Flood Modelling of the Huong River System in Thua Thien Hué, Vietnam

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Summary

The Thua Thien Hué province is a quite mountainous in the west part and very flat in the east part of the province, which easily leads to flash floods in the rivers. These floods lead to high inundation levels in this area resulting into huge economical losses and sometimes even to the losses of lives.
To prevent the future from these huge inundations again solutions have to be taken which gives the Huong River Basin a better ability to cope with these problems. However, before solutions can be taken, a model has to be set up which will be used to calculate the water level along the river and to investigate where solutions has to be taken and where these solutions has to be implemented. The objective of thesis is to make a calibrated model of the Huong River Basin with the use of the HEC-RAS software.
The Huong River Basin lies in the middle of Vietnam in the Thua Thien Hué province, which is a very wet climate. The annual rainfall in this region can reach up to 5,000 millimetres in the western mountains and up to 3,000 millimetres in the city of Hué, this city lies in the western part of the study area.
The Huong River Basin consists of four rivers, of which the Huong River is the main river. This river originates in the western mountains and flows then to the plain area near Hué and finally ends in the Tam Giang – Cau Hai lagoon. North of the Huong River originates the Bo river which flows also in eastern direction and confluences with the Huong River near the city of Hué. The two other rivers are the Loi Nong River and the Nham Bieu River. Both rivers originate out of the Huong River.
When the Huong River system is modelled in the HEC-RAS software two upstream boundaries are implemented and three downstream boundaries. The two upstream boundaries, one of the Huong River and one of the Bo River, exist out of a flood wave which will run through the model. The three downstream boundaries are needed to give a value for the amount of water which flows out of the river into the lagoon. However, because of the lack a data as downstream boundaries the water levels of the three water stations in the lagoon are used instead of the water level et the end of the river.
To calibrate the model the measured water level at Kim Long water station during the floods of November 1999 and November 2004 are compared with the water level calculated by HEC-RAS. To calibrate the model the Manning coefficients are adjusted to get a better fit with the measured water level. After the final en best calibration the goodness-of-fit for both the November 1999 and November 2004 flood are calculated. The November 1999 flood has a goodness-of-fit of 0.253 and the November 2004 flood has a goodness-of-fit of 0.322. This makes that the November 1999 flood has a better fit. Nevertheless gives also the November 2004 flood a indication that the model is well calibrated and useful to determine where problems arise during the November 1999 flood which will now be used as a design flood to calculate the measurements. But, there are still some problems in the model which can partial be solved by implementing better cross sections in the model. Also will downstream data of the rivers itself instead of the lagoon a better indication of the inundation problems in the area near the lagoon. But as is mentioned before, this model can now be a useful model to determine the problems in the Huong River Basin.

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Preface

This thesis is about the modelling of the Huong River System which lies in the Thua Thien Hue province in Vietnam. During a typhoon frequently flash floods occur in this river system resulting in huge inundations. Chapter one gives an introduction of the problems in this province and explains why a model is needed to analyse the Huong River System.

Chapter two gives a description of the study area focusing on the geographical aspect and on the river network. This information describes the difficulties of this river system because of the quite mountainous area in the west part of the province and the very plain area in the east part of the province. This eastern area is very vulnerable for floods because it is very flat and the rivers can't storage all the water, resulting in big floods because the water spreads over a big area. Besides, the eastern area is the most developed and cultivated area of the province, which lead to huge economical losses when this area gets damaged.

Afterwards in chapter three the river network will be described which is used in the model. The description of the Huong River System gives a general overview of the characteristics of the area and which rivers will be taken in account for modelling the Huong River Basin. Also will in this chapter the hydrologic data be described which is needed for the model. Every boundary needs an input data set and those will be described in this chapter.

For modelling the Huong River Basin, the software of HEC-RAS will be used. To get to know what to model does during a calculation, the general equation are described in chapter four among with an explanation how the model computes the water level for every time step and every cross section.

In chapter five the output of the model will be given for the calibration point which is gauging station Kim Long. Both the November 1999 and November 2004 flood are used for calibration and the goodness-of-fit of these calibrations will be given.

Chapter six will give a set up for the damage model which can be used in the future to determine what the losses are after a flood and how vulnerable or places with high economical value are affect by floods.

Finally, in Chapter seven the conclusion of this thesis will be given among with the recommendation. To model has now to ability to determine where the biggest floodings occur and where solutions have to be taken. However the recommendations could bring the model to a higher level and be able to determine better predications of the water level during a flood.

1 Introduction

This chapter will give an introduction on the problems which arise in the study area of the Thua Thien Hué province. This problem analysis results in an objective of this thesis and afterwards the research questions described which will be used to achieve the objective.

1.1 Background

History has shown that in the area of Southeast Asia problems frequently arise due to heavy rainfall and tropical storms. This results in floods with huge economical losses and the losses of human lives. Especially in the central region of Vietnam these problems occur frequently. One of the rivers which flows through this area is the Huong River.
The Huong River Basin is a basin of 2830 km^2 [Villegas, 2004], which has a large amount of rainfall. The rainfall can rise up to 3000 millimeters per year in the plain area and up to 5000 millimeters per year in the mountains [IUCN, 2006]. This results in high flood discharges, and a complex rainfall-runoff process.
In the area there are various national heritages and the ancient capital Hué, a world heritage in this area. In the downstream of the river basin, the terrain slope is small and being affected by the tides. This combination causes inundations and the difficulty in the flood drainage, leading to losses of human lives and economic properties. One of the biggest floods that has arisen in the area is the flood in November 1999. In only four days there was 2700 millimeters of rainfall which led to serious damage of the livelihood and to the economical activities in the area. Around 350 people died during this flood and 300 people were injured [IUCN, 2006]. The land was serious damaged by land erosion and land inundation which led to a losses of crops, animals and houses. Furthermore in the years of 1983, 2004 and 2005 there where serious inundations in the area, causing a lot of damage.
Although the geographical aspect plays a big role in the cause of the high inundations, also human activities can lead to problems which have a bad influence on the Huong River basin. The area has rapidly developed in the previous years, which leaded to a large increase of the infrastructure and the urban areas. These infrastructure and urban areas can lead to obstructions in the river, and on land during an inundation. Especially during an inundation this can lead to high velocities of the water which often results in huge damages. Also the obstruction of the Hoà Duân outlet of the Tam Giang – Cau Hai lagoon into the sea can result in bigger problems upstream of the river.
Because of these severe floods which happened in the past, a research is required in the assessment of the capacity of the Huong River Basin and which problems occur during severe floods, before appropriate measures can be taken to cope with these flood problems. This capacity of the Huong River is in fact the water drainage capacity of the river network to bring the water from the steep mountains to the sea. The flooding problems occur in the downstream part of the Huong (Perfume) River Basin, between the mountains and the sea, because this is where the area becomes plain and frequently problems arise. In the assessment of the flood drainage capacity it is important to investigate how and where the floods arise and how these floods and the inundations are affecting the livelihood assets in this area of the Huong River Basin.

1.2 Objectives and research questions

To better cope with the water problems in the Huong River Basin the problem has to be analyzed and with this analysis, measurements can be taken to cope with these problems. Because of the complexity of this problem and the use of a model to analyze where problems arise during severe floods, this thesis will only focus on the set up of the model which will be used for analyzing the Huong River Basin. Vermue will use this model to calculate where the problems occur and which measurements will be use full. This can be found in *"Flood Modelling and Measure Assement for the Huong River Basin"* by Vermue (2006).

The objective of this research is to develop a calibrated model which can be used to analyze and to determine inundations during the "November 1999-flood" in the downstream part of the Huong River Basin. To develop this model for the Huong River two floods which occurred in the past will be used, the "November 1999-flood" and the "November 2004-flood". The "November 1999-flood" was a huge flood in the past which led to a large inundated area. This flood will now be used as a design flood corresponding with a frequency of once in the 100 years and will be used to determine solutions to prevent the area from such huge inundations again. By developing a model which can determine the water levels during floods it will become possible to determine where inundations problems arise and also gives it the possibility to generate solutions and to calculate the effects of these solutions.
To calibrate the model also the "November 2004-flood" will be used, which was a smaller flood and had a different hydrograph compared to the "November 1999-flood". Using this flood also should give a better calibrated model because there will be more data available for calibration.

To achieve this goal the following questions has to be answered:

- What are the characteristics of the study area?
- What calibrated model can be used to determine the flood event of November 1999?
- Which damage model can be used for calculating the economical damage after a flood?

To answer the first question an analysis will be done to study the characteristics of the Huong River Basin. This analysis will focus on the geographical, meteorological, hydrological and sociol-economic characteristics of the area and will give a focus on the river and gauging network of the downstream part of the Huong River.
To answer the second question the HEC-RAS computer program will be used to set up a hydraulic model of the downstream part of the Huong River. This model will be used for routing both the "November 1999-flood" and the "November 2004-flood" along the river. This will give calculated water level data which will be compared with measured water level data which makes it possible to calibrate the model.
The third question will be answered by setting up a damage model which can be used by to determining the losses after a flood. The variables in this model will be the land use and the inundation depth. Also will be analyzed whether there is the issue of still data or information missing before this model can be used.

2 Study area

This chapter will give a description of all of the characteristics of the study area. First will be described where the study area is situated in Vietnam. Afterwards will the meteorolgy of the area be described, followed by the river and gauging network. This will give a description of the river network and where the gauging stations in this network are placed. Also will there be a description of the socio-economics in this area which will be used for setting up a damage model. At the end the flood of November 1999 will be described and the effects of this on the area.

2.1 Geography

Vietnam lies in Southeast Asia and is surrounded by China in the north and by Laos and Cambodia in the west. This western border is mainly formed by the Truong Son mountain range. At the Eastside and Southside of Vietnam the country is bounded by the South China Sea and the Gulf of Tonkin. The study area of the Huong River Basin lies in the Thua Thien Hué province, which lies in the centre of Vietnam; this is shown in Figure 2.1.

Figure 2.1 - The Thua Thien Hué province is shown in red [Vietnam Field study team, 2004]

The Thua Thien Hué province is around 127 km long and about 60 km wide in average. This area is in general bounded by two geographical aspects: At the westside, the area is bounded by the Truong Son mountain range and at the eastside it is bounded by the South China Sea. Between this there is a narrow delta, which is divided into plains.

The Huong River Basin, which is located from 16°00’ to 16°45’ of the north latitude and from the 107°00’ to 108°15’, has an area of 2830 km2 which is around half of the Thua Thien Hué province [Villegas, 2004]. The Huong River is used as a water resource in the river basin, but the river also leads to inundation problems. Because of the steep hills and mountains in the west, which cover over 80% of the total area, there is only a small plain strip left for cultivation before the river ends in the Tam Giang – Cau Hai lagoon and finally flows into the sea, which is also shown in figure 2.2. At this plain area near the lagoon the river is influenced by the tidal aspect of the sea. In case of high discharges at the river a high tide can increase the problems, which will lead to more and higher inundations and more losses.

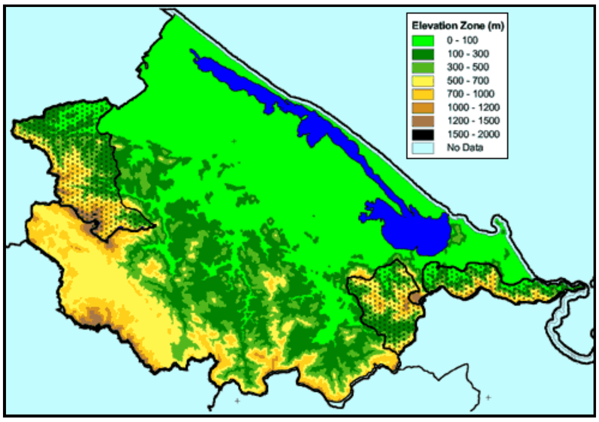

Figure 2.2 - Elevation of Thua Thien Hué province [Vietnam Field study team, 2004]

In this cultivated area lies the city of Hué, which is an ancient capital and a world heritage. The mountainous geography gives considerable potential for hydro power and water storage but at the same time it also leads to rapid raising floods and inundations in the lower areas and intensifies soil erosion.

2.2 Meteorology and Hydrology

The climate in the Thua Thien Hué Province is a tropical monsoon climate which can be divided into four seasons: a fresh spring, a very hot summer, a mild autumn and a windy and cold winter. In June, July and August the maximum temperature occurs, which can be up to 40°C. The lowest temperatures will be reached in November, December and January. The annual average temperature changes from 21 to 26°C [Villegas, 2004]. Furthermore the Huong River Basin can be described as a very wet climate where the annual rainfall can run up to 5000 millimeters in the mountains and up to 3000 millimeters in the city of Hué [IUCN, 2006]. This annual rainfall is mainly caused by the tropical storms which reach the area very often.

In Figure 2.3 an overview is given of the average monthly rainfall. In this diagram it becomes clear that most of the rainfall falls in September, October, November and December. The reason for this, is that in this period most of the tropical storms occur which leads to this heavy rainfall. In this period of time around 50 to 80 per cent of the total annual water quantity will fall down, although this amount of rainfall changes strongly year by year [Aerts & Brouwer, 2002]. In a year with many floods the annual water quantity can be up to threefold the annual water quantity compared with a year with fewer floods. In the period March until July, there is a south-western wind which comes from the Truong Son Mountain range which brings a hot and dry summer.

