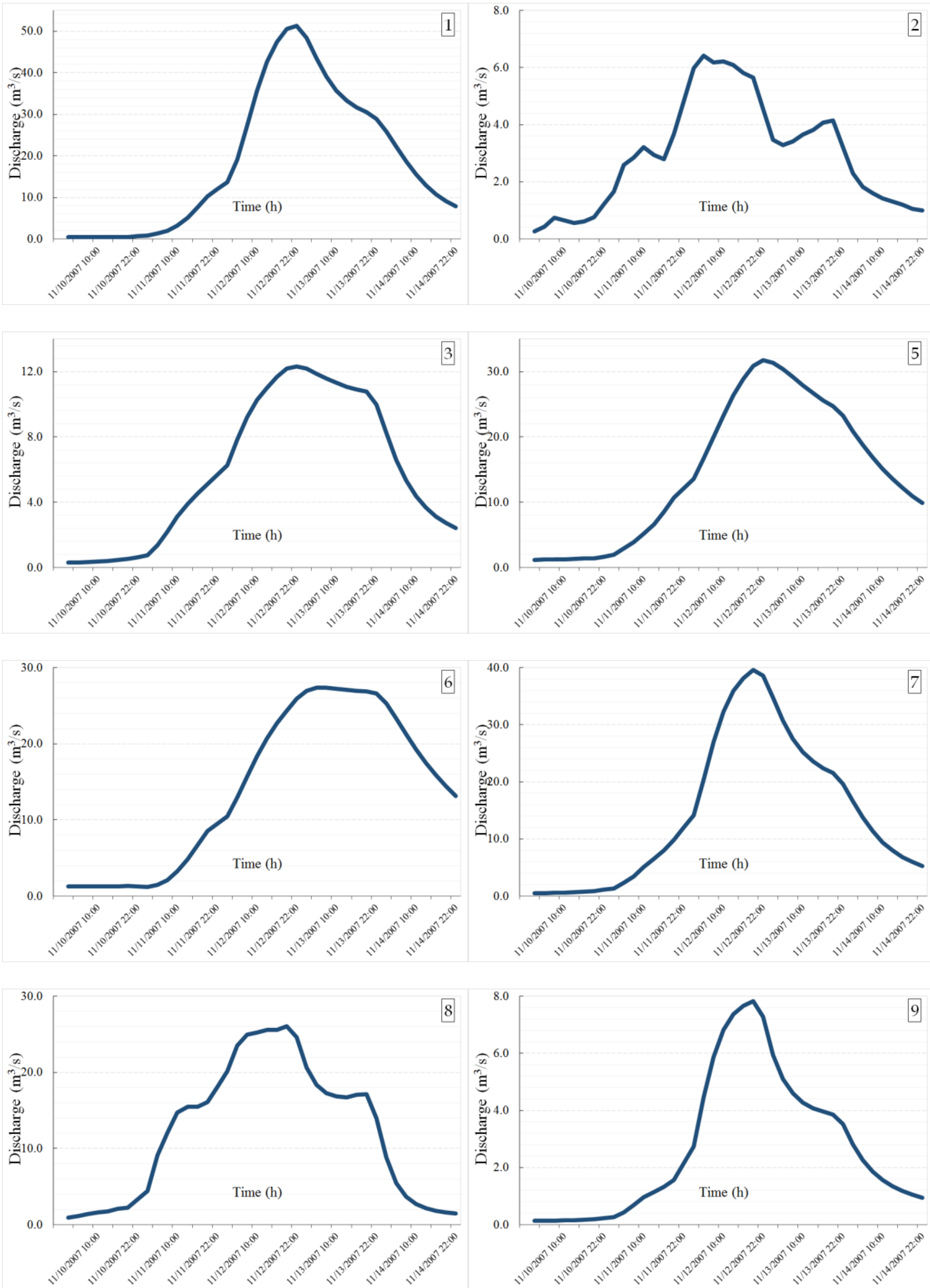


Figure E2. Input data corresponding with the setting in Figure E1

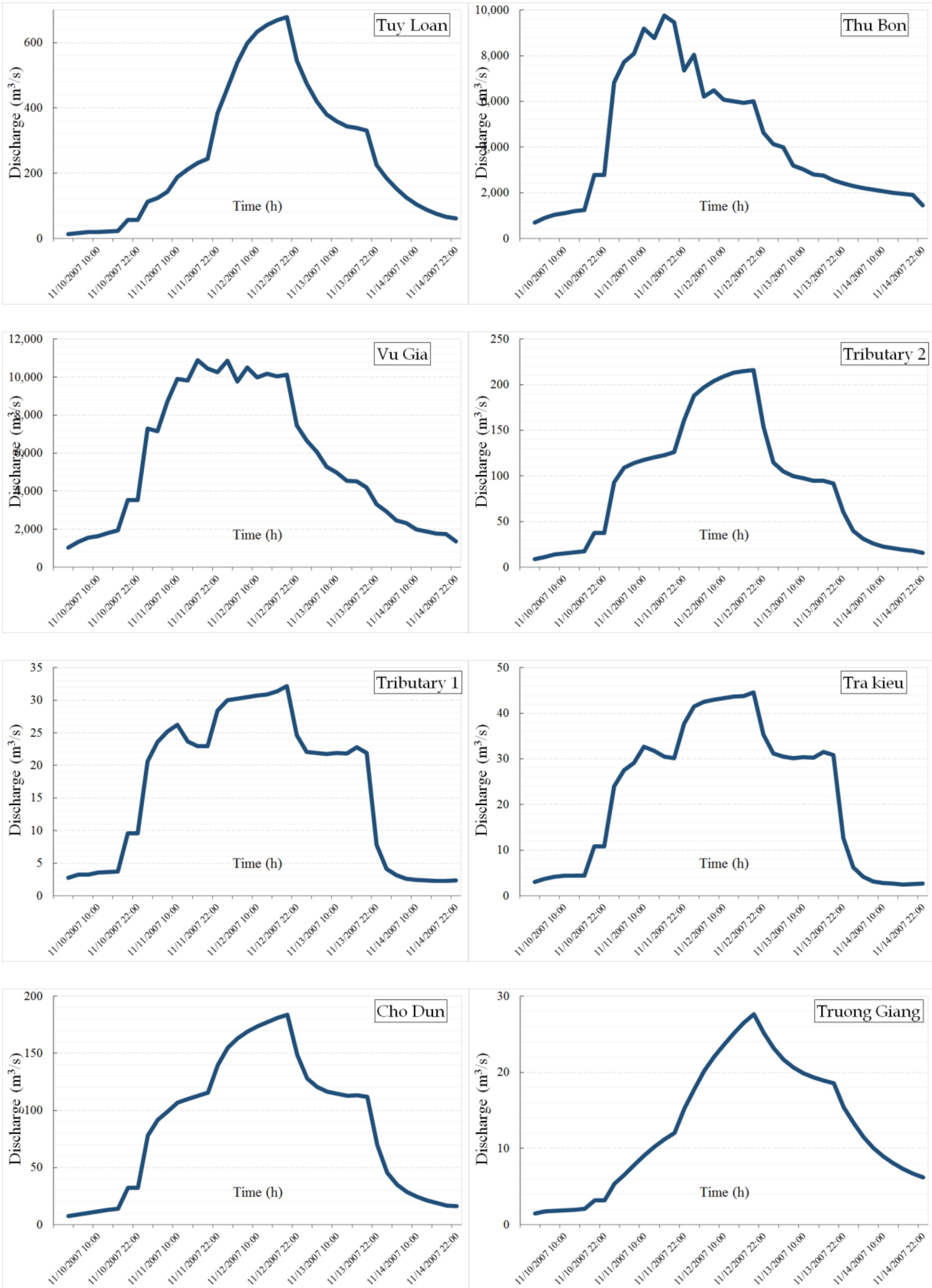


Figure E3. Input data corresponding with the setting in Figure E1

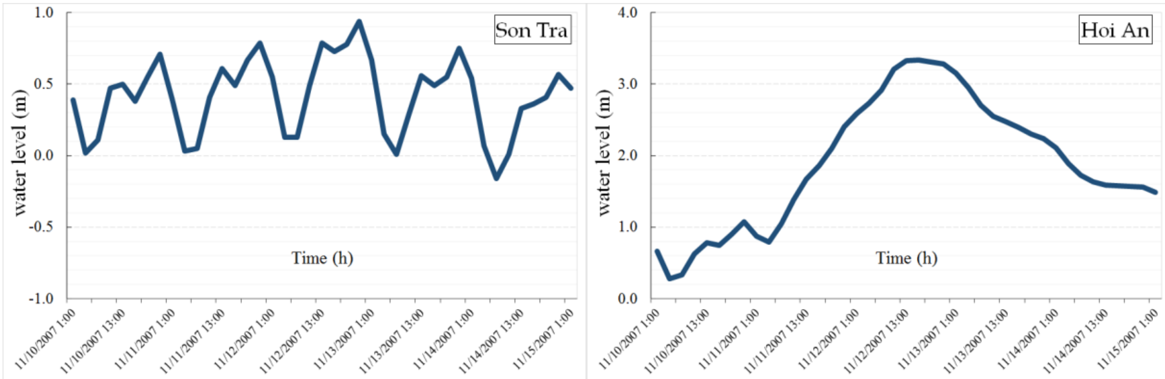


Figure E4. Input data corresponding with the setting in Figure E1

Appendix F: Data for climate change.

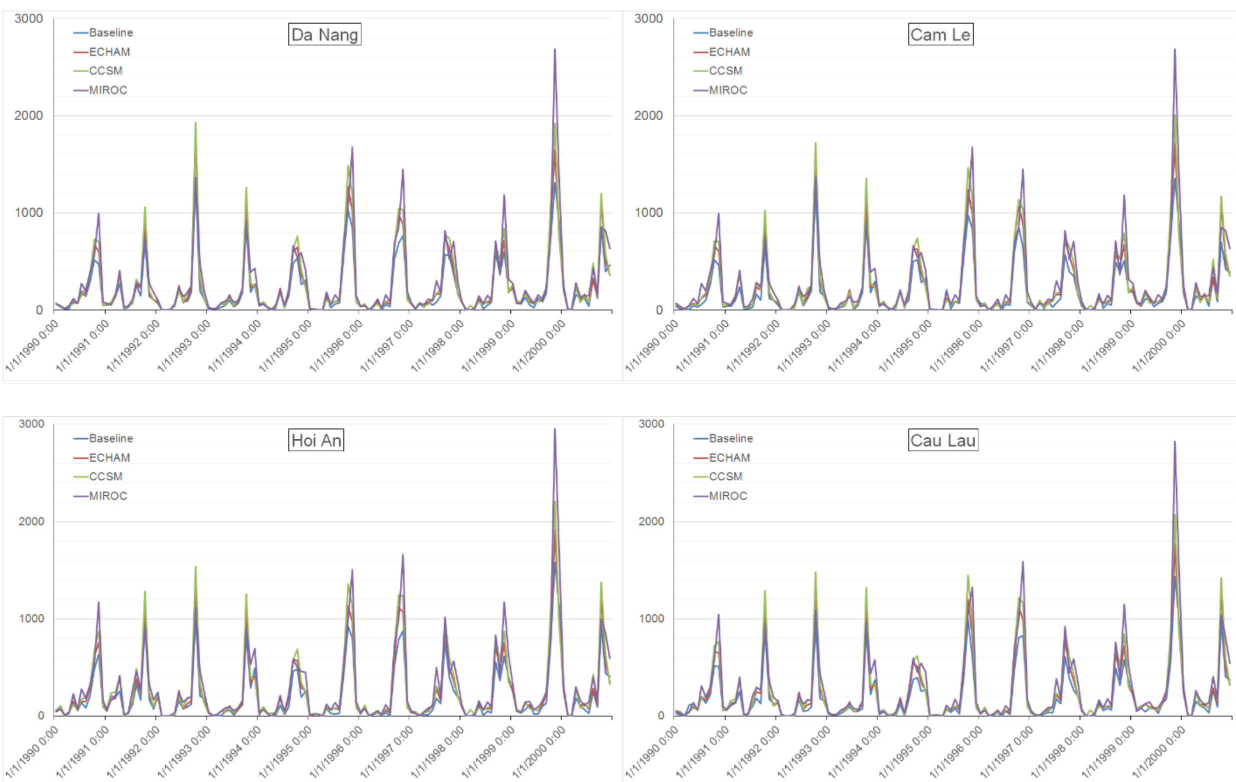


Figure E4. Rainfall scenario for future variation estimation.

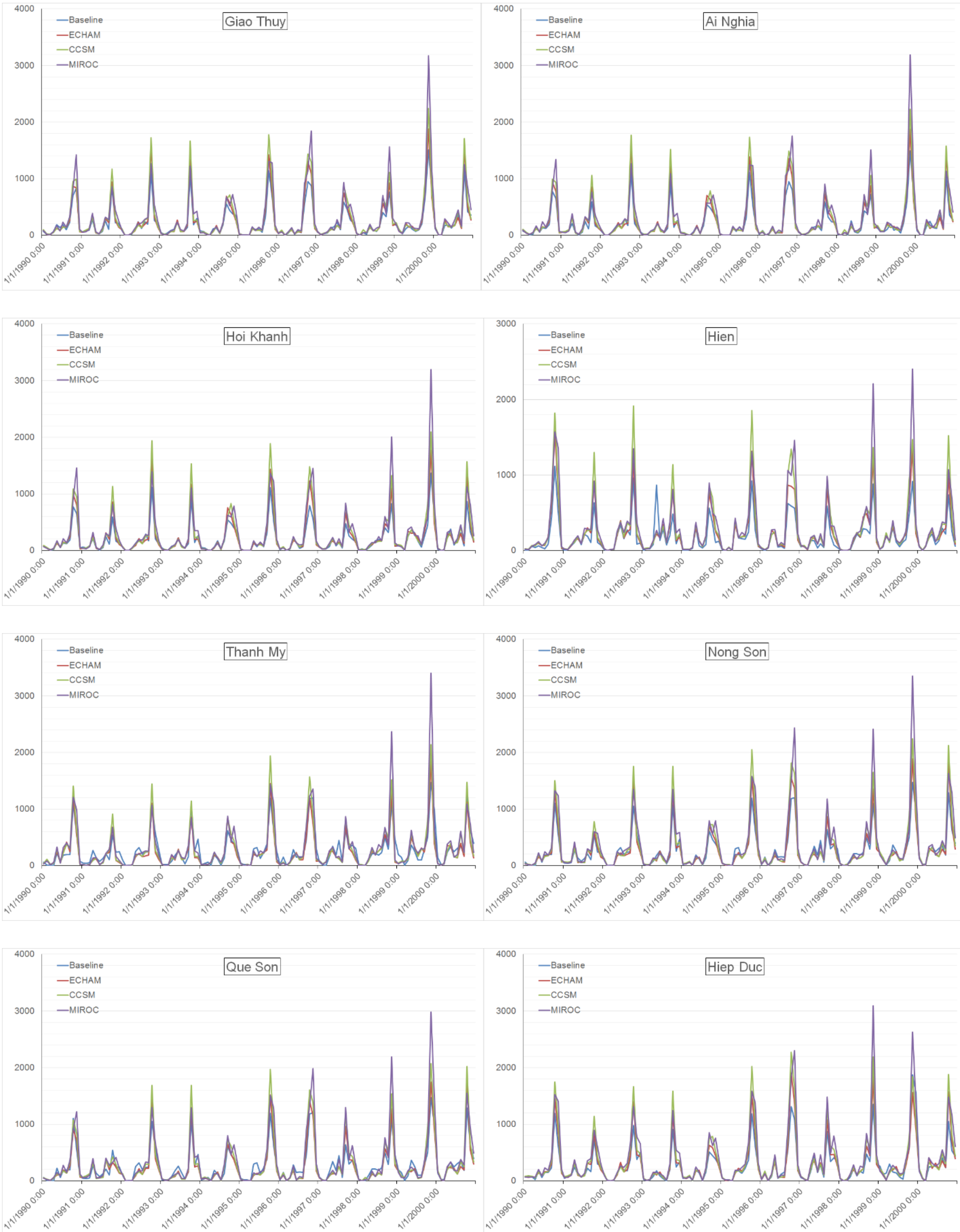


Figure E5. Rainfall scenario for future variation estimation.

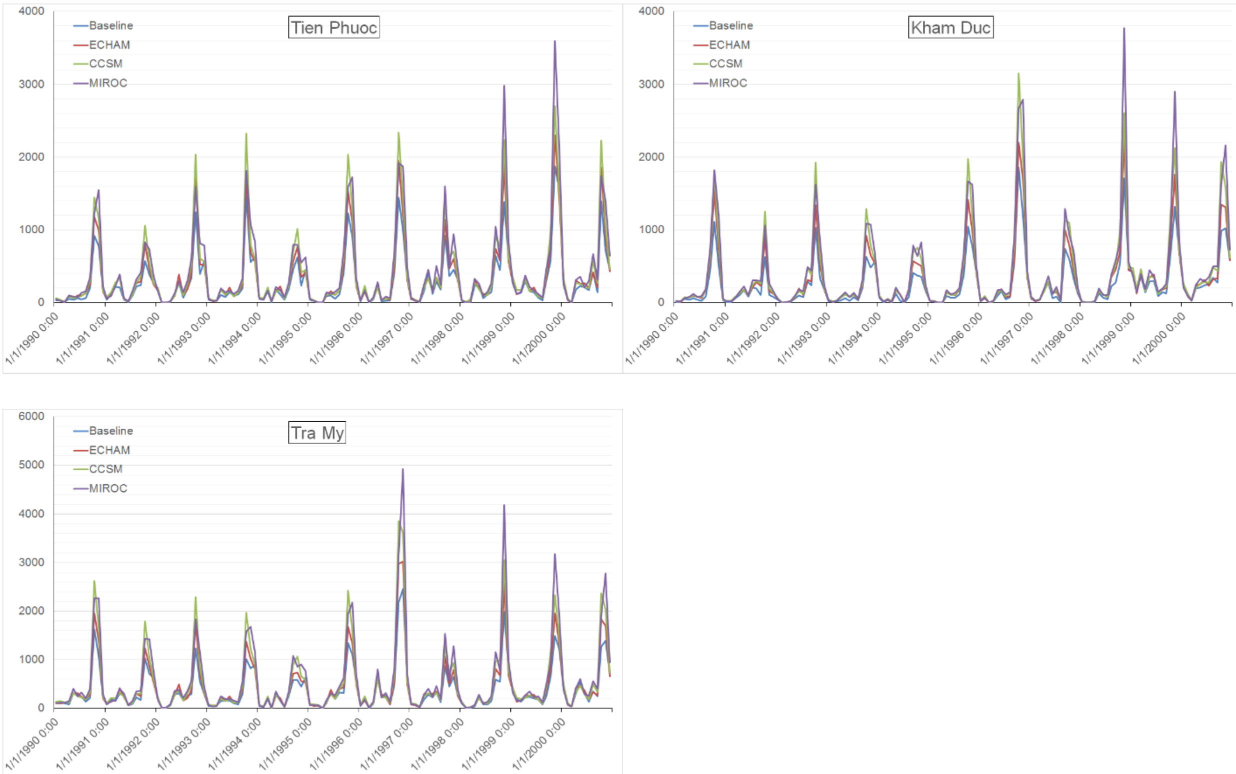


Figure E6. Rainfall scenario for future variation estimation of river flow.

