The World Bank Group

Innovative Approaches for Flood Risk Management and Financing in Agriculture

Flood Modeling in Upper Pasak River Basin Phetchaboon/Thailand

Final Roport

ASDECON CORPORATION CO.,LTD.

March 2008

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Chapter 1

Introduction

Chapter 1

Introduction

1.1 Background

Agriculture is one of livelihood that faces risks and uncertainties due to unpredictable weather conditions such as drought and flood. Agricultural insurance is therfore necessary to provide for farmers to have a safety net for possible crop failure. Since most of developing countries are lacking of agricultural insurance, the Commodity Risk Management Group (CRMG) of the World Bank has established a project on risk management and financing in agriculture for these countries. The CRMG has provided technical assistance to developing countries institutions to develop index-based insurance solutions to weather and disaster risks in the agricultural sector. Development of drought and flood indexes is required for insurance purposes. Drought indexes have been constructed with rainfall data using relatively established method. The use of rainfall-index insurance contracts for drought risk management has been successfully piloted by CRMG and partners in India, Malawi and Ethiopia since 2003. While feasibility studies and technical development work for flood index insurance are being conducted in Thailand, Vietnam and Bangladesh recently. Thailand is the first country where CRMG has started flood index insurance product development research. In November 2005, CRMG employed a team of experts led by PASCO Corporation, Japan, to develop a prototype flood index for rice production in the Upper Pasak river basin focusing on Phetchaboon province. The study was completed in July 2006 and resulted in a prototype flood index which quantifies the impact of flood duration and depth on rice yield loss during the flowering and pre-harvest time window. Although the study of PASCO has achieved significant groundwork for Phetchaboon, it was determined that the primary limitations in applying its flood modeling outputs to a pilot scheme arose from; (i) insufficient quality of topographic and hydro-meteorological data to parameterize and validate the chosen flood model, and (ii) the chosen modeling approach which is computationally too expensive to generate sufficient time series of outputs for the purpose of actuarial pricing. To address these limitations, CRMG has employed ASDECON Corporation Limited, Thailand, to carry out flood hazard assessment using an alternative flood modeling approach that allows; (i) better and more reliable quantification of the *long-term historical patterns of flood* in the region (which is required for actuarial evaluation), and (ii) better *characterization of the spatial flood patterns* in the flood plain of the Upper Pasak river basin, in particular with respect to flood depth and duration. That is, the model would have to resolve flood patterns at the daily timescale.

This study presents approaches and results of flood hazard assessment for Phetchaboon province focusing on the Muang Phetchaboon district. The flood index insurance has been developed by integrating informations from flood modeling, remote sening, hydrological analysis that incluses anaysis of rainfall and streamflow. Additional information with regards to farming practices, flood regime and management, and socio-economic impacts of flood on rice farmers is also included in this study in order to design an appropriate flood insurance scheme of the Muang Phetchaboon district.

1.2 Objectives

The main objective of this study is to support the flood insurance index by modeling of flood risk in the Upper Pasak river catchment, of which the Muang Petchaboon district had been chosen as a pilot study. The specified sub-objectives of this study are:

(i) Analyze hydrological data including rainfall and streamflow at the catchment level to estimate frequency and severity of flooding on the Muang Phetchaboon district.

(ii) Using a two-dimensional flow model to simulate inundation pattern, including flood extent, depth and duration in the flood plain of the Upper Pasak river basin, focusing on the Muang Phetchaboon district.

(iii) Develop flood indexes for rice production in the Muang Phetchaboon district.

(iv) Identify flood hazard zones based on inundation depth and inundation period (length) for different return periods that are derived from a simulation of daily streamflow.

(v) Identify flood hazard zones based on inundation depth and inundation period (length) for different time windows during the critical flooding months.

1.3 Scope of Work

To reach the above objectives, the scopes of work of this study are:

(i) Review related documents required for flood modeling of the Upper Pasak river basin.

(ii) Site inspection of the Muang Phetchaboon district and surrounding areas which includes cross sections, existing flood control facilities and flood marks and identification of flood loss criteria for rice crop growing of the study area.

(iii) Collection of long-term meteorological data, hydrological data, land use characteristics of the study area, and satellite imagery of selected flood events.

(iv) Selection of flood events for calibration and cross-validation of a developed flood modeling using archived satellite imagery and reconnaissance cause of flooding.

(v) Identify the critical flooding months of the Muang Phetchaboon district based on hydrological analysis results.

(vi) Analyze rainfall frequency and design patterns of rainfall with occurrence frequency of 2-5-, 10-, 20-, 50- and 100-year.

(vii) Design 50th-, 75th- and 95th-percentile rainfall patterns during the critical flooding months using the historical data.

(viii) Analyze flood frequency and design patterns of streamflow with occurrence frequency of 2-, 5-, 10-, 20-, 50- and 100- year.

(ix) Design 50th-, 75th- and 95th-percentile streamflow patterns during the critical flooding months using the historical data.

(x) Design combined maximum flood scenarios (weather patterns) at 2-, 5-, 10-, 20-, 50- and 100- year return periods by combining the designed rainfall and streamflow patterns obtained from (vi) and (viii) together. These combined maximum flood scenarios have been used to generate flood risk maps at different return periods.

(xi) Design combined weekly flood scenarios at 50th-, 75th- and 95th- percentile by combining the designed rainfall and streamflow patterns obtained from (vii) and (ix) together. These combined weekly flood scenarios have been used to generate flood risk maps at different time windows during the critical flooding months.

(xii) Setup MIKE11 model to represent the flow characteristics of the Upper Pasak river basin, particularly the area of the Muang Phetchaboon district.

(xiii) Calibrate MIKE11 model using flood events that occurred during 2000 to 2002. The calibration has been performed by comparing simulated water levels with observed river gauges data and the satellite observations.

(xiv) Validate MIKE11 model using flood events that occurred during 2003 to 2005.

(xv) Validate MIKE11 GIS using flood events that occurred during 2002, 2006 and 2007.

(xvi) Compute inundation depth and duration corresponding to the combined maximum flood scenarios at 2-, 5-, 10-, 20-, 50- and 100- year return periods obtained from (x).

(xvii) Compute inundation depth and duration corresponding to 50th-, 75th- and 95th-percentile of weekly flood scenarios obtained from (xi).

(xviii) Develop flood hazard zone maps of the Muang Phetchaboon district for different critical flood depths based on the results obtained from (xvi).

(xix) Develop weekly flood hazard zone maps during the critical flooding months based on the results obtained from (xvii).

(xx) Develop flood index-based insurance for rice production of the Muang Phetchaboon district.

Chapter 2

Study Area

Chapter 2
Study Area

The Muang Phetchaboon district of Phetchaboon province has been selected as a pilot area to develop flood index insurance product research. This area is located on the Upper Pasak river basin. To perform a flood hazard assessment of this study area, a flood model needs to be extent to cover the Upper Pasak river basin. Details of the Upper Pasak river basin are described below.

2.1 Topographic Features of the Upper Pasak River Basin

Most of the area of the Upper Pasak river basin is situated on the central part of Thailand. The total catchment area is approximately 9,500 sq. km. Almost of these areas are located in Phetchaboon province. The catchment lies from the North to the South which places between 14° 15' to 15° 15' N latitude and 100° 30' to 101° 30' E longitude. The Pasak river is the main river of this catchment. This river has an origination from the Phetchaboon mountain range at Dan-sai district of Loei province. It flows along a steep cliff from the North to the South via Phetchaboon, Lopburi and Saraburi and finally joins the Chao Praya river at Phranakhon Si Ayuttaya province. Most of tributaries of the Pasak river are short streams which are separated from the West and the East of the catchment. Topographic features and river system of the Upper Pasak river basin is illustrated in **Figure 2.1-1**. The upstream tributaries consist of i) Huai Num Phung which originates from the Phetchaboon mountain range at Dan-sai district of Loei province. The Hua-Num Phung tributary runs parallel to the Pasak river and finally joins each other at Lom-Sak district of Phetchaboon province; ii) Huai Khon Kaen which originates from the Northeast mountain range of Lom Sak district; iii) Lum Kong which originates from the Northeast of the highland located in Nong Phai district of Phetchaboon province. The downstream tributaries consist of i) Huai Hhao Kaew which originates from the mountain located on the natural border line between Phetchaboon and Lopburi provinces. The Haui Nong Phai meets the Pasak river at the South of Sithep district; ii) Lum Sonthi is the biggest tributary of the Pasak river which orginates from the mountain located on the natural border line between Phetchaboon and Chaiyapoom provinces. The tributaries of Lum Sonthi are Lum Phraya Klang. Lum-Sonthi meets the Pasak river at Chai Badan district of Lopburi Province. The river system of the Upper Pasak basin is shown in Figure 2.1-1.

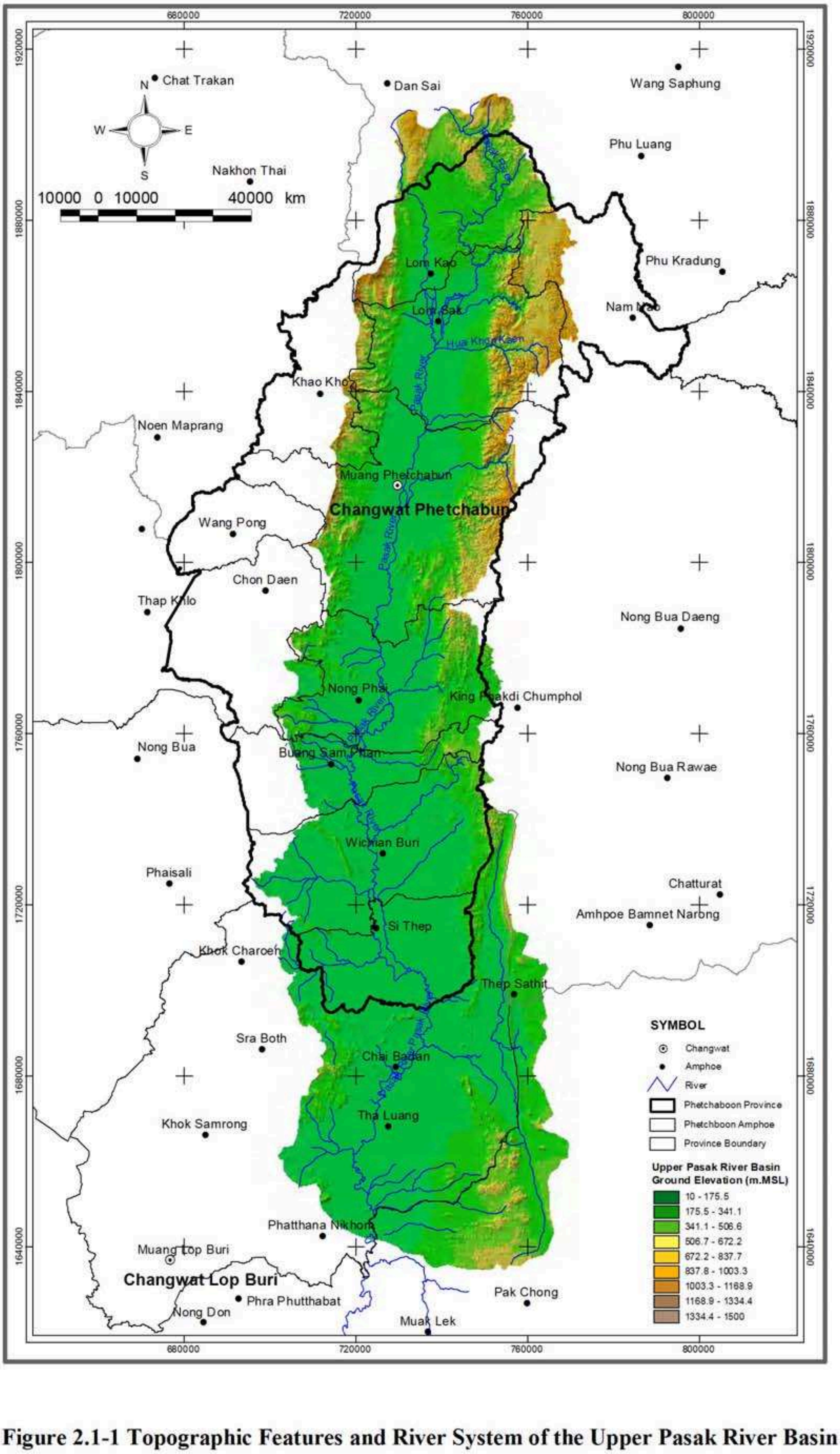


Figure 2.1-1 Topographic Features and River System of the Upper Pasak River Basin

2.2 Climate

2.2.1 General Climate in Thailand

The climate of Thailand is under the influence of monsoon winds of seasonal character i.e. Southwest monsoon and Northeast monsoon. The Southwest monsoon which starts in May brings a stream of warm moist air from the Indian Ocean towards Thailand causing abundant rain over the country, especially the windward side of the mountains. Rainfall during this period is not only caused by the Southwest monsoon but also by the Inter Tropical Convergence Zone and tropical cyclones which produce a large amount of rainfall.

The Southwest monsoon usually starts in mid-May and ends in mid-October while Northeast monsoon normally starts in mid-October and ends in mid-February and brings the cold and dry air from the anticyclone in China mainland over major parts of Thailand. **Figure 2.2-1** shows the moving direction and period of Thailand onset monsoon.

Thailand is very humid, with an overall average humidity of 66% to 81% depending on the season and time of the day. Temperature can drop to 14 ^{o} C at night during the winter. From the meteorological point of view the climate of Thailand may be divided into three seasons as follows:

(a) <u>Rainy</u> (mid-May to mid-October). The Southwest monsoon prevails over Thailand and abundant rain occurs over the country. The wettest period of the year is August to September.

(b) <u>Winter</u> (mid-October to mid-February). This is the mild period of the year with quite cold in December and January.

(c) <u>Summer</u> (mid-February to mid-May). This is the transitional period from the Northeast to Southwest monsoons. The weather becomes warmer, April is the hottest month.

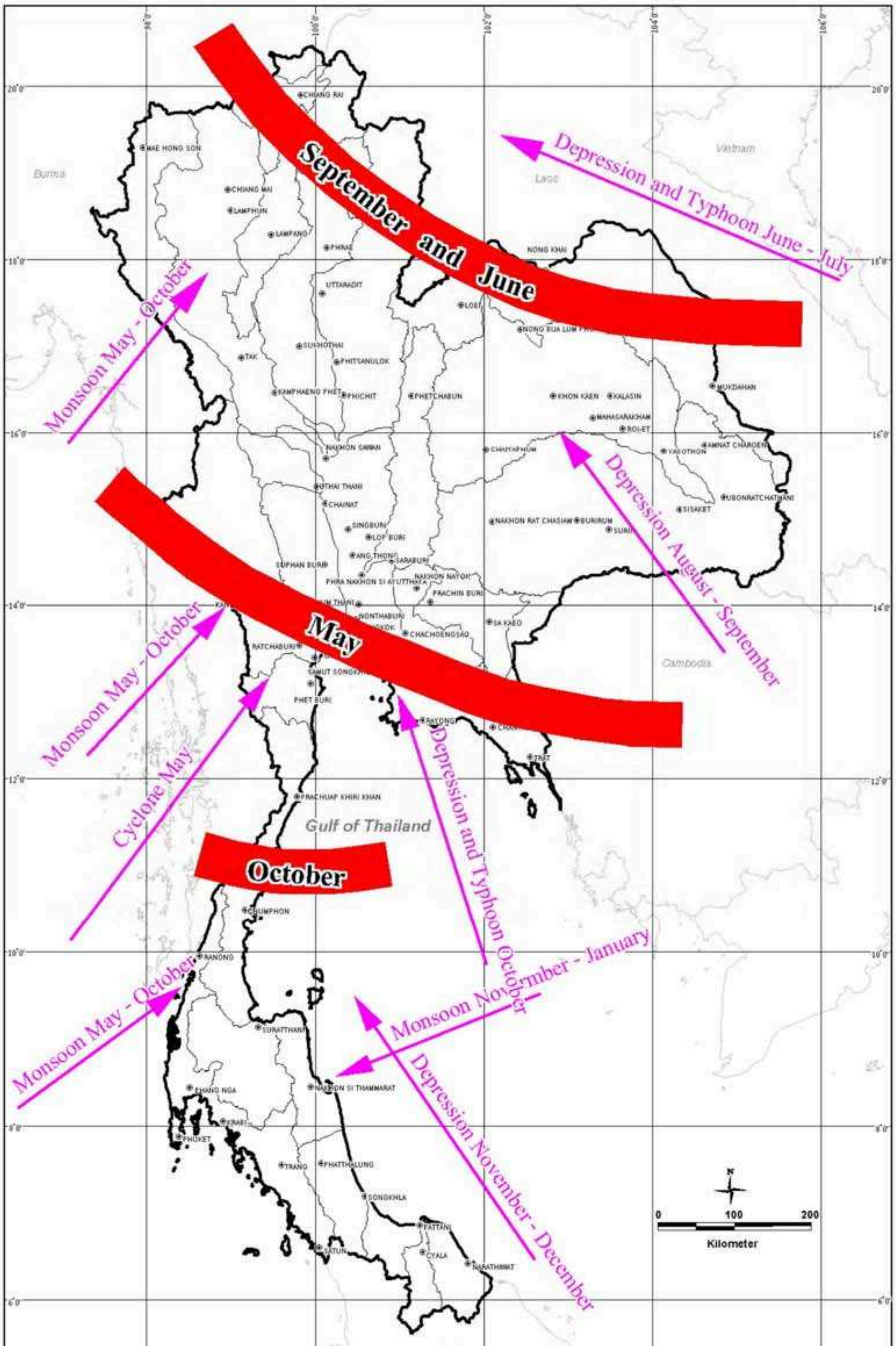


Figure 2.2-1 Direction and Period of Monsoon Winds over Thailand

2.2.2 Meteorological Data Collection

The climate of the study area is Monsoon. It is humid tropical, influenced by Northeast and Southwest monsoons, with dry (winter), hot (summer) and rainy seasons. Generally, the rainy season is between May to October while the dry period is from November to April. Monsoon rain is unpredictable, and each year variation of rainfall is considerable. Every 3-5 years rainfall may be so extreme leading to crops failure because of flood or drought. The meteorological data used in this study were collected from the meteorological stations located within the Upper Pasak river basin which include Phetchaboon, Lom Sak and Wichianburi stations. Locations of these stations are shown in **Figure 2.2-2**. All of these stations are belonged to the Thai Meteorological Department (TMD). The meteorological data are of these station are available during 1977 to present.