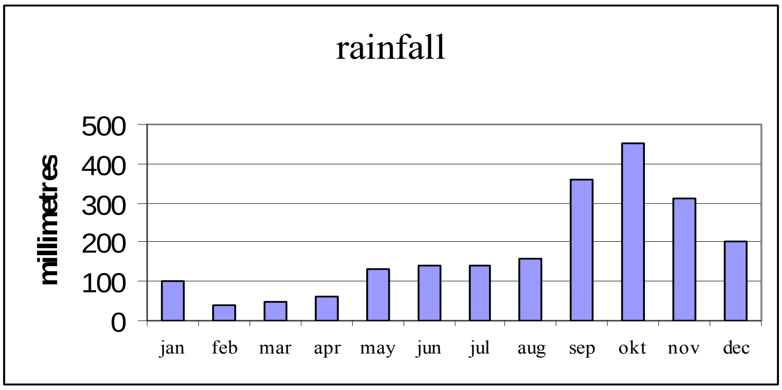

Figure 2.3 – average monthly rainfall [Aerts & Brouwer, 2002]

2.3 River and Gauging Networks

The Huong River Basin covers the majority area of the Thua Thien Hué province that is located east of the Truong Son mountain range and north of the Bach Ma range. The main flow of the Huong River has a length of 104 km. Because of the very mountainous beginning of the river and it's relatively short length results in a very steep river. When the Huong River reaches the plains near Hué the river becomes less steep, from there on it is only a short distance to the Tam Giang – Cau Hai lagoon where the river ends.
The Huong River has two sources which both begin in the Truong Son mountain range. The Ta Trach, or "Left Tributary", comes from the Truong Son Mountains and flows through a mountainous area to the Tuan confluence. The Huu Trach, or "Right Tributary", which has a length of 50 km and flows through a mountainous area as well. At the Tuan confluence the two flows meet and becomes the Huong River. From this point the Huong River flows for a distance of 30 km to a very plain area until it finally ends in the Tam Giang – Cau Hai lagoon.
At the point where the Huong River flows through Hué a sub flow begins, which is called the Loi Nong River. This river has a length of 27 km and ends in the southeastern part of the lagoon.
At the left side of the Huong river lays the Bo River. This river has a length of 94 km and confluence with the Huong River at the Sinh cross-river, which is a distance of 9 km from the lagoon. The total area of the Huong River basin is 2830 km^2 [Villegas, 2004].
For modelling of the Huong river Basin data will be collected from gauging stations. For the upstream boundaries data is obtained from the Phu Oc station and from the Tuan confluence. The data of Phu Oc station is measured water level data but the data at the Tuan confluence is generated data by HEC-HMS. For HEC-HMS input data is used from the Nam Dông, Thương Nhât and Bình Dien gauging stations. Nam Dông and Bình Dien are rainfall stations and Thương Nhât measures the discharge at the river. Furthermore the station of Kim Long will be used as a calibration point, because this gauging station measures the water level. These gauging stations are shown in Figure 2.4.
Furthermore data of the water levels of three outlets of the lagoon are available, which are the Thuan An, the Hoà Duân and the Vinh Hien outlet.

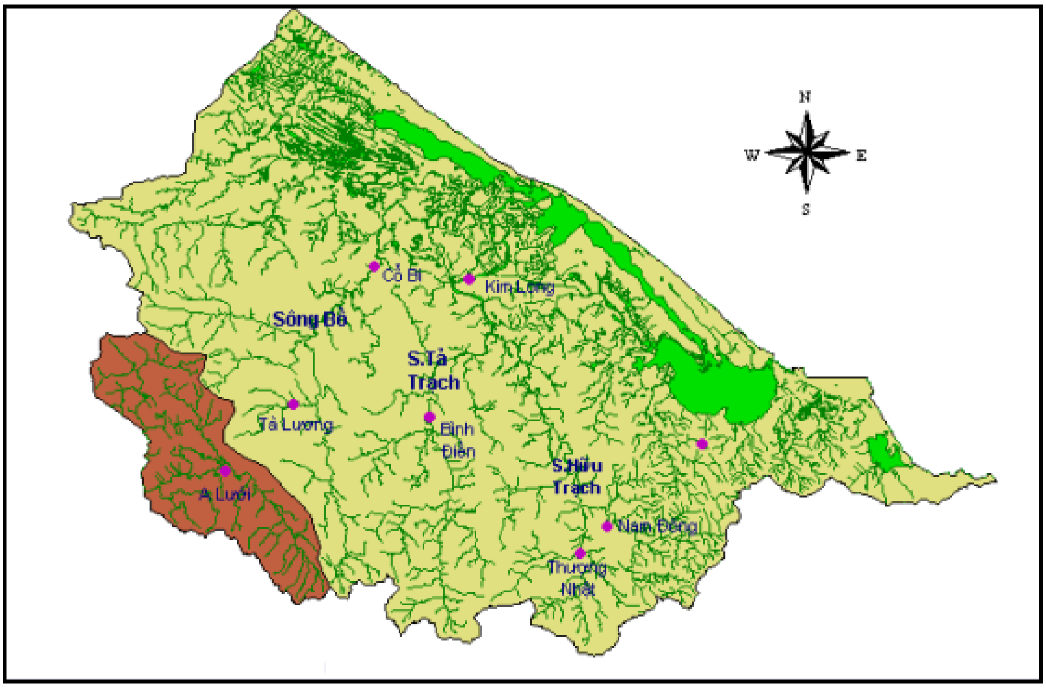

Figure 2.4 – River network and hydrometeorology gauging stations in Huong River Basin

2.4 Socio-economics

As mentioned before the Thua Thien Hué province is very narrow and mountainous in the east so most of the activities which take place in the area are concentrated on a very narrow piece of land. This results that the biggest, western part of the area is only used as forest land and other land of nature. In this area there are some small villages, especially near some non-forest areas like grassland and rivers.
Near the coastline where the land is plainer, the activities lead by people take place. This is the main urban area and also the area where most of the agriculture is situated. The total number of inhabitants of the study area is around 1 million people, of which 300.000 people lives in the city of Hué. In the area several activities take place like residential, services, working, agriculture and industry. Also the area is used for infrastructure like roads and railways. In the plain area the Huong river flows through the city of Hué and along agricultural land, which means that in case of a flood these socio-economical important activities will be inundated which will lead to social and economical losses. The rapid growing urban areas also lead to environmental degration of the river basin [Wunder, 2006]. Due to the growing cities and the increasment of agricultural and industrial activities more and more land is used, which lead to less space for the river to flow.
In spite of this it is important to notice that inundation of the forestry and nature areas also will lead to serious losses, especially because of the danger of landslides in mountainous areas and for the status of the forest and nature for a longer period. Nevertheless it will be more difficult to investigate these losses and to predict a financial loss of it. In appendix A a figure shows an overview of the several socio-economical activities which take place in the area.

2.5 Flooding and Inundation Characteristics

In the end of October and the beginning of November a flood occurred in the Huong River Basin due to the heaviest rainfall that had hit the area in 40 years. This heavy rainfall was caused by the tropical storm "Eve" which on the first of November 1999 caused problems in provinces stretching from Nghe An to Binh Dinh [Villegas, 2004]. This leaded to the alarm level "very dangerous" because of the uncontrollable flooding and landslides which lead to damages on infrastructures. At Hué the flood resulted in a river level of 5.81 meters at the Kim Long station in the Huong River and the city itself was inundated by a water level of 3 meters high [Villages, 2004]. The November 1999 flood damaged nearly 200,000 houses and destroyed over 3500 hectares of crops in Thua Thien Hué province. This leaded to a total damage which was estimated at USD 122 million [IUCN, 2006]. Also did this flood lead to a change of the shape of the Tam Giang – Cau Hai lagoon and the creation of three new outlets. This November 1999 flood was a historical flood, corresponding to a design flood with a frequency of 1%. To avoid these huge problems and losses measures have to be taken to prevent the area from these floods. In the next chapter an analysis will be given of the problems during this November 1999 flood.

3 Methodology

In this chapter the necessary input data for the HEC-RAS program is described. First the geographical data will be described with the flowchart of how the Huong River Basin is schematized in HEC-RAS. Second will the hydrological data be described and how these data is implemented in the HEC-RAS program.

3.1 Flowchart

The model of the Huong River Basin used in HEC-RAS is a schematization of the river network shown in Figure 3.1 The river network consists of four rivers and has two upstream boundaries and three downstream boundaries. These boundaries are shown in this picture to make it more clear where the model is situated in reality. Figure 3.2 shown the schematization of the Huong River Basin network, which is used in HEC-RAS for the model.

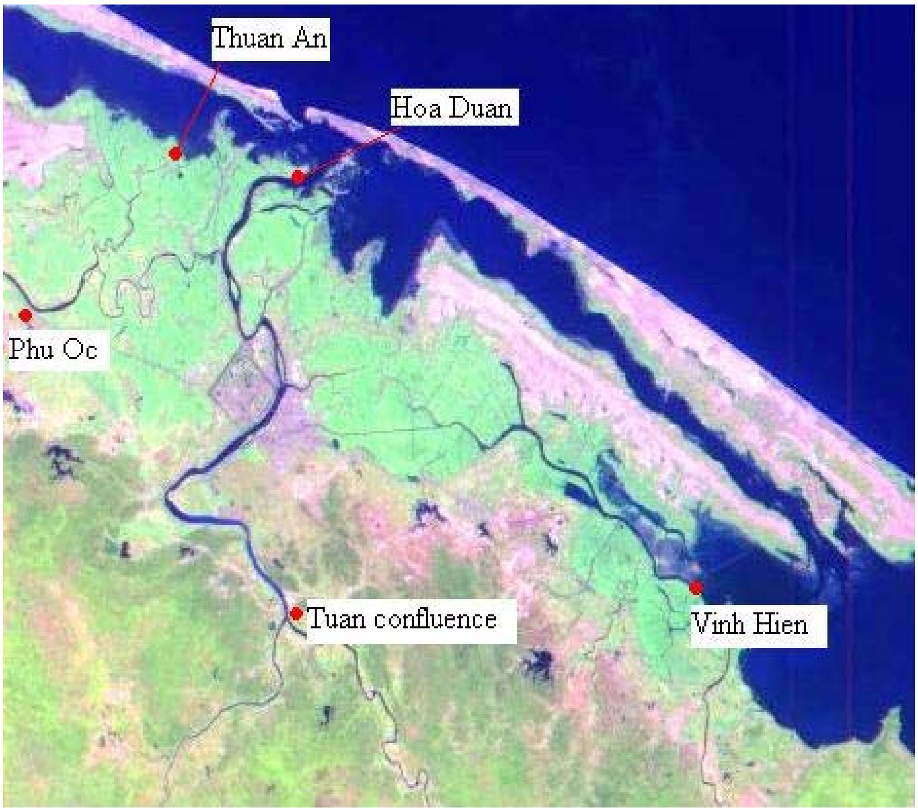

Figure 3-1 Satellite photo of model area with up- and downstream boundaries

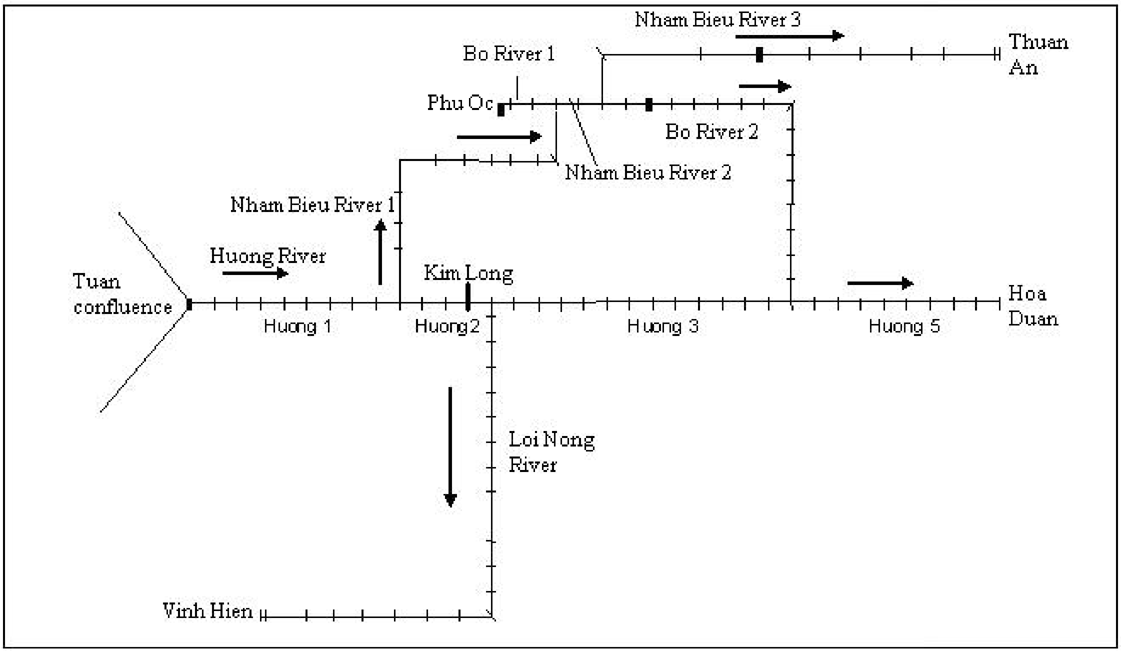

Figure 3.2 - Outline of the Huong River Basin

The main river in the scheme is the Huong River, which flows from the upstream boundary, Tuan confluence, to the downstream boundary Hoà Duân, where the river ends in the Tam Giang – Cau Hai lagoon. This river exists in the model out of four segments (Huong 1, Huong 2, Huong 3 and Huong 5) because the river contains some splits and confluences. This Huong River has near the city of Hué a gauging station called Kim Long which will be used for the calibration of the model.
The total length of the Huong River from the Tuan Confluence until the Tam Giang – Cau lagoon is 32 kilometers. Furthermore has the Huong River an average width of 367 meter and the average width of the river segments doesn't change much although is river section Huong 5 a bit wider.
At the Huong River, 23 kilometers before ending in the lagoon (at the start of river segment Huong 2), a tributary originates which is called the Nham Bieu River. This River flows all the way down to Thuan An where this river ends in the lagoon. The total length of this river is 26.4 kilometers. The river has an average width of 124 meters but the width changes very much over the three river segments. The first river segment Nham Bieu 1, which is between the Huong and the confluence with the Bo river, has an average width of 52 meters, while the Nham Bieu 2 and Nham Bieu 3 river segments have an average width of 201 and 220 meters. Where the segment Nham Bieu 2 is the segment where the Bo and the Nham Bieu river confluence and Nham Bieu 3 is the segment where the Bo river has split again.
In the Northern part of the Thua Thien Hué province originates the Bo River. For this river the Phú Oc gauging station will be used as an upstream boundary. The Bo river confluence for a short distance with the Nham Bieu River, called Nham Bieu 2 river segment, until these rivers split and the Bo River (river segment Bo 2) goes its way and finally confluence with the Huong River. The Bo River has a total length of 29.2 kilometers, of which 13.2 kilometers is the length before it confluences with the Nham

Bieu River (river segment Bo 1) and 16 kilometers is the length of the Bo River between the Nham Bieu and the Huong River, where the Bo River ends. River segment Bo 1 has an average width of 224 meters, while the other river segment Bo 2 is much smaller with an average width of 118 meters.
In Hué the Loi Nong River originates at a split of the Huong River. This tranch is 18.7 kilometers before the Huong River ends in the lagoon. This Loi Nong River flows over a length of 26 kilometers and with an average width of 162 meters to Vinh Hien where the river ends in the eastern part of the lagoon. An overview of all the lengths and widths of each river and river segment is shown in appendix B.
There is also a fifth river in the network which is called the Dap Da River. This River originates out of the Huong River only 2 kilometers downstream from where the Loi Nong River originates. This Dap Da River is around 15 kilometers long and confluence with Loi Nong River, 17 kilometers before this river ends in the lagoon. This Dap Da River is taken out of the network after a few attempts in HEC-RAS because it made the network too complicated to run the model, causing some big errors in the output data. Therefor the assumption is made that the water which normally flows through the Dap Da River and than confluences in the Loi Nong River, now directly flows into the Loi Nong River.