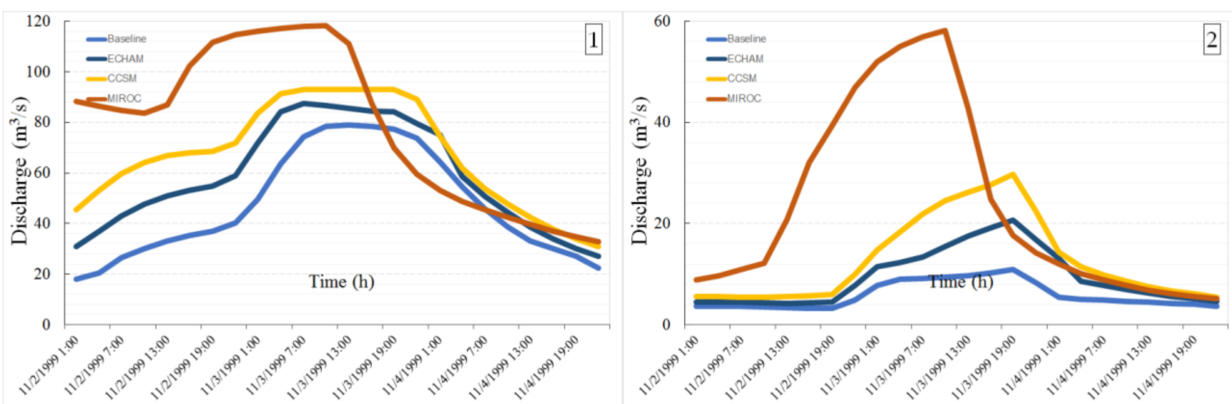


Figure E7. Boundary data for future variation estimation of inundation area.

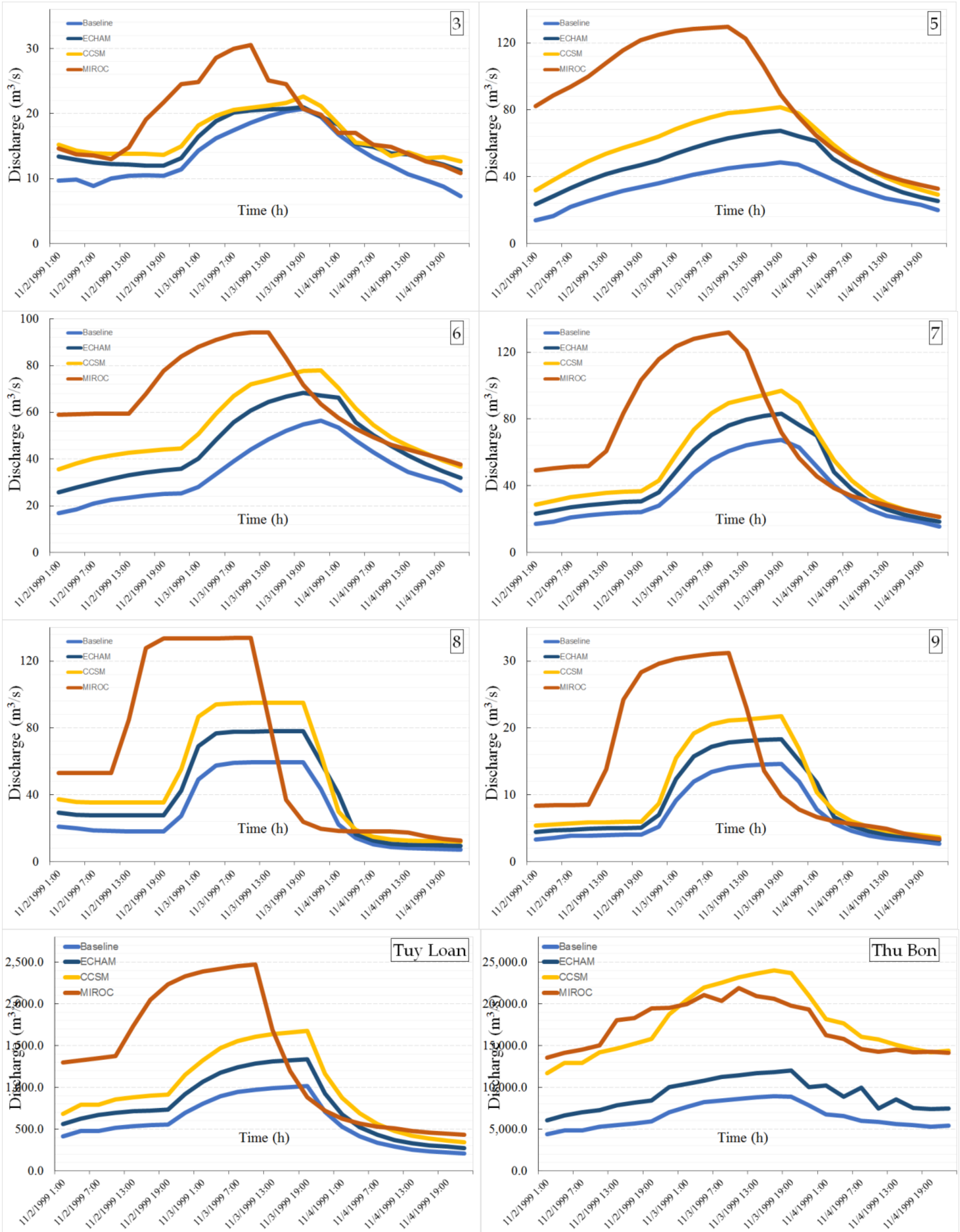


Figure E8. Boundary data for future variation estimation of inundation area.

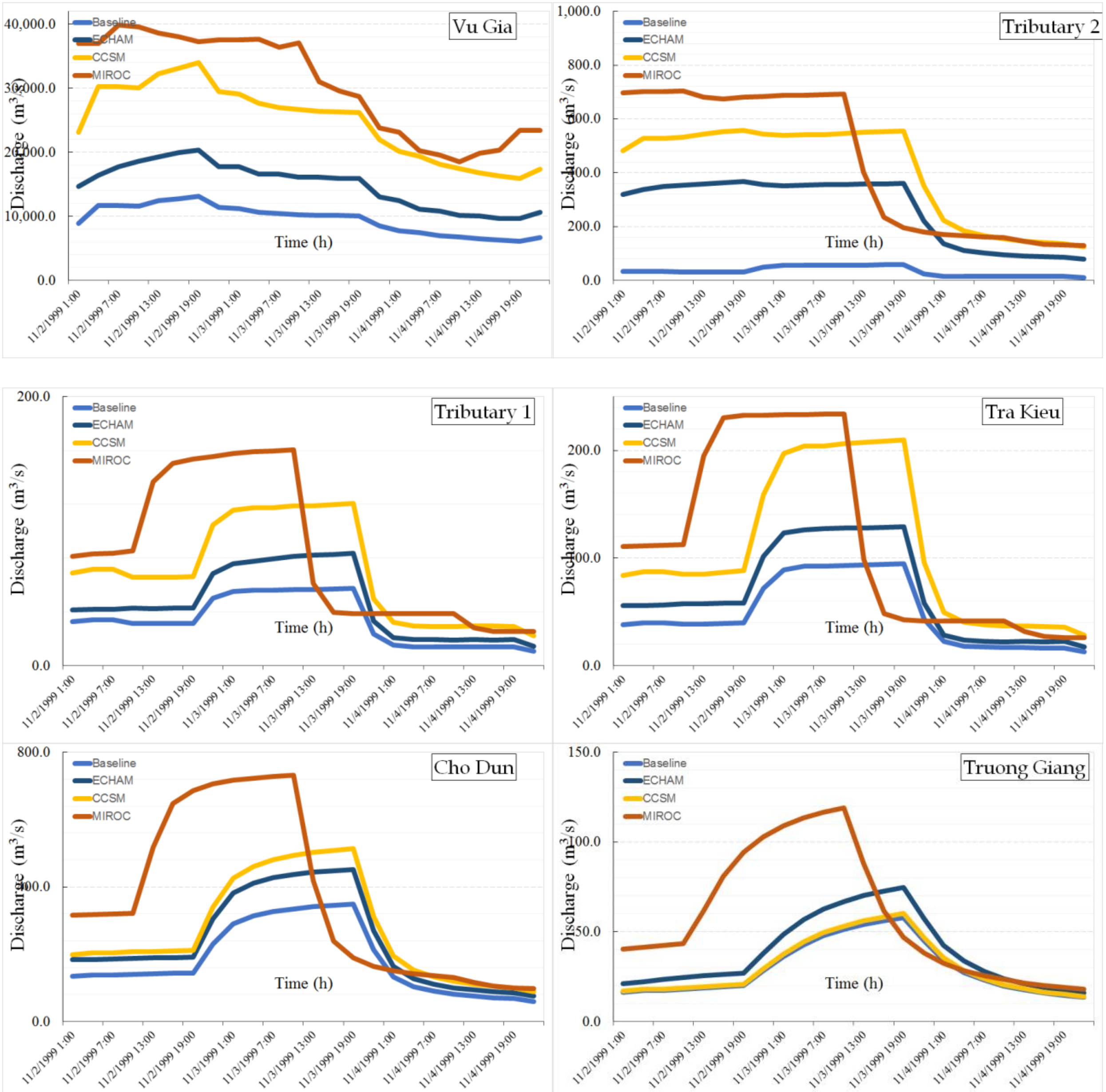
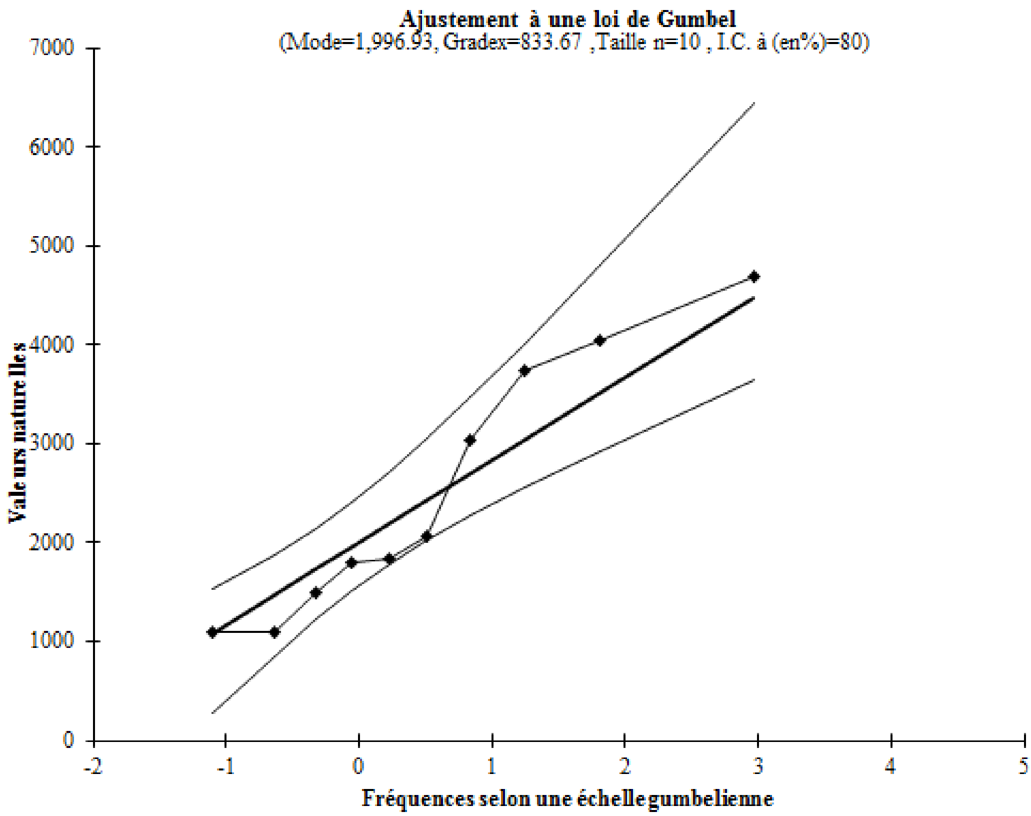


Figure E9. Boundary data for future variation estimation of inundation area.

Appendix F: La méthode de renouvellement

The “méthode du renouvelement” is a new issue what is generated by EDF group to solve the weakness when estimating the frequency for a short data time series (MeteoFrance, 2014). The main principle of this method is to generalize the classical POT by allowing the exceedances over the threshold to follow a probability distribution which can differ from the Generalised Pareto Distribution (GPD). Weibull or gamma exceedances are sometimes preferred to GPD exceedances. The special case of exponential exceedances (which falls in the three families: GPD, Weibull and gamma) has a special interest since it allows exact inference for the (scalar) parameter and for the quantiles form OT data (only) (Deville & IRSN, 2015). This method is generally used by hydrologists for estimating extreme values of inundation. It has a possibility to evaluate exceptional events (occurring is on average once every 5, 10, 20, 30, 50 and 100 years) for series with at least 10 years of data. Selecting all higher than a threshold event which keeps in general more than one event per year (MeteoFrance, 2014).

Application: Due to the limit of measured data in Vu Gia Thu Bon catchment, méthode du renouvelement is applied to estimate the change in frequency of extreme river flow between current period and future. In this study, the méthode du renouvelement is realized under the support of Hydrolab 2010 which is one small software writing on Excel environment by Professor J.P. LABORDE



Ajustement à une loi de Gumbel

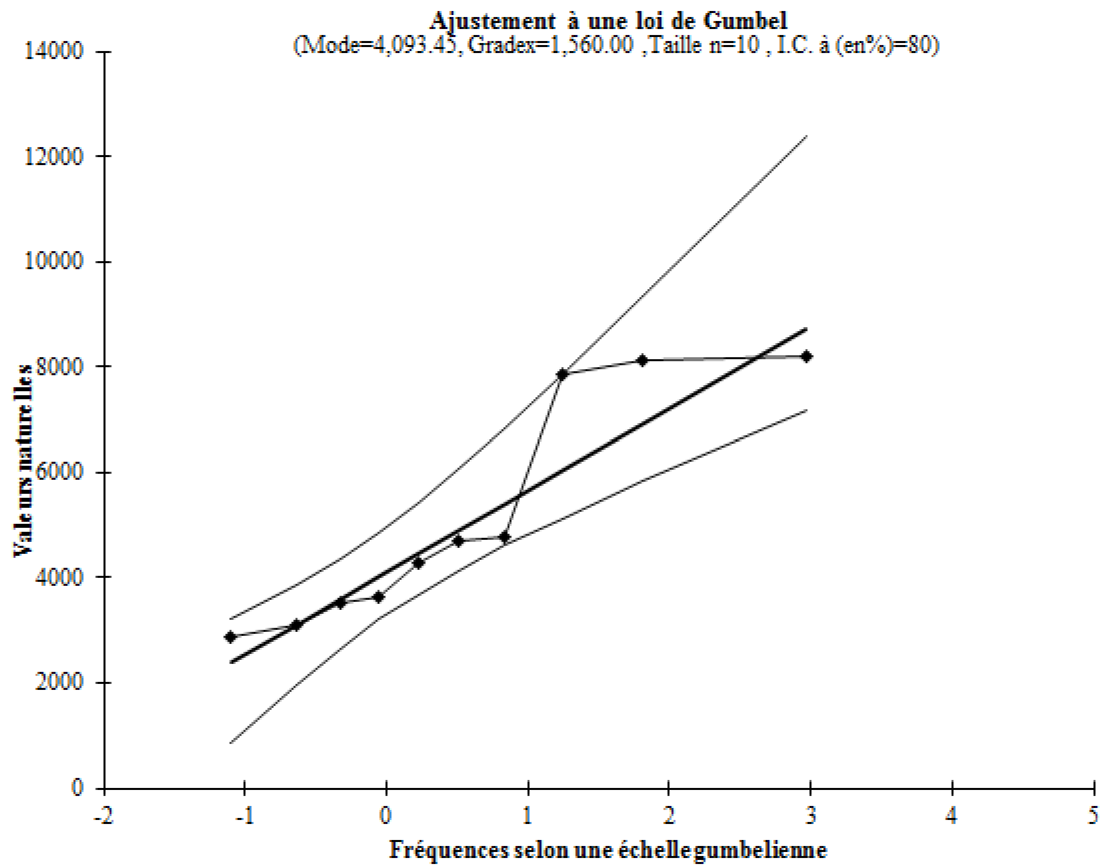
% U Anderson = 0.197

Mode= 1996.9305 | Taille n= 10 | I.C. à (en%)= 80

Gradex= 833.67033 | Nb au départ (10) | U Gauss= 1.282

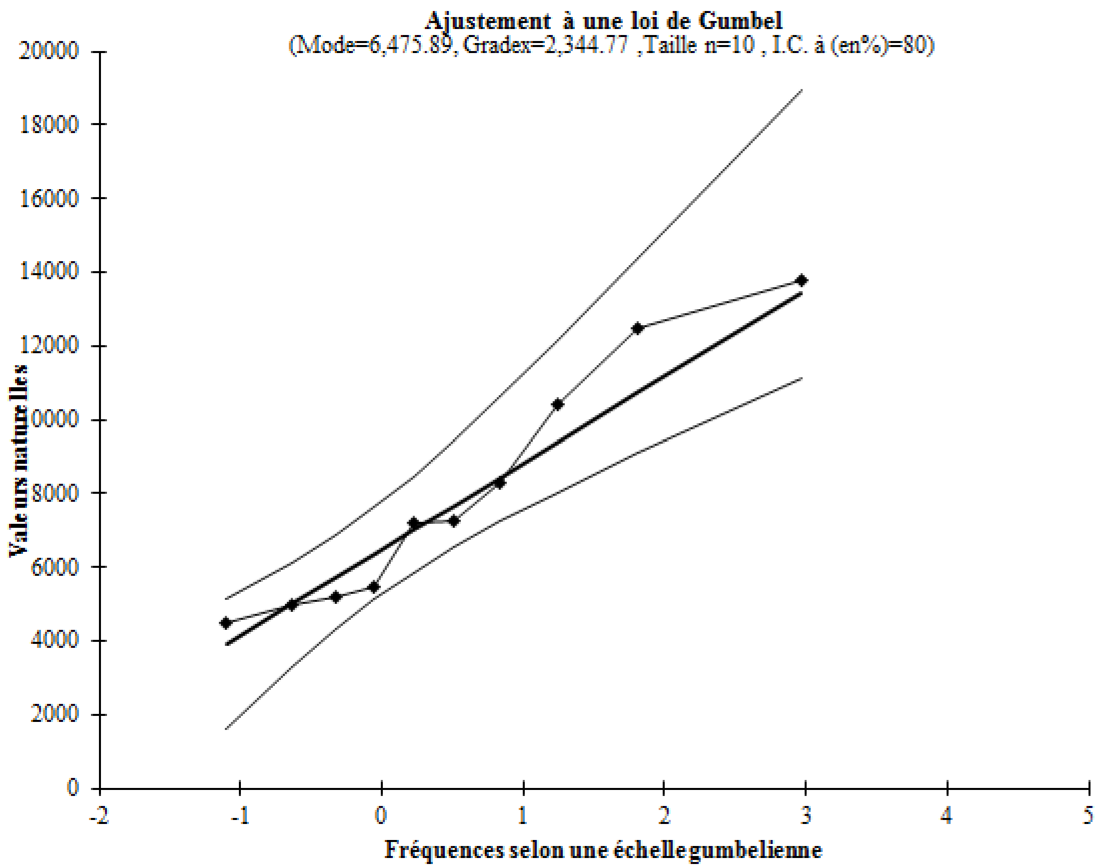
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	1090.52	1	0.0500	-1.097	1090.52	1082.2368	269.9264	1522.412
Obs.3	1091.27	2	0.1500	-0.640	1091.27	1463.1006	854.04886	1868.1709
Obs.2	1487.62	3	0.2500	-0.327	1487.62	1724.6252	1222.443	2138.2909
Obs.5	1795.93	4	0.3500	-0.049	1795.93	1956.3968	1517.7452	2408.8606
Obs.4	1828.38	5	0.4500	0.225	1828.38	2184.5152	1777.2019	2706.3564
Obs.7	2064.04	6	0.5500	0.514	2064.04	2425.8015	2021.8383	3050.8221
Obs.10	3025.13	7	0.6500	0.842	3025.13	2699.0068	2271.546	3468.147
Obs.9	3738.24	8	0.7500	1.246	3738.24	3035.5998	2553.9387	4007.5483
Obs.6	4040.23	9	0.8500	1.817	4040.23	3511.6768	2927.3122	4796.5199
Obs.8	4692.34	10	0.9500	2.970	4692.34	4473.0941	3641.4448	6429.6941

Figure F1. Frequency estimation of “la méthode de renouvellement“ for Thanh My station at present.