The climatological data of each station were analyzed and presented in Appendix A (**Tables A-1 to A-3**). According to the records from these three meteorological stations, the climate of the Upper Pasak river basin can be summarized in **Table 2.2-1**

Table 2.2-1 Average Climatology Condition of the Upper Pasak River Basin

Climatologically Parameters	Monthly	Annual
Temperature (Celsius)	23.8 - 30.8	27.4 - 28.02
Relative Humidity (%)	60 - 84	70.42 - 72.75
Sunshine Duration (hr.)	3.4 - 7.8	6.2
Rainfall		
- Mean (mm.)	3.5 - 233.9	1,052 – 1,181.3
- Mean rainy day (days)	1.69 - 20.41	109.91 - 121.72
- Daily maximum (mm.)	21.5 - 156.4	79.92 - 91.64

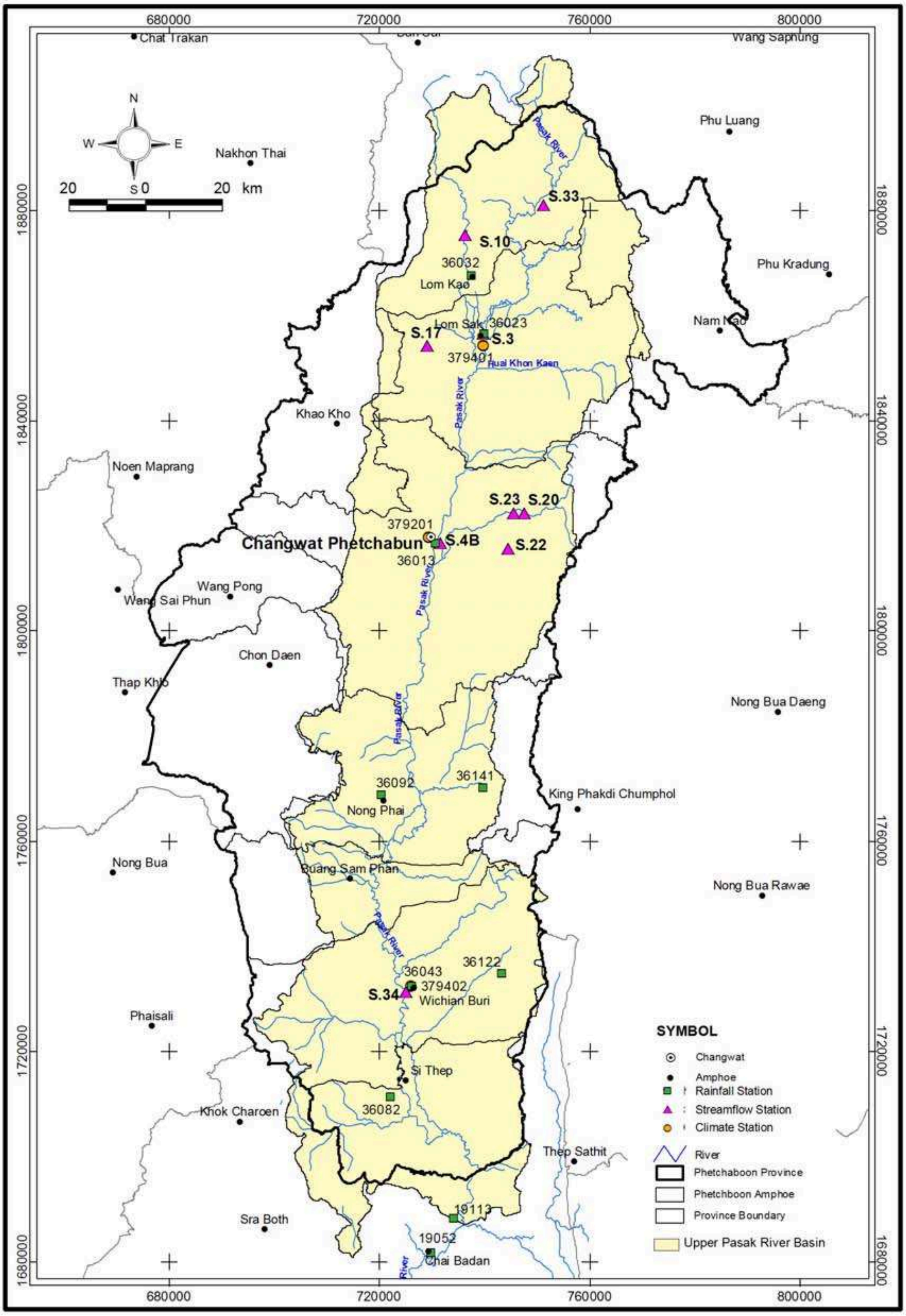


Figure 2.2-2 Location of Meteorological and Hydrological Stations of the Upper Pasak River Basin

2.2.3 Rainfall

Rain gauge rainfall data obtained from 10 rain gauge stations that are owned and operated by the TMD and the Royal Irrigation Department (RID) were used to analyze and develop mean annual rainfall map of the Upper Pasak river basin as illustrated in **Figure 2.2-3**. Locations of these rain gauge stations are shown in Figure 2.2-2. Mean annual rainfall of the Upper Pasak river basin is about 1,164.6 mm. Most of the rain comes during May to October. An average rainfall during the rainy season is about 1,002.4 mm which is approximate 86% of mean annual rainfall. Variation of mean monthly rainfall on the Upper Pasak river Basin is presented in **Table 2.2-2.** More details on rainfall data analysis are presented in Chapter 3.

Table 2.2-2 Mean Monthly Rainfall of the Upper Pasak River Basin

unit :mm

Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Wet	Dry	Annual
77.6	155.1	143.8	154.4	201.2	243.7	104.2	15.6	3.8	5.0	16.1	44.1	1002.4	162.2	1,164.6

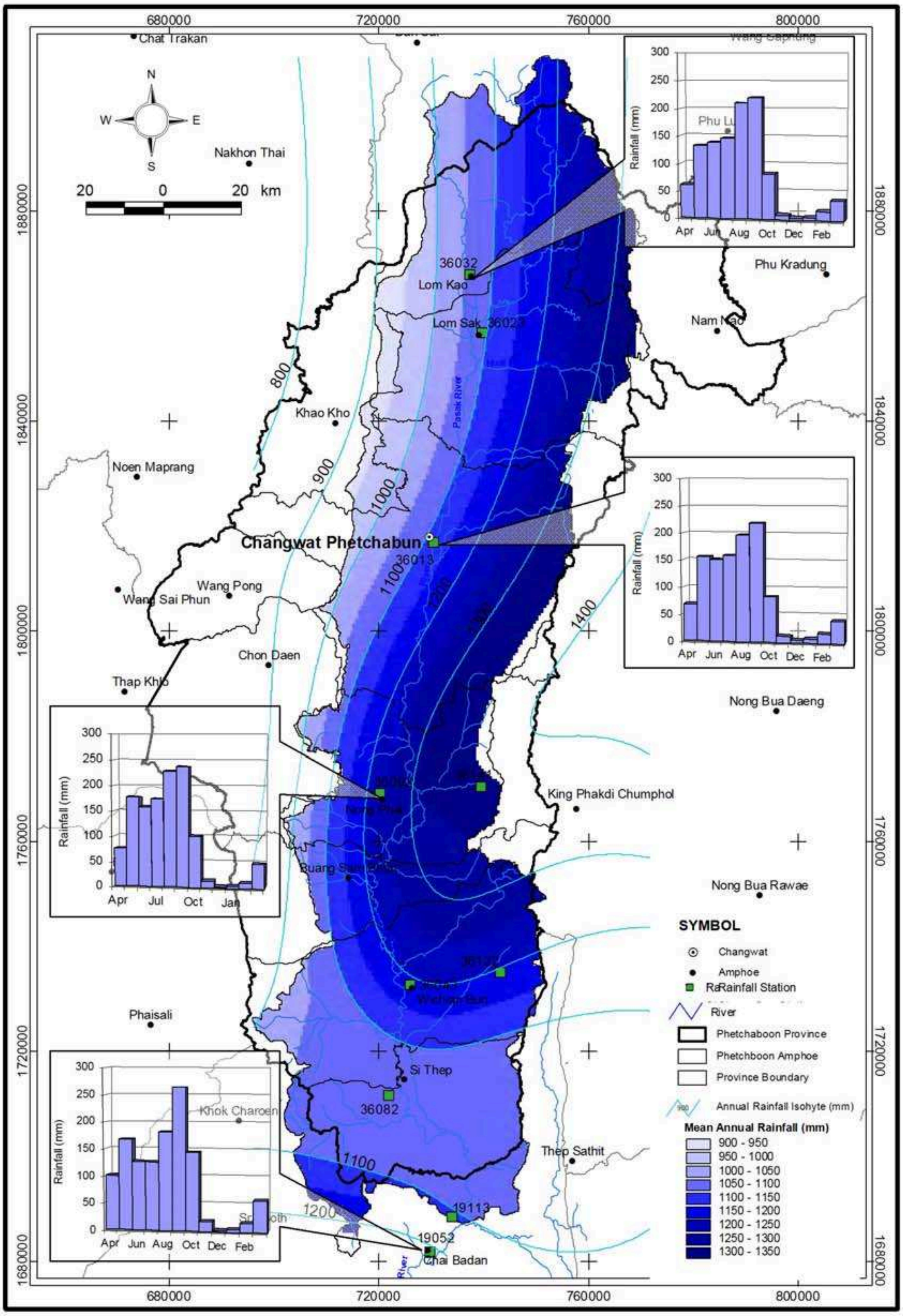


Figure 2.2-3 Variation of Mean Annual and Mean Monthly Rainfall of the Upper Pasak River Basin

2.2.4 Streamflow

Streamflow analysis results from "*The Integrated Plan Formulation for Water Resources Management in Pasak Basin Project*" prepared for Department of Water Resources (DWR) in 2003, can be summarized as follows. The Upper Pasak river basin covers an area of approximately 9,500 sq.km. It has mean annual natural streamflow of 1,450.48 MCM or 4.84 litre/second/sq.km. 93% of the total flow is the streamflow of the wet season (equivalent to 1,350.54 MCM) while 7% is the flow of the dry season (equivalent to 99.94 MCM). Mean monthly streamflow of the Pasak river basin is presented in **Table 2.2-3** and variation of mean annual streamflow of each sub-catchment is shown in **Figure 2.2-4**.

Table 2.2-3 Mean Monthly Streamflow of the Upper Pasak River Basin

unit : MCM

Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Wet	Dry	Annual
1.83	6.79	25.07	90.10	192.36	516.00	520.21	70.36	18.87	6.65	0.98	1.25	1,350.54	99.94	1,450.48

From the historical records summarized on the above table, it can be seen that high flows of the Upper Pasak river basin occur in October, September and August, respectively. This corresponds to the site inspection which have been found that most of the past flood events occurred during these three months. Therefore, we consider that high flood risk months of the Muang Phetchaboon district are between August to October. More details on streamflow data analysis are presented in Chapter 3.

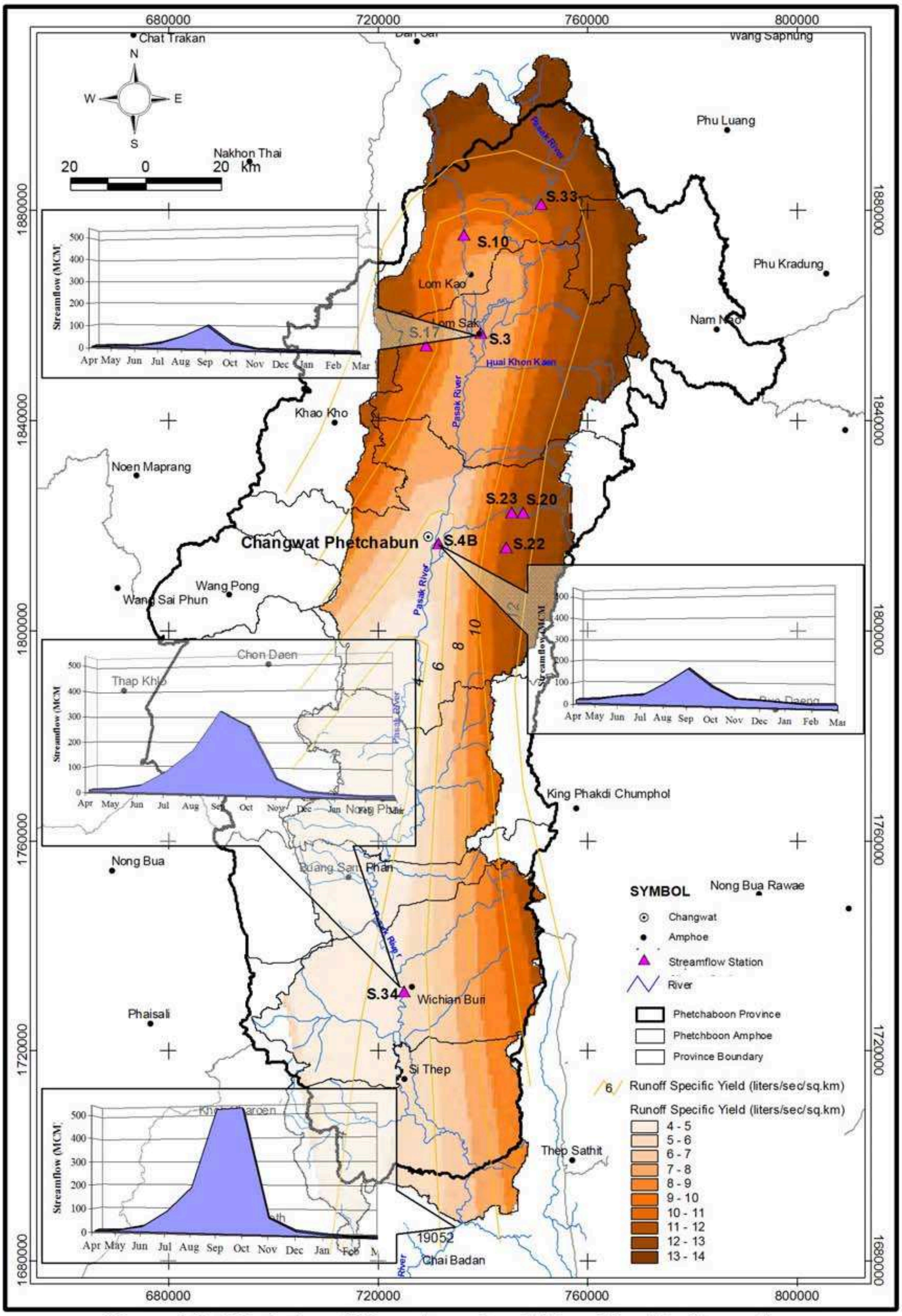


Figure 2.2-4 Variation of Mean Annual and Mean Monthly Streamflow of the Upper Pasak River Basin

2.2.5 Flooding Condition/Flood Damage

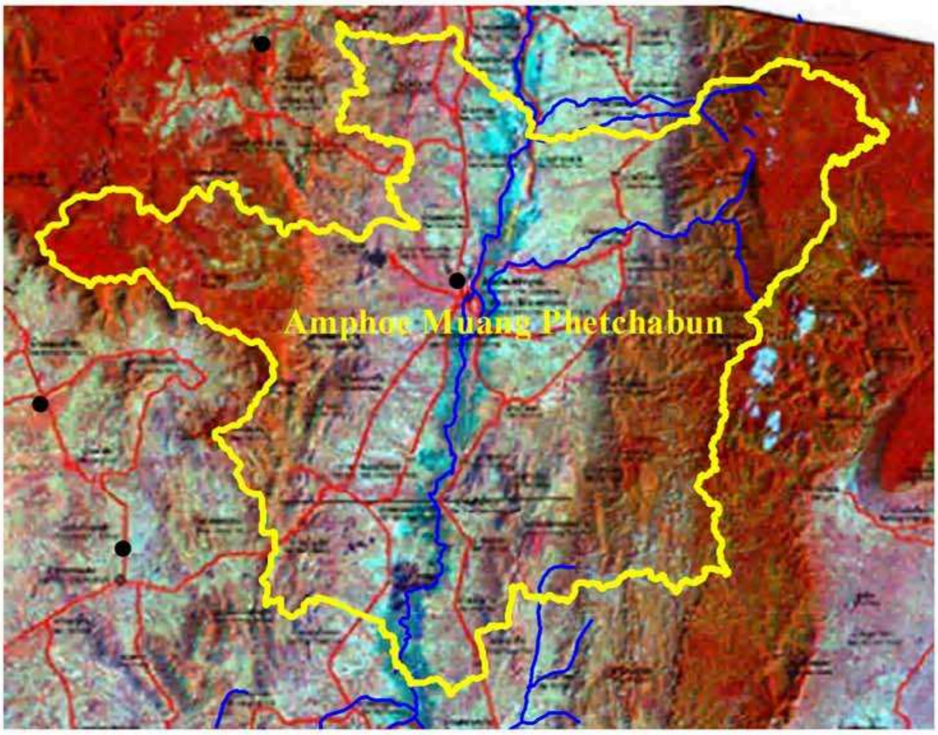
Flooding in the Upper Pasak river basin is due to its topographic features. The narrow shape basin which is surrounded by mountains as horseshoe shape (as illustrated in Figure 2.1-2) and deterioration of resources from missed land use cause a high flood risk of the study area. The downhill areas have a severe impact from flash floods. The areas located along the Pasak river face overflow from the river. In addition most of the local communities are situated along the Pasak river, the road network has been constructed parallel to the river which blocks the existing natural drainage system. This causes flood on the upstream of the drainage structure points. Moreover, the roads that lie parallel to the Pasak river also block the overflow from the river leading to high flood depth at the areas located between the road and the river.