3.2 Hydrologic Data collection

For each of the five boundaries in the model a stage hydrograph or a flow hydrograph has to be put in the model. Because of the available data, the Tuan confluence upstream boundary exists out of a flow hydrograph and all of the other boundaries exist out of a stage hydrograph.

The flow hydrograph of the Tuan confluence is calculated by the program HEC-HMS. This program calculates the runoff out of the rainfall in a certain area. These data was calculated by Phuong (2005), this discharge is calculated out of the heavy rainfall of November 1999 and November 2004 causing these big floods. The peak discharge at the Tuan confluence is 12640 m^3[1]/s in November 1999 and 10282 m^3/s in November 2004. A diagram of these flow hydrographs are shown in appendix C-1 for 1999 and appendix D-1 for 2004.

The other upstream boundary, located at the Bo River is a stage hydrograph which is obtained out of the available data measured by Phú Oc water station. This hydrograph shows a huge rise of the water level at the beginning of the flood the water level rises in just a few hours from 1.2 meters to 4.3 meters which still rises to a peak of 5.2 meters in November 1999. Afterwards the water level very slowly declines to 4.3 meters at the end of the model time. In November 2004 the maximum water level in the Bo River reaches a level of 4.95 meters. This level declines to a level of 2.7 meters at the end of the flood. A diagram of these flow hydrographs are shown in appendix C-2 for 1999 and appendix D-2 for 2004.

All of the downstream boundaries end in the Tam Giang – Cau Hai lagoon, but at these points where the rivers ends in the lagoon there is no water level data available. The nearest available water levels are at the outlets were the lagoon is connected with sea.

There are three outlets and all of these a nearby one of the rivers. With the assumption that the water level at the outlet is the same as at the river outflow and the other assumption that the tidal effect of sea is the same at the river as at the outlet, the outlet data will be used as downstream boundary for the three rivers. These three datasets contains a tidal effect which varies from 0.25 meter above sea level till 0.2 meter below sea level. Diagrams of these stage hydrographs for the Huong, Nham Bieu and Loi Nong River are shown in appendix C-3,4,5 for 1999 and appendix D-3,4,5 for 2004.

4 The HEC-RAS Model

In this section the theoretical background from HEC-RAS is shown. First the theoretical background for steady flow analysis is shown after which unsteady flow analysis is elaborated.

4.1 Steady flow

Steady flow means a flow which does not change over time, i.e. the water surface level and velocity do not change over time [Ribberink & Hulscher, 2006].

For the steady flow analysis the governing equation is the energy equation. This equation, 3-1, is used to match total energy heads of two cross sections. The equation contains the height of the river bed, the water depth, the velocity head (equation 4.1) and the head loss.

$$Y_2 + Z_2 + \frac{\alpha_2 V_2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1}{2g} + h_e$$

Equation 4.1 - Energy equation

Where:	Y_1, Y_2	=	depth of water at cross sections
	Z_1, Z_2	=	elevation of the main channel inverts
	V_1, V_2	=	average velocities (total discharge/total flow area)
	α_1, α_2	=	velocity weighting coefficient
	g	=	gravitational acceleration
	h_e	=	energy head loss

The subscripts $_1$ and $_2$ refer to the different cross sections. Cross section 1 is situated downstream of cross section 2. The total energy (the left or right side of the equation) at each cross section has to be the same as no energy is lost in a sense that it disappears. The total energy is split up in the terms in the energy equation as the vertical distance of the water to the datum is potential energy (gravitational acceleration). Furthermore, the velocity is a form of energy and the head loss, resulting from friction and contraction or expansion losses also represents energy. With including all these terms all energy related aspects of the water have been implemented in the energy equation.

The energy equation is used to calculate the water depth, and thus the water surface level, at the next cross section. In the section computation (Appendix E) more can be found about how this equation is used to calculate water levels.
The output of the energy equation, the water surface elevation, is bounded by the critical depth. The critical depth is the depth at which the energy is minimal for a given rate of flow. When the water surface level is lower than the critical depth, the profile is probably supercritical as velocity dominates the total energy instead of water surface level. So, if the calculated water surface levels are lower than the critical depth, the profile is instead of subcritical, supercritical according to the program. The critical depth can be determined using the total energy head, equation 4.2.

$$H = WS + \frac{\alpha V^2}{2g}$$

Equation 4.2 - Total energy head.

Where:

	H	=	total energy head
	WS	=	water surface elevation
	$\frac{\alpha V^2}{2g}$	=	velocity head

The water surface is being varied and as Q remains constant for the cross section, the velocity has to change in order to keep Q constant. Due to the fact that V has to change, the energy changes with it, this is because of the velocity head. In this way a minimum possible energy and a critical depth can be attained. In the section computation is explained when the critical depth is used as a boundary for the outcomes of the energy equation.

At locations where water surface levels do not satisfy the critical depth boundary the energy equation is not considered applicable. For this and other problem river reaches where flow varies rapidly the momentum equation can be used or is used. The momentum equation is derived from Newton's second law of motion and contains the following terms: momentum flux, hydrostatic pressure forces, weight of water force and force of external friction. In equation 4.3 the momentum equation is formulated.

$$P_2 - P_1 + W_x - F_f = Q\rho\Delta V_x$$

Equation 4.3 - Momentum equation

Where:

	P	=	Hydrostatic pressure force at locations 1 and 2.
	W_x	=	Force due to the weight of water in the X direction.
	F_f	=	Force due to external friction losses from 2 to 1.
	Q	=	Discharge
	ρ	=	Density of water
	ΔV_x	=	Change in velocity from 2 to 1, in the X (flow)

direction.

Using this equation, in a different form though (equation 4.4.1&4.4.2), HEC-RAS can compute water surface levels for rapidly changing flow.

$$\left\{\gamma A_2 \overline{Y}_2 - \gamma A_1 \overline{Y}_1\right\}_P + \left\{\gamma\left(\frac{A_1 + A_2}{2}\right) L S_0\right\}_{W_x} - \left\{\gamma\left(\frac{A_1 + A_2}{2}\right) L \overline{S_f}\right\}_{F_f} = \left\{\frac{Q\gamma_1}{gA_1}\beta_1 V_1 - \frac{Q_2\gamma_2}{gA_2}\beta_2 V_2\right\}_{Q\rho\Delta V_x}$$

Equation 4.4.1- Momentum equation 2

In this equation there has been assumed that there can be a difference between two cross sections in discharge, for instance through a new tributary. The equation can be simplified to:

$$\frac{Q_2\beta_2}{gA_2} + A_2\overline{Y}_2 + \left(\frac{A_1 + A_2}{2}\right)L\overline{S_0} - \left(\frac{A_1 + A_2}{2}\right)L\overline{S_f} = \frac{Q_1\beta_1}{gA_1} + A_1\overline{Y_1}$$

Equation 4.4.2 - Simplified momentum equation

Where: Q_1, Q_2 = discharges at the cross sections
β_1, β_2 = momentum coefficients that account for varying velocity distribution in irregular channels
g = gravitational acceleration
A_1, A_2 = wetted area of the cross sections
$\overline{Y_1}$, $\overline{Y}_2$ = Depth measured from the water surface to the centroid of the cross sectional area of the cross sections
L = Distance between two cross sections measured along the x-axis
S_0 = Slope if the channel based on mean channel elevations
$\overline{S_f}$ = slope of the energy grade line (friction slope)

A number of assumptions have been made in order to attain water surface levels. These assumptions are:
Flow is steady (the water depth and flow velocity do not vary in time)
Flow is gradually varied, except at structures where empirical equations and the momentum equation are used. (The assumption is based on the premise that for equation 3.1 hydrostatic pressure distribution must exist.)
Flow is one dimensional.
River channels have small slopes, this has to do with the pressure head Y in equation 4.1 as this is assumed to be vertically.

4.2 Unsteady flow

An unsteady flow is defined as a flow which varies both in space (water surface level) and time.

For the unsteady flow there are two principles considering a control volume in a river which are used to compute water surface levels. These principles are the conservation of mass and the conservation of momentum.

The principle of conservation of mass states that *the net rate of flow into the volume be equal to the rate of change of storage inside the volume*. This means that no mass is lost over time, either this flows out of the control volume or more mass is stored in the control volume due to higher inflow than outflow. In HEC-RAS this principle is contained in the continuity equation (equation 4.5).

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0$$

Equation 4.5 - Continuity equation for unsteady flow

Where: A_T = the total storage
Q = the net discharge into the control volume
q_l = the lateral inflow per unit length

The second principle, the principle of conservation of momentum states that the net rate of momentum entering the volume (momentum flux) plus the sum of all external forces acting on the volume be equal to the rate of accumulation of momentum. This principle is stating the same as the principle of conservation of mass, only now it is momentum which should not be lost over time. In HEC-RAS this principle is contained in the momentum equation (equation 4.6)

$$\left\{\rho \Delta x \frac{\partial Q}{\partial t}\right\}_{acc} = -\left\{\rho \frac{\partial QV}{\partial x} \Delta x\right\}_{mom} - \left\{\rho g A \frac{\partial h}{\partial x} \Delta x\right\}_{pre} - \left\{\rho g A \frac{\partial z_0}{\partial x} \Delta x\right\}_{gra} - \left\{\rho g A S_f \Delta x\right\}_{bou}$$

Equation 4.6 - Momentum equation

Where: ρ = Density of water
Q = discharge at the cross section
Δx = length in the x-direction
t = time
A = wetted area of the cross section
h = water depth
Z_0 = vertical distance to datum
S_f = friction slope

The equation contains five terms: the pressure forces, gravitational force, boundary drag and the net rate of momentum flux and the net rate of accumulation. In equation 4.6 the formulation of the different forces can be found using the subscripts acc (accumulation of momentum flux), mom (net rate of momentum flux), pre (pressure forces), gra (gravitational force) and bou (boundary drag) in the equation.

The momentum equation can be simplified, as we know that the elevation of the water surface is build up by two terms, the water depth and the vertical distance to the datum ($z=z_0+h$). This simplifies equation 4.6 to equation 4.7

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0$$

Equation 4.7 - Simplified momentum equation

In HEC-RAS the two dimensional process of flooding is calculated in a 1-D way. This is done by representing the main channel and the flood plains as separate channels (figure 4.1). The horizontal water surface level of both channels is assumed to be the same.

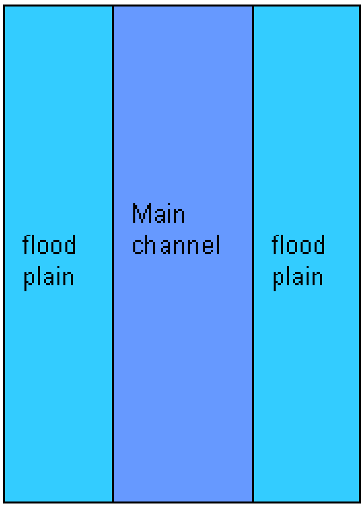

Figure 4.1 - Schematic representation of the different parts of the river, the floodplains are summed up as one channel

A more detailed description of the computation method can be found in Appendix E. This parts analysis the method how the HEC-RAS software calculates it's output, like water level, velocity and discharge.

Note: A lot of information in this chapter has been obtained by using the documentation of HEC-RAS itself, like the hydrologic capabilities, in order to keep this chapter readable, only here the reference will be shown: [HEC-RAS, 2002]. Furthermore is this chapter also published in Vermue (2006).

5 Results of flood routing modelling

Both the “November 1999 flood” and the “November 2004 flood” are simulated in HEC-RAS to calculate the water level along the river. Both simulations will be described in this chapter and after that, the goodness of fit will be calculated for both floods including the calibration and validation of the model.