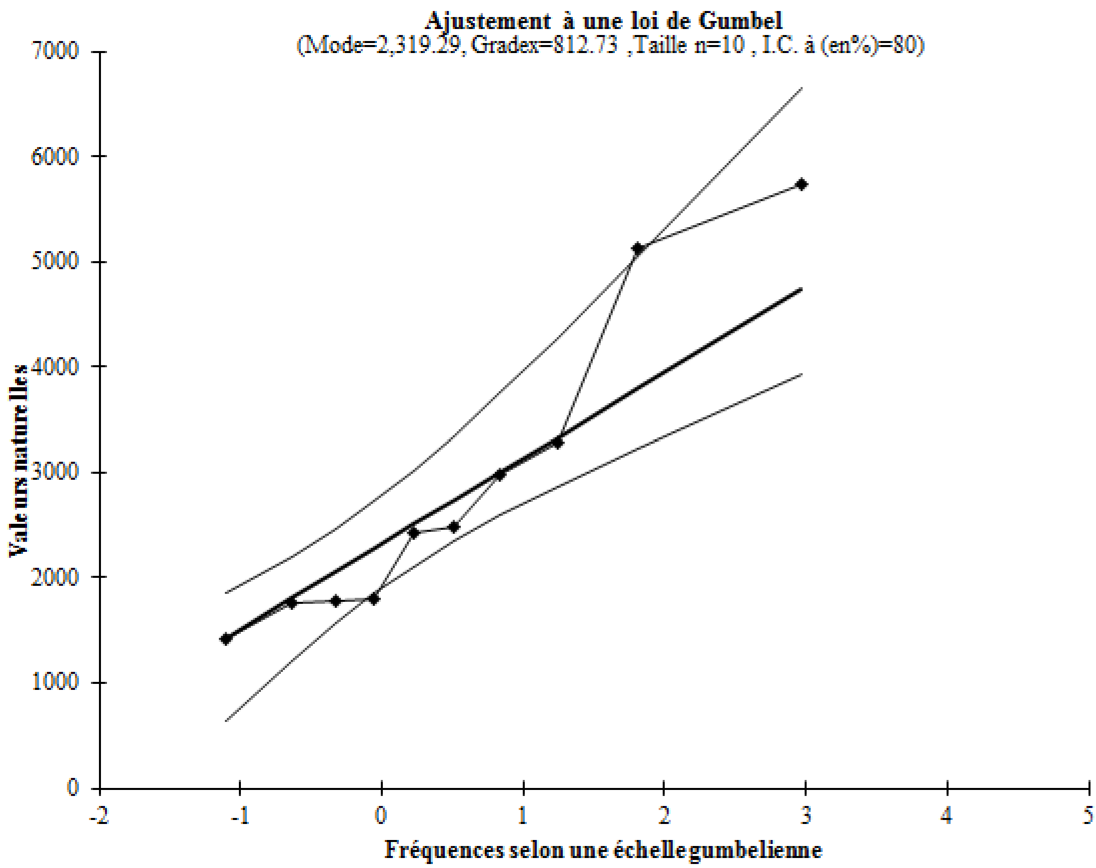
							% U Anderson =	0.244
		Ajustement à une loi de Gumbel						
	Mode=	4093.446269			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1560.001			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	2861.99	1	0.0500	-1.097	2861.99	2381.83	861.80	3205.51
Obs.3	3083.91	2	0.1500	-0.640	3083.91	3094.52	1954.84	3852.51
Obs.5	3536.8	3	0.2500	-0.327	3536.8	3583.90	2644.19	4357.97
Obs.1	3638.43	4	0.3500	-0.049	3638.43	4017.60	3196.77	4864.27
Obs.7	4288.7	5	0.4500	0.225	4288.7	4444.46	3682.28	5420.96
Obs.4	4695.02	6	0.5500	0.514	4695.02	4895.97	4140.05	6065.54
Obs.10	4781.79	7	0.6500	0.842	4781.79	5407.20	4607.32	6846.45
Obs.6	7870.32	8	0.7500	1.246	7870.32	6037.05	5135.74	7855.80
Obs.9	8118.79	9	0.8500	1.817	8118.79	6927.91	5834.42	9332.16
Obs.8	8188.22	10	0.9500	2.970	8188.22	8726.95	7170.73	12388.23

Figure F2. Frequency estimation of “la méthode de renouvellement“ for Nong Son station at present.



							% U Anderson =	0.309
		Ajustement à une loi de Gumbel						
	Mode=	6475.893136			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2344.77			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	4491.89	1	0.0500	-1.097	4491.89	3903.24	1618.54	5141.27
Obs.2	4997.76	2	0.1500	-0.640	4997.76	4974.45	3261.44	6113.75
Obs.3	5188.81	3	0.2500	-0.327	5188.81	5710.01	4297.58	6873.48
Obs.5	5461.97	4	0.3500	-0.049	5461.97	6361.89	5128.14	7634.48
Obs.4	7186.78	5	0.4500	0.225	7186.78	7003.49	5857.89	8471.22
Obs.7	7233.02	6	0.5500	0.514	7233.02	7682.13	6545.95	9440.05
Obs.10	8266.56	7	0.6500	0.842	8266.56	8450.54	7248.27	10613.82
Obs.6	10413.2	8	0.7500	1.246	10413.2	9397.24	8042.53	12130.93
Obs.8	12476	9	0.8500	1.817	12476	10736.25	9092.67	14349.98
Obs.9	13804.2	10	0.9500	2.970	13804.2	13440.32	11101.23	18943.42

Figure F3. Frequency estimation of “la méthode de renouvellement“ for Giao Thuy station at present.

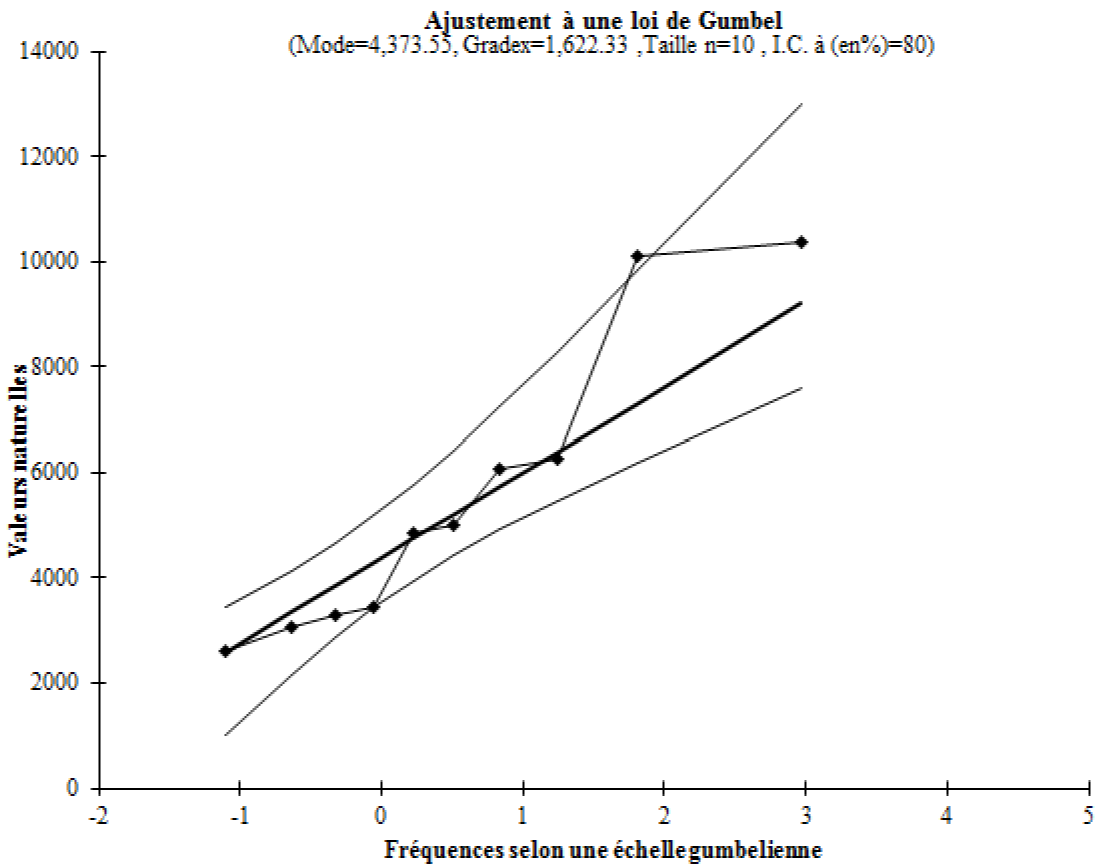


Ajustement à une loi de Gumbel

				% U Anderson =	0.187
Mode=	2319.292968	Taille n=	10	I.C. à (en%)=	80
Gradex=	812.728	Nb au départ	(10)	U Gauss=	1.282

Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	1426.42	1	0.0500	-1.097	1426.42	1427.58	635.67	1856.69
Obs.3	1751.87	2	0.1500	-0.640	1751.87	1798.87	1205.12	2193.77
Obs.5	1781.4	3	0.2500	-0.327	1781.4	2053.83	1564.26	2457.10
Obs.2	1791.06	4	0.3500	-0.049	1791.06	2279.78	1852.15	2720.88
Obs.4	2423.93	5	0.4500	0.225	2423.93	2502.17	2105.08	3010.90
Obs.7	2477.97	6	0.5500	0.514	2477.97	2737.39	2343.58	3346.71
Obs.10	2974.79	7	0.6500	0.842	2974.79	3003.73	2587.01	3753.55
Obs.6	3287.21	8	0.7500	1.246	3287.21	3331.87	2862.31	4279.40
Obs.8	5128.73	9	0.8500	1.817	5128.73	3795.99	3226.30	5048.55
Obs.9	5744.37	10	0.9500	2.970	5744.37	4733.25	3922.50	6640.70

Figure F4. Frequency estimation of “la méthode de renouvellement“ for Cau Lau station at present.



Ajustement à une loi de Gumbel

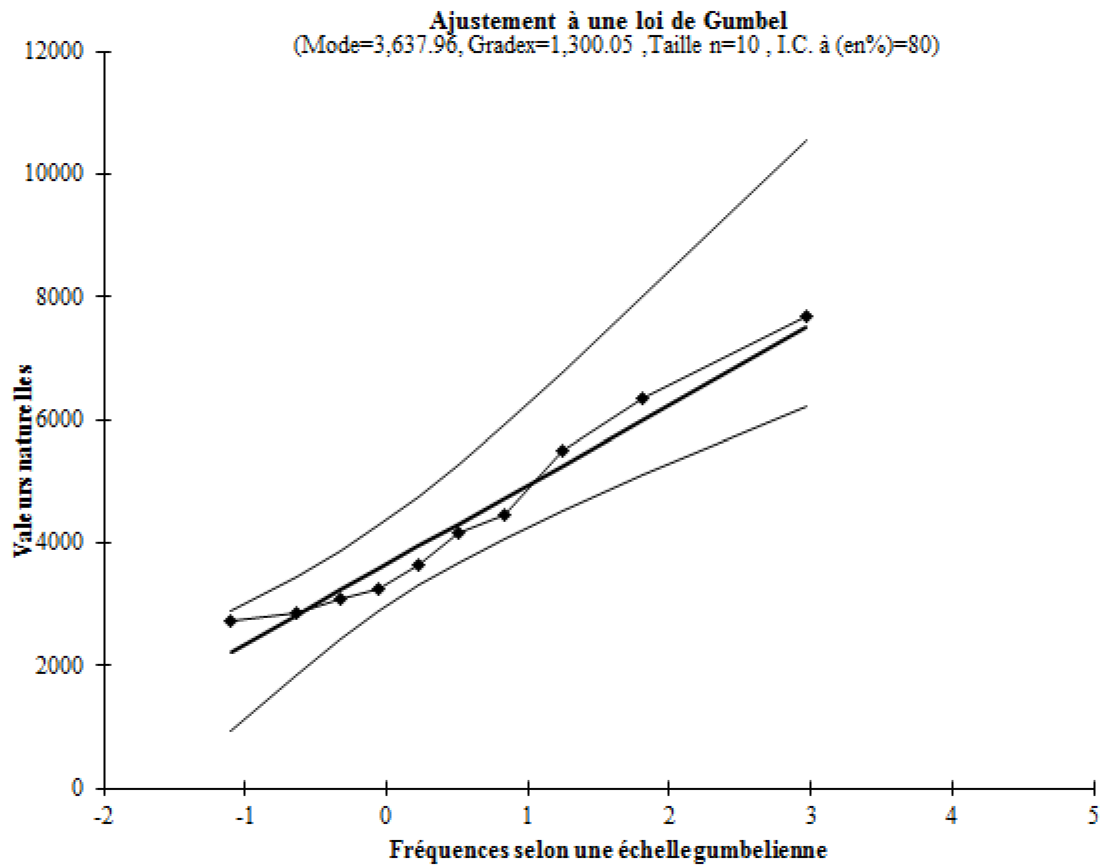
% U Anderson = 0.211

Mode= 4373.553505 | Taille n= 10 | I.C. à (en%)= 80

Gradex= 1622.331667 | Nb au départ (10) | U Gauss= 1.282

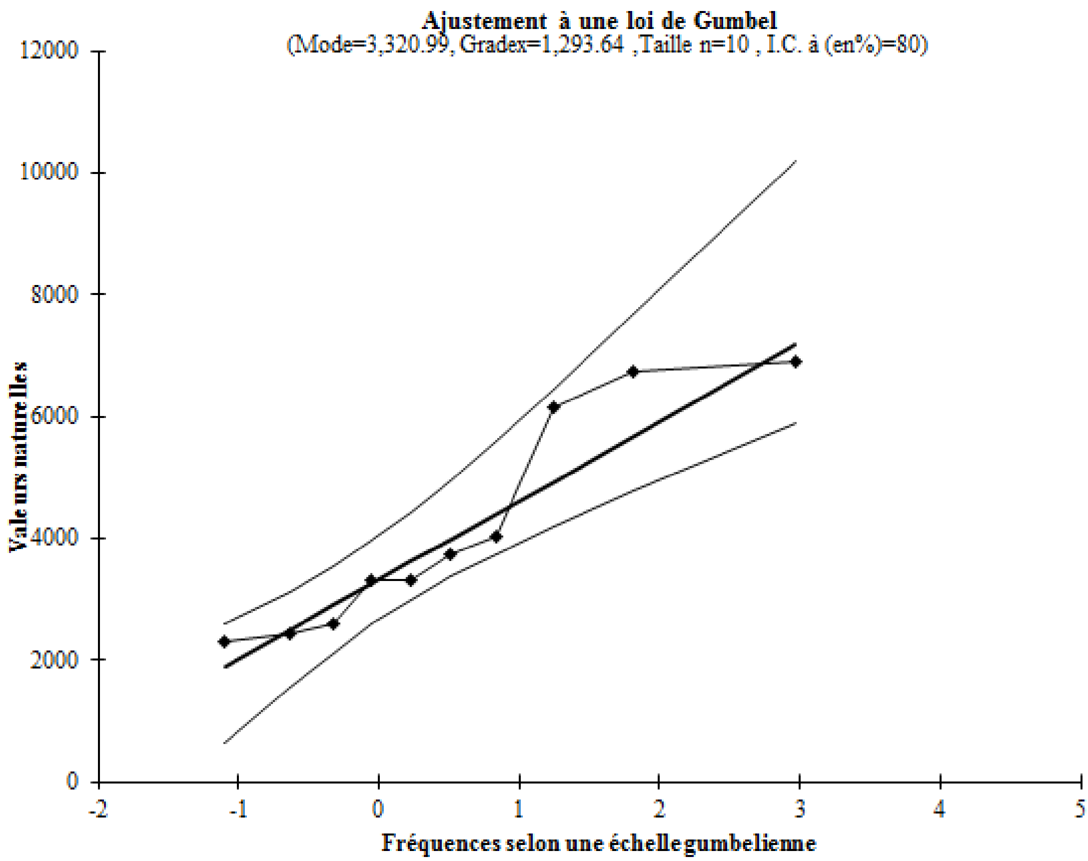
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	2591.24	1	0.0500	-1.097	2591.24	2593.55	1012.78	3450.14
Obs.3	3073.05	2	0.1500	-0.640	3073.05	3334.71	2149.49	4122.99
Obs.5	3299.34	3	0.2500	-0.327	3299.34	3843.64	2866.39	4648.64
Obs.2	3450.6	4	0.3500	-0.049	3450.6	4294.67	3441.05	5175.17
Obs.7	4867.19	5	0.4500	0.225	4867.19	4738.60	3945.96	5754.10
Obs.4	5001.51	6	0.5500	0.514	5001.51	5208.14	4422.02	6424.44
Obs.6	6077.25	7	0.6500	0.842	6077.25	5739.80	4907.96	7236.56
Obs.10	6260.16	8	0.7500	1.246	6260.16	6394.82	5457.50	8286.24
Obs.9	10084.7	9	0.8500	1.817	10084.7	7321.27	6184.09	9821.59
Obs.8	10348.4	10	0.9500	2.970	10348.4	9192.20	7573.80	12999.76

Figure F5. Frequency estimation of “la méthode de renouvellement“ for Hoi Khanh station at present..