From site visit, it has been learnt that heavy rainfall within the boundary of the Muang Phetchaboon district and overflow from the Pasak river are two main factors that cause flooding in the Muang Phetchaboon district. In the past, flooding in the Upper Pasak river basin occurred several times such as year 2000, 2002, 2003, 2006 and 2007. Available Satellite Images correspond to the dates of these flood events are shown in **Figure 2.2-5** to **Figure 2.2-7**.

2.2.6 Site Visit of The Muang Phetchaboon District

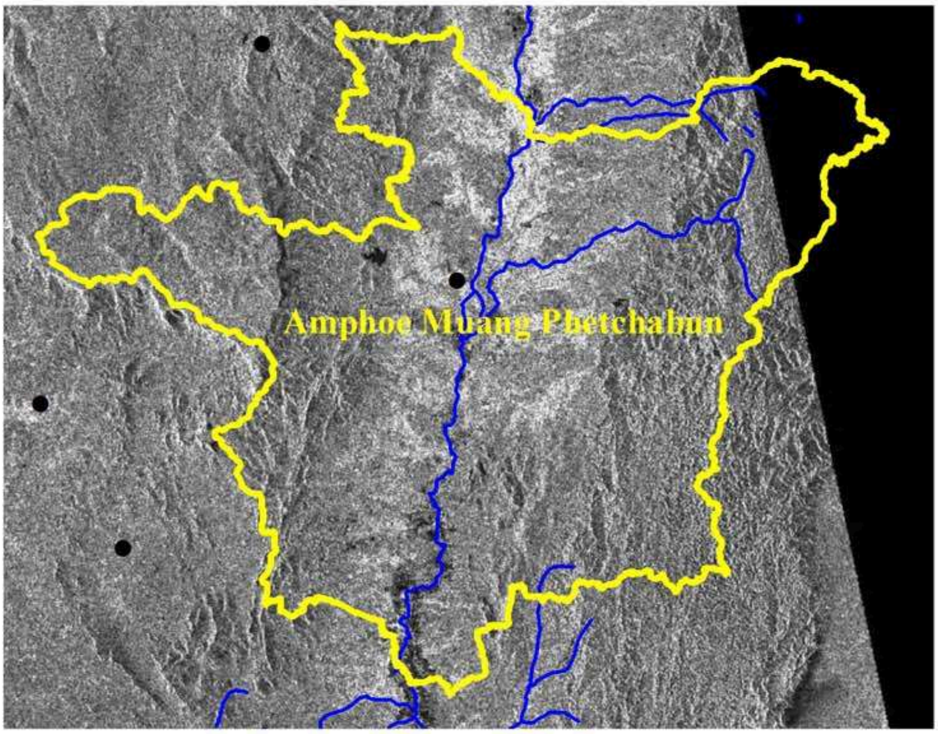
Information gained from site visit of the Muang Phetchaboon district during the week of November 2007 can be summarized below.

- Damages arose from 2007 flood (18 September – 5 October) were more than 2006 flood.
- Due to heavy rainfall at the upstream of Huai PaDang reservoir, flows had been released from this reservoir via Huai PaLao stream leading to flooding in the Muang Phetchaboon district during September 2002.
- Flash flood rushes down from the Eastern and the Western mountain ranges that are located parallel to the area of the Muang Phetchaboon district.
- Flash flood from Khao Kho meets the Pasak river at Tumbol ThaPol, leading to rice crop failure in this area.
- Inundation during 1-5 days leads to damage on rice field.
- The possible rice crop cycles of the study area can be up to 4 cycles as details presented in the **Table 2.2-4**. Note that this information has been obtained from the discussion with the staffs from the Bank of Agriculture and Agricultural Co-operative (BAAC) and the rice experts of the Rice Department, Thailand. According to the information presented in **Table 2.2-4,** flood depth and duration that inflicts on rice crop failure for each rice crop growth stage can be summarized as details are presented in chapter 5.



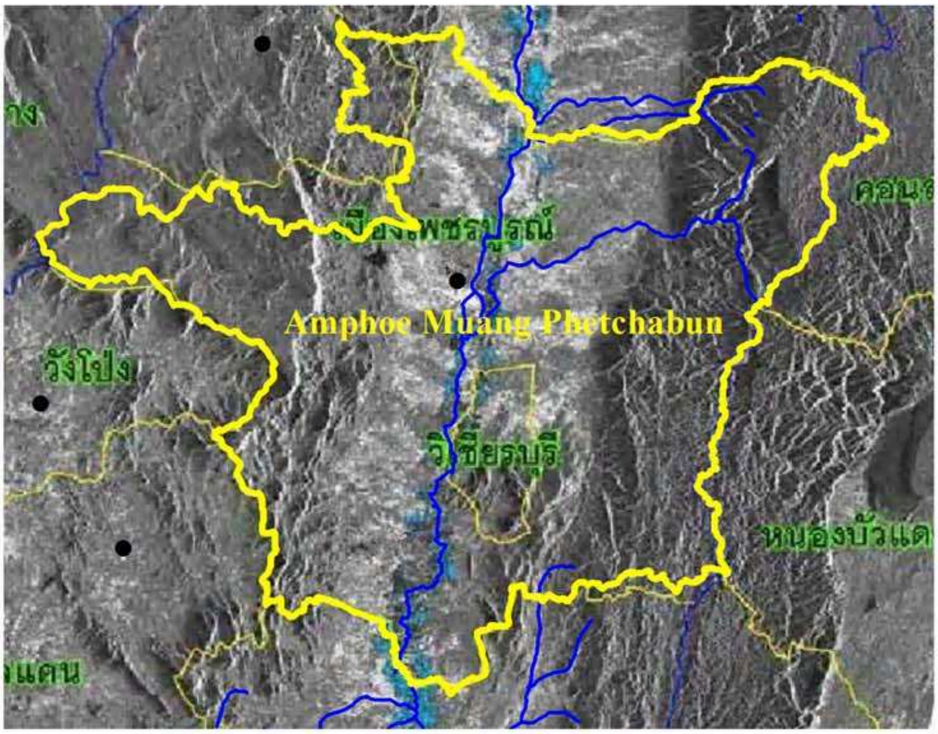
<u>RADARSAT-1 Satellite Image Shows Inundated Area on 10 September 2002</u>

Figure 2.2-5 Satellite Image of 2002 Flood Event



RADARSAT-1 Satellite Image Shows Inundated Area on 1 October 2006

Figure 2.2-6 Satellite Image of 2006 Flood Event



<u>RADARSAT-1 Satellite Image Shows Inundated Area on 12 October 2007</u>

Figure 2.2-7 Satellite Image of 2007 Flood Event

Table 2.2-4. Possible Rice Crop Cycles of the Muang Phetchaboon District

	June	July	Aug	Sep	Oct	Nov	Dec
	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Rice crop cycle 1		seeding	Tillering	Booting	Flowering / Grain Filling		Harvest
Rice crop cycle 2	seeding	Transplant	Tillering	Booting	Flowering / Grain Filling		Harvest
Rice crop cycle 3	seeding		Tillering	Booting	Flowering / Grain Filling	Harvest	
Rice crop cycle 4	seeding	Tillering		Booting	Flowering / Grain Filling	Harvest	
	21 days / 5 days		49 - 70 days	14 days	14 days / 21 days	depends on available machines and labors	
Avg rice growth stage	Seeding	Transplant	Tillering	Growing / Booting	Flowering	Grain Filling	Harvest
Avg rice height (cm)	0-25	25-50	50-70	50-70 / 70-110	110-160	160	160
Critical water depth (cm)	25	25	40	70 / 20	160	160	160
Critical flooding time (days)	>3	>3	>4	>4	>4	>4	>4

- The photos of site visit are shown in **Appendix A**, **Table A-4**.

From the above information, we can summarize that three reasons that causes flooding in the study area are; i) Heavy rainfall in the Muang Phetchaboon district particularly on the Eastern and Western hills; ii) High flows from the North (Lom Sak and Lom Kao districts) cause overflow from the Pasak river and iii) A combination between (i) and (ii). Since the critical flood depth and duration that causes rice crop failure is varied according to rice growth state. Thus, flood hazard maps have been produced according to different critical flood loss criterion of each critical month. More detailed are presented in Chapter 5.

Chapter 3

Hydrological Analysis

Chapter 3

Hydrological Analysis

As mentioned in previous chapter, it has been learnt that there are three main reasons that cause flooding in the Muang Phetchaboon district. Firstly is due to heavy rainfall that occurs in the mountain ranges located along the Western and Eastern boundaries of the Upper Pasak river basin. Steamflow arises from this heavy rainfall flows from the Eastern and Western steep mountains to the plain area around the central part of the catchment where the Muang Phetchaboon district is located, leading to flood flash in this area. The second reason is due to overflow from the Pasak river as a result of high flow from North of the study catchment. The last reason is due to the combination between high flow from the North of the basin and heavy rainfall within the area of Muang Phetchaboon district. This chapter presents hydrological analysis including rainfall and streamflow at the catchment level. Results of the analysis have been used to develop flood indexes of the Muang Phetchaboon district.

3.1 Categorization of Flood Study

The most sever flood situations are considered for flood insurance purpose. To accommodate this fact, flood scenarios should be developed using annual maximum rainfall and streamflow data, hereafter referred as "*flood hazard scenarios*". The designed flood hazard scenarios at different return periods will be input to a developed flood model to simulate flood maps so called "*flood hazard maps*". These flood hazard maps can be used for rice crop insurance purpose including evaluation of insurance premium and rice crop failure claiming.

For the cases where the rice farmers might not plant at the same time which will shift rice crop calendar for each group of farmers. Production of flood maps of each week during the critical flood period based on "*weekly flood scenarios*" will be useful for BAAC and farmers. These *"weekly flood risk maps"* can be used by BAAC for risk management and it can be used as references to recommend the farmers regarding to the suitable rice crop calendar of each area. Details of developing flood hazard scenarios and weekly flood scenarios are given in this chapter.

3.2 Rainfall Analysis

Ten daily rain gauge stations are located within the Upper Pasak river basin. Nine of these rain gauge stations are operated and owned by the TMD and the rest one station (station no. 36141) is belonged to RID. Details and locations of these stations are presented in **Table 3.2-1** and Figure 2.2-2, respectively. The monthly and annual rainfall of these stations are shown in Appendix A (**Tables A-5 to A-14**). The historical daily rainfall data from 5 rain gauge stations namely 36013, 36023, 36032, 36043 and 36141 stations located upstream and within the Muang Phetchaboon district were used in this study. Details of rainfall analysis are presented next.

3.2.1 Variation of rainfall in the Muang Phetchaboon District

From Figure 2.2-2, it can be seen that only A. Muang Petchaboon rain gauge station (Station No.36013) is located close to the Eastern and the Western mountain ranges. Rainfall data from this station have been used to represent rainfall in the Eastern and the Western mountain ranges and rainfall within the vicinity of the Muang Phetchaboon district. **Figure 3.2-1** shows the variation of monthly rainfall during 1952 – 2006 of the 36013 station. It is indicated that the rainy season of the study area is between May to October. Lots of rain occurs in the months of August and September in which September has the maximum monthly rainfall. This corresponds to information gained from site visit which have been found that flash floods in the Muang Phetchaboon district due to heavy rainfall within the Western and Eastern mountains and the vicinity area of the Muang Phetchaboon district commonly occur during these two months. According to the historical rainfall data and the information from site investigation received from interviewing the local rice farmers, we consider that the high flood risk months of the Muang Phetchaboon district caused by heavy rainfall are September and August, respectively. However, in 2007, flooding in the Muang Phetchaboon district taken place two times. The first flood event that occurred during the middle of September to the beginning of October was due to high flow from Lom Sak and Lom Kao districts together with heavy rainfall in the Muang Phetchaboon district. The second flood event taken place during the end of October to the beginning of November was due to heavy rainfall from the depression that passed the Muang Phecthaboon district and surrounding areas. It is to be noted that, In general, flood event due to heavy rainfall does not commonly occurs in this area during this time of the year.

Table 3.2-1 List of Rainfall Stations and Mean Rainfall of the Upper Pasak river basin

No.	Code	Station Name	Province	Peroid	Monthly Rainfall (mm)												
					Apr	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Annual**
1	19052	A. Chai Badan	Lopburi	1952 - 2006	100.5	167.5	127.4	126.5	182.8	264.4	145.1	19.0	1.9	5.1	17.1	58.5	1,215.8
				(Rainy Days)	*(5.3)*	*(9.8)*	*(8.9)*	*(9.9)*	*(12.6)*	*(14.2)*	*(8.3)*	*(1.7)*	*(0.4)*	*(0.6)*	*(1.1)*	*(3.3)*	*(76.1)*
2	19113	A. Bua Chum	Lopburi	1969 - 2006	85.1	134.3	124.3	118.3	172.1	273.9	120.7	21.5	3.3	4.2	14.2	42.8	1,114.6
				(Rainy Days)	*(7.4)*	*(14.0)*	*(13.0)*	*(13.6)*	*(16.9)*	*(18.0)*	*(10.5)*	*(2.8)*	*(0.8)*	*(0.8)*	*(1.8)*	*(4.4)*	*(103.8)*
3	36013	A. Muang	Phetchaboon	1952 - 2006	68.8	156.1	151.5	159.9	196.6	218.8	84.2	12.0	4.9	7.9	17.7	42.0	1,120.5
				(Rainy Days)	*(7.1)*	*(15.2)*	*(16.6)*	*(18.1)*	*(20.4)*	*(18.4)*	*(10.1)*	*(2.3)*	*(0.7)*	*(1.1)*	*(2.3)*	*(4.2)*	*(116.5)*
4	36023	A. Lom Sak	Phetchaboon	1952 - 2006	62.7	154.1	151.3	141.4	193.1	220.1	82.4	12.9	4.3	4.6	19.0	45.6	1,091.6
				(Rainy Days)	*(6.9)*	*(12.8)*	*(14.4)*	*(15.7)*	*(17.6)*	*(16.5)*	*(8.7)*	*(2.0)*	*(0.6)*	*(1.0)*	*(2.1)*	*(4.2)*	*(102.5)*
5	36032	A. Lom Kao	Phetchaboon	1952 - 2006	60.8	132.3	138.8	146.5	209.8	220.2	82.4	8.3	3.7	5.2	16.8	36.4	1,061.2
				(Rainy Days)	*(4.9)*	*(9.4)*	*(10.7)*	*(12.1)*	*(14.5)*	*(12.5)*	*(5.6)*	*(0.9)*	*(0.3)*	*(0.8)*	*(1.5)*	*(2.9)*	*(76.1)*
6	36043	A. Wichian Buri	Phetchaboon	1952 - 2006	78.3	162.0	132.9	163.3	192.3	236.6	121.2	19.5	3.5	7.8	20.0	49.1	1,186.6
				(Rainy Days)	*(6.4)*	*(13.3)*	*(12.7)*	*(14.7)*	*(17.0)*	*(17.1)*	*(10.4)*	*(2.4)*	*(0.5)*	*(0.7)*	*(1.7)*	*(3.5)*	*(100.3)*
7	36082	Khok Sa-At School, A. Si Thep	Phetchaboon	1965 - 2006	88.6	133.7	124.3	126.7	168.5	228.2	98.3	19.9	4.5	3.2	12.3	42.2	1,050.4
				(Rainy Days)	*(6.0)*	*(10.8)*	*(10.0)*	*(10.6)*	*(12.8)*	*(14.3)*	*(7.3)*	*(1.4)*	*(0.4)*	*(0.5)*	*(1.4)*	*(3.1)*	*(78.4)*
8	36092	A. Nong Phai	Phetchaboon	1965 - 2006	75.1	177.4	158.1	173.4	230.1	238.1	101.4	13.6	2.4	3.7	11.8	48.9	1,234.2
				(Rainy Days)	*(6.0)*	*(12.0)*	*(11.4)*	*(13.3)*	*(15.0)*	*(14.1)*	*(7.8)*	*(1.4)*	*(0.3)*	*(0.4)*	*(1.1)*	*(2.9)*	*(85.7)*
9	36122	Nam Ron Sub-District, A. Wichian Buri	Phetchaboon	1970 - 2006	71.9	143.1	142.5	180.8	224.1	250.3	104.8	16.1	3.4	6.5	14.7	34.5	1,192.6
				(Rainy Days)	*(4.2)*	*(10.0)*	*(9.6)*	*(10.8)*	*(12.9)*	*(13.5)*	*(6.9)*	*(1.1)*	*(0.2)*	*(0.4)*	*(0.9)*	*(2.1)*	*(72.8)*
10	36141	Ban Wang Thadi (S.12), A. Nong Phai	Phetchaboon	1978 - 2006	83.7	190.1	186.7	207.6	242.7	286.2	101.0	13.0	5.7	2.2	17.8	41.2	1,377.8
				(Rainy Days)	*(6.6)*	*(14.3)*	*(15.1)*	*(17.1)*	*(17.3)*	*(19.0)*	*(9.8)*	*(1.5)*	*(0.6)*	*(0.3)*	*(1.3)*	*(3.0)*	*(105.7)*
				Average over Upper Pasak River Basin	77.6	155.1	143.8	154.4	201.2	243.7	104.2	15.6	3.8	5.0	16.1	44.1	1,164.6
				(Rainy Days)	*(6.1)*	*(12.2)*	*(12.2)*	*(13.6)*	*(15.7)*	*(15.8)*	*(8.5)*	*(1.8)*	*(0.5)*	*(0.7)*	*(1.5)*	*(3.4)*	*(92.0)*