5.1 Process of Modelling

To model the floods of November 1999 and November 2004, all the data which are described in chapter 3 must be imported in the computer program, in appendix F the flowchart is given of how the river system is implemented in HEC-RAS. The only data which is still lacking after implementing these data is the Manning-coefficient. Because these data is not available for the Huong river system an assumption has to be made and so these parameter will be used for calibrating the model. Each cross section in the model exists out of a left overbank, main channel and right bank and for each part and for each cross section a different Manning-coefficient can be implemented.
The biggest problem which occurred during the use of the program HEC-RAS was that in the first runs the model didn’t work. The program gave errors when the very first data set of hydrology data was used in the model. This could be solved by using warm-up steps. With this the model makes some calculations before the implemented data set is used, so the model has already calculated output before the model time range starts. This makes that model can better cope with big raises of water level of discharge in the beginning of the model time range. This made that the model could run, but lead to big errors and unrealistic water levels.
Because the model didn’t work well with the entire river system in the program, only the Huong River, which is the main river of the network, would be implemented in the program. This lead for the first time to realistic water levels and discharges in the Huong River, although still some warm-up steps were needed. Afterwards every other river is one by one added to this river system and every time a model run was made to see whether the program could handle the new river. After adding the Bo River, the Nham Bieu River and the Loi Nong River the model still worked well, but after adding the fifth River, the Dap Da River, all the problems of the beginning were back. This Dap Da River is a small river which originates from the Huong River and ends in the Loi Nong River. Because the Loi Nong River also originates out of the Huong River, it might be possible that this Dap Da River leads to loops in the river network.
Normally when water flows through a River network, it starts at an upstream boundary of the network and flows through the network to a downstream boundary where the water dissapares from the model network. When a loop is in the network, it is possible that water in the network, by using several rivers and tributaries, makes circles (loops) which leads that water doesn’t flows out the network, but stays in the network giving uncorrect and unrealistic water levels and discharges. In reality this wouldn’t happen because water would always flow from a high point to a lower point in the area, but in a model mistakes in the geographical data or wrong assumptions can lead to these loops. Altough there is a tool in the program which can check for loops and which didn’t find one, it is most likely that the Dap Da River could result into a loop in the model. For this reason the Dap Da

River is not implemented in the geographical data of the model. Because the Dap Da River is a small river and orginates out of the Huong River like the Loi Nong River and also confluences with the Loi Nong River, the assumption is made that all the water which normally flows through the Dap Da River in the model directly flows through the Loi Nong River.
Now the geographical data is well implemented it can be calibrated by using the "November 1999 flood" and the "November 2004 flood". The "November 2004 flood" is a smaller flood than the "November 1999 flood", which leads to the assumption that it should be easier to calibrate this flood than the "November 1999 flood". However, when the first run is made for both floods, the "November 1999" flood has already a better fit than the "November 2004 flood". When a closer look is taken at the discharge hydrograph at the Tuan confluence (Appendix C-1 and D-1) it shows that the "November 2004 flood" has a lower peak discharge and a lower total amount of water during the flood than the "November 1999 flood". But the "November 2004 flood" has more increases and decreases of the water discharge during the flood time range. These steep ups and downs in the hydrograph make it more difficult to get a good fit for the calibration. For this reason both of the floods are used for calibration. The reason to take two flood scenarios is because these give more data which is favorable for a good calibration.
For calibrating the model the Manning-coefficient is used. There is no data available of the Manning-coefficients along the river, so therefore assumptions about the Manning-coefficient has to be made and those will be changed during the calibration. In the initial run of the model the Manning-coefficients are based on the relief of the cross section. For the main channel is lead in general to a value of 0.035 and for the overbanks a value of 0.04 and 0.045. To calibrate the model the water level in the model for each flood was compared with the water level which was measured during each flood at the Kim Long water station. First the flood of November 1999 was used for calibration and when this gave a good result, the November 2004 flood was used for calibration. Because changes in favor of one flood led to unfavorable changes for the other flood, a balance had to be found between both floods, so a good fit for one flood would also give a good fit with the other flood. The best calibrated models are described in paragraph 5.2 for the "November 1999 flood" and paragraph 5.3 for the "November 2004 flood".

5.2 Flood routing modelling of "November 1999 flood"

The November 1999 flood took place from the first of November at 12 o' clock in the afternoon until the 7th of November at midnight according to the input data. When these data was used in the model it shown that the computed data was running exactly 12 hours in front to make a good fit with the measured data at Kim Long water station. For that reason it is chosen to shift the input data, at the Tuan confluence, for 12 hours. Because the Tuan confluence input data is a flow hydrograph out of the program HEC-HMS it could be possible that this caused the difference of exactly 12 hours. When the new input data is used the following water surface is calculated at the Kim Long water station (blue line) compared with the measured water surface (red line) see figure 5.1.
A look at the figure shows that the calculated water surface fit quite well with the measured water surface. Only at the points where the measured water surface makes high

rises or falls in the water surface the calculated water surface the difference becomes at bit bigger. Although it is almost impossible to get a very good fit during these rises and falls, it is a disadvantage that the calculated water surface doesn't reach the maximum measured water surface.

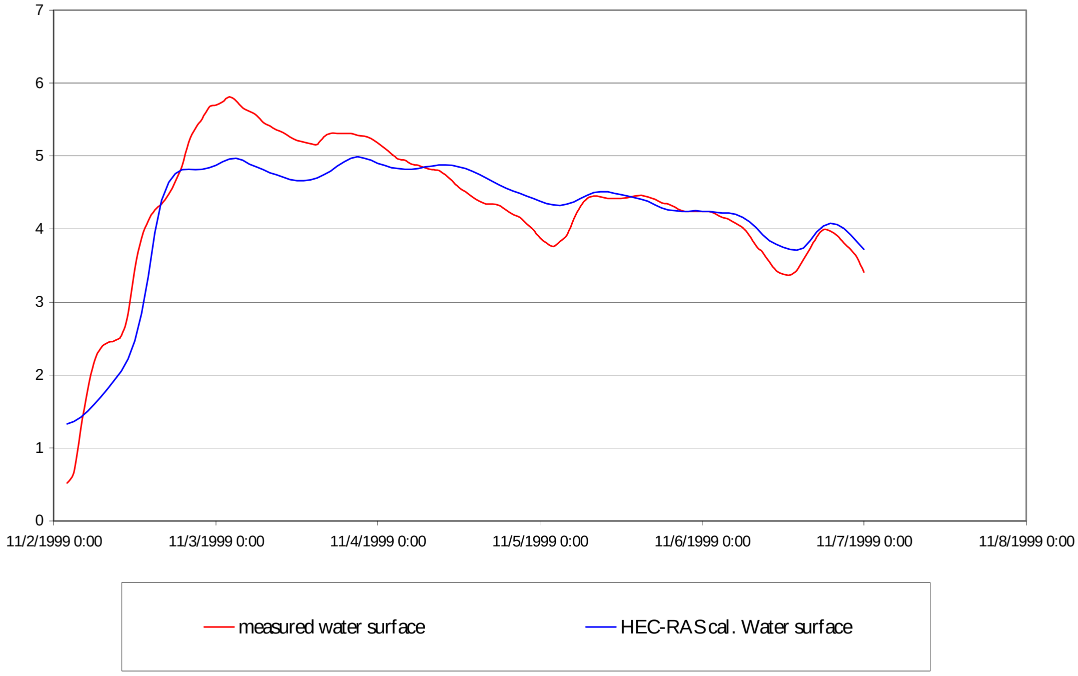

Figure 5-1 - compare between the calculated and measured water surface at Kim long station for "November 1999 flood"

5.3 Flood routing modelling of "November 2004 flood"

The November 2004 flood appeared from the 24th of November in the evening until the night of the 30th of November. This flood was not as big as the "November 1999-flood" which is also shown in the measured water surface where the maximum water surface in 2004 just reaches the 4 meters, where in November 1999 the water surface reached a height of nearly 6 meters. Although as described in paragraph 5.1 this flood has more and steeper rises and falls of the water discharge during the flood, this can have a negative effect on the goodness-of-fit of this flood. During these changes the calculated water level rises far too high than it would be in reality. Figure 5-2 shows that the calculated water surface has a less accurate fit than the "November 1999 flood". The calculated water surface is in average too high compared with the measured water surface.

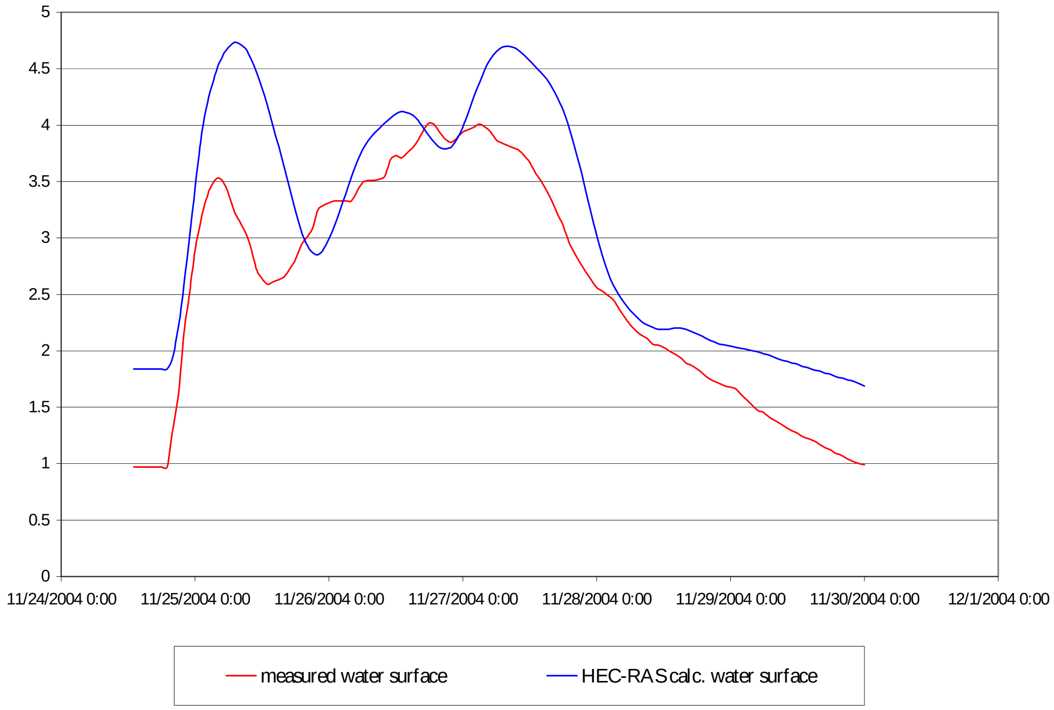

Figure 5-2 - compare between the calculated and measured water surface at Kim long station for "November 2004 flood"

5.4 Calibration and validation of the model

For calibration and validation of the model a compare is made between the calculated water surface and the measured water surface at Kim Long water station. To calculate the goodness of fit of these two water surfaces the a Mean Error index test is used. This test, which is called the Relative Root Mean Square Error (RRMSE) gives an index how good the observed data match with the calculated data. The formula for determining the RRMSE index is as follows:

$$RRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{(Y_i - X_i)^2}{X_i^{\,2}}}$$

where: Y_i = obtained data by the model for time step i

X_i = observed data for time step i

n = number of data pairs

The advantage of using this method is that it is a "sample size independent method" which is favorable because the November 1999 flood and the November 2004 flood have different time ranges and thus a different number of data pairs. Computing the RRMSE for both floods result in the following values:

November 1999 flood RRMSE: 0.253
November 2004 flood RRMSE: 0.322

As also could be seen in the two graphs that compare the observed and measured data, the model of the “November 1999 flood” has a better fit as the model of the “November 2004 flood” and the RRMSE values proves the same. If the observed data and measured data have a perfect fit than the RRMSE will be zero. With the RRMSE method there is no reference value which decides whether a model fits well with the reality.
Based on the rather good fit of the “November 1999 flood” compared with the observed data and the little bit worse, but also quite reasonable fit of the “November 2004 flood” it is assumed that the model is well calibrated. The good fit of the “November 1999 flood” gives also reason to assume that model is validated to be used for determining and calculating the effects of solutions against floods like those which appeared in November 1999 in this study area.

6 Flood Damage Assessment

To compute the economical losses of a modelled inundation in HEC-RAS, a model has to be developed which determines for every land use, the financial and economic damage. This chapter will give a set up of the model and will analyze which data must be collected to calculate the damage after a simulated flood. The first paragraph will give an analysis of the land use data and the second paragraph will give an analysis of the needed economical data. The third paragraph will give the total set up of the model.

6.1 Land use data

As also is described in paragraph 2.4 there are several types of land use in the Thua Thien Hué province. Focusing on the study area and the area which is modelled in HEC-RAS three main land use area remain, which are agriculture, industry and residential. Between the Tuan confluence and the city of Hué there is also some forestry. Furthermore there are also several roads and a railway which are going through the area. At last there are also some non-used and grassland areas which from now on will be described as nature. This means that there are five different classes which are relevant for the flood damage.

6.2 Economic data

To describe the damage caused by a flood, this damage can be divided in three components: immobile land use, mobile property and profit loss. Immobile land use are buildings or other objects which can’t be moved, mobile property is property which can be moved like household inventory or machinery and profit loss is damages which arises when for example a factory can’t produce it’s products caused by the inundation, these type of damage is also called as economical damage where the other two are called financial damage.
For each land use classes and for each component a property density value can be added. This is a value in dong (VND) per squared meter which describes the total value of a squared meter for the associated land use class. These property density value is now not available for Vietnam thus before this model can be used these data has to be obtained.

Because the water surface level has an influence on the damage the “relative flood damage” will be used. This is a formula, with the inundation level a variable, for each different land use and components which calculates the percentage of the property density value must be taken in account. Also this information in lacking for Vietnam and although these formulas are money independent, it is very difficult to say whether existing European relative flood damage equations can be used. So it is recommended that before this model will be used first a research must be done achieve the “property density value” and the “relative flood damage equations” for Vietnam.

6.3 Set up damage model

The goal of the damage model is to make it possible to calculate the damage caused by the water surface for every particular cell. To calculate a good prediction of the damage, the whole area must be divided in cells with a size of for example 100 by 100 meters, because maximum water surface and land use differ from place to place. When the whole study area is divided in cells, now for each cell the maximum water surface and land use can be added, these data will be obtained by Vermue [Vermue, 2006]. With the formula to calculate the relative water damage and the property density values for each component, now it is possible to determine the damage for each cell and component.

6.4 Factors which influence the damage

In the model described in the previous paragraph, only the water surface height is taken in account to calculate the damage. Other factors which can also play a role in the height of the damage are the water velocity and the duration of inundation. A high water velocity can result in very high damages because the water force increases very much in such case, especially when water is forced to flow through narrow streets or in case water is obstructed by infrastructure.
The duration of the inundation has also an influence on the height of the damage. Especially the component “profit loss” is very much dependable of the time duration takes, because the longer the industry is out of business the more money they loose.