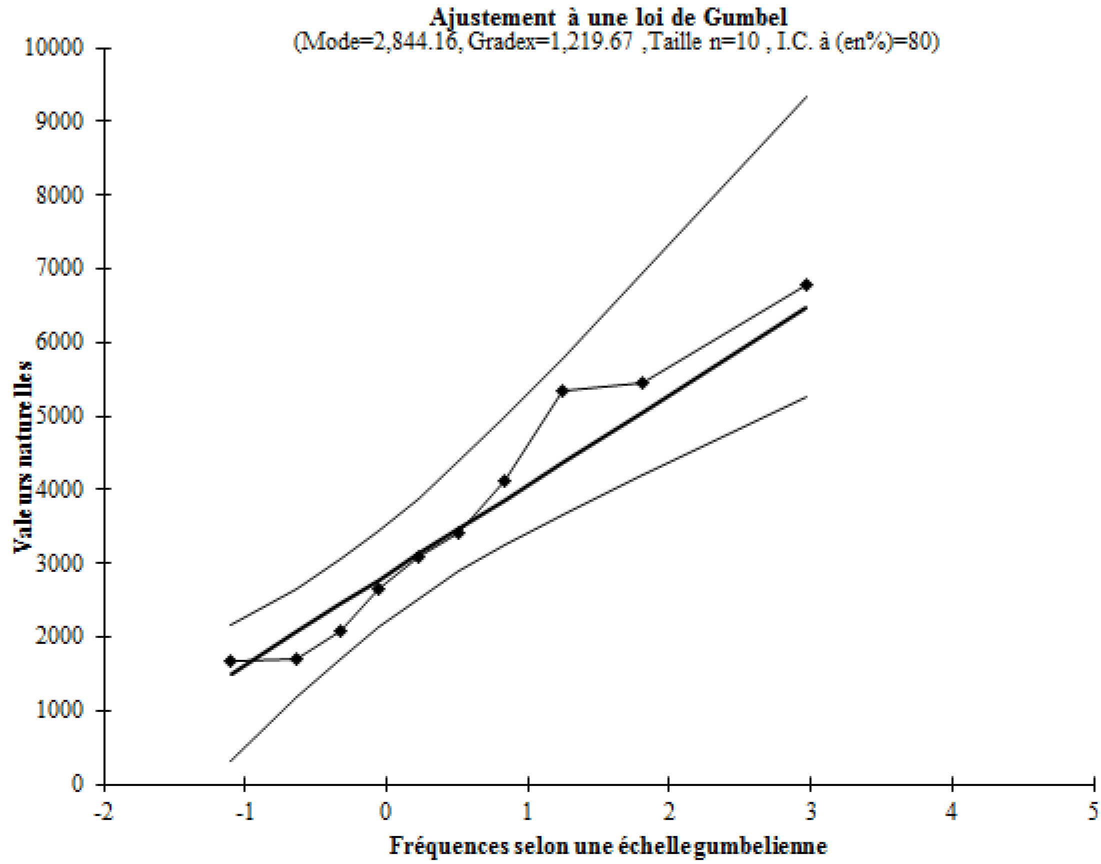
							% U Anderson =	0.351
			Ajustement à une loi de Gumbel					
	Mode=	3637.956033			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1300.054667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	2716.89	1	0.0500	-1.097	2716.89	2211.55	944.81	2897.98
Obs.3	2866.14	2	0.1500	-0.640	2866.14	2805.48	1855.71	3437.16
Obs.2	3079.32	3	0.2500	-0.327	3079.32	3213.31	2430.19	3858.40
Obs.5	3237.72	4	0.3500	-0.049	3237.72	3574.75	2890.70	4280.33
Obs.4	3645.79	5	0.4500	0.225	3645.79	3930.48	3295.30	4744.26
Obs.7	4164.36	6	0.5500	0.514	4164.36	4306.75	3676.80	5281.43
Obs.10	4455.05	7	0.6500	0.842	4455.05	4732.80	4066.20	5932.22
Obs.6	5480.98	8	0.7500	1.246	5480.98	5257.69	4506.57	6773.38
Obs.8	6340.91	9	0.8500	1.817	6340.91	6000.10	5088.83	8003.73
Obs.9	7684.48	10	0.9500	2.970	7684.48	7499.37	6202.47	10550.56

Figure F6. Frequency estimation of “la méthode de renouvellement“ for Cau Lau station at present.



			Ajustement à une loi de Gumbel				% U Anderson =	0.266
	Mode=	3320.987703			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1293.639			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	2287.58	1	0.0500	-1.097	2287.58	1901.62	641.13	2584.66
Obs.3	2415.25	2	0.1500	-0.640	2415.25	2492.62	1547.53	3121.19
Obs.5	2593.07	3	0.2500	-0.327	2593.07	2898.44	2119.19	3540.34
Obs.1	3293.94	4	0.3500	-0.049	3293.94	3258.09	2577.42	3960.20
Obs.7	3317.35	5	0.4500	0.225	3317.35	3612.07	2980.03	4421.83
Obs.10	3735.59	6	0.5500	0.514	3735.59	3986.48	3359.64	4956.35
Obs.4	4016.68	7	0.6500	0.842	4016.68	4410.43	3747.12	5603.93
Obs.9	6155.76	8	0.7500	1.246	6155.76	4932.73	4185.32	6440.94
Obs.8	6724.3	9	0.8500	1.817	6724.3	5671.48	4764.70	7665.22
Obs.6	6906.76	10	0.9500	2.970	6906.76	7163.35	5872.85	10199.48

Figure F7. Frequency estimation of “la méthode de renouvellement“ for Hiep Duc station at present.



Ajustement à une loi de Gumbel

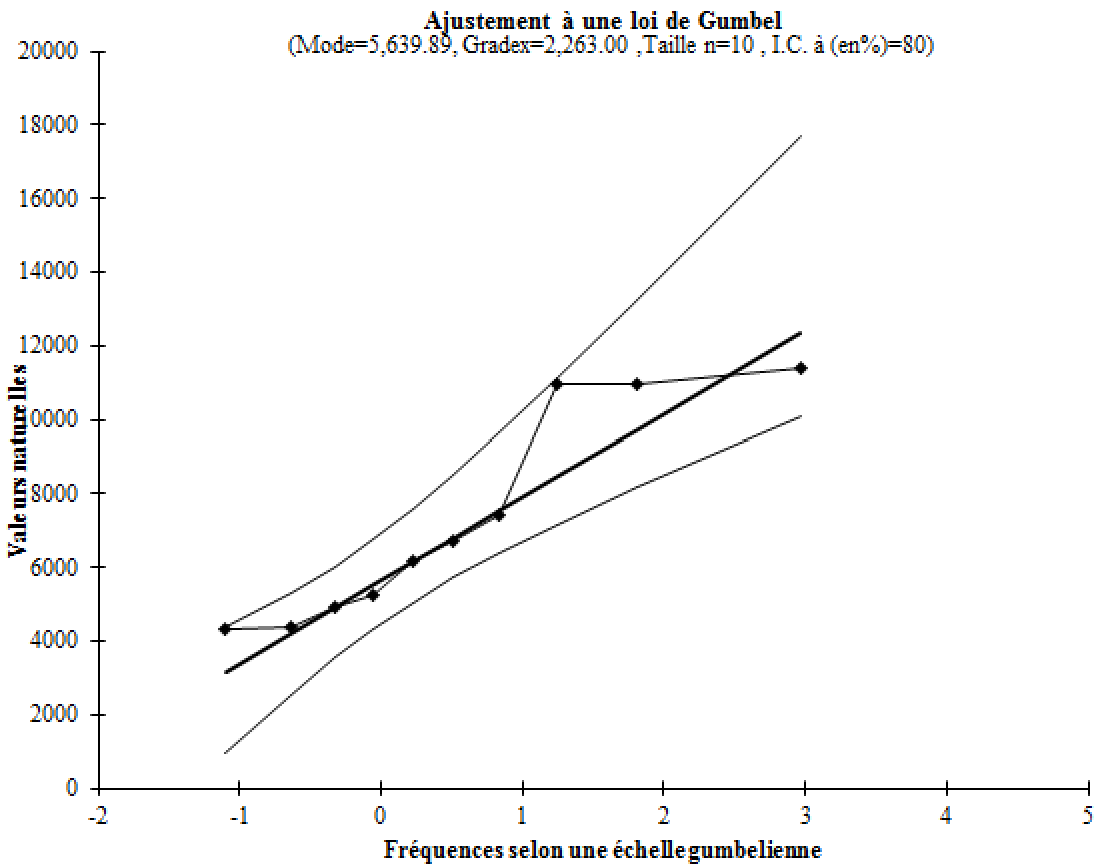
% U Anderson = 0.308

Mode= 2844.159577 | Taille n= 10 | I.C. à (en%)= 80

Gradex= 1219.674667 | Nb au départ (10) | U Gauss= 1.282

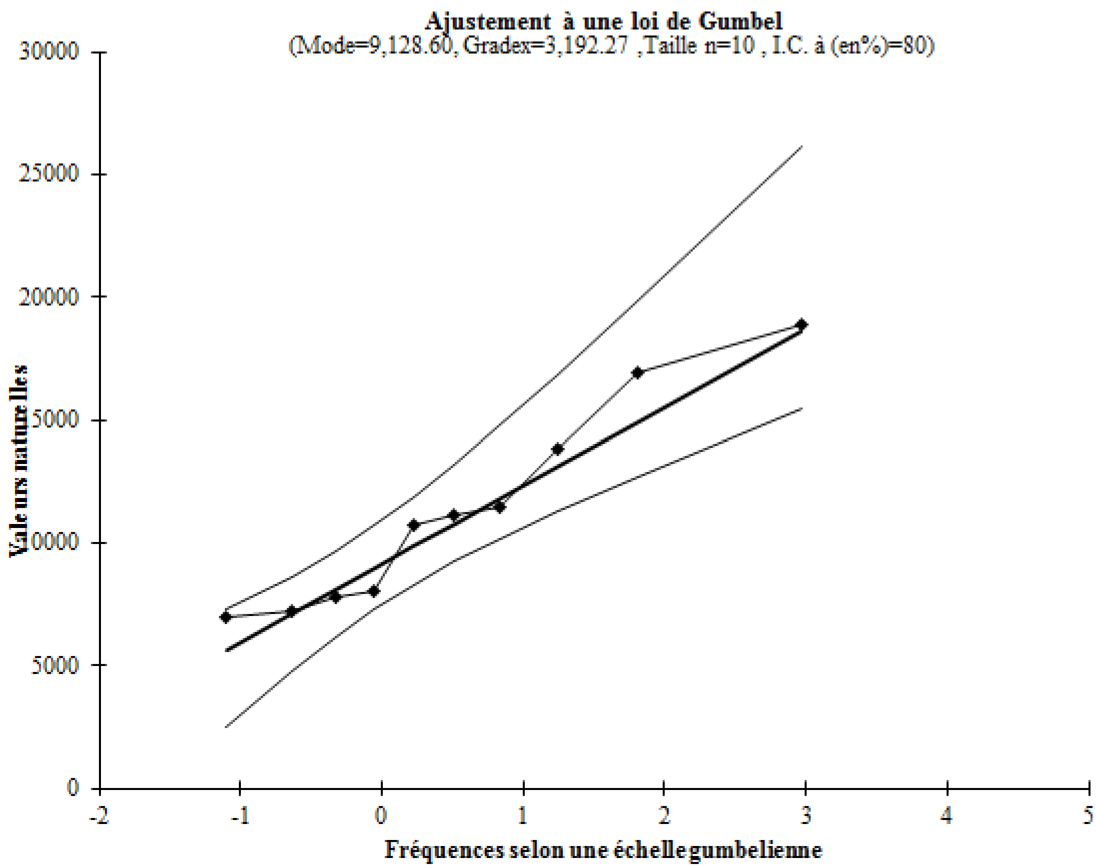
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.3	1664.24	1	0.0500	-1.097	1664.24	1505.95	317.52	2149.93
Obs.1	1701.84	2	0.1500	-0.640	1701.84	2063.16	1172.10	2655.78
Obs.2	2078.05	3	0.2500	-0.327	2078.05	2445.77	1711.07	3050.97
Obs.5	2645.42	4	0.3500	-0.049	2645.42	2784.86	2143.10	3446.82
Obs.7	3091	5	0.4500	0.225	3091	3118.60	2522.69	3882.06
Obs.4	3421.07	6	0.5500	0.514	3421.07	3471.61	2880.60	4386.02
Obs.10	4106.64	7	0.6500	0.842	4106.64	3871.31	3245.93	4996.58
Obs.6	5352.32	8	0.7500	1.246	5352.32	4363.75	3659.07	5785.73
Obs.9	5446.06	9	0.8500	1.817	5446.06	5060.26	4205.32	6940.01
Obs.8	6789.27	10	0.9500	2.970	6789.27	6466.83	5250.11	9329.37

Figure F8. Frequency estimation of “la méthode de renouvellement“ for Thanh My station at 2091-2100 with ECHAM scenario.



			Ajustement à une loi de Gumbel				% U Anderson =	0.265
	Mode=	5639.892905			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2263.003			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.3	4319.93	1	0.0500	-1.097	4319.93	3156.95	951.93	4351.81
Obs.2	4370.84	2	0.1500	-0.640	4370.84	4190.81	2537.53	5290.37
Obs.5	4904.92	3	0.2500	-0.327	4904.92	4900.72	3537.54	6023.62
Obs.1	5240.14	4	0.3500	-0.049	5240.14	5529.86	4339.14	6758.08
Obs.7	6146.92	5	0.4500	0.225	6146.92	6149.09	5043.44	7565.63
Obs.4	6698.46	6	0.5500	0.514	6698.46	6804.07	5707.51	8500.69
Obs.10	7396.37	7	0.6500	0.842	7396.37	7545.68	6385.34	9633.52
Obs.9	10966.9	8	0.7500	1.246	10966.9	8459.37	7151.89	11097.73
Obs.8	10976.5	9	0.8500	1.817	10976.5	9751.68	8165.42	13239.39
Obs.6	11378.6	10	0.9500	2.970	11378.6	12361.45	10103.94	17672.66

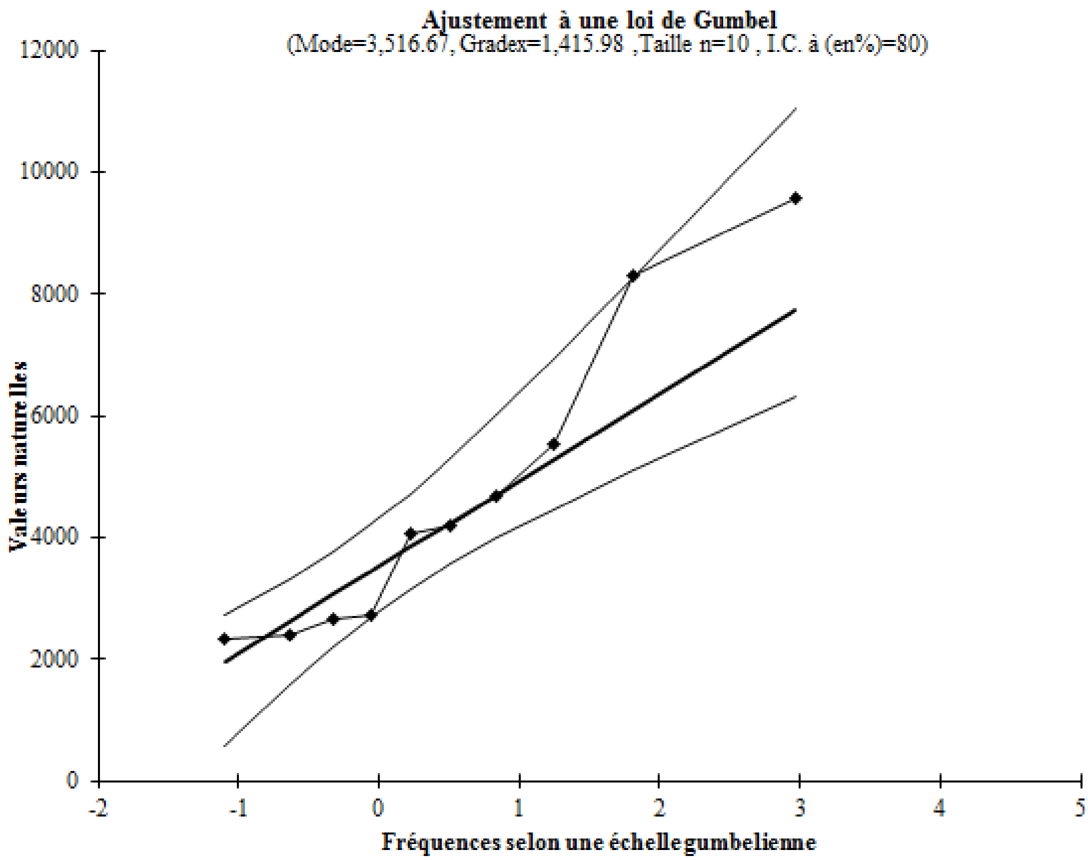
Figure F9. Frequency estimation of “la méthode de renouvellement“ for Nong Son station at 2091-2100 with ECHAM scenario.