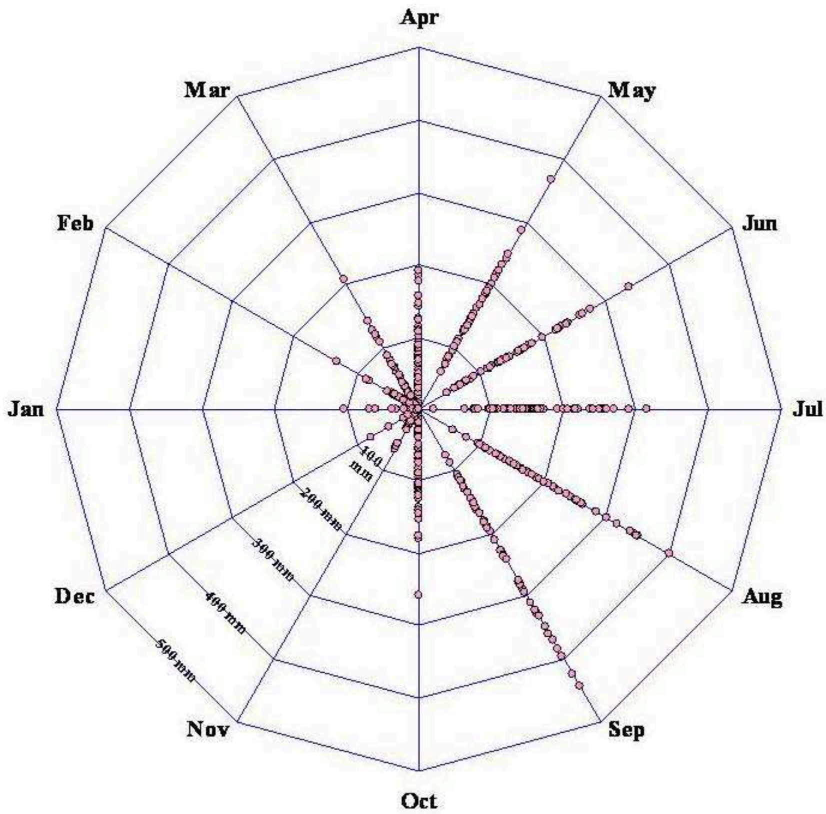


Figure 3.2-1 Variation of Monthly Rainfall of 36013 Station: A.Muang, Phetchaboon (data period: 1952 to 2006)

Frequency analysis of daily rainfall data of those 5 rain gauge stations were carried out as result presented in the next section. The frequency analysis results will be used for designing of rainfall patterns of the study area at different return periods. It is to be noted that "*designed rainfall pattern*" is expressed the expected pattern of rainfall for the study area at a specified probability of occurrence. The designed rainfall patterns will then input to the developed flood model to simulate flood maps for different flood scenarios. Details of the frequency analysis are presented next.

3.2.2 Rainfall Frequency Analysis

To simulate flood hazard zoning maps of the study area at different probability of occurrences of heavy rainfall that might occur in the upstream and the Eastern and the Western mountain ranges located parallel to the area of the Muang Phetchaboon district and rainfall occur within the vicinity of the Muang Phetchaboon district, the frequency analysis of maximum rainfall data of the 5 rain gauge stations were analyzed. The historical annual maximum 1-day, 2-day, 3-day and

4-day accumulated rainfall recorded during 1952 – 2006 of these rain gauge stations as presented in **Appendix A** (**Tables A-15 to A-19**) were used in the analysis. The Weibull formula has been used for plotting position as shown in Equation below.

$$P(X \geq x_m) = \frac{m}{N+1} \quad (1)$$

where $P(X \geq x_m)$ = the exceedence probability of the $X \geq X_m$ value,

m = is the rank of a value in a list ordered by descending magnitude

N = number of data used in the analysis

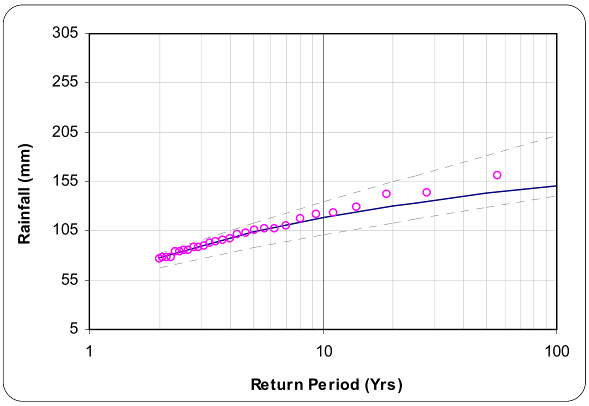
Commonly, the Gumbel distribution is used to fit the maximum rainfall data in Thailand. In this study, this distribution was applied to fit the annual maximum 1-day to 4-day accumulated rainfall. The comparison of the plotting position and the Gumbel distribution of the annual maximum 1-day to 4-day accumulated rainfall and their 95% confidence intervals of these 5 rain gauge stations are shown in **Figures 3.2-2 to 3.2-6,** respectively. These Figures are evident that the Gumbel distribution fits the observed annual maximum rainfall data well as all of the annual maximum rainfall values at different exceedence probabilities lie within 95% confidence intervals.

The exceedence probability can be written in term of return period (T_r) as follow.

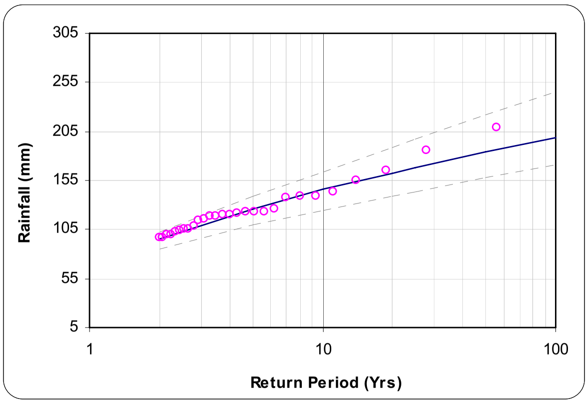
$$T_r = \frac{1}{P(X \geq X_{T_r})} \quad (2)$$

where T_r = the time between occurrences of $X > X_{Tr}$

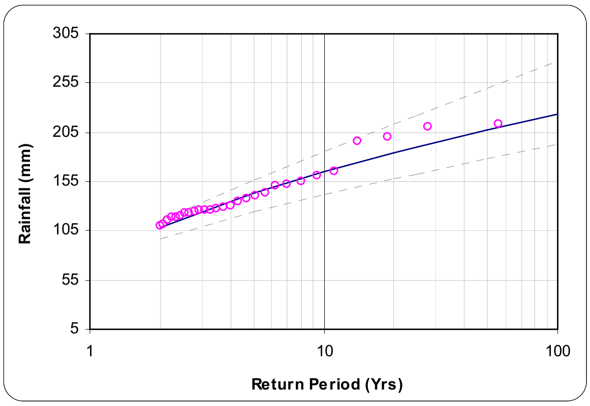
Table 3.2-2 summarizes the annual maximum 1-day to 4-day cumulative rainfalls of each return period based on the Gumbel distribution for these 5 rain gauge stations. The data presented in **Table 3.2-2** will be used to design 1- to 4-day rainfall patterns at different return periods of each rain gauge station.



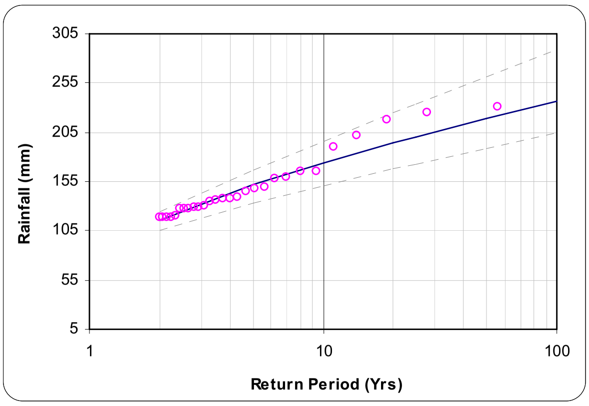
Maximum 1-day Cumulated Rainfall



Maximum 2-day Cumulated Rainfall



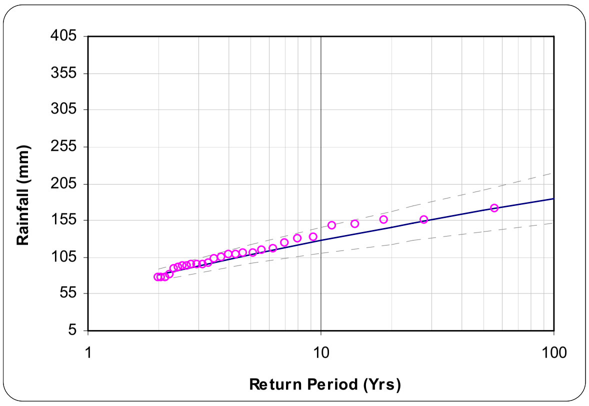
Maximum 3-day Cumulated Rainfall



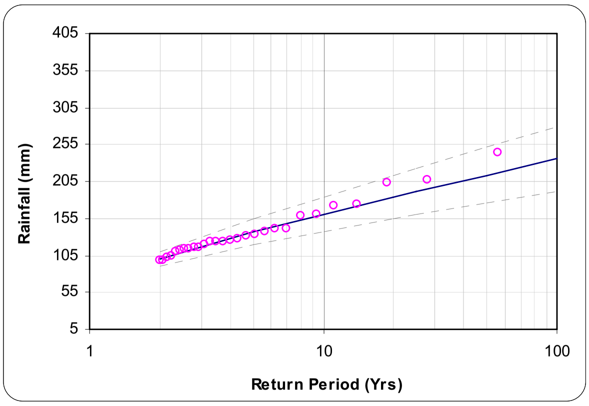
Maximum 4-day Cumulated Rainfall

Historical Record   Gumbel Distribution   95% Confidence Interval

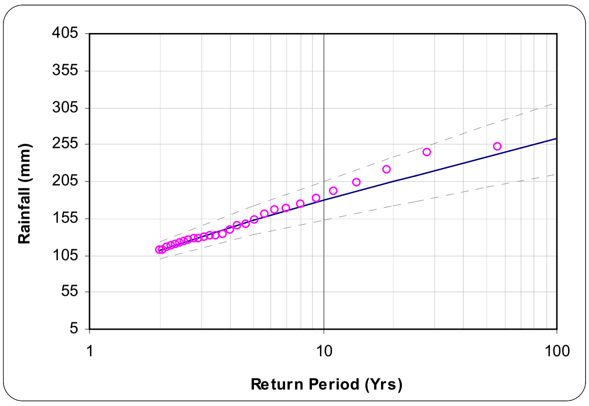
Figure 3.2-2 Fitting of Gumbel Distribution to Annual Maximum 1- to 4- day Accumulated Rainfall of 36013 Station (A. Muang, Phetchaboon)



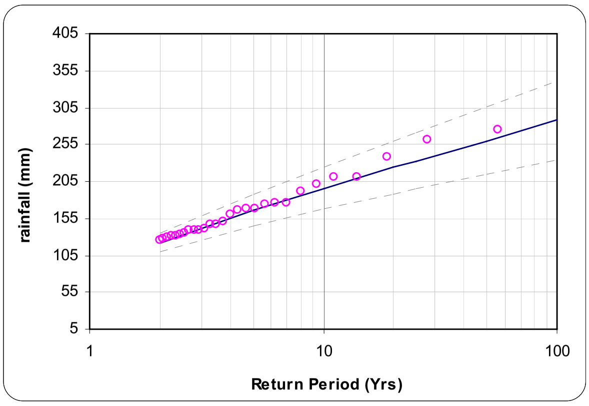
Maximum 2-day Cumulated Rainfall



Maximum 1-day Cumulated Rainfall



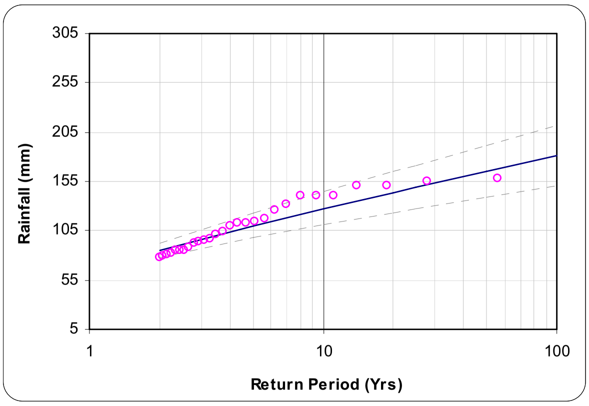
Maximum 3-day Cumulated Rainfall



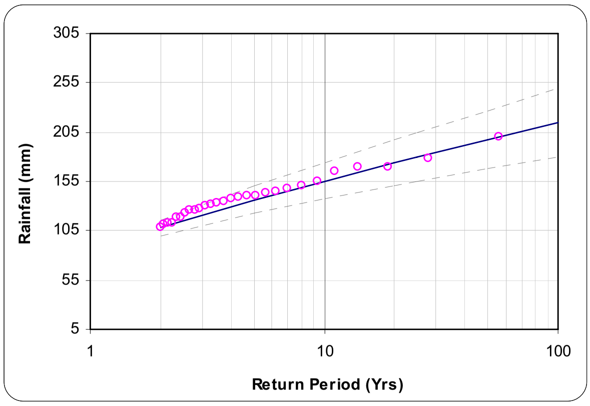
Maximum 4-day Cumulated Rainfall

Historical Record   Gumbel Distribution   95% Confidence Interval

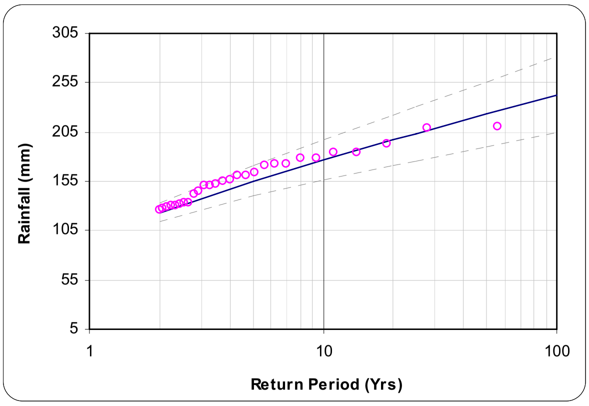
Figure 3.2-3 Fitting of Gumbel Distribution to Annual Maximum 1- to 4- day Accumulated Rainfall of 36023 Station (A. Lom Sak, Phetchaboon)