7 Discussion and Conclusion

The Thua Thien Hué province is a quite mountainous in the west part and very flat in the east part of the province, which easily leads to flash floods in the rivers. These floods lead to heavy inundations in the plain area causing huge damages to the urban areas and land used for agriculture and industry. This results in huge economical damages and even losses of lives.
To prevent the Huong River Basin in the Thua Thien Hué province to get flooded again like it did in November 1999 and November 2004 measurements has to be taken. But before solutions will be taken, first the Huong River System has to be analysed and has to be determined where floods occurred during the "November 1999 flood" because this flood will be used as a design flood to calculate solutions. For this reason the model of the Huong River System is made with the computer program HEC-RAS which gives the ability to determine where floods occur during hypothetical design floods and floods which occurred in the past. In the next paragraph a discussion will be given of the HEC-RAS model and in paragraph 7.2 there will be an overall discussion and conclusion over the whole project.

7.1 Discussion of the HEC-RAS model.

The model of the Huong River Basin, which contains four rivers and five boundaries, has been calibrated by the use of Kim Long water station for the flood of November 1999 and November 2004. This calibration is carried out by changing the Manning coefficients. Because there where no measured Manning coefficients these coefficients where assumed and changed during the calibration.

One problem of the model is the missing data in the cross section. In general a cross section contains now the main channel of the river and some land around this main channel, which are called overbanks. When these overbanks also get flooded over the whole cross section, the program HEC-RAS automatically extends the cross section vertically, while in real case the water would spread over a bigger surface. This results that the model will give a higher inundation level on the overbanks than it would be in reality. Because the model is calibrated with the available data this over-estimation of the water surface is now compensated by the Manning coefficient, so in reality the Manning coefficients will be higher than now used in the model.

Another problem is the lack of available data about the downstream boundaries. From all of the three rivers which end in the lagoon, none of them has available water levels or discharges during the November 1999 and November 2004 flood. So in this model now the water levels of the outlets are used with the assumption that there isn't much difference between the end of river and the outlet between the lagoon and the sea. This assumption is probably right during a normal discharge on the river but when a big flood occurs it is very good possible that the flood wave on the river will be much greater than the tidal wave, resulting in a higher water level at the downstream boundaries. Because the very plain area near the end of the river and the lagoon this can lead to bigger

inundations than know are calculated in this area. However the data which was now available it was of very good use to set up the model. Improvements can always be made when more data is available, but of the data which was now available it was very good possible to set up this model. It was very useful that of every river in the area the cross section could be implemented in the model and that all the flood waves could be imported in the model.
The last disadvantage of this model is that it has a very large and complex network, however the calibration is done with the use of only one calibration point. Although one point is always affect by several upstream and downstream cross sections, one point is not enough to calibrate the whole model. Until this moment there are no other water stations in the area but it would be favourable if more data becomes available on how the whole river system behaves during a flood, this can be achieved by adding a few calibration points in the model, for example having for every river a calibration point.

Despite the just mentioned disadvantages of the model it is for very good use to determine where the biggest inundation problems arise. With the model the amount of water can be calculated which cannot be stored in the river and where for measurements has to be taken. Furthermore the model gives an overview of how all the rivers behave during a flood and how the water during a flood spreads over all of the four rivers. Especially with such a complicated network it is important to be aware of this. However, to calculate the precise inundation depths during a flood the adjustments and improvements have to be made which are just mentioned.

7.2 Discussion and conclusion of the Huong River Basin

As is mentioned before, the model of HEC-RAS is a very useful tool to analyze the problems in the Huong River System but it can use some improvements. Another option could be the use of a 2-D model which makes it easier to analyze the inundations on land; this can avoid the problem of the HEC-RAS model which now vertical extends the cross sections if too much water is in the cross section. However, a 2-D model is not easy to set up and needs more information than now is available.
Another big problem is that the flood of November 1999 and also November 2004 had so much water that it will be almost impossible to implement measurements to keep all the water in the river network. Therefore it is good to not only focus on the model area, but also to the area where the rivers originate. The Huong and Bo River both originate in the area at the west of middle Vietnam which is a very mountainous area. These mountains has a big influence on the floods, because of the narrow valleys the rivers are also very narrow which makes that the floods are very concentrated and flow fast downstream to the plain area. When these fast flowing, concentrated floods come in the plain area it result in very big flash floods spreading out over the whole area and are very devastating by their high velocity. For this reason it would be wise to not only focus on the downstream area for finding solutions but also to analyze the upstream area, for example to find measurements to slow down the floods by (temporarily) storage the water in the mountainous area.

After all, this project has shown that the Huong River Basin is a very complex river system which suffers a lot by the floods that frequently occur. Also has this project

shown that the model in HEC-RAS can be a useful tool for analyzing the problems in the Huong River system, nevertheless will the recommendations improve the model.
When in the future more work can be done to this project, if the model can be improved by adding more data and information and if the model area can by extend by adding also the mountainous area to the project, it can become reality that the people who live in the Huong River Basin won't get flooded every year. Despite of this it will be really hard to prevent the plain area of getting flooded during severe floods like those who happened in November 1999 unless serious measurements will be taken in the mountainous area.

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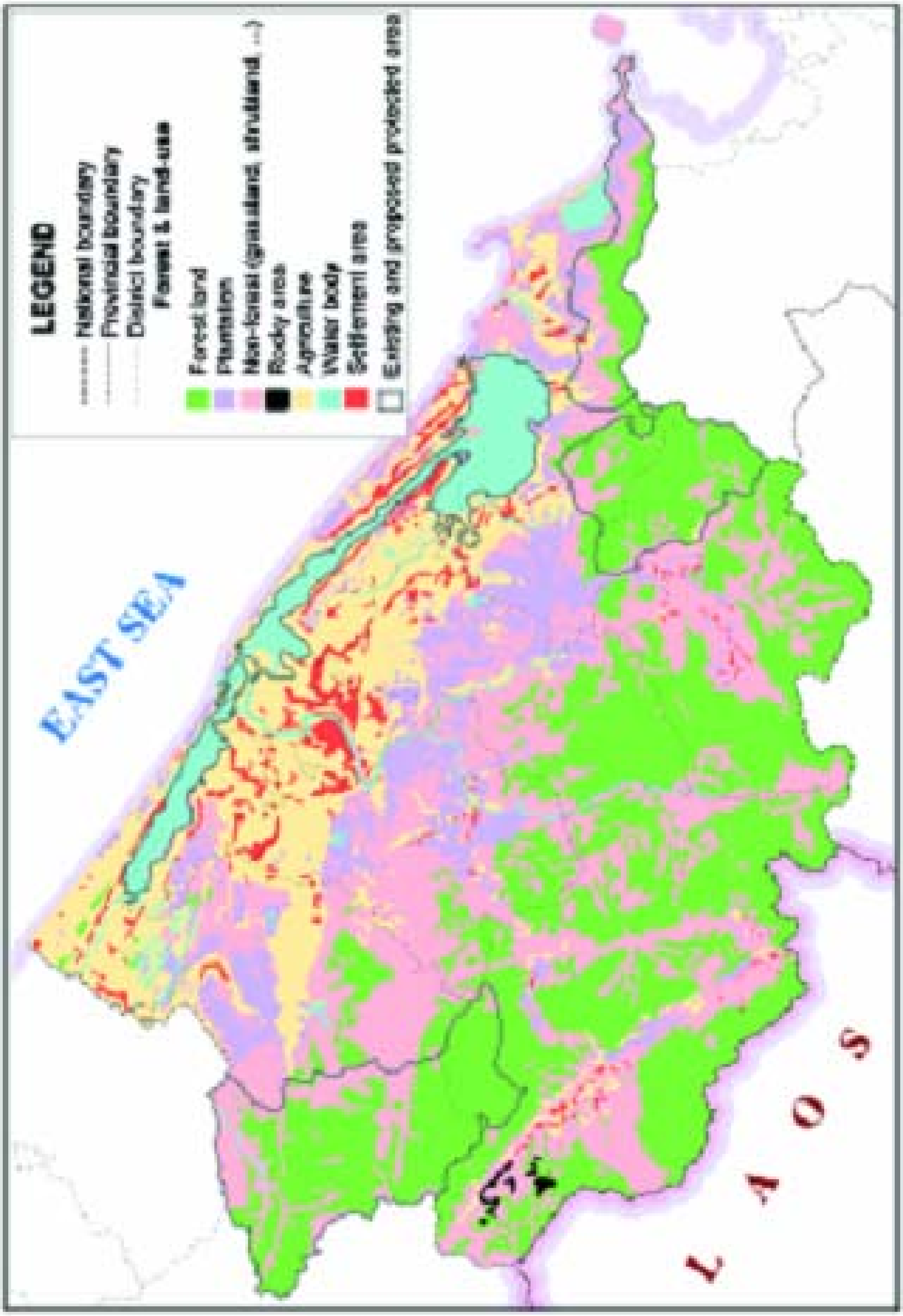
Appendix A

Land use in the Thua Thien Hué province [Vietnam field study team, 2004]



Appendix B

These tables show the length and the average width (main channel) of each river and of each river section.

	average width (m)	length (m)
Huong River	367.3	31970.8
River sections:		
Huong 1	384.0	9131.9
Huong 2	366.1	3976.9
Huong 3	312.3	9825
Huong 5	410.8	9037

	average width (m)	length (m)
Nham Bieu River	124.3	26420.1
River sections:		
Nham Bieu 1	52.0	14762.3
Nham Bieu 2	201.2	2526.3
Nham Bieu 3	220.0	9131.5

	average width (m)	length (m)
Bo River	166.5	29243
River sections:		
Bo 1	224.2	13228.6
Bo 2	118.8	16014.4