Ajustement à une loi de Gumbel

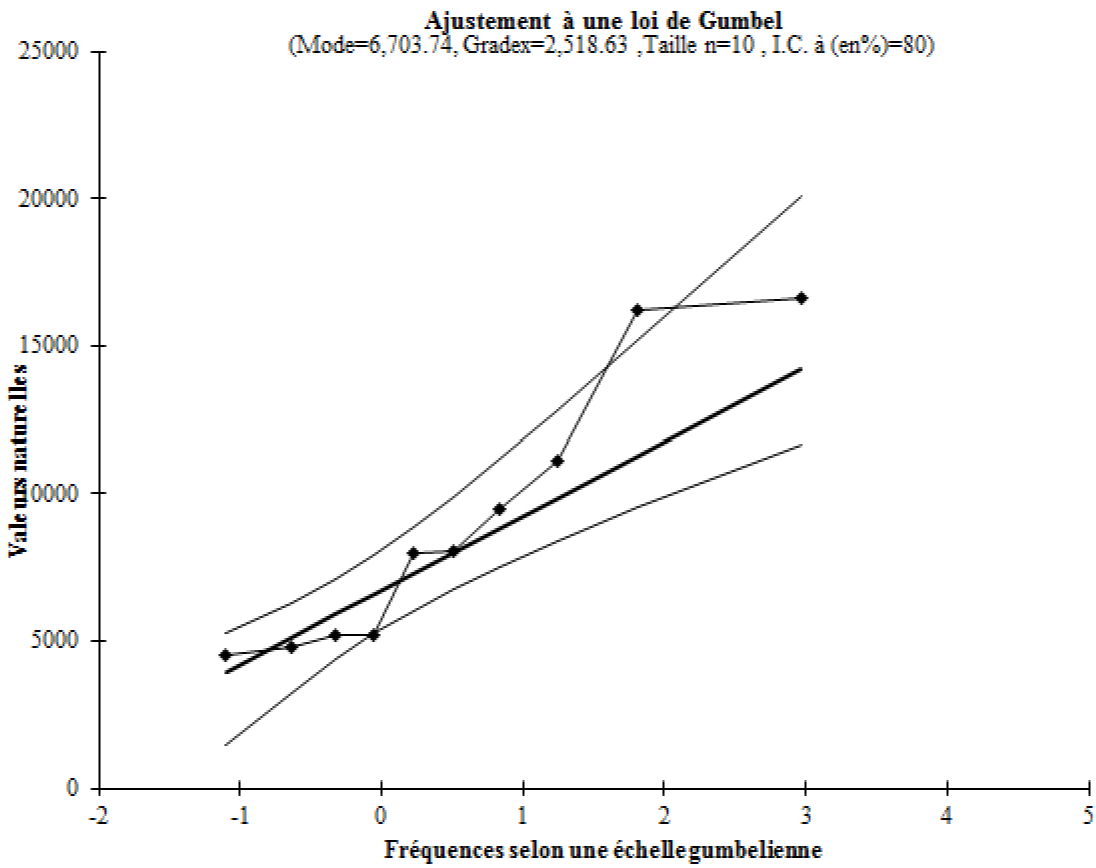
							% U Anderson =	0.321
	Mode=	9128.603755			Taille n=	10	I.C. à (en%)=	80
	Gradex=	3192.267			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	6991.29	1	0.0500	-1.097	6991.29	5626.08	2515.61	7311.59
Obs.2	7212.03	2	0.1500	-0.640	7212.03	7084.48	4752.31	8635.56
Obs.3	7757.83	3	0.2500	-0.327	7757.83	8085.90	6162.96	9669.90
Obs.5	8002.03	4	0.3500	-0.049	8002.03	8973.39	7293.72	10705.96
Obs.7	10683.9	5	0.4500	0.225	10683.9	9846.90	8287.23	11845.12
Obs.4	11141.7	6	0.5500	0.514	11141.7	10770.82	9223.98	13164.14
Obs.10	11454.8	7	0.6500	0.842	11454.8	11816.97	10180.15	14762.14
Obs.6	13837.7	8	0.7500	1.246	13837.7	13105.85	11261.48	16827.61
Obs.8	16950.6	9	0.8500	1.817	16950.6	14928.83	12691.20	19848.71
Obs.9	18907.3	10	0.9500	2.970	18907.3	18610.26	15425.73	26102.42

Figure F10. Frequency estimation of “la méthode de renouvellement“ for Giao Thuy station at 2091-2100 with ECHAM scenario.



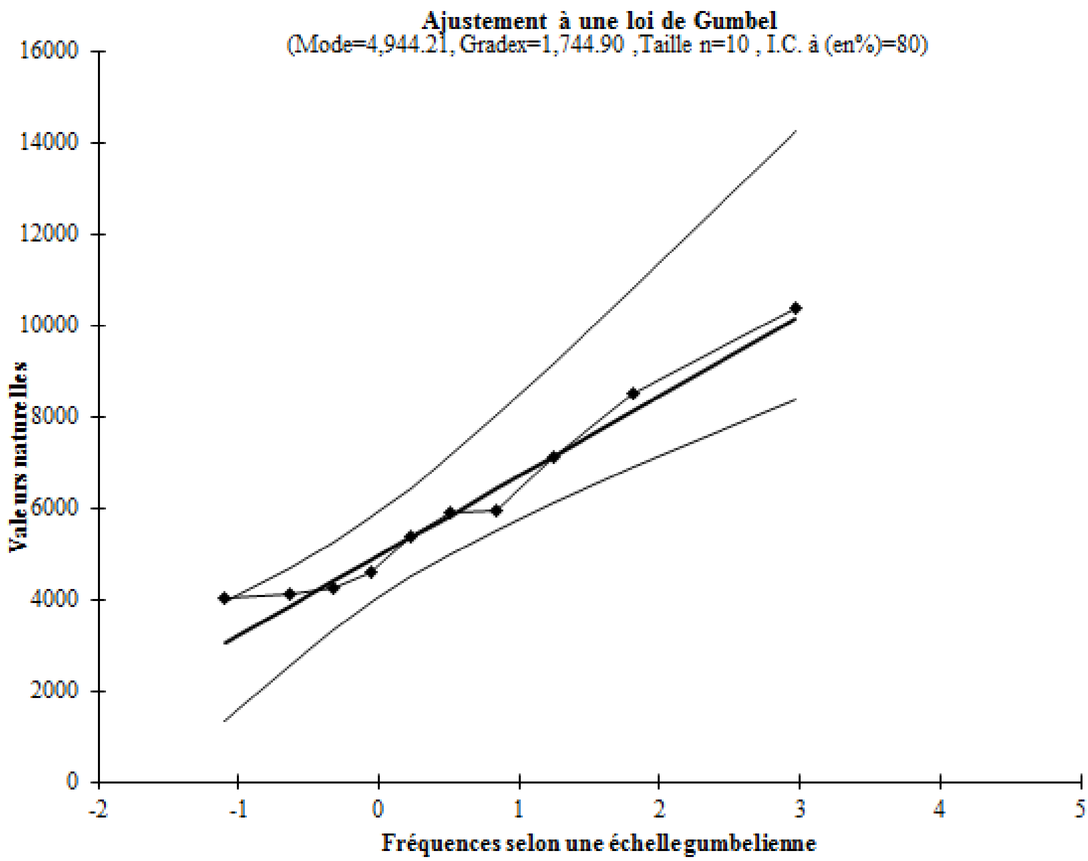
							% U Anderson =	0.213
			Ajustement à une loi de Gumbel					
	Mode=	3516.674127			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1415.981			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	2340.49	1	0.0500	-1.097	2340.49	1963.08	583.37	2710.71
Obs.2	2395.56	2	0.1500	-0.640	2395.56	2609.97	1575.50	3297.98
Obs.5	2665.48	3	0.2500	-0.327	2665.48	3054.17	2201.21	3756.77
Obs.3	2732.94	4	0.3500	-0.049	2732.94	3447.83	2702.78	4216.33
Obs.7	4065.24	5	0.4500	0.225	4065.24	3835.28	3143.47	4721.63
Obs.10	4196.49	6	0.5500	0.514	4196.49	4245.11	3558.98	5306.70
Obs.6	4682.4	7	0.6500	0.842	4682.4	4709.14	3983.11	6015.52
Obs.4	5526.03	8	0.7500	1.246	5526.03	5280.84	4462.75	6931.69
Obs.8	8307.75	9	0.8500	1.817	8307.75	6089.46	5096.92	8271.75
Obs.9	9576.11	10	0.9500	2.970	9576.11	7722.41	6309.87	11045.68

Figure F11. Frequency estimation of “la méthode de renouvellement“ for Ai Nghia station at 2091-2100 with ECHAM scenario.



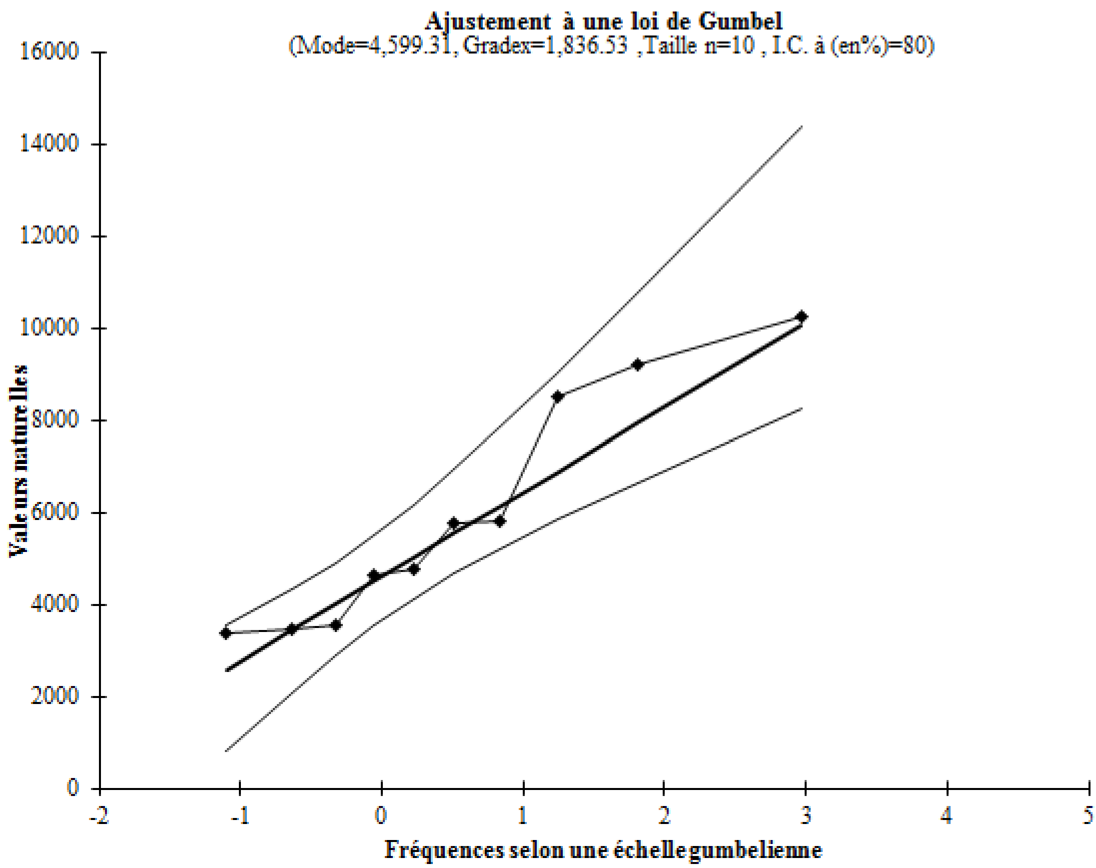
			Ajustement à une loi de Gumbel				% U Anderson =	0.169
	Mode=	6703.742741			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2518.625333			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	4498.69	1	0.0500	-1.097	4498.69	3940.34	1486.24	5270.16
Obs.1	4801.44	2	0.1500	-0.640	4801.44	5090.97	3250.95	6314.74
Obs.3	5168.57	3	0.2500	-0.327	5168.57	5881.07	4363.92	7130.81
Obs.5	5211.62	4	0.3500	-0.049	5211.62	6581.29	5256.06	7948.24
Obs.10	7999.31	5	0.4500	0.225	7999.31	7270.46	6039.91	8847.01
Obs.7	8048.56	6	0.5500	0.514	8048.56	7999.42	6778.99	9887.68
Obs.6	9498.54	7	0.6500	0.842	9498.54	8824.81	7533.39	11148.48
Obs.4	11124.9	8	0.7500	1.246	11124.9	9841.70	8386.54	12778.08
Obs.9	16202.5	9	0.8500	1.817	16202.5	11279.99	9514.55	15161.66
Obs.8	16618.3	10	0.9500	2.970	16618.3	14184.55	11672.03	20095.69

Figure F12. Frequency estimation of “la méthode de renouvellement“ for Hoi Khanh station at 2091-2100 with ECHAM scenario.



							% U Anderson =	0.333
		Ajustement à une loi de Gumbel						
	Mode=	4944.208216			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1744.899667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	4032.49	1	0.0500	-1.097	4032.49	3029.72	1329.53	3951.03
Obs.3	4102.79	2	0.1500	-0.640	4102.79	3826.88	2552.12	4674.71
Obs.2	4247.99	3	0.2500	-0.327	4247.99	4374.26	3323.18	5240.08
Obs.5	4565.65	4	0.3500	-0.049	4565.65	4859.37	3941.26	5806.39
Obs.4	5381.11	5	0.4500	0.225	5381.11	5336.83	4484.31	6429.06
Obs.7	5908.66	6	0.5500	0.514	5908.66	5841.85	4996.34	7150.04
Obs.10	5953.89	7	0.6500	0.842	5953.89	6413.68	5518.99	8023.51
Obs.6	7107.29	8	0.7500	1.246	7107.29	7118.18	6110.04	9152.50
Obs.8	8498.58	9	0.8500	1.817	8498.58	8114.62	6891.53	10803.84
Obs.9	10365.2	10	0.9500	2.970	10365.2	10126.90	8386.23	14222.13

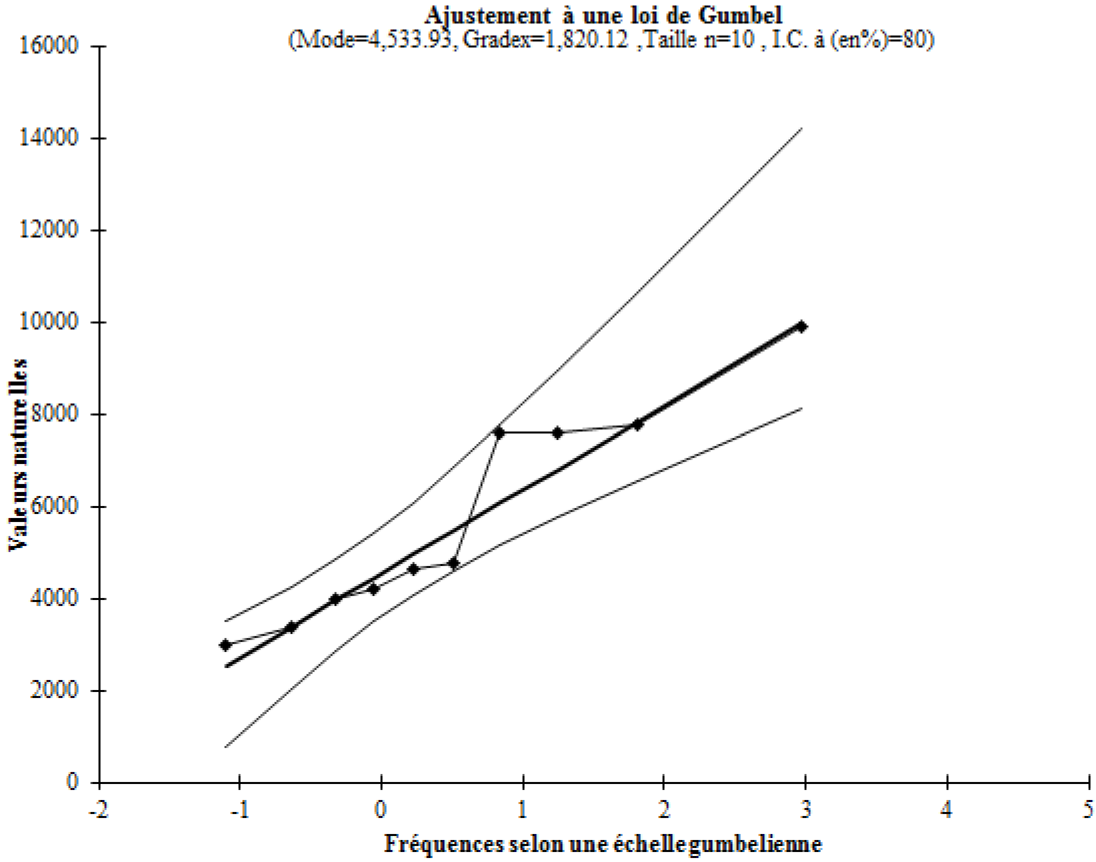
Figure F13. Frequency estimation of “la méthode de renouvellement“ for Cau Lau station at 2091-2100 with ECHAM scenario.



Ajustement à une loi de Gumbel

							% U Anderson =	0.280
	Mode=	4599.305525			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1836.531			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.3	3370.04	1	0.0500	-1.097	3370.04	2584.28	794.81	3553.97
Obs.2	3443.05	2	0.1500	-0.640	3443.05	3423.31	2081.60	4315.66
Obs.5	3531.52	3	0.2500	-0.327	3531.52	3999.43	2893.15	4910.71
Obs.7	4639.28	4	0.3500	-0.049	4639.28	4510.01	3543.69	5506.77
Obs.1	4766.95	5	0.4500	0.225	4766.95	5012.54	4115.26	6162.13
Obs.10	5755.15	6	0.5500	0.514	5755.15	5544.09	4654.18	6920.97
Obs.4	5783.32	7	0.6500	0.842	5783.32	6145.94	5204.27	7840.32
Obs.9	8495.14	8	0.7500	1.246	8495.14	6887.44	5826.36	9028.59
Obs.8	9211.41	9	0.8500	1.817	9211.41	7936.21	6648.89	10766.65
Obs.6	10231.4	10	0.9500	2.970	10231.4	10054.16	8222.08	14364.45

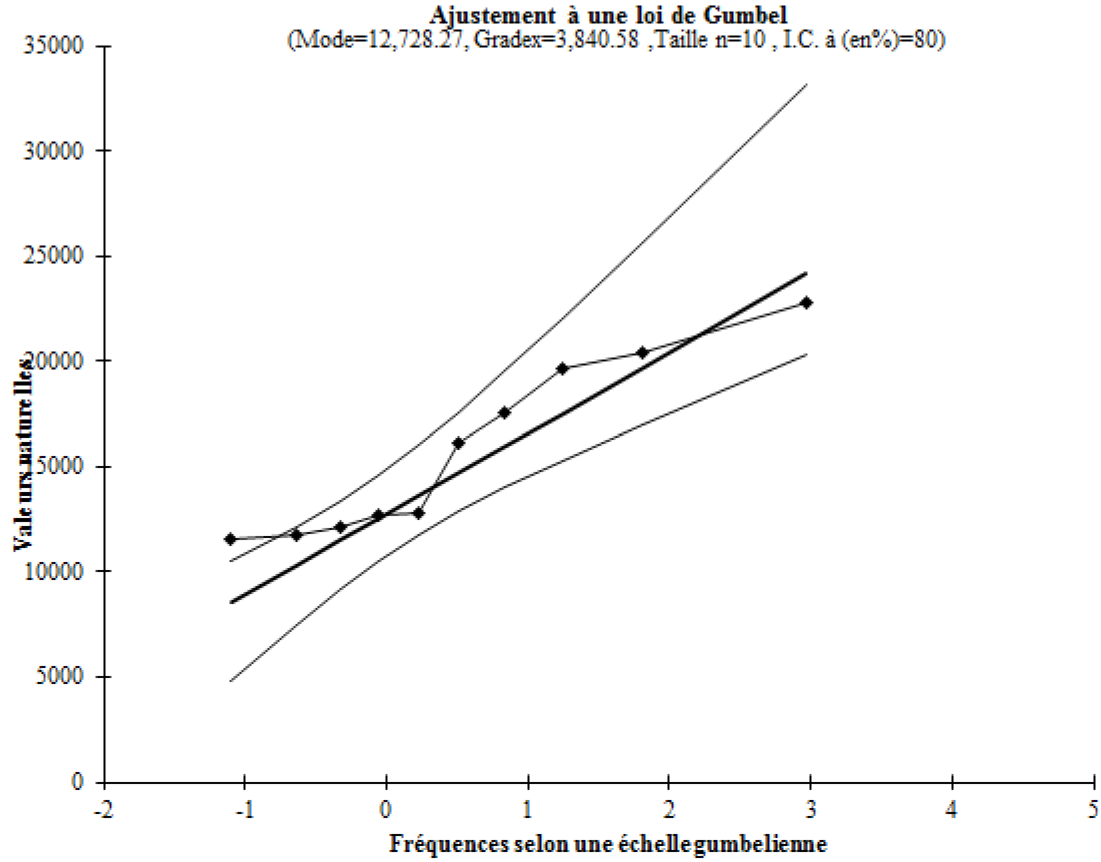
Figure F14. Frequency estimation of “la méthode de renouvellement“ for Hiep Duc station at 2091-2100 with ECHAM scenario.