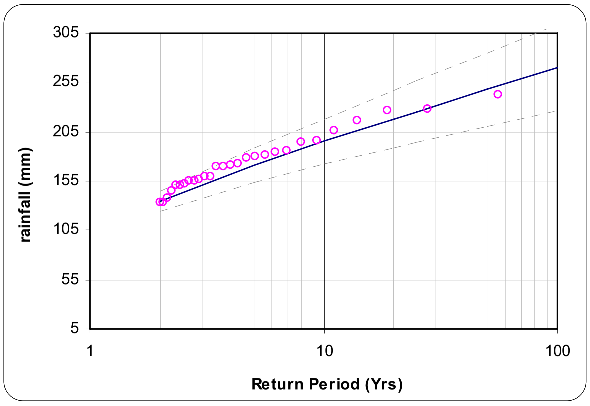
Maximum 1-day Cumulated Rainfall



Maximum 2-day Cumulated Rainfall



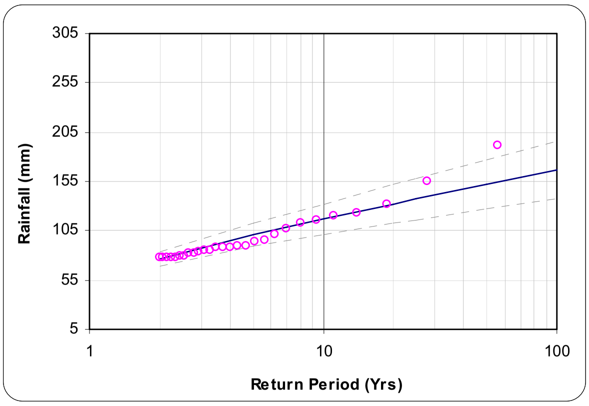
Maximum 3-day Cumulated Rainfall



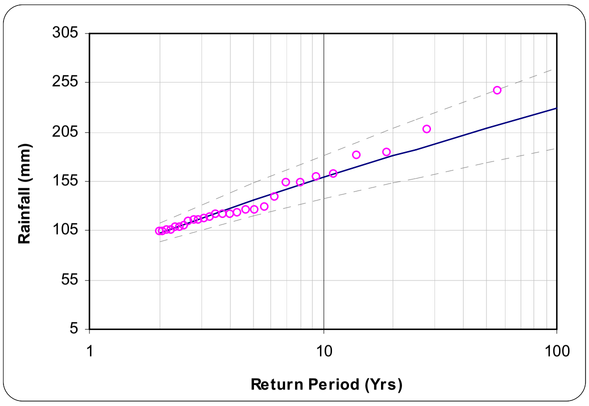
Maximum 4-day Cumulated Rainfall

Historical Record   Gumbel Distribution   95% Confidence Interval

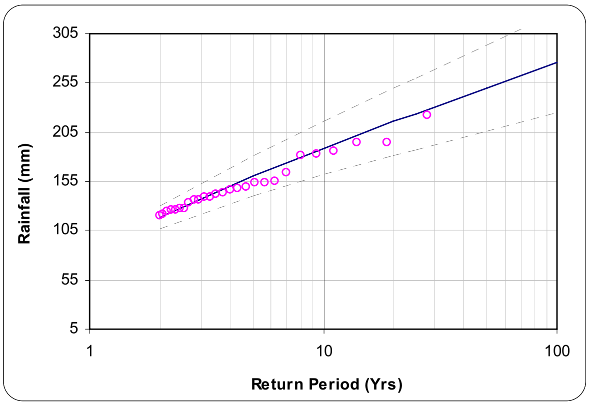
Figure 3.2-4 Fitting of Gumbel Distribution to Annual Maximum 1- to 4- day Accumulated Rainfall of 36032 Station (A. Lom Kao, Phetchaboon)



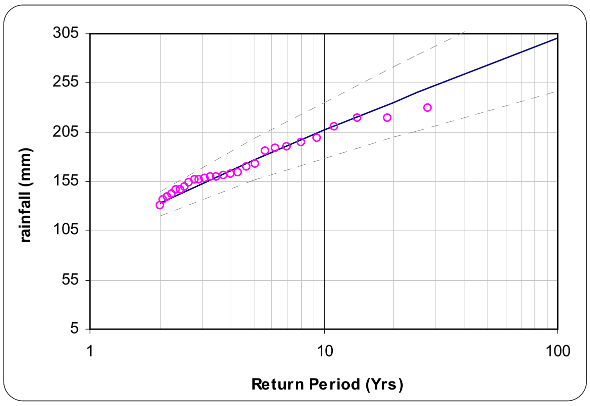
Maximum 1-day Cumulated Rainfall



Maximum 2-day Cumulated Rainfall



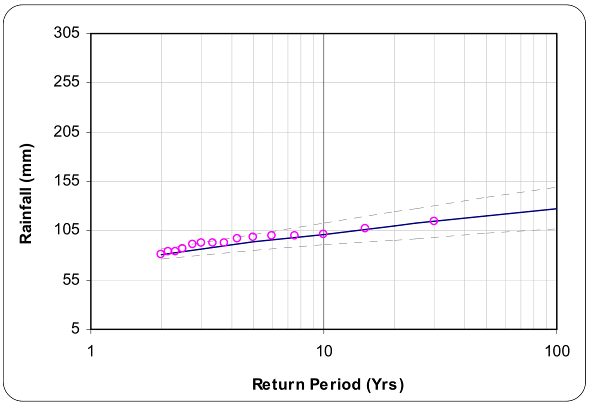
Maximum 3-day Cumulated Rainfall



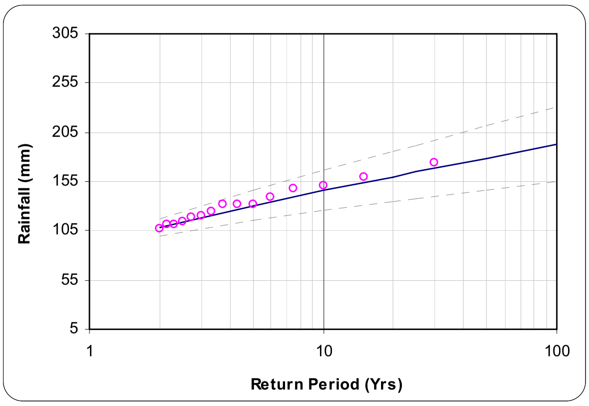
Maximum 4-day Cumulated Rainfall

Historical Record   Gumbel Distribution   95% Confidence Interval

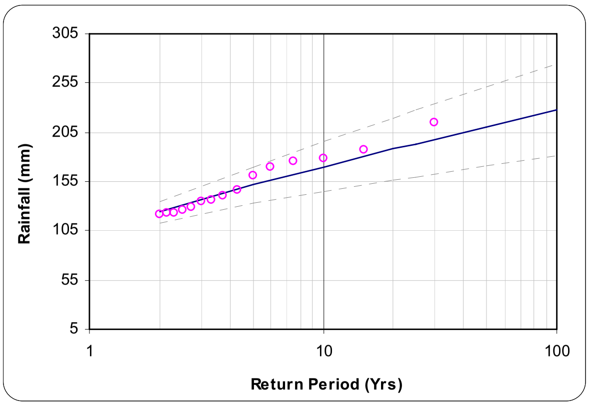
Figure 3.2-5 Fitting of Gumbel Distribution to Annual Maximum 1- to 4- day Accumulated Rainfall of 36043 Station (A. Wichain Buri, Phetchaboon)



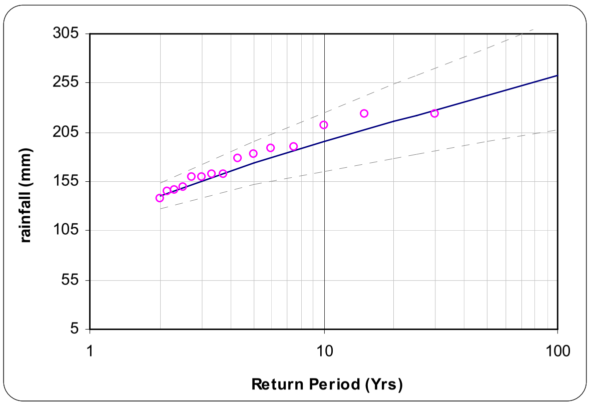
Maximum 1-day Cumulated Rainfall



Maximum 2-day Cumulated Rainfall



Maximum 3-day Cumulated Rainfall



Maximum 4-day Cumulated Rainfall

Historical Record　Gumbel Distribution　95% Confidence Interval

Figure 3.2-6 Fitting of Gumbel Distribution to Annual Maximum 1- to 4- day Accumulated Rainfall of 36141 Station (A. Nong Phai, Phetchaboon)

Table 3.2-2 Estimated Annual Maximum 1- to 4-day Accumulated Rainfall of Each Return Period Using Gumbel Distribution Function.

unit : mm

Station Code	Station Name	Duration of Rainfall (Days)	Return Period (Years)					
			2	5	10	20	50	100
36013	A. Muang, Phetchaboon	1	77.97	103.85	118.02	129.77	142.83	151.33
		2	94.79	126.47	145.65	162.85	183.71	198.48
		3	107.68	143.11	164.51	183.68	206.88	223.29
		4	116.39	152.06	174.09	194.22	219.12	237.13
36023	A. Lom Sak, Phetchaboon	1	81.43	109.28	127.72	145.40	168.30	185.45
		2	99.95	136.34	160.44	183.55	213.46	235.88
		3	111.20	151.97	178.97	204.87	238.38	263.50
		4	121.78	166.16	195.53	223.71	260.19	287.52
36032	A. Lom Kao, Phetchaboon	1	84.60	110.45	127.57	144.00	165.25	181.18
		2	107.90	136.48	155.41	173.57	197.07	214.68
		3	123.59	155.49	176.62	196.88	223.11	242.76
		4	135.10	171.17	195.06	217.97	247.62	269.85
36043	A. Wichian Buri, Phetchaboon	1	76.53	100.77	116.81	132.20	152.13	167.05
		2	102.72	136.74	159.26	180.87	208.83	229.79
		3	118.50	160.71	188.65	215.45	250.15	276.14
		4	132.68	177.48	207.15	235.60	272.43	300.03
36141	A. Nong Phai, Phetchaboon	1	80.89	93.47	101.80	109.78	120.12	127.87
		2	108.39	130.88	145.77	160.05	178.54	192.39
		3	123.93	151.77	170.20	187.87	210.76	227.90
		4	140.46	173.36	195.14	216.03	243.07	263.34

3.3 Streamflow

High flow from the North of the Upper Pasak river basin is another factor that causes flooding in the Muang Phetchaboon district. In the Pasak river, there are 2 river gauges stations located upstream and within the Muang Phetchaboon district as illustrated in Figure 2.2-2. The S.4B station has longer historical data records. It is located in the Muang Phetchaboon district. While the S.3 station is located upstream of S.4B at the Lom Sak district and has recorded data during the last 10 years. The streamflow data recorded from these 2 river gauge stations were used for hydrological and frequency studies of the study area.

3.3.1 Variation of Streamflow in the Muang Phetchaboon District

From the measuring of RID, flow capacity of the Pasak river at the S.4B station is about 174 cms with approximate depth of 9 m. The river cross section of S.4B station is shown in **Figure 3.3-1**. From that figure, it can be seen that when the water levels at S.4B station are higher than 9.5 m (Assume Datum), flooding will occur in A. Muang Phetchaboon district.

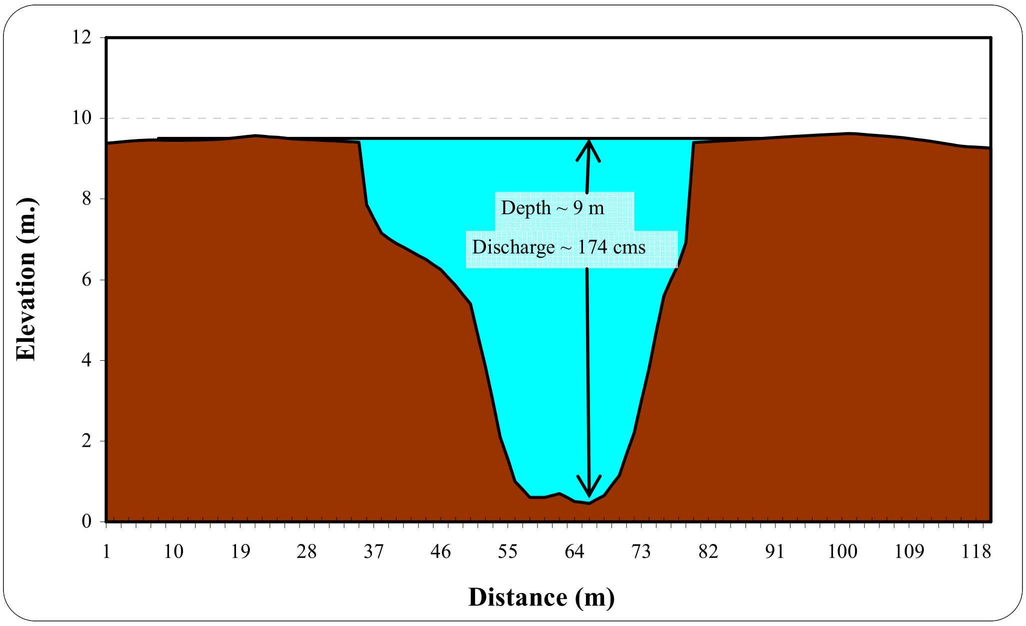


Figure 3.3-1 River Cross Section of S.4B Station: A. Muang, Phetchaboon

The gauge height data from the S.4B station have been considered to use as an indicator to measure severity of flood in the Muang Phetchaboon district. The historical records of monthly gauge height of the S.4B station during 1966 – 2006 (as presented in **Appendix A, Table A-20**) was used to analyze the variation of gauge height by plotting a radar chart as shown in **Figure 3.3-2**. From this figure, it indicates that the high flow period (water depth > 9 m) is between August to October in which September has the maximum monthly water depth.

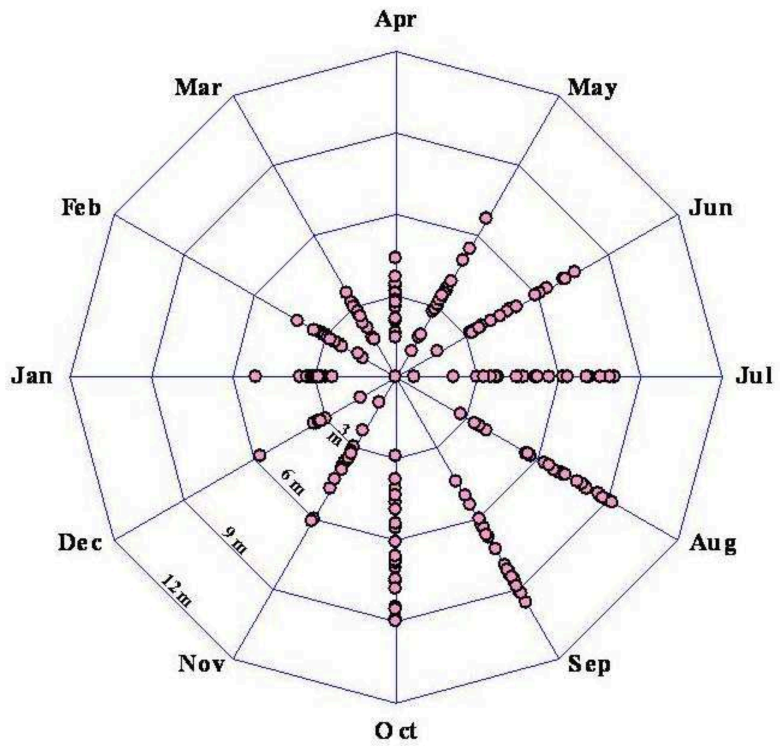
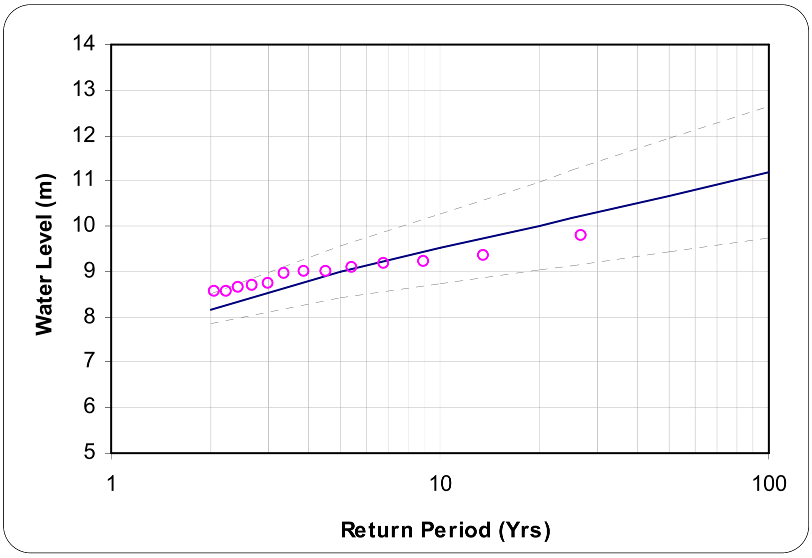


Figure 3.3-2 Monthly Water Depth of S.4B Station: A.Muang, Phetchaboon

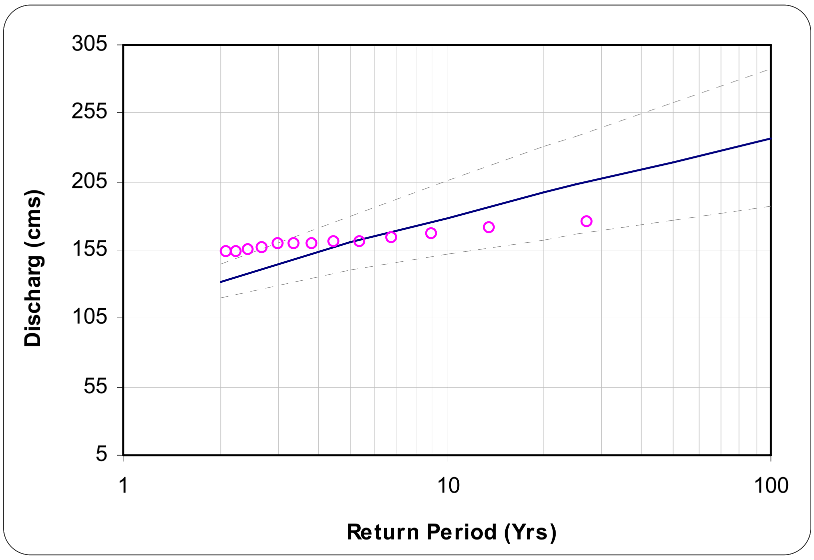
From the hydrological study of the Muang Phetchaboon district based on rainfall data at the 36013 station (Figure 3.2-1) and the streamflow data at the S.4B station (Figuer 3.3-2), it has been shown that the critical months of the Muang Phetchaboon district are during August to October in which September has been considered as the most critical month. However, in some years when rain comes late, floods probably occur in early of November (i.e. the 2007 flood event). To cover such situations, the month of November has also been considered as a critical month of the study area.