	average width (m)	length (m)
Loi Nong River	163.1	25978

Appendix C

Appendix C- 1

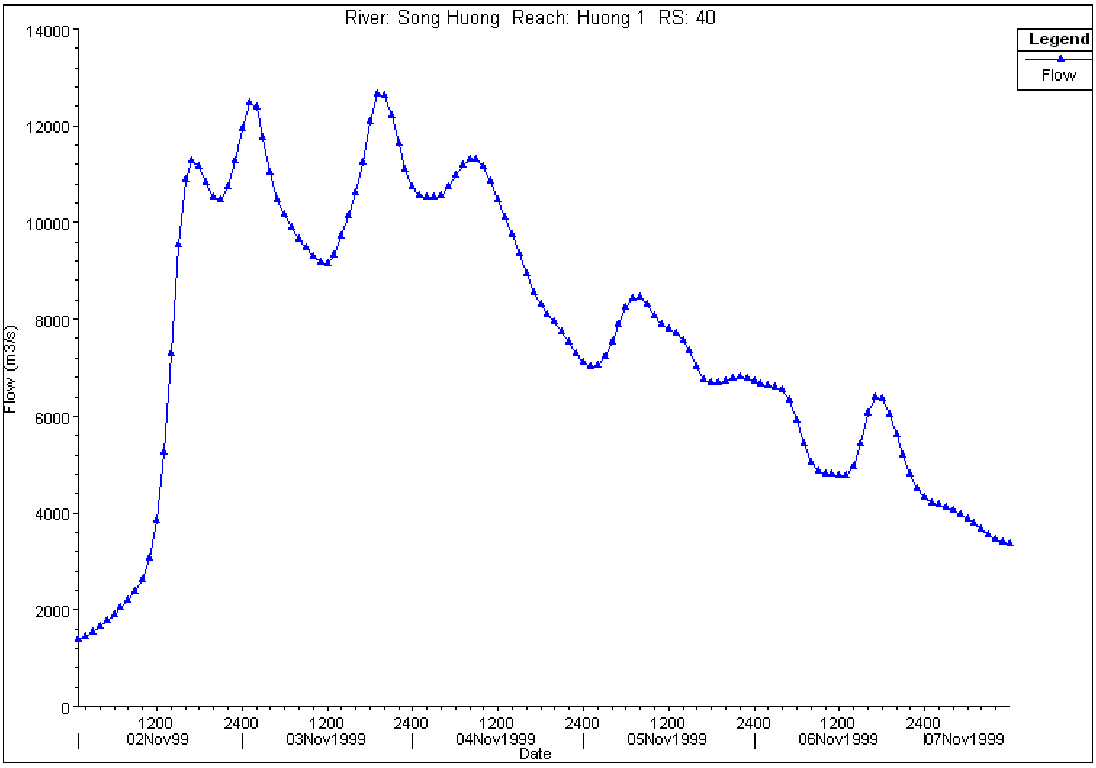


Figure C-1 - Flow Hydrograph at the Tuan Confluence November 1999

Appendix C- 2

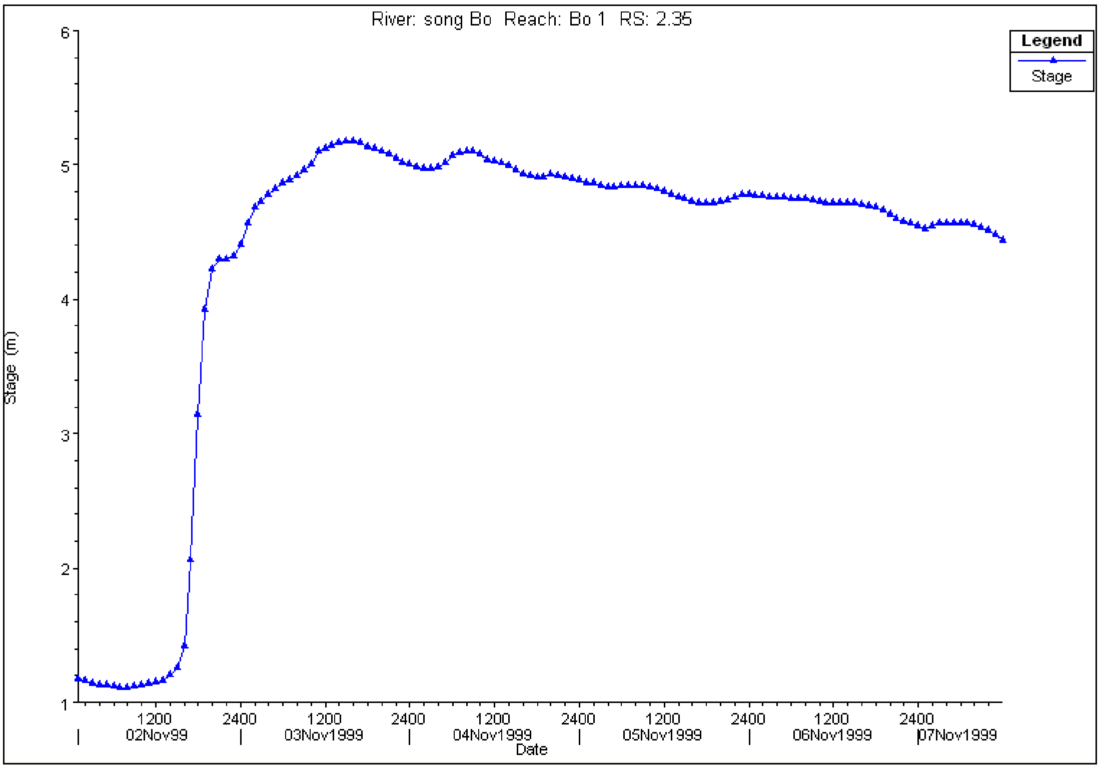


Figure C-2 - Upstream stage hydrograph of the Bo River November 1999

Appendix C- 3

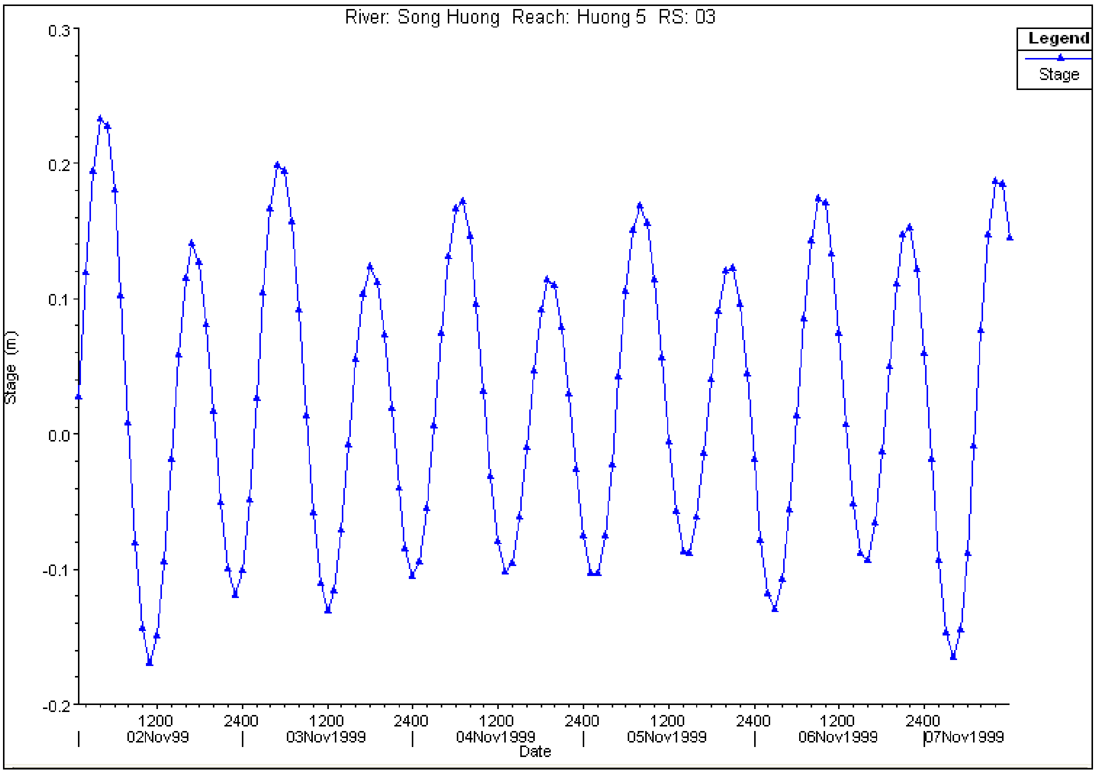


Figure C-3 - Downstream stage hydrograph of the Huong River November 1999

Appendix C- 4

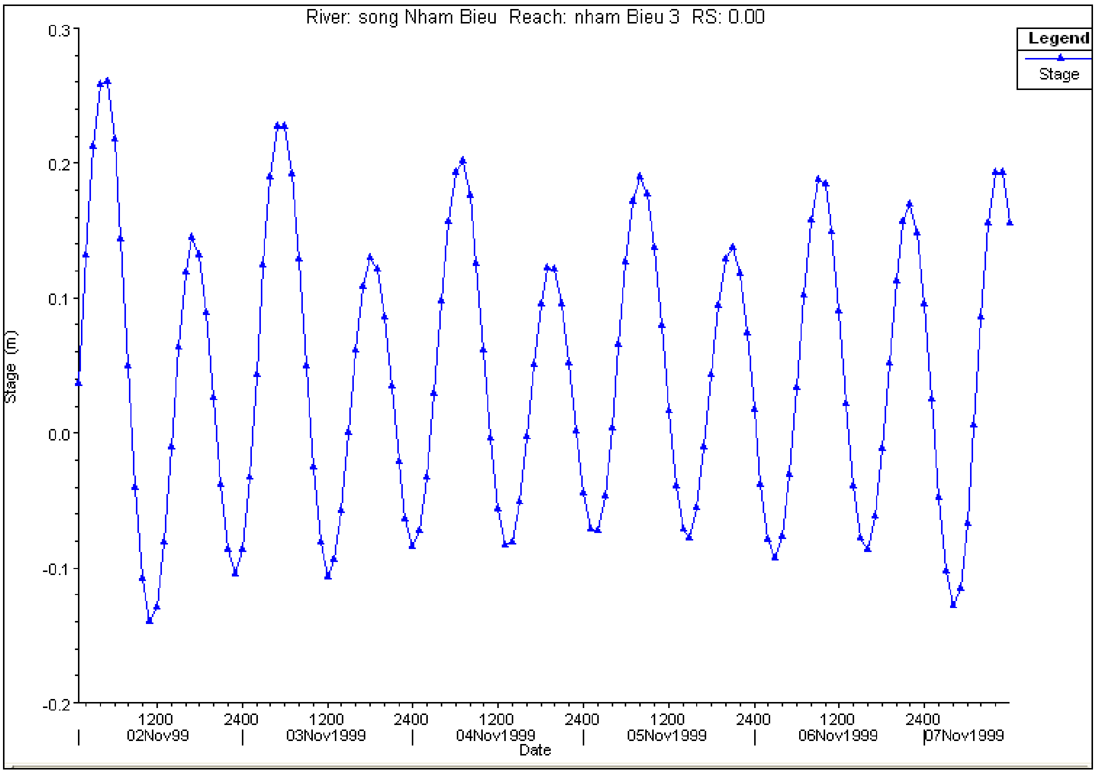


Figure C-4 - Downstream stage hydrograph of the Nham Bieu River November 1999

Appendix C- 5

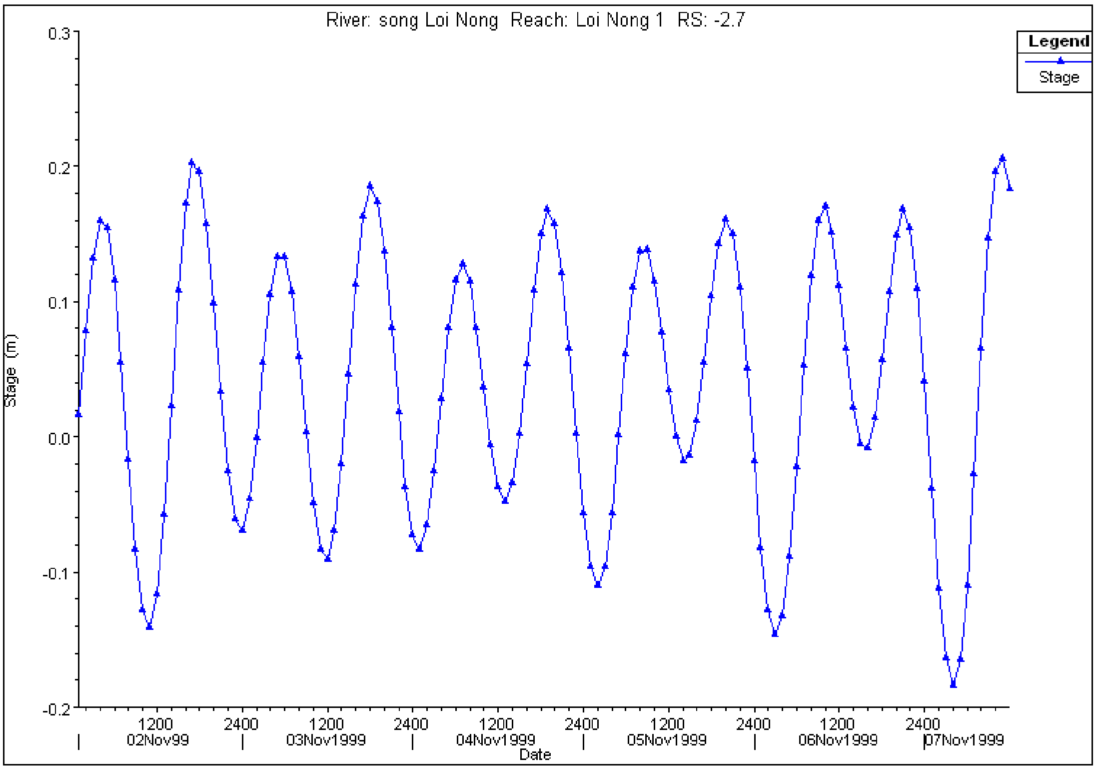


Figure C-5 - Downstream stage hydrograph of the Loi Nong River November 1999

Appendix D

Appendix D-1

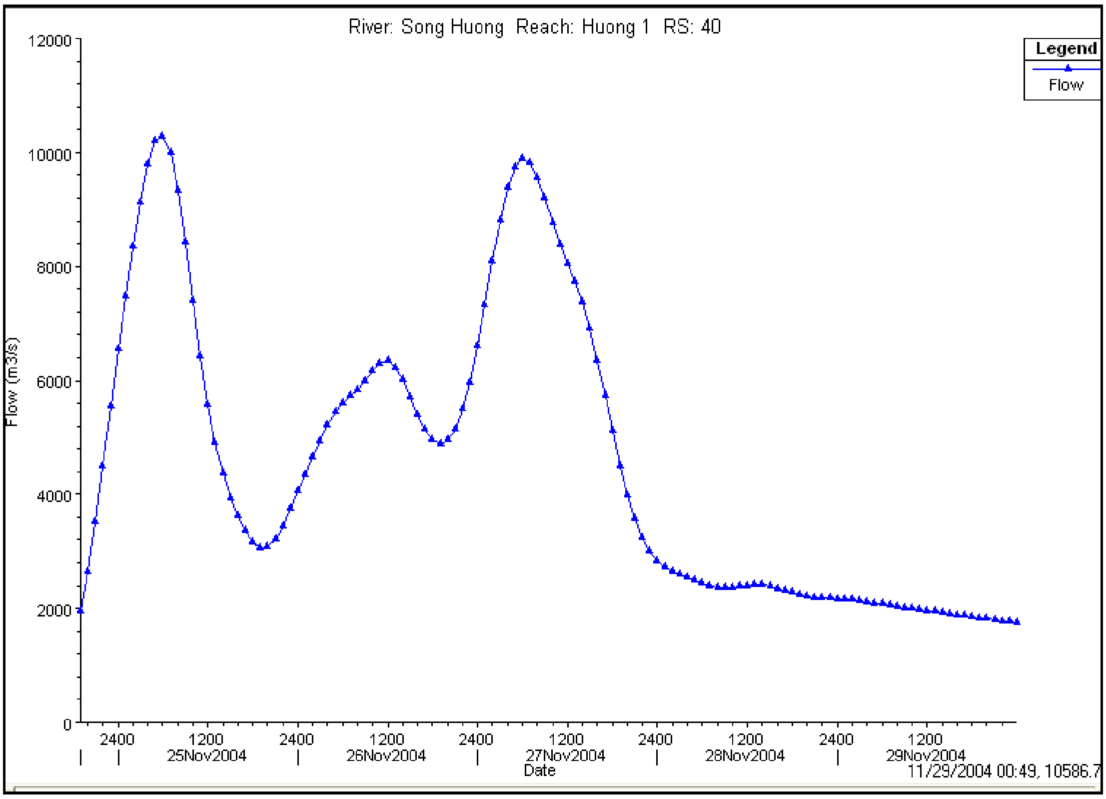


Figure D-1 Flow Hydrograph at the Tuan Confluence November 2004

Appendix D- 2

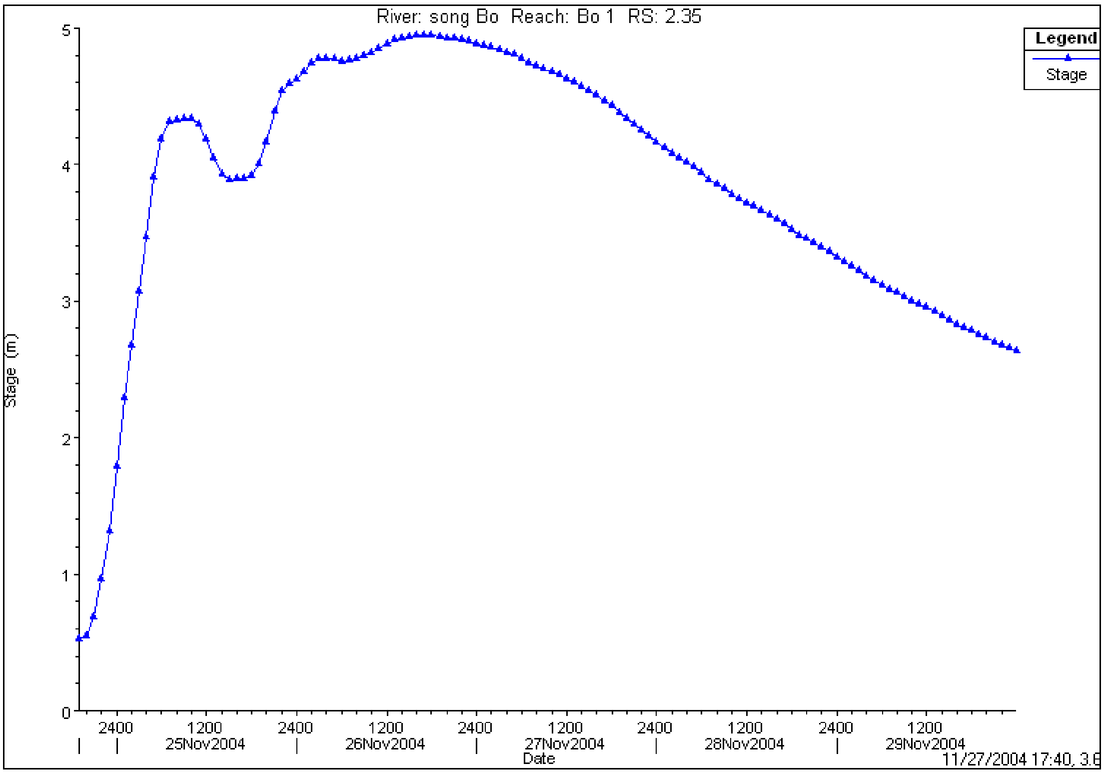


Figure D-2 - Upstream stage hydrograph of the Bo River November 2004

Appendix D- 3

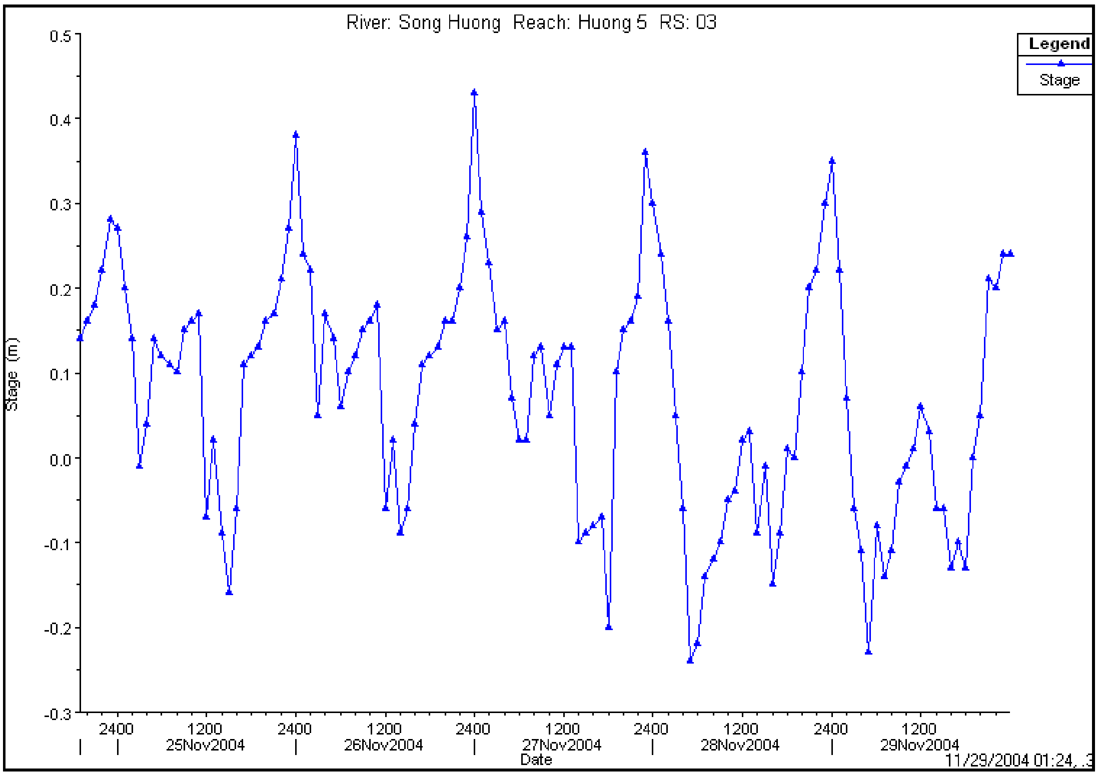


Figure D-3 - Downstream stage hydrograph of the Huong River November 2004

Appendix D- 4

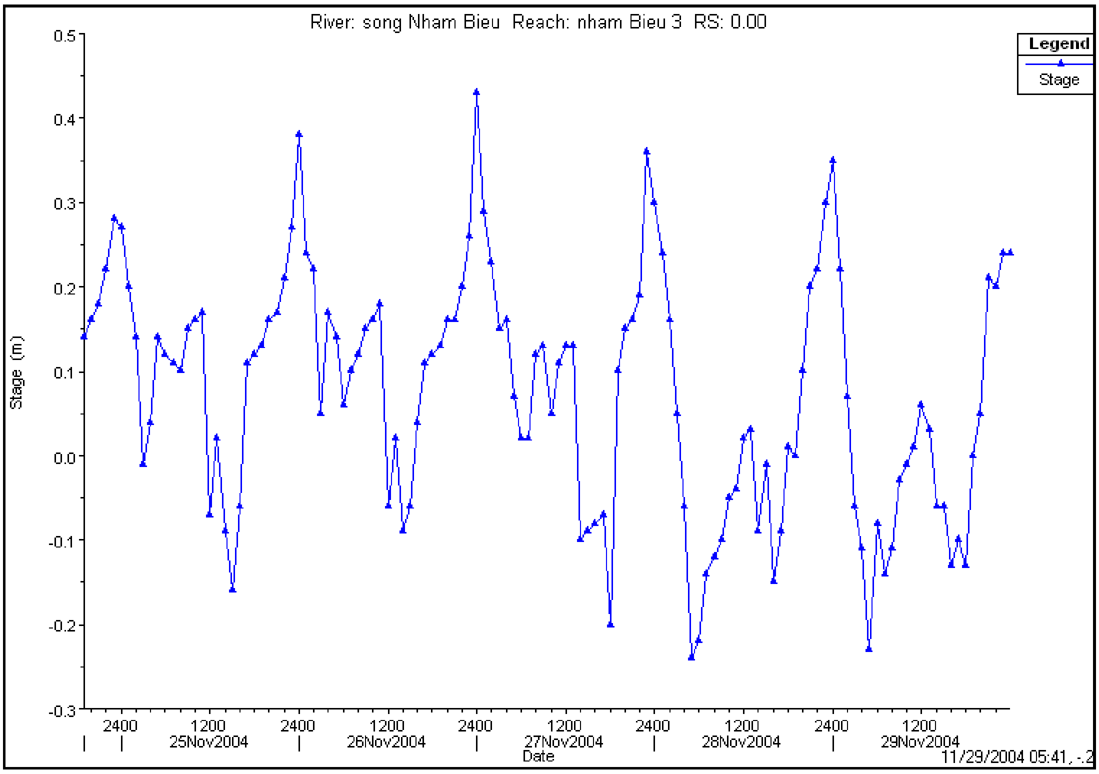


Figure D-4 - Downstream stage hydrograph of the Nham Bieu River November 2004

Appendix D- 5

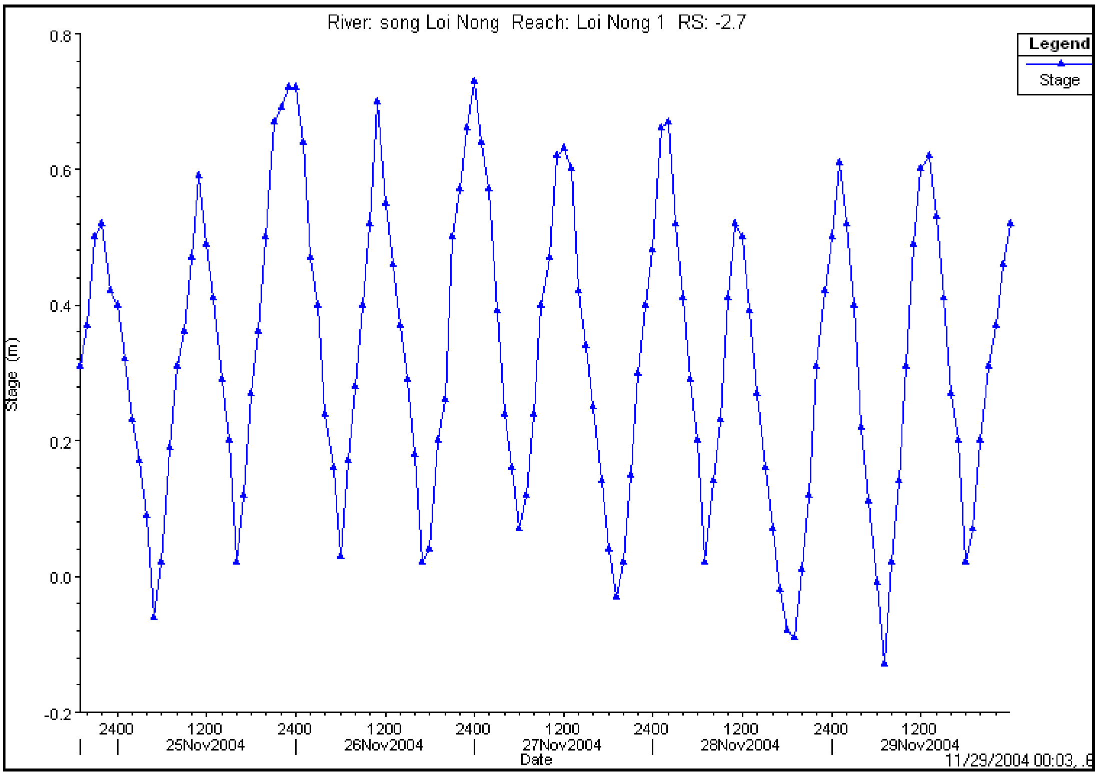


Figure D-5 - Downstream stage hydrograph of the Loi Nong River November 2004

Appendix E - Computation method of HEC-RAS

The computation method of HEC-RAS is described below. As in the theoretical background, here also the steady flow is first described and then the unsteady flow.

Steady flow

The computation method consists of an iterating procedure which is taken several times for each cross section to obtain water surface elevations for that cross section. Depending on whether the flow is sub- or supercritical the computation method begins downstream or upstream. In this description the flow is subcritical. When computing the water surface at a new cross section the following parameters and variables are known in advance:

Known	Explanation
The discharge Q	The discharge changes through the complex river system as the Huong river splits and receives water from tributaries, but these quantities are known, so at each cross section Q is known.
The manning coefficient n	For each cross section the manning coefficient is determined
Profile cross section	The profile of the cross section is measured.
The contraction coefficient C	The contraction or expansion coefficient is adjusted by HEC-RAS depending on flow differences between two cross sections
The gravity constant g	Gravitational acceleration
User defined tolerance	The user defined tolerance is a tolerance which, according to the user, is the tolerance that defines the acceptable error ($WS_{assumed} - WS_{computed}$). If, in the iterative process, an error is obtained within the boundaries set by the user defined tolerance the process will stop and the obtained water surface will be used.