Ajustement à une loi de Gumbel

							% U Anderson =	0.283
	Mode=	4533.929861			Taille n=	10	I.C. à (en%)=	80
	Gradex=	1820.123333			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.3	2985.51	1	0.0500	-1.097	2985.51	2536.91	763.42	3497.93
Obs.1	3351.26	2	0.1500	-0.640	3351.26	3368.44	2038.72	4252.81
Obs.7	3974.38	3	0.2500	-0.327	3974.38	3939.42	2843.02	4842.56
Obs.2	4186.94	4	0.3500	-0.049	4186.94	4445.43	3487.74	5433.28
Obs.5	4615.46	5	0.4500	0.225	4615.46	4943.48	4054.20	6082.79
Obs.4	4763.2	6	0.5500	0.514	4763.2	5470.27	4588.31	6834.85
Obs.9	7579.73	7	0.6500	0.842	7579.73	6066.75	5133.49	7745.99
Obs.10	7597.56	8	0.7500	1.246	7597.56	6801.62	5750.03	8923.64
Obs.8	7758.77	9	0.8500	1.817	7758.77	7841.02	6565.20	10646.18
Obs.6	9885.52	10	0.9500	2.970	9885.52	9940.05	8124.34	14211.83

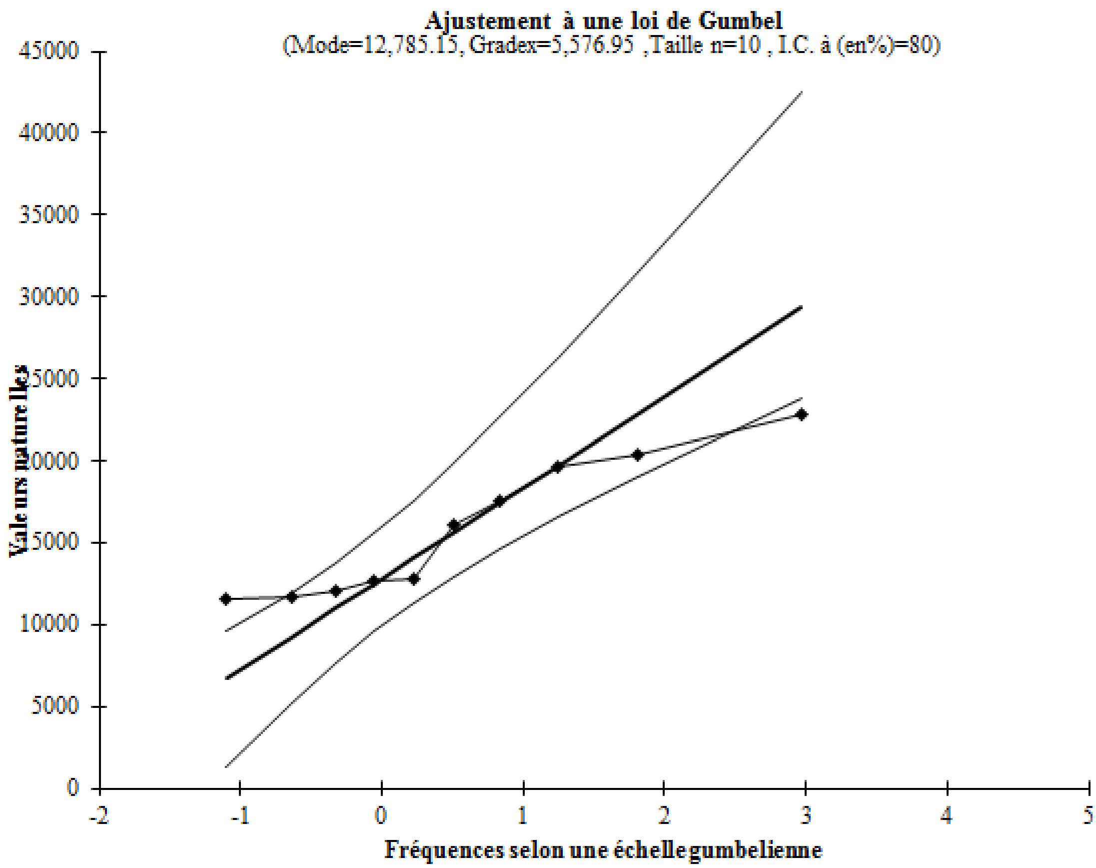
Figure F15. Frequency estimation of “la méthode de renouvellement“ for Thanh My station at 2091-2100 with CCSM scenario.



Ajustement à une loi de Gumbel

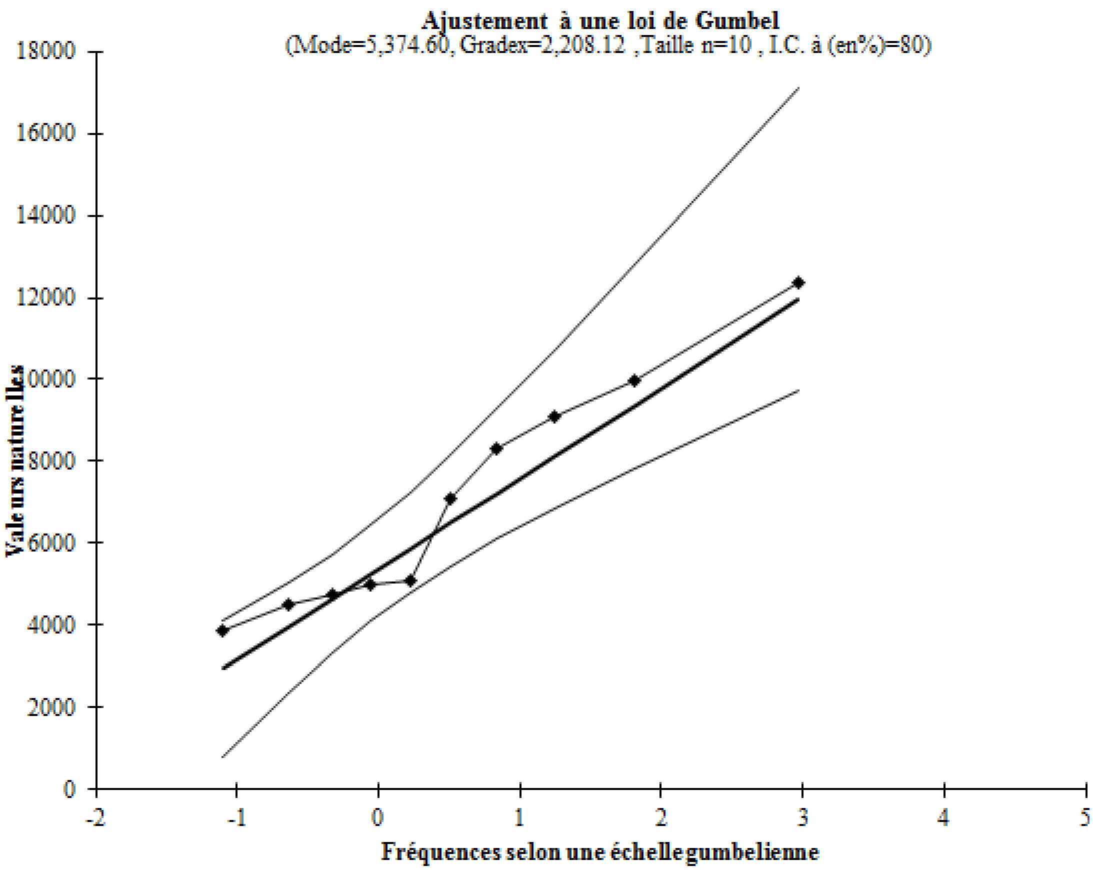
							% U Anderson =	0.207
Mode=	12728.26875				Taille n=	10	I.C. à (en%)=	80
Gradex=	3840.580333				Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	11562.3	1	0.0500	-1.097	11562.3	8514.43	4772.25	10542.24
Obs.3	11733.9	2	0.1500	-0.640	11733.9	10269.00	7463.20	12135.09
Obs.2	12091.7	3	0.2500	-0.327	12091.7	11473.80	9160.33	13379.49
Obs.5	12712.2	4	0.3500	-0.049	12712.2	12541.54	10520.74	14625.96
Obs.7	12830.8	5	0.4500	0.225	12830.8	13592.44	11716.02	15996.48
Obs.4	16086.5	6	0.5500	0.514	16086.5	14704.01	12843.01	17583.37
Obs.10	17549	7	0.6500	0.842	17549	15962.62	13993.38	19505.92
Obs.8	19624	8	0.7500	1.246	19624	17513.25	15294.31	21990.85
Obs.6	20376.5	9	0.8500	1.817	20376.5	19706.45	17014.38	25625.51
Obs.9	22799.3	10	0.9500	2.970	22799.3	24135.54	20304.27	33149.27

Figure F16. Frequency estimation of “la méthode de renouvellement“ for Nong Son station at 2091-2100 with CCSM scenario.



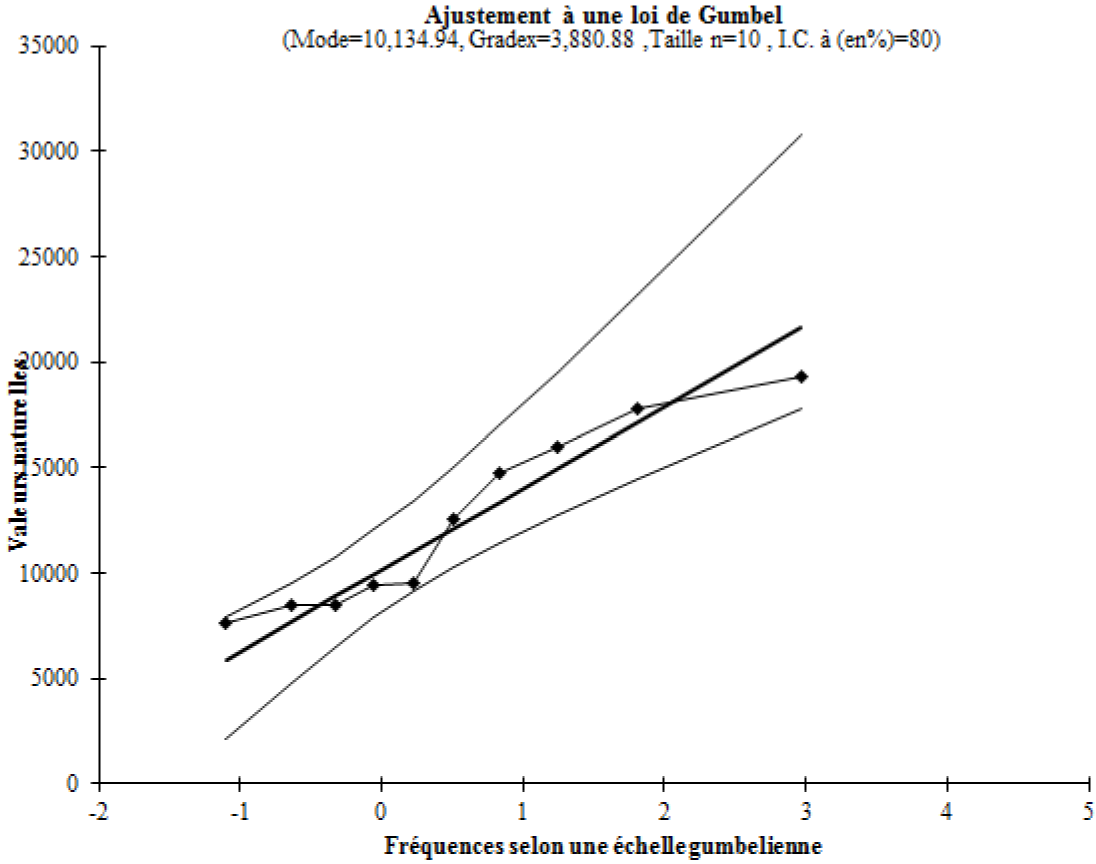
							% U Anderson =	0.187
		Ajustement à une loi de Gumbel						
	Mode=	12785.15068			Taille n=	10	I.C. à (en%)=	80
	Gradex=	5576.945333			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	11562.3	1	0.0500	-1.097	11562.3	6666.19	1232.13	9610.80
Obs.3	11733.9	2	0.1500	-0.640	11733.9	9214.03	5139.70	11923.80
Obs.2	12091.7	3	0.2500	-0.327	12091.7	10963.53	7604.12	13730.80
Obs.5	12712.2	4	0.3500	-0.049	12712.2	12514.00	9579.58	15540.81
Obs.7	12830.8	5	0.4500	0.225	12830.8	14040.02	11315.25	17530.95
Obs.4	16086.5	6	0.5500	0.514	16086.5	15654.14	12951.77	19835.29
Obs.10	17549	7	0.6500	0.842	17549	17481.78	14622.23	22627.04
Obs.8	19624	8	0.7500	1.246	19624	19733.46	16511.33	26235.44
Obs.6	20376.5	9	0.8500	1.817	20376.5	22918.24	19009.06	31513.37
Obs.9	22799.3	10	0.9500	2.970	22799.3	29349.77	23786.34	42438.70

Figure F17. Frequency estimation of “la méthode de renouvellement“ for Giao Thuy station at 2091-2100 with CCSM scenario.



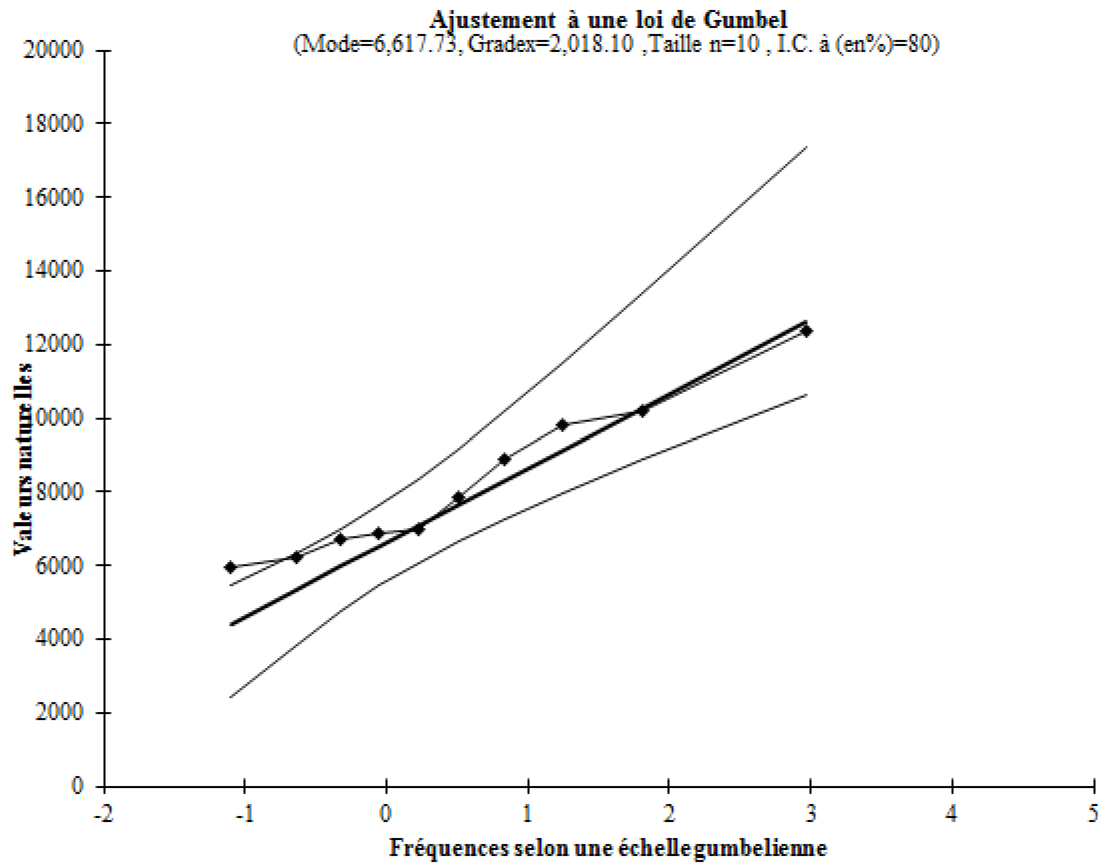
		Ajustement à une loi de Gumbel					% U Anderson =	0.287
	Mode=	5374.599231			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2208.121333			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	3856.89	1	0.0500	-1.097	3856.89	2951.87	800.33	4117.75
Obs.3	4521.28	2	0.1500	-0.640	4521.28	3960.66	2347.48	5033.56
Obs.5	4747.3	3	0.2500	-0.327	4747.3	4653.35	3323.23	5749.02
Obs.2	4976.93	4	0.3500	-0.049	4976.93	5267.24	4105.39	6465.67
Obs.7	5117.47	5	0.4500	0.225	5117.47	5871.45	4792.61	7253.64
Obs.4	7086.55	6	0.5500	0.514	7086.55	6510.54	5440.57	8166.02
Obs.10	8304.11	7	0.6500	0.842	8304.11	7234.17	6101.97	9271.37
Obs.6	9084.84	8	0.7500	1.246	9084.84	8125.70	6849.93	10700.07
Obs.8	9983.69	9	0.8500	1.817	9983.69	9386.67	7838.88	12789.80
Obs.9	12345.1	10	0.9500	2.970	12345.1	11933.15	9730.38	17115.55

Figure F18. Frequency estimation of “la méthode de renouvellement“ for Ai Nghia station at 2091-2100 with CCSM scenario.