3.3.2 Streamflow Frequency Analysis

Annual momentary peak of streamflow data of S.4B and S.3 stations (as details presented in **Appendix A**, **Tables A-21** and **A-22**) were used for streamflow frequency analysis. As same as maximum rainfall data, the Gumbel distribution function was applied to fit the annual momentary peak of the streamflow data and the Weibull plotting position formular was used to estimate the probability of exceedences. Comparisons between the plotting position and the Gumbel distribution of the annual momentary peak of streamflow data and the 95% confidence intervals are shown in **Figures 3.3-3 to 3.3-4.** The estimated annual maximum streamflow data of these two river gauge stations at different return period are established in **Table 3.3-1**.



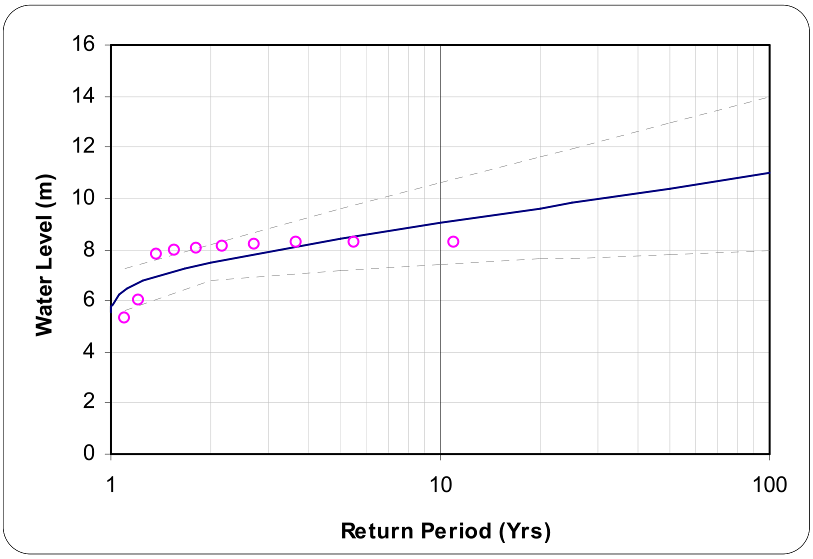
Annual Momentary Peak of Water Level



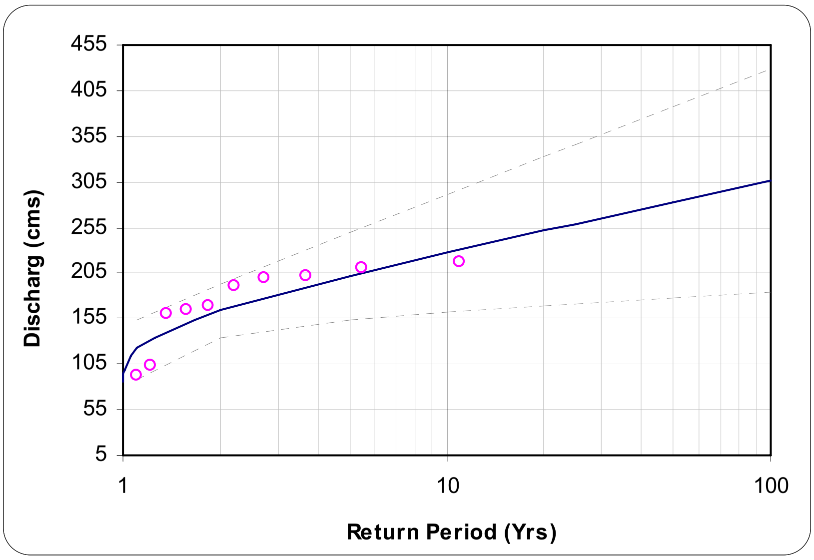
Annual Momentary Peak of Discharge

Historical Record   Gumbel Distribution   95% Confidence Interval

Figure 3.3-3 Fitting of Gumbel Distribution to Annual Momentary Peak of Streamflow Data of S.4B Station



Annual Momentary Peak of Water Level



Annual Momentary Peak of Discharge

Historical Record   Gumbel Distribution   95% Confidence Interval

Figure 3.3-4 Fitting of Gumbel Distribution to Annual Momentary Peak of Streamflow Data of S.3 Station

It is to be noted that fitting of the Gumbel distribution function to the annual momentary peak of the streamflow data is slightly worse than the fitting of this distribution to maximum rainfall data. This is possible due to the river cross sections of the periods before and after flooding might not be stable because of deposition or erosion. The water levels and discharges of the non-flooded and flooded year could not be compared using the same criteria. However, most of the observed annual momentary peak of both water levels and discharges lie within 95% confidence intervals, therefore we can consider that the observed annual momentary peak of streamflow data fit to the Gumbel distribution function.

Table 3.3-1 Estimated Annual Maximum Streamflow of Each Return Period Using Gumbel Distribution Function

Station S.4B : A.Muang Phetchaboon

Return	Probability	Maximum Water Level (m)			Maximum Discharge (cms)		
Period	Exceedence	Gumbel	95% Confidence Limit		Gumbel	95% Confidence Limit	
(Years)	(%)	Distribution	Upper	Lower	Distribution	Upper	Lower
2	50	8.13	8.51	7.84	146.21	144.15	120.65
5	20	8.94	9.55	8.41	174.20	180.18	140.61
10	10	9.47	10.28	8.74	192.74	205.66	152.21
20	5	9.98	10.99	9.05	210.52	230.47	162.96
50	2	10.64	11.92	9.44	233.54	262.85	176.62
100	1	11.14	12.62	9.74	250.79	287.20	186.75

Station S.3 : A.Lom Sak, Phetchaboon

Return	Probability of	Maximum Water Level (m)			Maximum Discharge (cms)		
Period	Exceedence	Gumbel	95% Confidence Limit		Gumbel	95% Confidence Limit	
(Years)	(%)	Distribution	Upper	Lower	Distribution	Upper	Lower
2	50	7.46	8.16	6.75	163.37	191.89	134.86
5	20	8.40	9.58	7.22	201.75	249.77	153.73
10	10	9.03	10.63	7.43	227.16	292.02	162.30
20	5	9.63	11.65	7.61	251.54	333.47	169.60
50	2	10.40	11.97	7.66	283.09	346.72	171.82
100	1	10.99	12.98	7.83	306.73	387.73	178.44

Discharge at the S.4B station should be higher than discharge at the S.3 station because the S.4B station is located downstream of the S.3 station. However, based on the recorded data, the discharge at the S.4B station are lower than the S.3 station. This is possible due to overflow from the Pasak river into flood plain areas between the S.3 and S.4B stations. For this reason, we consider to use water depth at the S.4B station as flood index of the Muang Phetchaboon district instead of discharge data.

3.4 Designing of Flood Scenarios

In many situations, the occurrence of flood in the study area might be due to high flow from the North of the basin and heavy rainfall within the area of Muang Phetchaboon district. To accommodate this fact, the flood scenarios were designed by combining rainfall and streamflow data together, hereafter referred as *"combined flood scenarios"*. The combined flood scenarios are considered to be more realistic than the standalone rainfall and streamflow scenarios. Therefore, in this study, flood hazard maps were simulated according to the combined flood scenarios only**.** Rainfall patterns of the 5 rain gauge stations and streamflow patterns of the S.3 station that are the most likely cause of flood at different probability of occurrence were investigated and presented in sections 3.4.2 and 3.4.3, respectively. The combined flood scenarios were designed using these rainfall and streamflow patterns.

3.4.1 Designing of Combined Maximum Flood Scenario

For flood hazard study, we consider that flow from the North of the basin (represented by the discharge at S.3 station) and rainfall within the vicinity of the Muang Phetchaboon district (represented by rainfall at the 5 rain gauge stations) are independent to each other because these rain gauge stations are located downstream of the S.3 station. Rainfall from these 5 rain gauge stations does not have any significant influence on runoff of the upstream catchment. High flows at the S.3 station are therefore due to rainfall that occurs in the upstream area of the S.3 station. For this reason, the occurrence of streamflow at the S.3 station is considered to be not correlated with the occurrence of rainfall at those 5 rain gauge stations. Considering that these two variables are dependent will lead to an overestimated of any specified probabilities of occurrence of flood of the study area. Thus, these rainfall and streamflow data were combined together to generate combined maximum flood scenarios (weather patterns) at difference probabilities of occurrence as details shown in equation below.

If events A and B are independent then;

$$P(A \cap B) = P(B)P(A) \qquad (3)$$

where A = occurrence of streamflow at the S.3 station
B = occurrence of rainfall at the downstream of the S.3 station

For simplicity, the occurrences of event A and B are assumed to be equal. From the above equation, the combined flood scenarios at different return periods were designed by combining the designed 4-day annual maximum rainfall patterns of the 5 rain gauge stations (see details in section 3.4.2) and designed annual maximum streamflow patterns at the S.3 station (see details in section 3.4.3) together. Since the annual maximum rainfall and streamflow data were used for designing of the combined flood scenarios, these designed combined flood scenarios are called "*combined maximum flood scenario*". For example, 2-year return period of combined maximum flood scenario was derived from 1.41-year return period of these designed streamflow and rainfall patterns; (50% probability of occurrence of combined maximum flood scenarios = probability of occurrence of streamflow at the S.3 station multiplied by probability of occurrence of rainfall at the 5 rain gauge stations, assuming that the probability of occurrence of streamflow and rainfall are the same).

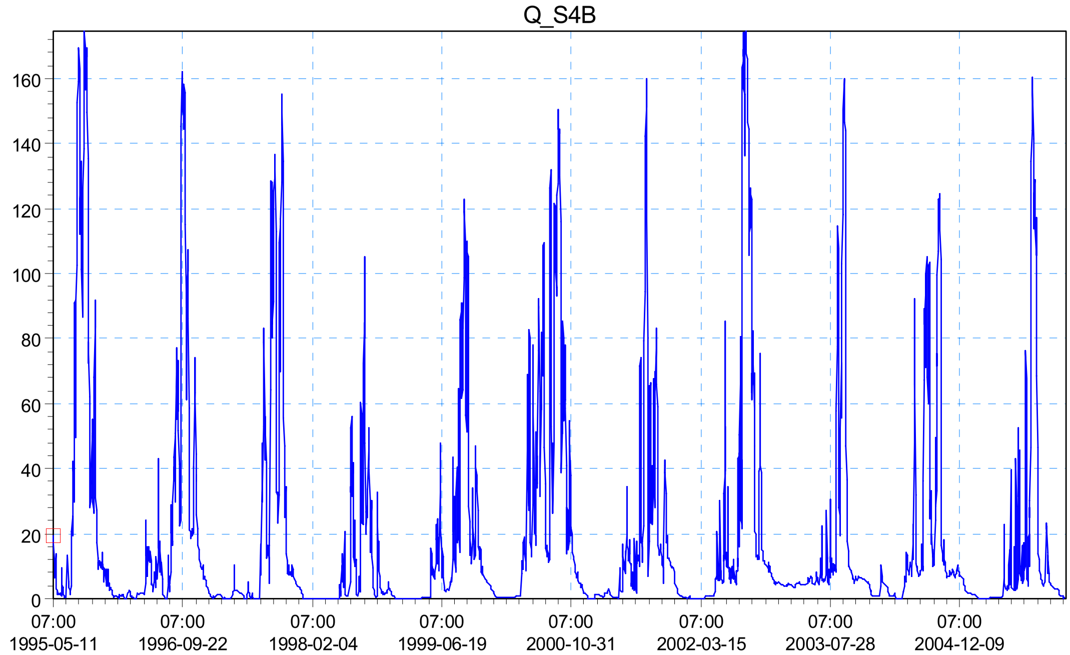
3.4.2 Designed Rainfall Patterns

The study of PASCO indicates that 1-day high intensity rainfall causes the occurrence of flood, lasting rainfall such as 3- and 4-day, is considered to be the most likely cause of severe flood. They reported that flood events occurred in 1990, 1994, 1995, 2000 and 2002 have relatively larger maximum 4-day accumulation rainfall, except for 2000. From this fact, they concluded that 4-day accumulation rainfall has strong relationship to the occurrence of severe flood and it has been adopt for the production of flood scenario. According to result from the study of PASCO, in this study, we consider to use the maximum 4-day accumulation rainfall to develop flood scenario due to heavy rainfall. To analyze flood hazard zones in probabilistic term, the maximum 4-day accumulation rainfall patterns at different exceedence probabilities of the 5 rain gauge stations were developed.

The maximum 4-day rainfall patterns of 2-,5-,10-,20-,50- and 100-year return periods of each rain gauge station were designed by calculating increments between maximum 1-, 2-, 3-, and 4-day accumulated rainfall at the same return period, rainfall of the considered day is equal to the increment between maximum accumulated rainfall of that day and maximum accumulated rainfall of the previous day. For example, rainfall of the second day is equal to the maximum 2-day rainfall minus the maximum 1-day rainfall, etc. **Tables A23** shows the designed maximum 1- to 4 day accumulated rainfall at different return periods of the 5 rain gauge stations. These designed rainfall patterns will then combined with the designed streamflow pattern (as will be described next) to develop combined maximum flood scenarios (weather patterns at different probabilities of exceedence).

3.4.3 Designed Streamflow Patterns

Flow patterns of the S.3 station at each return period were designed based on the frequency analysis results. To design flow patterns, at first the climatological (normal) year was identified. This was performed by comparing discharge time series of the S.4B and S.3 stations which can be used to represent hydrological characteristic of the Muang Phetchaboon district as shown in **Figure 3.4-1**.



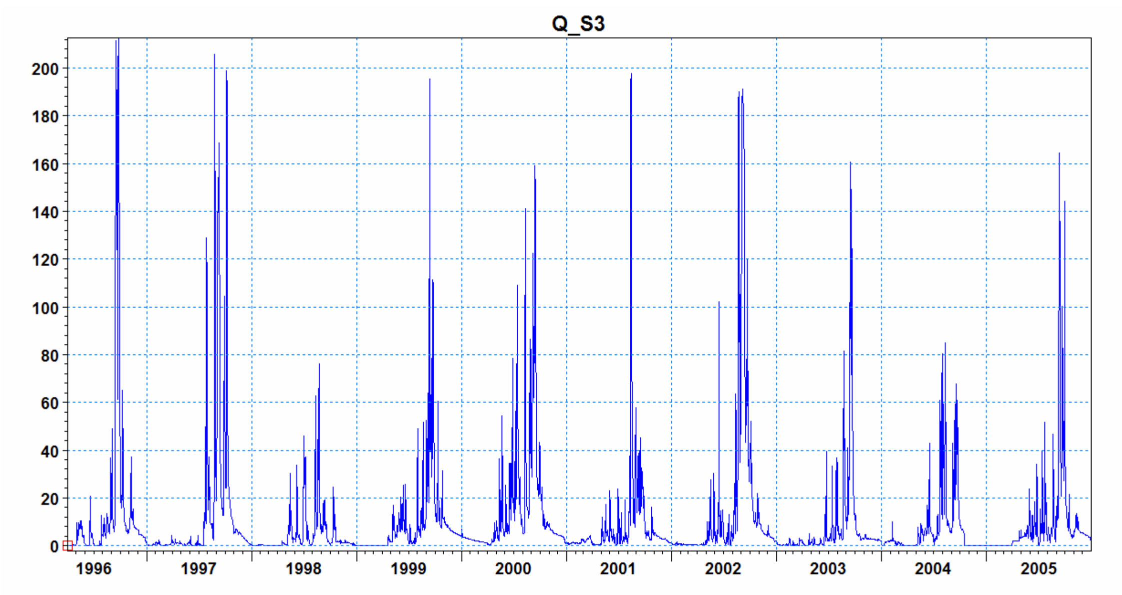


Figure 3.4-1 Discharge (cms) Time Series at S.4B and S.3 Stations between 1995 – 2005 (11 Years)

There are only eleven years (from 1995 to 2005) of streamflow data at the S.3 station are available. Commonly, a hydrological cycle is about 30 years. The mean of these available 11 years streamflow data are not long enough to represent climatlogical streamflow of this station. Moreover, using the mean longer term of stream flow data will misshape the streamflow peak and pattern. Since, there was no flood in the year 2005 and the mean streamflow of this year lies between the dry and wet year as illustrated in Figure 3.4-1. Therefore, in this study, streamflow at the year 2005 was selected to represent climatological year of the study area.

The flow patterns of the S.3 station were designed as follows. The discharge time series during 01/09/2005 – 30/09/2005 of the S.3 station were selected to represent the climatological flow pattern during the highest flood risk month (September). The designed flow patterns of each return period were created by multiplying the climatological discharge time series with Q_{Tr}/Q_{peak} factor where Q_{Tr} is the discharge at the required return period (Tr) and Q_{peak} is the maximum discharge of the climatological flow time series of the S.3 station. It should be noted that multiplying Q_{Tr}/Q_{peak} factor to the climatological flow pattern will make the peak of the designed flow pattern to be equal to discharge of the specified return period. **Table A24** show the designed flow patterns and (Q_{Tr}/Q_{peak}) factors at each return period.