Pre defined tolerance	The pre defined tolerance is a tolerance that defines the maximum error which is accepted by the user when the iteration process fails to get an error between the boundaries of the user defined tolerance

The computation is as follows:
Assume the water surface elevation for the upstream cross section, this is done by projecting the water depth of the cross section downstream on the upstream cross section. See also figure E.1

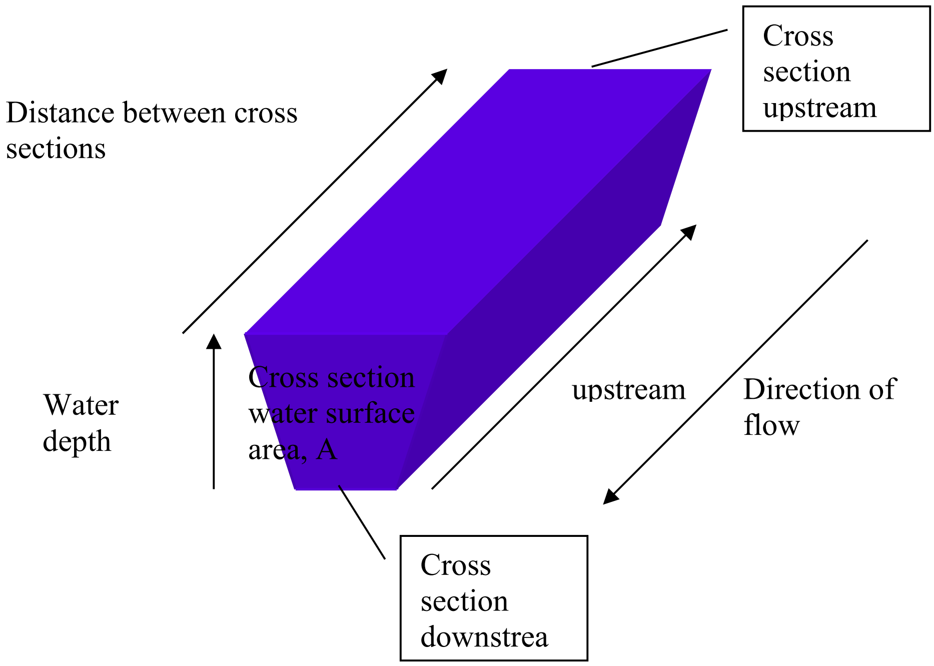


Figure E.1 - Schematic representation of computation scheme

With this water surface elevation (WS) and the cross section profile the cross sectional water surface area, A, can be calculated. This is done for three specific parts, the main channel, left and right overbank. The points where the overbanks go over into the main channel have to be determined by the user in the cross section profile and are arbitrary. With the water surface area the conveyance, K, can be calculated for the three different parts (main channel and the overbanks).
The velocity coefficient, α, can be calculated using equation E.1, the average velocity, V, can be calculated as Q and A are known. Using equation E.2 an average velocity can be computed. With the average velocity a velocity head can be computed, using equation E.3.
Using equation E.4, the friction slope coefficient can be calculated, S_f. With equation E.5 the energy head loss, h_e can be computed.
Finally, using equation 4.1, the energy equation the water surface level at the cross section can be computed, where only the water depth is unknown.
After this, the computed water surface level is compared to the assumed water level. This is done using equation E.6 . The outcome, WS_{new}, will be used to start another round of computing in which the secant afterwards is used to assume a new water surface, equation E.7 is the equation used in the secant method.
If in the iteration process a water surface elevation is computed for which the error ($WS_{assumed} - WS_{computed}$) is lower than the user defined tolerance than this water surface elevation is used. This water surface elevation is checked with the critical depth to check if the energy equation is satisfied.
If in the iteration process, after the maximum number of iterations, no water surface elevation is computed that satisfies the user defined tolerance, then the minimum error water surface, the water surface for which the error is the smallest, is used. The minimum error water surface is checked with the pre defined tolerance and the critical depth. If the

minimum error water surface does not satisfy the pre defined tolerance, but does satisfy the critical depth, the critical depth is used as water surface elevation. If the pre defined tolerance is satisfied but the critical depth is not, then the critical depth will be used as water surface elevation. If both checks are satisfied the minimum error water surface is used. In all cases a warning message is given that certain tolerances were not satisfied.