			Ajustement à une loi de Gumbel				% U Anderson =	0.299
	Mode=	10134.93759			Taille n=	10	I.C. à (en%)=	80
	Gradex=	3880.884667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	7632.38	1	0.0500	-1.097	7632.38	5876.87	2095.42	7925.97
Obs.3	8466.23	2	0.1500	-0.640	8466.23	7649.86	4814.62	9535.54
Obs.5	8522.79	3	0.2500	-0.327	8522.79	8867.31	6529.56	10793.00
Obs.7	9407.05	4	0.3500	-0.049	9407.05	9946.25	7904.24	12052.55
Obs.2	9500.28	5	0.4500	0.225	9500.28	11008.18	9112.06	13437.44
Obs.4	12525.6	6	0.5500	0.514	12525.6	12131.41	10250.89	15040.99
Obs.6	14783.7	7	0.6500	0.842	14783.7	13403.23	11413.32	16983.71
Obs.10	15974.7	8	0.7500	1.246	15974.7	14970.13	12727.91	19494.72
Obs.8	17823.6	9	0.8500	1.817	17823.6	17186.35	14466.03	23167.53
Obs.9	19272.1	10	0.9500	2.970	19272.1	21661.92	17790.45	30770.25

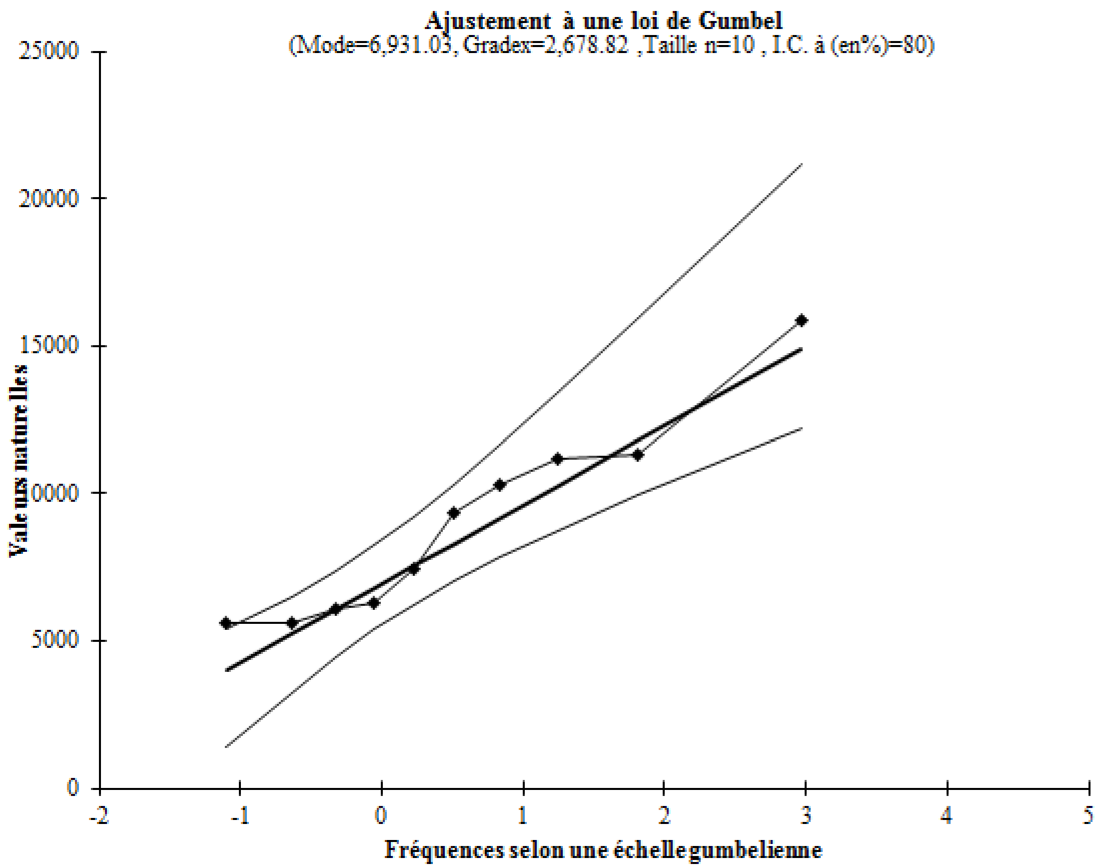
Figure F19. Frequency estimation of “la méthode de renouvellement“ for Hoi Khanh station at 2091-2100 with CCSM scenario.



Ajustement à une loi de Gumbel

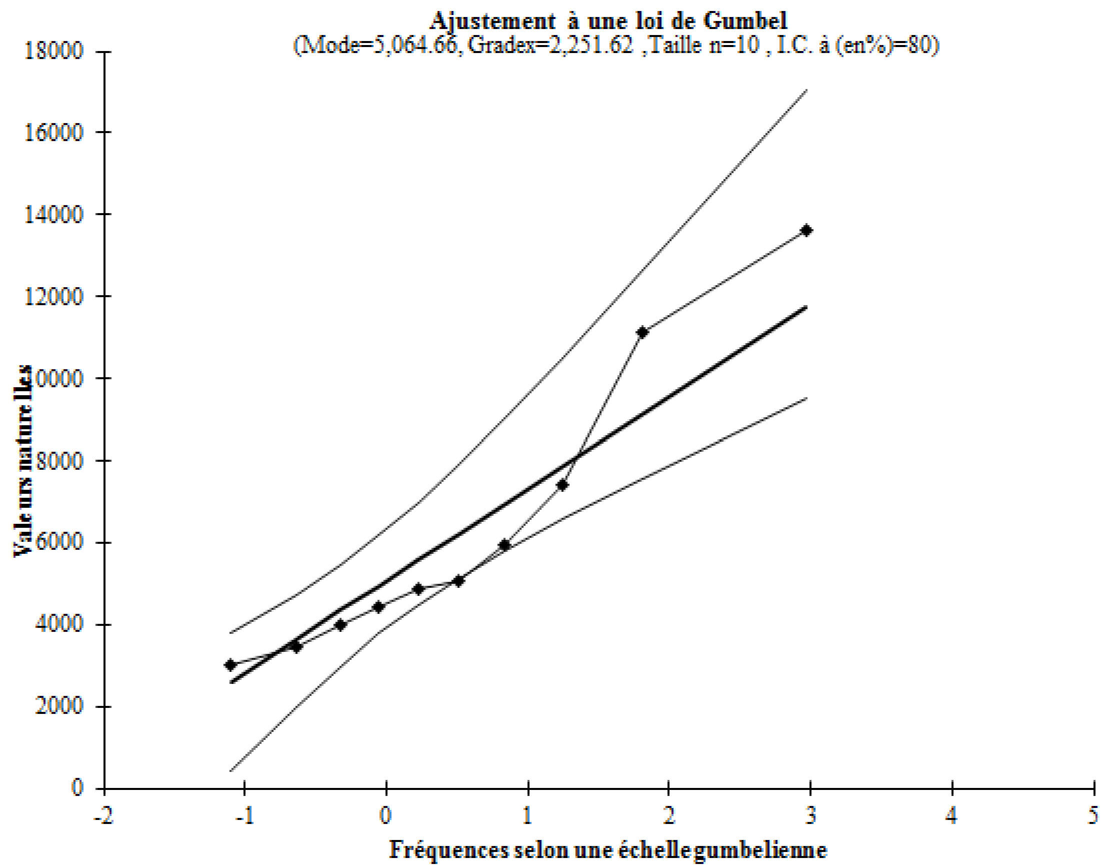
							% U Anderson =	0.217
	Mode=	6617.730193			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2018.100667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.3	5976.34	1	0.0500	-1.097	5976.34	4403.49	2437.10	5469.04
Obs.1	6223.02	2	0.1500	-0.640	6223.02	5325.47	3851.11	6306.04
Obs.2	6719.96	3	0.2500	-0.327	6719.96	5958.55	4742.90	6959.93
Obs.5	6895.03	4	0.3500	-0.049	6895.03	6519.61	5457.75	7614.91
Obs.7	6980.7	5	0.4500	0.225	6980.7	7071.82	6085.82	8335.07
Obs.4	7865.32	6	0.5500	0.514	7865.32	7655.92	6678.03	9168.93
Obs.10	8898.24	7	0.6500	0.842	8898.24	8317.28	7282.50	10179.17
Obs.8	9803.24	8	0.7500	1.246	9803.24	9132.08	7966.10	11484.92
Obs.6	10184.4	9	0.8500	1.817	10184.4	10284.54	8869.94	13394.81
Obs.9	12369.1	10	0.9500	2.970	12369.1	12611.88	10598.67	17348.31

Figure F20. Frequency estimation of “la méthode de renouvellement“ for Cau Lau station at 2091-2100 with CCSM scenario.



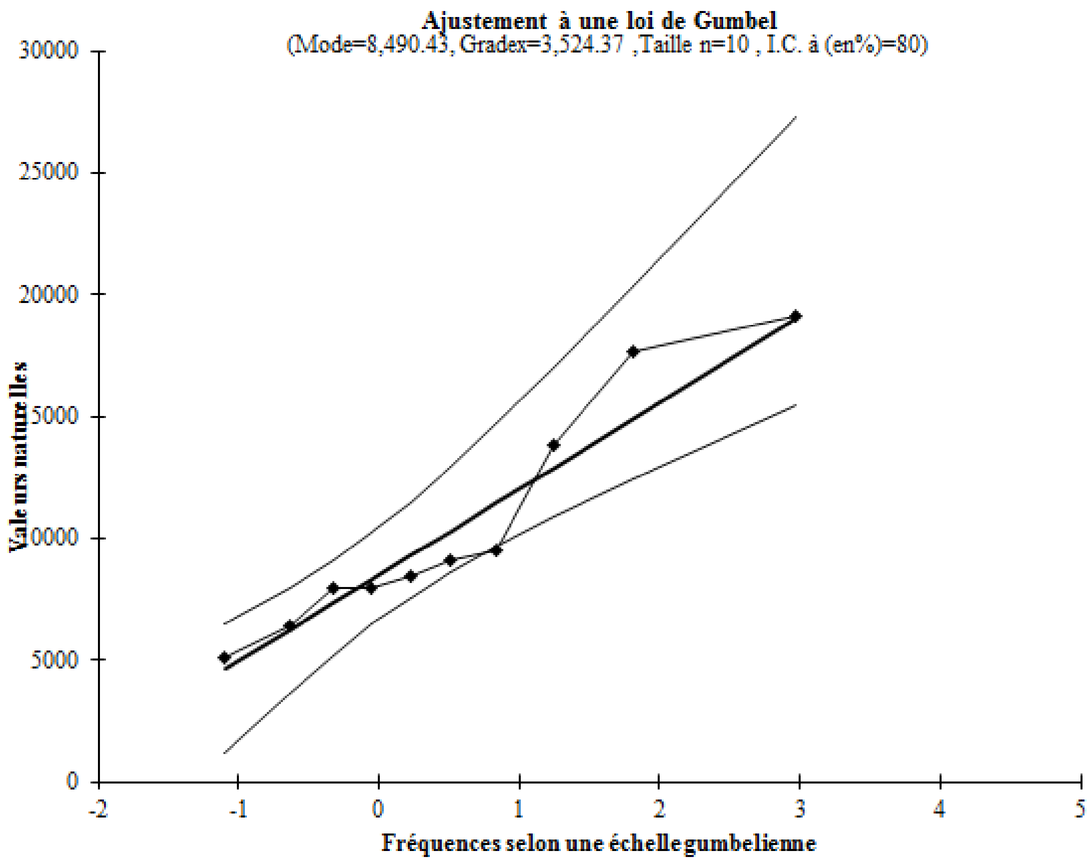
		Ajustement à une loi de Gumbel					% U Anderson =	0.284
	Mode=	6931.026036			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2678.821333			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	5588.8	1	0.0500	-1.097	5588.8	3991.85	1381.67	5406.26
Obs.3	5608.81	2	0.1500	-0.640	5608.81	5215.68	3258.62	6517.28
Obs.7	6062.42	3	0.2500	-0.327	6062.42	6056.03	4442.38	7385.26
Obs.5	6269.01	4	0.3500	-0.049	6269.01	6800.78	5391.27	8254.68
Obs.1	7435.42	5	0.4500	0.225	7435.42	7533.79	6224.98	9210.61
Obs.10	9333.99	6	0.5500	0.514	9333.99	8309.11	7011.06	10317.48
Obs.4	10290.6	7	0.6500	0.842	10290.6	9187.00	7813.44	11658.47
Obs.8	11199.9	8	0.7500	1.246	11199.9	10268.57	8720.85	13391.72
Obs.9	11285.6	9	0.8500	1.817	11285.6	11798.34	9920.61	15926.91
Obs.6	15869.5	10	0.9500	2.970	15869.5	14887.65	12215.32	21174.76

Figure F21. Frequency estimation of “la méthode de renouvellement“ for Hiep Duc station at 2091-2100 with CCSM scenario.



							% U Anderson =	0.245
		Ajustement à une loi de Gumbel						
	Mode=	5064.656669			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2251.619333			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	3028.07	1	0.0500	-1.097	3028.07	2594.21	400.28	3783.05
Obs.2	3443.58	2	0.1500	-0.640	3443.58	3622.86	1977.90	4716.90
Obs.3	3984.3	3	0.2500	-0.327	3984.3	4329.20	2972.88	5446.45
Obs.7	4434.93	4	0.3500	-0.049	4434.93	4955.18	3770.45	6177.22
Obs.5	4853.29	5	0.4500	0.225	4853.29	5571.30	4471.20	6980.71
Obs.4	5071.5	6	0.5500	0.514	5071.5	6222.97	5131.93	7911.06
Obs.10	5929.14	7	0.6500	0.842	5929.14	6960.86	5806.35	9038.19
Obs.6	7413.28	8	0.7500	1.246	7413.28	7869.95	6569.05	10495.04
Obs.9	11145.3	9	0.8500	1.817	11145.3	9155.76	7577.48	12625.93
Obs.8	13611.3	10	0.9500	2.970	13611.3	11752.41	9506.24	17036.89

Figure F22. Frequency estimation of “la méthode de renouvellement“ for Thanh My station at 2091-2100 with MIROC scenario.

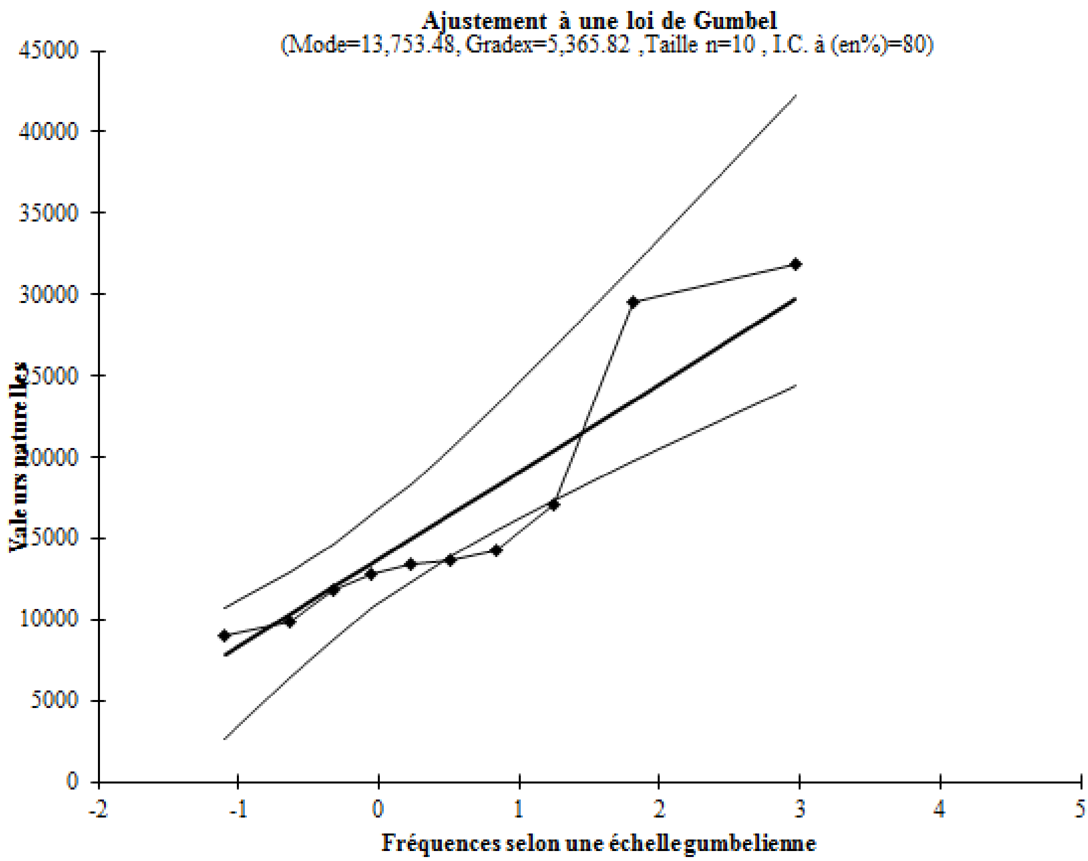


Ajustement à une loi de Gumbel

% U Anderson = 0.291

	Mode=	8490.429488			Taille n=	10	I.C. à (en%)=	80
	Gradex=	3524.373			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	5068.73	1	0.0500	-1.097	5068.73	4623.53	1189.45	6484.38
Obs.3	6394.89	2	0.1500	-0.640	6394.89	6233.64	3658.85	7946.09
Obs.4	7943.57	3	0.2500	-0.327	7943.57	7339.25	5216.25	9088.04
Obs.5	7949.86	4	0.3500	-0.049	7949.86	8319.07	6464.66	10231.88
Obs.10	8464.3	5	0.4500	0.225	8464.3	9283.45	7561.52	11489.55
Obs.7	9107.81	6	0.5500	0.514	9107.81	10303.50	8595.73	12945.80
Obs.1	9465.79	7	0.6500	0.842	9465.79	11458.48	9651.38	14710.05
Obs.6	13792.9	8	0.7500	1.246	13792.9	12881.44	10845.20	16990.39
Obs.8	17619	9	0.8500	1.817	17619	14894.08	12423.65	20325.80
Obs.9	19100.9	10	0.9500	2.970	19100.9	18958.51	15442.68	27230.11