3.4.4 Combined Maximum Flood Scenarios

The combined maximum flood scenarios were designed by the equation (3). The designed rainfall and streamflow patterns as presented in sections 3.4.2 and 3.4.3 were combined together to generate the combined maximum flood scenarios (weather patterns) at different return periods as presented in **Figures 3.4-2 to 3.4-7.** The red bar charts shown in these figures represented daily designed rainfall patterns of the specified rain gauge stations while the streamflow time series (blue line) are represented the daily designed streamflow patterns of the S.3 station. The most extreme flood event might occur in the Muang Phetchaboon district when heavy rainfall within the Muang Phetchaboon district and high flow from the North of the basin take place at the same time. To cover such situation, the combined maximum flood scenarios were designed by considering the time of occurrence of rainfall and streamflow are the same as shown in Figures 3.4-2 to 3.4-7.

Since, the original designed streamflow pattern (September 2005) has two peaks, thus the second peak appears in the streamflow time series at different return periods of combined maximum flood scenarios as shown in Figures 3.4-2 to 3.4-7 are imitative of the original designed streamflow pattern. Details of the rainfall and streamflow values of the combined maximum flood scenarios at different return periods are established in **Table 3.4-1**.

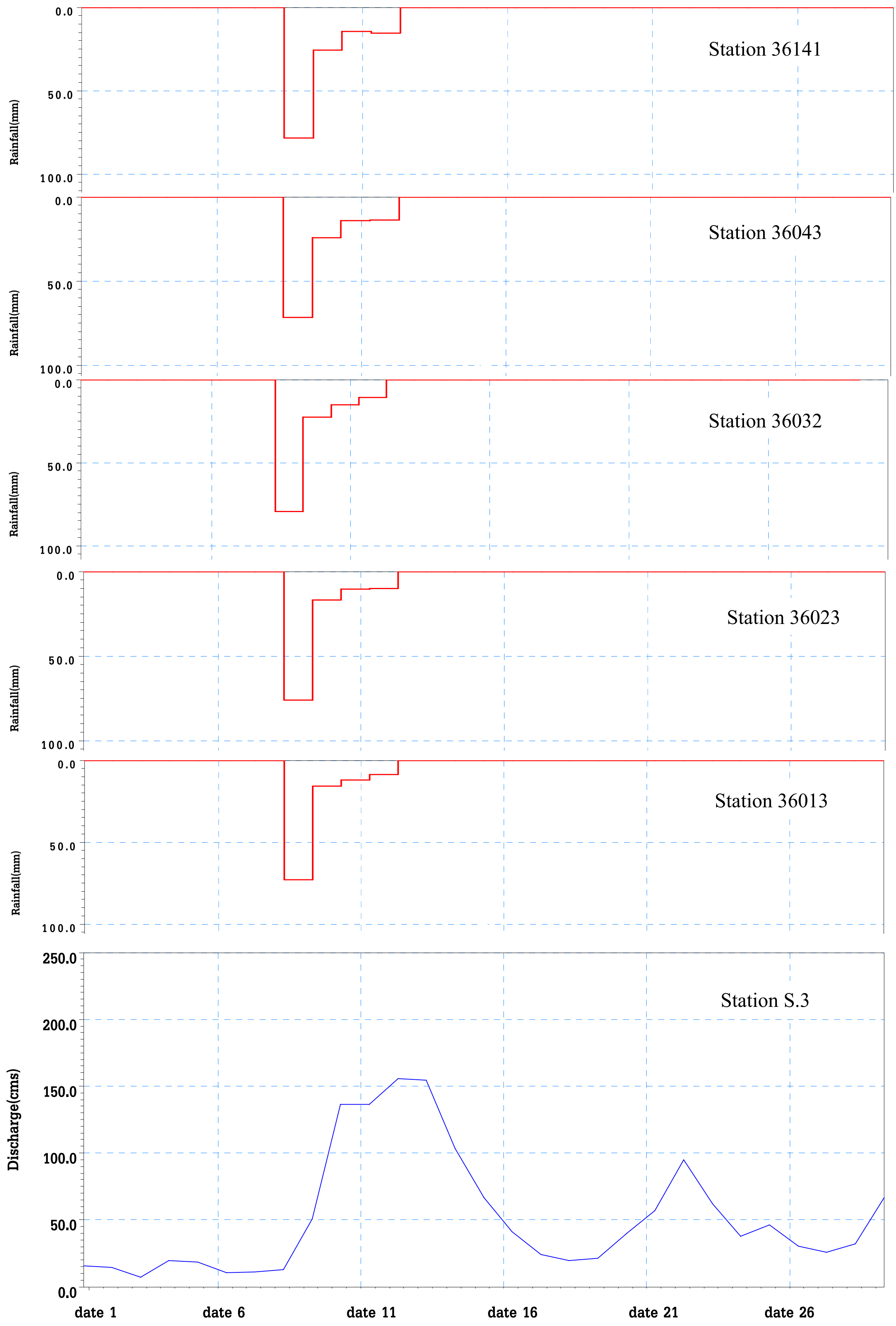


Figure 3.4-2 2-Year Combined Maximum Flood Scenario
(1.41-Year Return Period of Annual Maximum Streamflow and Rainfall Patterns)

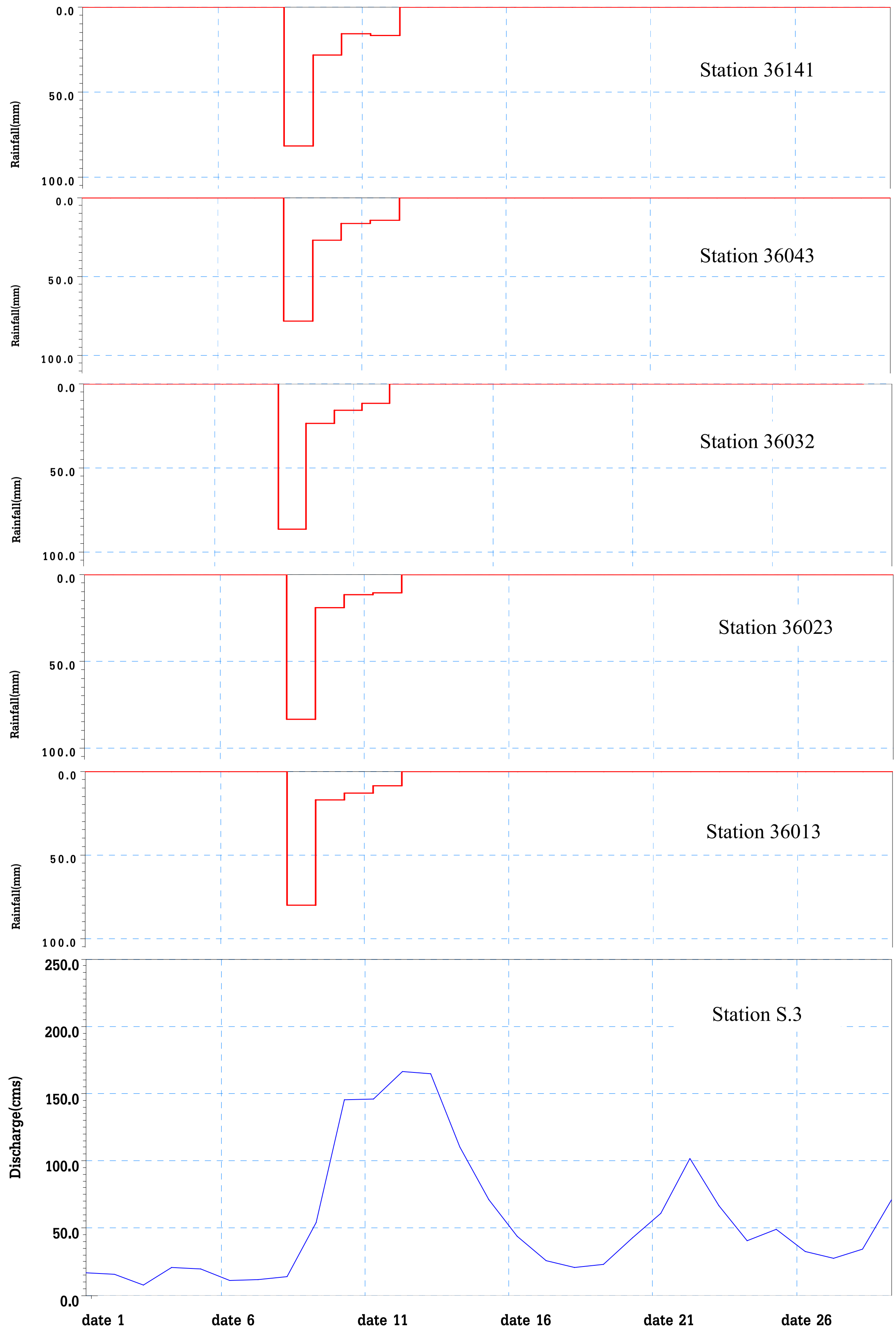


Figure 3.4-3 5-Year Combined Maximum Flood Scenario
(2.24-Year Return Period of Annual Maximum Streamflow and Rainfall Patterns)

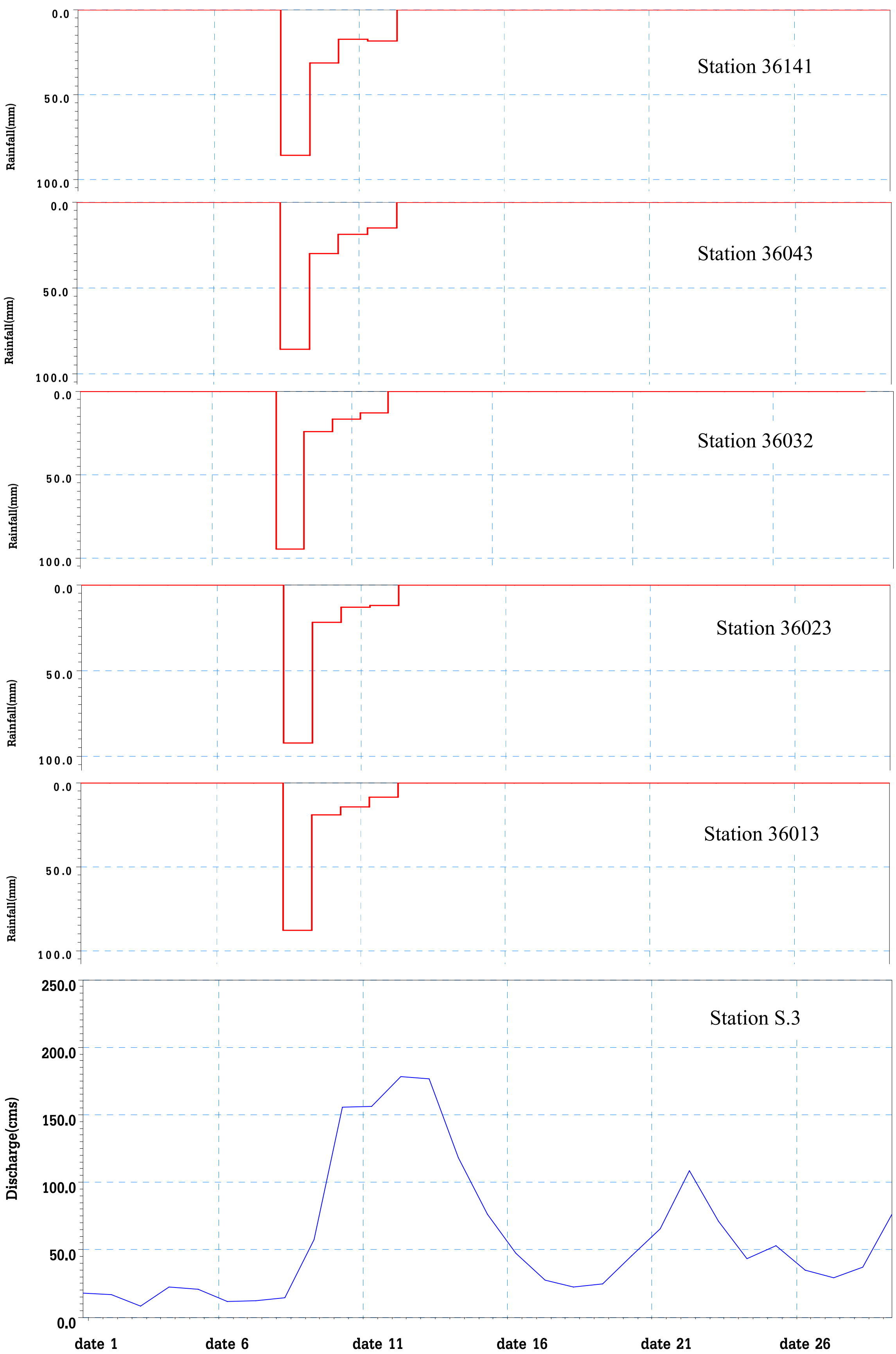


Figure 3.4-4 10-Year Combined Maximum Flood Scenario

(3.16-Year Return Period of Annual Maximum Streamflow and Rainfall Patterns)

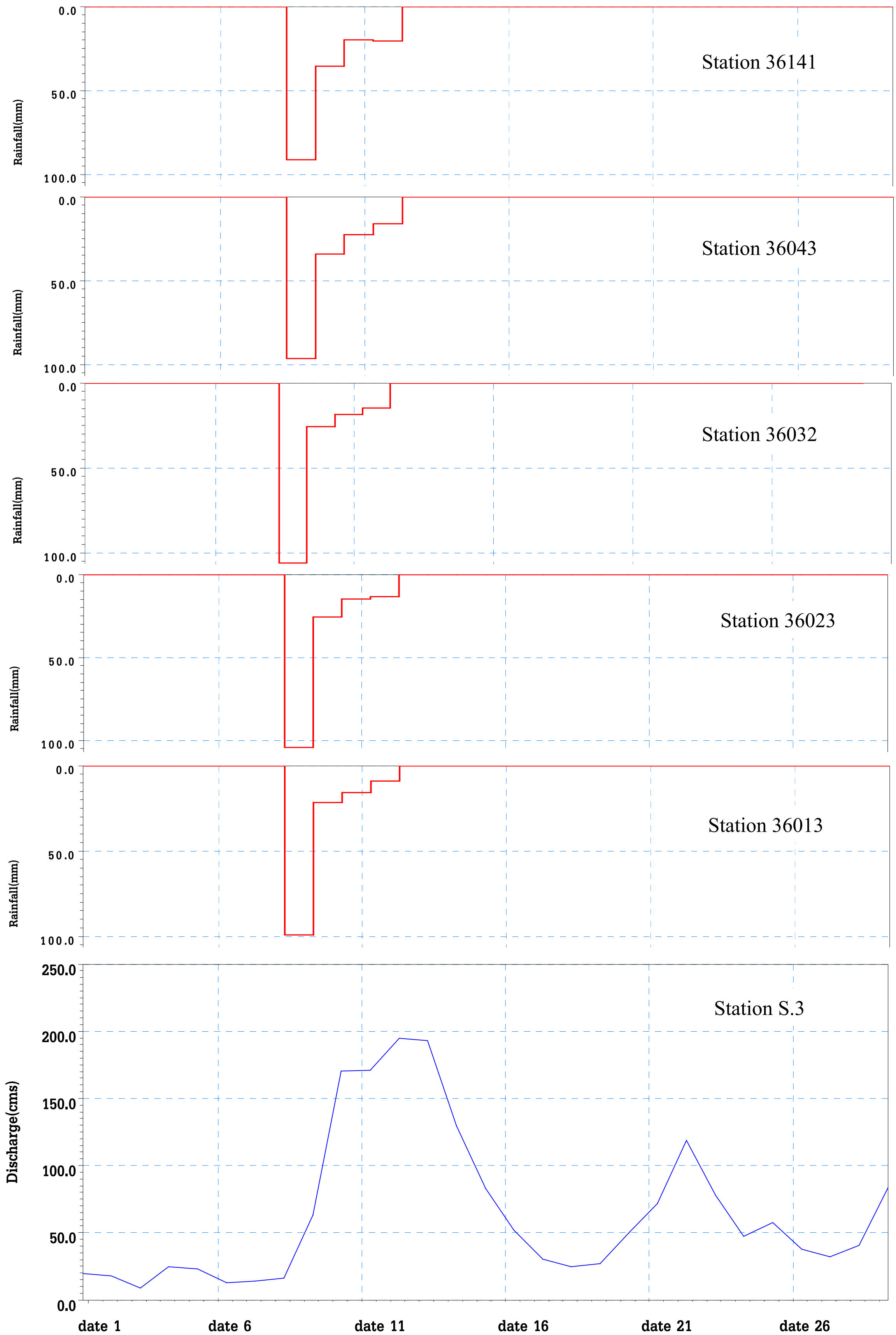


Figure 3.4-5 20-Year Combined Maximum Flood Scenario

(4.47-Year Return Period of Annual Maximum Streamflow and Rainfall Patterns)