Equations:

$$\alpha = \frac{(A_t)^2 \left[\frac{K_{lob}^3}{A_{lob}^2} + \frac{K_{ch}^3}{A_{ch}^2} + \frac{K_{rob}^3}{A_{rob}^2} \right]}{K_t^3}$$

Equation E.1 - velocity coefficient

Where: A_t = total flow area of cross section
A_{lob}, A_{ch}, A_{rob} = flow areas of left overbank, main channel and right overbank, respectively
K_t = total conveyance of cross section
K_{lob}, K_{ch}, K_{rob} = conveyances of left overbank, main channel and right overbank, respectively

$$V_{average} = \frac{Q_t}{A_t}$$

Equation E.2 - Velocity

Where: Q_t = total discharge of cross section in m^3/s
A_t = total flow area of cross section in m^2

$$\frac{\alpha V^2}{2g}$$

Equation E.3 - Velocity head

Where: V= average velocity in m/s
g = gravitational acceleration in m/s^2

$$\overline{S}_f = \left(\frac{Q_1 + Q_2}{K_1 + K_2} \right)^2$$

Equation E.4 - Friction slope

Where: Q_1, Q_2 = discharges from cross section upstream and downstream, respectively
K_1, K_2 = conveyances form cross section upstream and downstream, respectively

$$h_e = L S_f + C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right|$$

Equation E.5 - Head loss

Where: L = discharge weighted reach length in m

$\overline{S_f}$ = slope of the energy grade line (friction slope)

C = expansion or contraction loss coefficient

$W.S._{new} = W.S._{assumed} + 0.7 * (W.S._{computed} - W.S._{assumed})$

Equation E.6 - Iteration equation

$W.S_1 = W.S_{1\text{-}2} - Err_{1\text{-}2} * Err\_Assum / Err\_Diff$

Equation E.7 - Secant method

Unsteady flow

Because the unsteady flow introduces a time dependency into the model, this has to be taken into account in the computation of the water surfaces. Because of the time dependency and the variations with time, the whole river is calculated for each time step. This is done using the four point implicit scheme. The four point implicit scheme can be viewed as a grid like in figure E.2. The rows n in the grid stand for a particular time and the columns j stand for a particular cross section. A row thus stands for the water surface levels in the whole reach of the river at a particular time. A column stands for the water surface levels for the whole time period at a certain location/cross section.

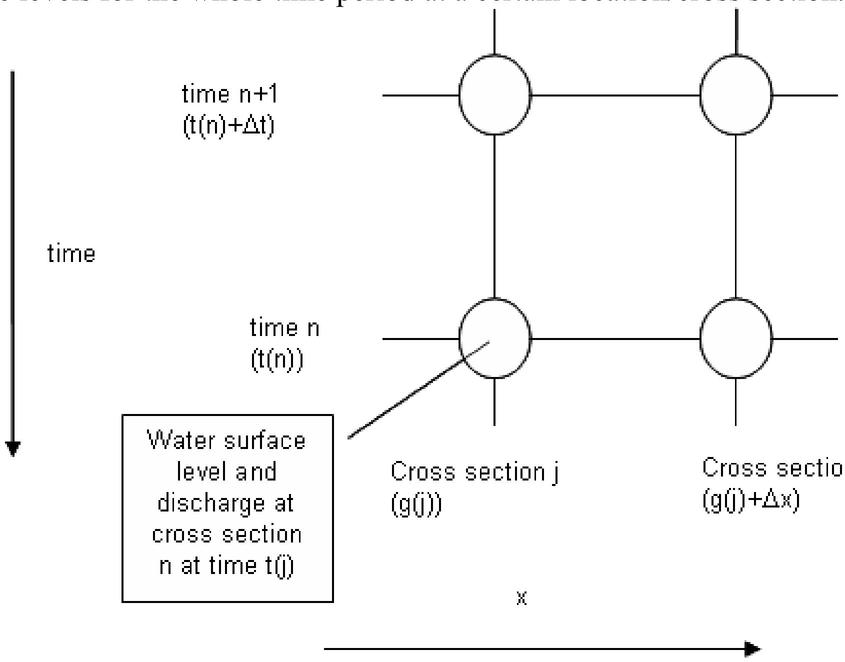


Figure E.2 - Four point implicit method

The scheme's axes are defined according figure E.2. Because of the assumed subcritical flow, in the grid from left to right means downstream. The subcritical flow means downstream cross sections determine the behaviour of the river upstream; therefore you start downstream in the right column of the grid.

A reach in a river, defined as a part of the river between two junctions, has N computational nodes which bound N-1 finite difference cells. From these cells 2N-2 equations can be developed. In the scheme you start from the above and the right with conditions set for this reach. In the column to the utter right downstream boundary conditions, whether external or internal, are set. External boundaries are set by the user; this has to be done when this reach is not connected to a reach downstream. Internal boundaries are set by HEC-RAS, this is done by computing the downstream reach and using this data as input for the connecting cross section of the upstream reach.

In the grid a point stands for a function value at a particular cross section j at time n. This function value contains both the water surface level and the discharge. The function value is therefore defined as a vector:

$$f = \begin{Bmatrix} z \\ Q \end{Bmatrix}$$

Equation E.8 - Function value of a grid point in the four point implicit finite difference scheme

The two governing equations, the conservation of mass and the conservation of momentum can be formulated, like in equation E.9.

$$\int_{x_1}^{x_2} \left(A_{t_2} - A_{t_1}\right) dx + \int_{t_1}^{t_2} \left(Q_{x_2} - Q_{x_1}\right) dt = 0 \text{ (conservation of mass)}$$

$$\int_{x_1}^{x_2} \left(Q_{t_2} - Q_{t_1}\right) dx + \int_{t_1}^{t_2} \left[\left(v^2 A + gI_1\right)_{x_2} - \left(v^2 A + gI_1\right)_{x_1}\right] dt \text{ (conservation of momentum)}$$

Equation E.9 - integral conservation equations

These equations were derived by Cunge and Verwey [Cunge&Verwey, 1980]. Both equations are the integral form of, respectively, the conservation of mass and the conservation of momentum. In both equations the first term is integrated over dx and the second term over dt. Using this information we can write both equations in a vector of the form in equation E.10.

$$\oint \left[f dx + G(f) dt \right] = 0$$

Equation E.10 - general vector form

Where:

$$f = \begin{Bmatrix} z \\ Q \end{Bmatrix}$$

$$G(f) = \begin{Bmatrix} Q \\ \dfrac{Q^2}{A} + gI_1 \end{Bmatrix}$$

If we use from now on the following notation for the function values:

$$f(x_j, t_n) = f_j^n$$
$$G[f(x_j, t_n)] = G_j^n$$

With this the values between the grid points can be expressed in terms of the values of these functions at the grid points using θ and ψ as symbols to define the position of the evaluated point on, respectively the time and space axis (see figure 4.3). For instance, the position, between f_j and f_{j+1}, on the time axis could be defined using equation 4.11.

$$f(x, t_n) = \psi f_{j+1}^n + (1-\psi) f_j^n$$

Equation 4.11 - position on time axis

Similar equations can be setup for $G(x_j, t)$, $G(x_{j+1})$ and $f(x, t_{n+1})$. If these equations are substituted in equation E.10, the following equation results:

$$\int_{x^j}^{x_{j+1}} \left\{ \left[\psi f_{j+1}^{n+1} + (1-\psi) f_j^{n+1}\right] - \left[\psi f_{j+1}^n + (1-\psi) f_j^n\right] \right\} dx +$$
$$\int_{t_n}^{t_{n+1}} \left\{ \left[\theta G_{j+1}^{n+1} + (1-\theta) G_{j+1}^n\right] - \left[\theta G_j^{n+1} + (1-\theta) G_j^n\right] \right\} dt = 0$$

Equation E.12

Integration of this equation and substituting x_{j+1}-x_j=Δx and t_{j+1}-t_j=Δt leads to a finite difference approximation of the conservation laws:

$$\left\{ \left[\psi f_{j+1}^{n+1} + (1-\psi) f_j^{n+1}\right] - \left[\psi f_{j+1}^n + (1-\psi) f_j^n\right] \right\} \Delta x +$$
$$\left\{ \left[\theta G_{j+1}^{n+1} + (1-\theta) G_{j+1}^n\right] - \left[\theta G_j^{n+1} + (1-\theta) G_j^n\right] \right\} \Delta t = 0$$

Equation E.13 - finite difference approximation of the conservation laws for unsteady flow-

This equation is, next to the integral relationship, an approximation of the differential system seen in equation E.14.

$$\frac{\partial f}{\partial t} + \frac{\partial G(f)}{\partial x} = 0$$

Equation E.14 - differential system

This becomes obvious when you divide equation E.13 by the product ΔxΔt, this produces approximations of $\frac{\partial f}{\partial x}$ and $\frac{\partial f}{\partial t}$.

In order to get to the four point scheme, also known as the Preissman 4-point scheme of finite differences ψ is set to ½. The time derivative is then approximated by:

$$\frac{\partial f}{\partial x} \approx \frac{\left(f_{j+1}^{n+1} + f_{j}^{n+1}\right) - \left(f_{j+1}^{n} + f_{j}^{n}\right)}{2\Delta t}$$

Equation E.15 - Finite difference approximation of the time derivative

θ is given a value between 0.5 and 1 as for these values the scheme is theoretically unconditionally stable. For values below 0.5 the scheme is unstable and for 0.5 the scheme is conditionally stable. Equation E.15 shows why the scheme is called a four point scheme as four points in the grid are in the equation. With the obtained approximation like in equation E.15 the unknowns can be computed using N-1 systems of equations (for each cell one), this gives 2N-2 equations (because of the two variables in f, z and Q). There are N computational points and thus 2N unknowns (z and Q), so there are 2 values missing in order to compute all the unknowns. To be able to compute the unknowns two boundary conditions are therefore needed. These are given by the initial conditions and the external or internal boundary conditions

Appendix F

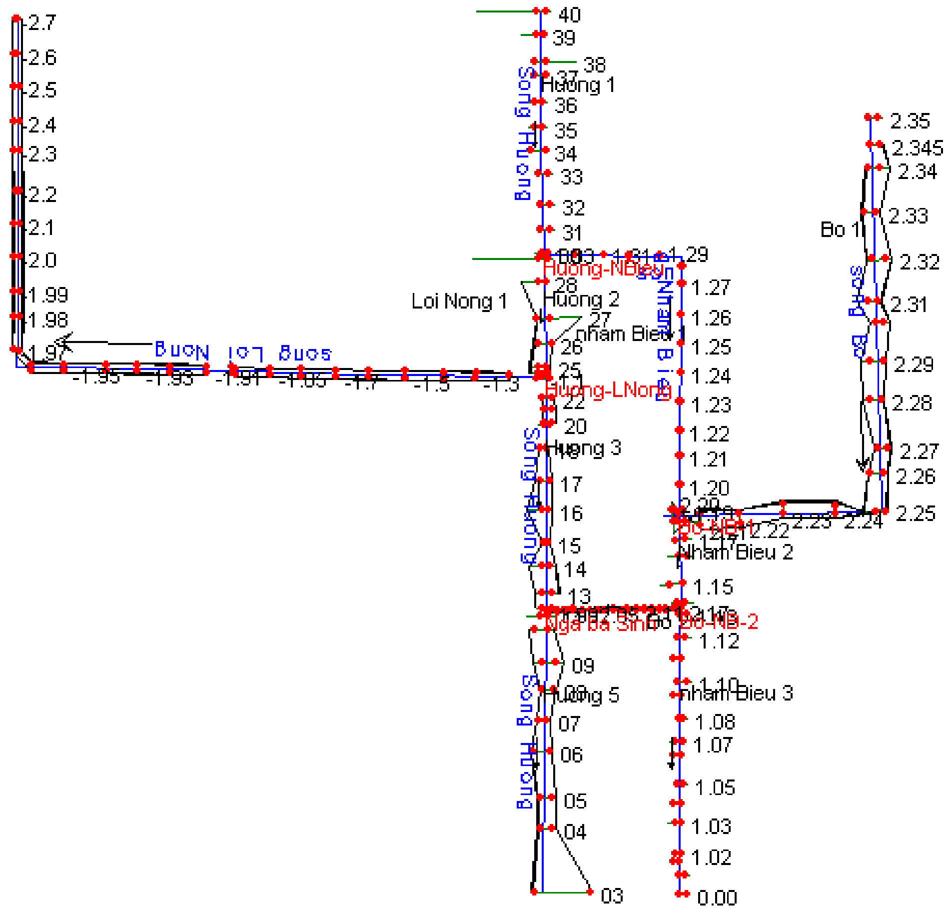


Figure F-1 - Hydraulic outline of the Huong River Basin