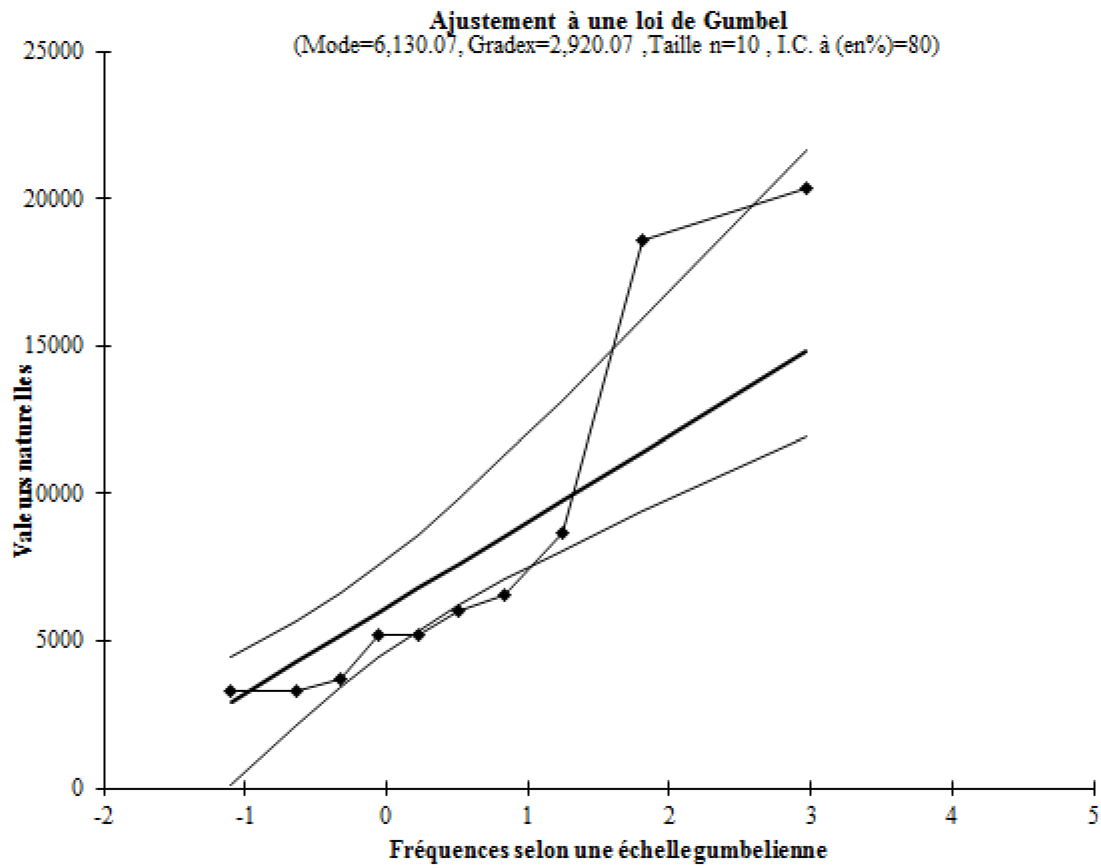
Figure F23. Frequency estimation of “la méthode de renouvellement“ for Nong Son station at 2091-2100 with MIROC scenario.



Ajustement à une loi de Gumbel

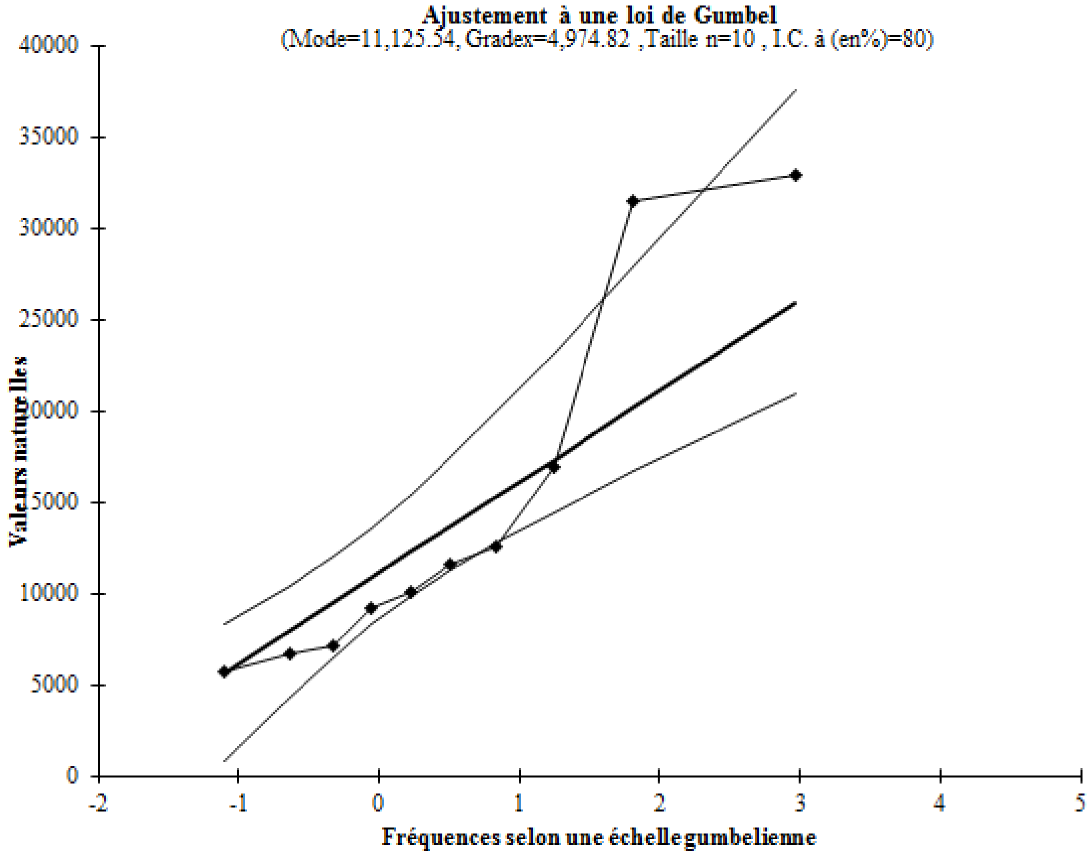
							% U Anderson =	0.173
	Mode=	13753.48249			Taille n=	10	I.C. à (en%)=	80
	Gradex=	5365.817			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	8954.5	1	0.0500	-1.097	8954.5	7866.17	2637.83	10699.30
Obs.3	9805.75	2	0.1500	-0.640	9805.75	10317.55	6397.46	12924.74
Obs.1	11759.9	3	0.2500	-0.327	11759.9	12000.82	8768.59	14663.33
Obs.5	12814.4	4	0.3500	-0.049	12814.4	13492.59	10669.27	16404.82
Obs.7	13425.4	5	0.4500	0.225	13425.4	14960.85	12339.23	18319.62
Obs.10	13593.7	6	0.5500	0.514	13593.7	16513.86	13913.80	20536.73
Obs.4	14256.4	7	0.6500	0.842	14256.4	18272.31	15521.01	23222.79
Obs.6	17037.5	8	0.7500	1.246	17037.5	20438.75	17338.60	26694.58
Obs.8	29526.4	9	0.8500	1.817	29526.4	23502.96	19741.77	31772.70
Obs.9	31894.4	10	0.9500	2.970	31894.4	29691.01	24338.20	42284.42

Figure F24. Frequency estimation of “la méthode de renouvellement“ for Giao Thuy station at 2091-2100 with MIROC scenario.



		Ajustement à une loi de Gumbel					% U Anderson =	0.074
	Mode=	6130.067716			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2920.072667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.3	3320.73	1	0.0500	-1.097	3320.73	2926.20	80.94	4467.99
Obs.2	3323.47	2	0.1500	-0.640	3323.47	4260.24	2126.93	5679.07
Obs.1	3731.35	3	0.2500	-0.327	3731.35	5176.27	3417.29	6625.21
Obs.7	5172.78	4	0.3500	-0.049	5172.78	5988.09	4451.64	7572.92
Obs.5	5191.43	5	0.4500	0.225	5191.43	6787.12	5360.43	8614.95
Obs.10	5996.07	6	0.5500	0.514	5996.07	7632.26	6217.31	9821.50
Obs.4	6555.03	7	0.6500	0.842	6555.03	8589.21	7091.96	11283.25
Obs.6	8663.06	8	0.7500	1.246	8663.06	9768.18	8081.08	13172.60
Obs.8	18604	9	0.8500	1.817	18604	11435.73	9388.89	15936.11
Obs.9	20364.3	10	0.9500	2.970	20364.3	14803.25	11890.26	21656.58

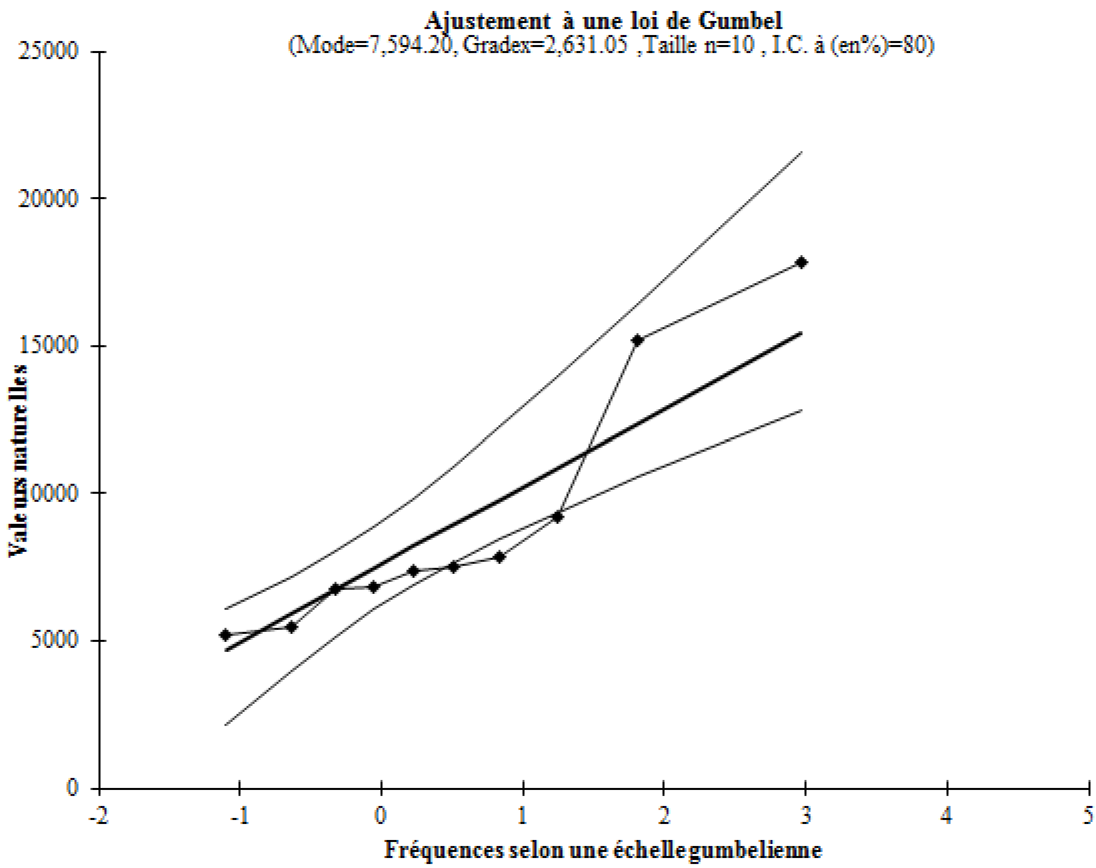
Figure F25. Frequency estimation of “la méthode de renouvellement“ for Ai Nghia station at 2091-2100 with MIROC scenario.



Ajustement à une loi de Gumbel

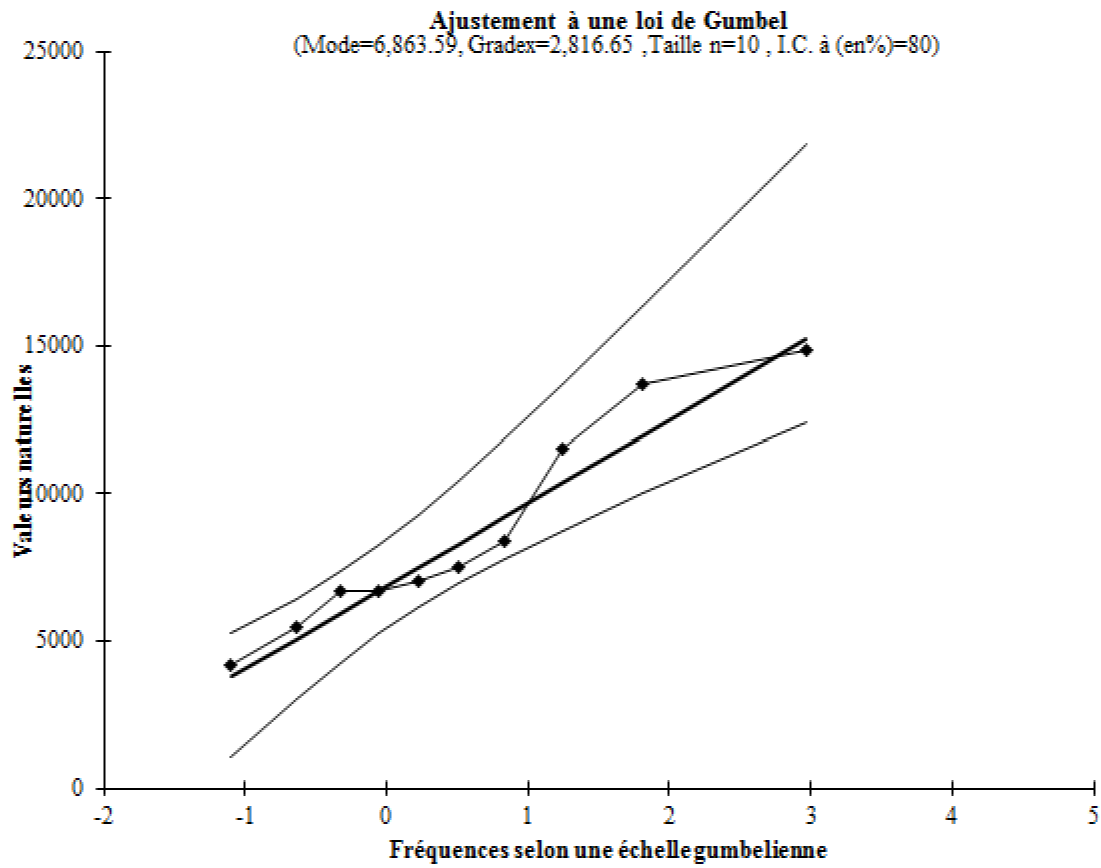
							% U Anderson =	0.114
	Mode=	11125.53582			Taille n=	10	I.C. à (en%)=	80
	Gradex=	4974.817667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.1	5698.26	1	0.0500	-1.097	5698.26	5667.22	819.87	8293.91
Obs.3	6724.23	2	0.1500	-0.640	6724.23	7939.98	4305.54	10357.18
Obs.2	7143.67	3	0.2500	-0.327	7143.67	9500.59	6503.88	11969.09
Obs.7	9143.86	4	0.3500	-0.049	9143.86	10883.66	8266.06	13583.67
Obs.5	10025.6	5	0.4500	0.225	10025.6	12244.92	9814.33	15358.94
Obs.10	11592.6	6	0.5500	0.514	11592.6	13684.77	11274.17	17414.50
Obs.4	12544.6	7	0.6500	0.842	12544.6	15315.08	12764.27	19904.83
Obs.6	16876.5	8	0.7500	1.246	16876.5	17323.66	14449.41	23123.63
Obs.8	31486.1	9	0.8500	1.817	31486.1	20164.58	16677.47	27831.72
Obs.9	32912.9	10	0.9500	2.970	32912.9	25901.72	20938.96	37577.47

Figure F26. Frequency estimation of “la méthode de renouvellement“ for Hoi Khanh station at 2091-2100 with MIROC scenario.



							% U Anderson =	0.160
		Ajustement à une loi de Gumbel						
	Mode=	7594.203496			Taille n=	10	I.C. à (en%)=	80
	Gradex=	2631.049667			Nb au départ	(10)	U Gauss=	1.282
Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	5221.14	1	0.0500	-1.097	5221.14	4707.45	2143.81	6096.63
Obs.3	5447.93	2	0.1500	-0.640	5447.93	5909.45	3987.29	7187.84
Obs.1	6768.88	3	0.2500	-0.327	6768.88	6734.81	5149.93	8040.33
Obs.5	6812.47	4	0.3500	-0.049	6812.47	7466.28	6081.90	8894.25
Obs.7	7380.13	5	0.4500	0.225	7380.13	8186.22	6900.74	9833.14
Obs.10	7520.45	6	0.5500	0.514	7520.45	8947.71	7672.81	10920.27
Obs.4	7835.04	7	0.6500	0.842	7835.04	9809.94	8460.89	12237.34
Obs.6	9196.15	8	0.7500	1.246	9196.15	10872.23	9352.11	13939.68
Obs.8	15213.7	9	0.8500	1.817	15213.7	12374.72	10530.47	16429.66
Obs.9	17808.7	10	0.9500	2.970	17808.7	15408.93	12784.26	21583.93

Figure F27. Frequency estimation of “la méthode de renouvellement“ for Cau Lau station at 2091-2100 with MIROC scenario.



Ajustement à une loi de Gumbel

				% U Anderson =	0.332
Mode=	6863.59143	Taille n=	10	I.C. à (en%)=	80
Gradex=	2816.654667	Nb au départ	(10)	U Gauss=	1.282

Observations classées	Valeurs classées	Ordre de classement	Fréquence expérimentale	Variable réduite	Valeur expérimentale	Valeur théorique	Borne inférieure	Borne supérieure
Obs.2	4198.7	1	0.0500	-1.097	4198.7	3773.19	1028.70	5260.37
Obs.3	5496.47	2	0.1500	-0.640	5496.47	5059.98	3002.23	6428.56
Obs.5	6668.34	3	0.2500	-0.327	6668.34	5943.58	4246.89	7341.19
Obs.4	6672.42	4	0.3500	-0.049	6672.42	6726.64	5244.61	8255.35
Obs.10	7063.93	5	0.4500	0.225	7063.93	7497.37	6121.21	9260.47
Obs.7	7483.3	6	0.5500	0.514	7483.3	8312.58	6947.75	10424.29
Obs.1	8417.08	7	0.6500	0.842	8417.08	9235.64	7791.41	11834.27
Obs.6	11486.1	8	0.7500	1.246	11486.1	10372.86	8745.51	13656.70
Obs.8	13709.3	9	0.8500	1.817	13709.3	11981.34	10007.00	16322.34
Obs.9	14870.8	10	0.9500	2.970	14870.8	15229.61	12419.78	21840.21

Figure F28. Frequency estimation of “la méthode de renouvellement“ for Hiep Duc station at 2091-2100 with MIROC scenario.