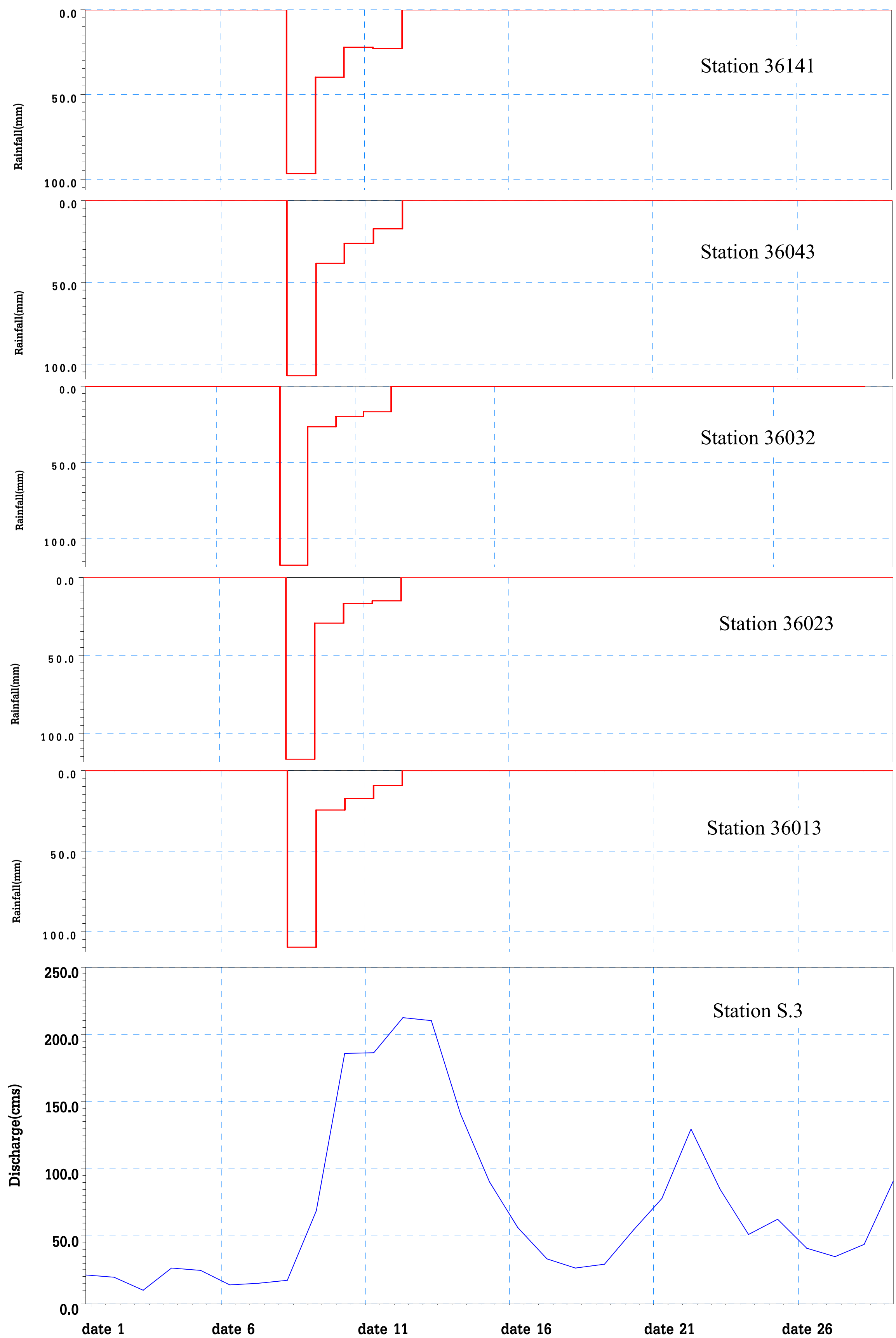


Figure 3.4-6 50-Year Combined Maximum Flood Scenario

(7.07-Year Return Period of Annual Maximum Streamflow and Rainfall Patterns)

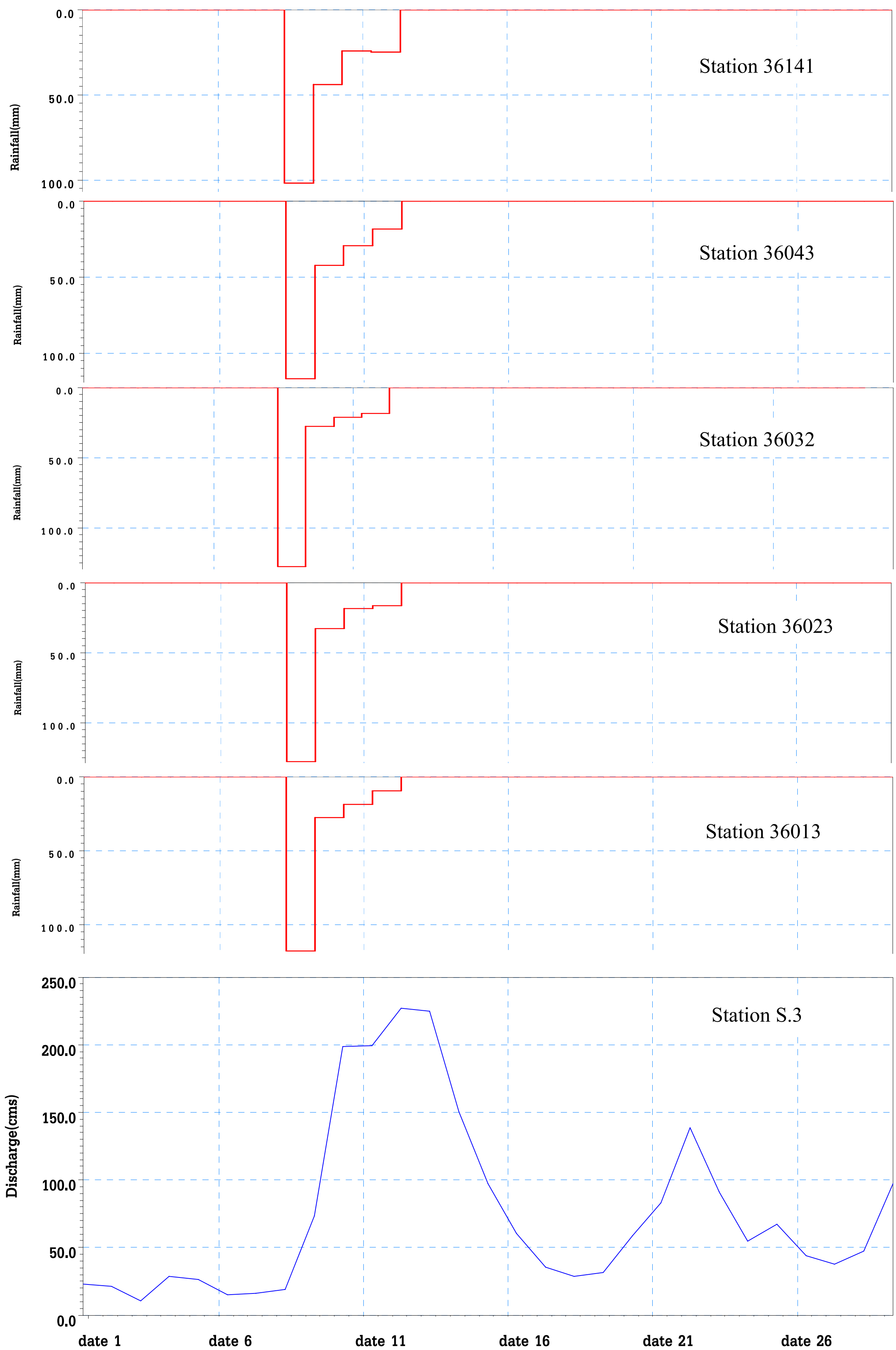


Figure 3.4-7 100-Year Combined Maximum Flood Scenario

(10-Year Return Period of Annual Maximum Streamflow and Rainfall Patterns)

Table 3.4-1 Summarized Rainfall and Streamflow Values of The Combined Maximum Flood Scenarios at Different Return Periods.

Station Code	Station Name	Flood Condition	Return Period (Years)					
			2	5	10	20	50	100
36013	A. Muang, Phetchaboon	Accumulated 4-day rainfall (mm)	109.37	119.24	130.18	145.76	161.18	174.09
36023	A. Lom Sak, Phetchaboon	Accumulated 4-day ainfall (mm)	113.05	125.33	138.94	158.32	178.32	195.53
36032	A. Lom Kao, Phetchaboon	Accumulated 4-day rainfall (mm)	128.01	137.99	149.05	164.80	181.06	195.06
36043	A. Wichian Buri, Phetchaboon	Accumulated 4-day rainfall (mm)	123.87	136.26	150.00	169.57	189.76	207.15
36141	A. Nong Phai, Phetchaboon	Accumulated 4-days rainfall (mm)	133.99	143.09	153.18	167.55	182.38	195.14
S.3	A.Lom Sak	Peak discharge (cms)	155.82	166.44	178.21	194.97	212.27	227.16

The combined maximum flood scenarios at different return periods as presented in Figures 3.4-2 to 3.4-7 were used as input to the developed flood model for producing flood hazard maps at different probabilities of occurrence.

3.4.5 Designing of Combined Weekly Flood Scenario

To generate weekly flood maps during the flood risk months, daily rainfall at 5 rain gauge stations and streamflow patterns at the S.3 river gauge station during the 4 critical months were designed. The 50th, 75th and 95th percentiles of daily rainfall and streamflow data at these stations during 1st August to 30th November were calculated, thereafter they were used to design combined flood patterns at different percentiles, so called "*combined weekly flood scenarios*".

The weekly combined flood scenarios at different percentiles are shown in **Figures 3.4-8 to 3.4-10**. Note that the red bar charts presented in Figures 3.4-8 to 3.4-10 represented the 50th, 75th and 95th percentiles of individual rain gauge rainfall of each specified day during the critical months, respectively. The 50th-percentile of daily rainfall is the magnitude of rainfall such that 50th percent of the rainfall data at that day have magnitude less than this value, etc. Thus, rainfall patterns designed from the 50th, 75th and 95th percentiles can be used to represent lower quantile, middle quantile (median), and upper quantile of rainfall data of the considered day, respectively. Consequently, any inundation area that are caused by the 50th, 75th and 95th percentiles of the combined weekly flood scenarios can be considered as high, moderate and low flood risk zones. It is to be mentioned that 25th-percentile rainfall and streamflow patterns do not lead to flooding in the study area, thus they were excluded from the analysis.

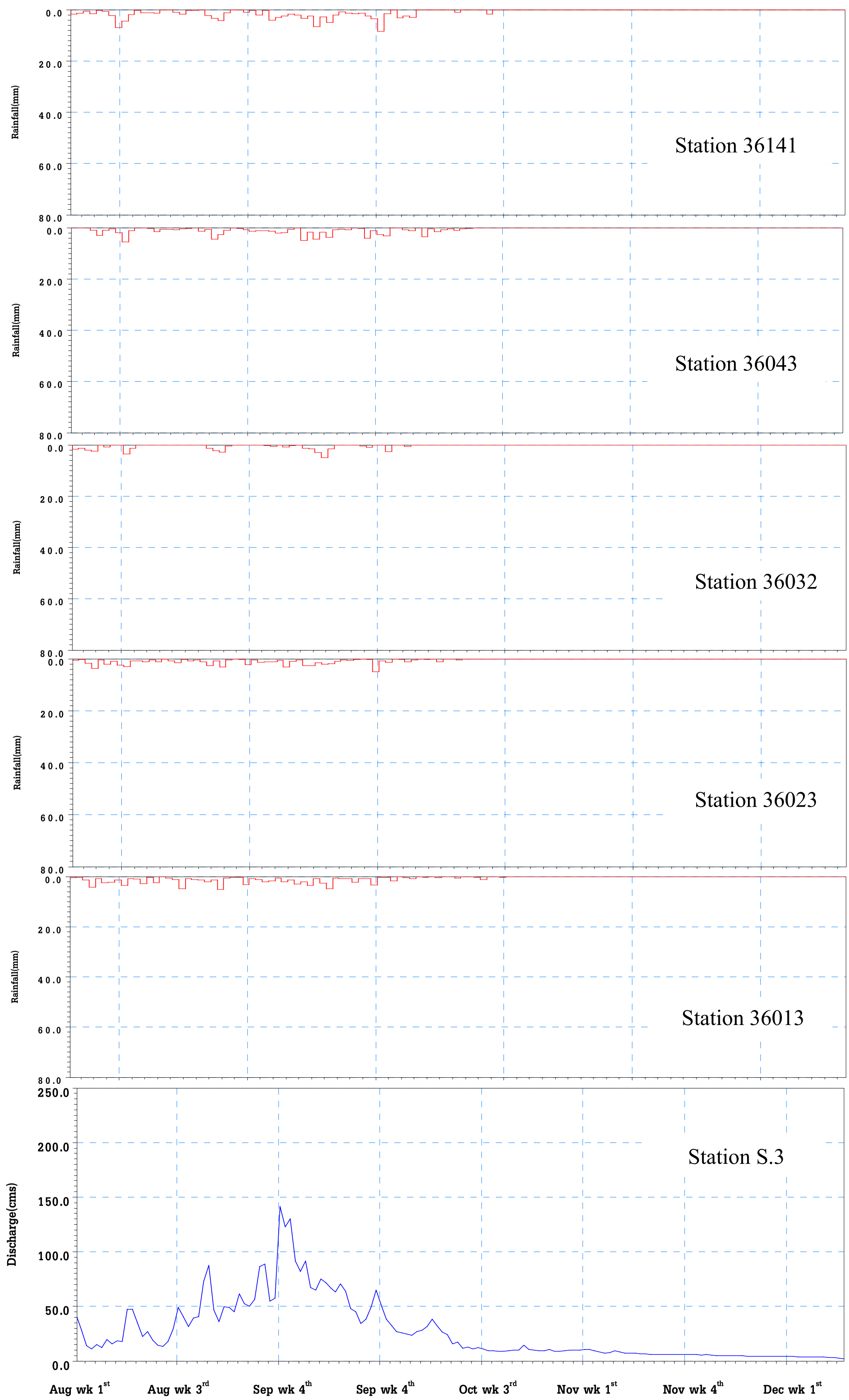


Figure 3.4-8 50th-Percentile Combined Weekly Flood Scenario

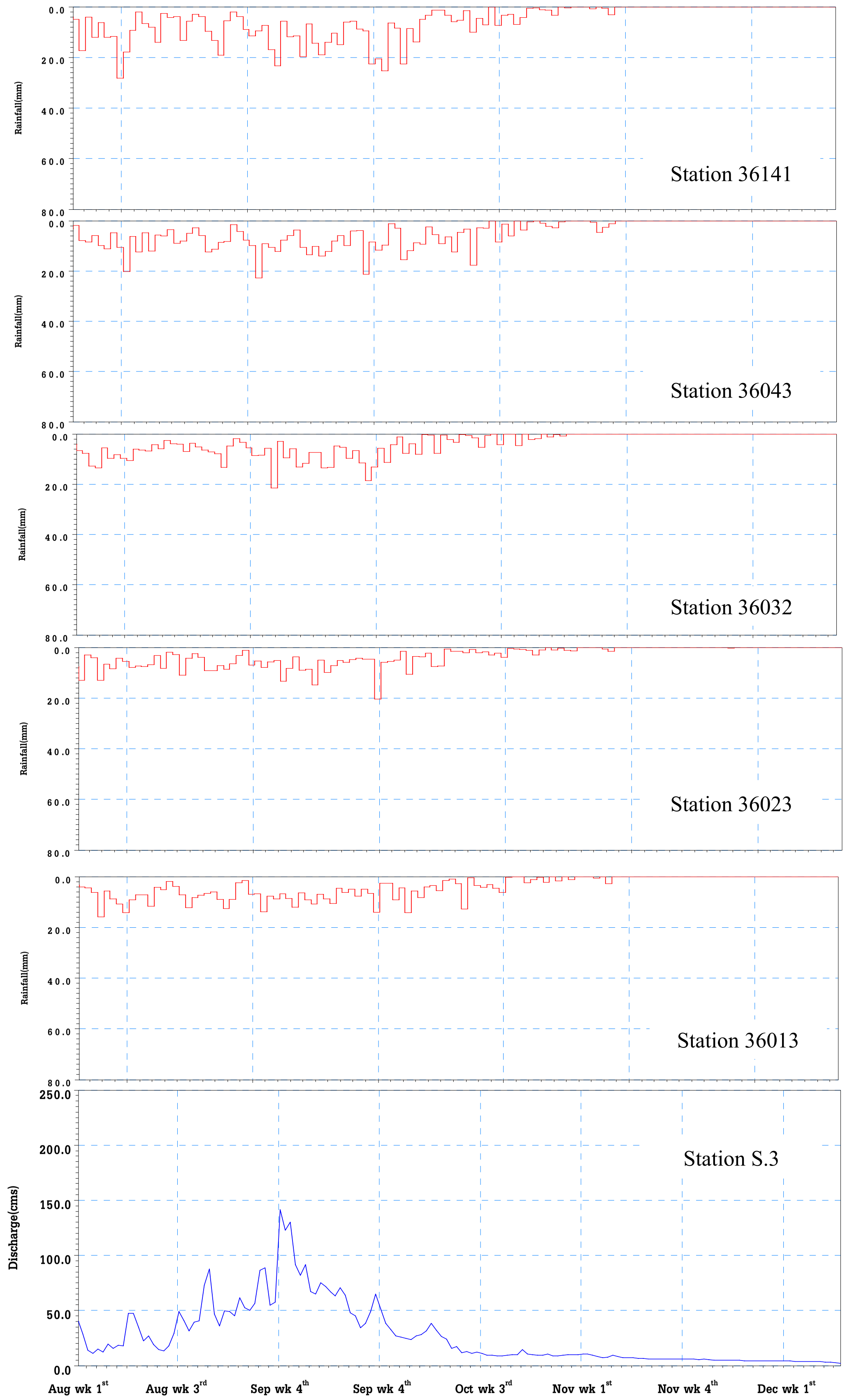


Figure 3.4-9 75th- Percentile Combined Weekly Flood Scenario

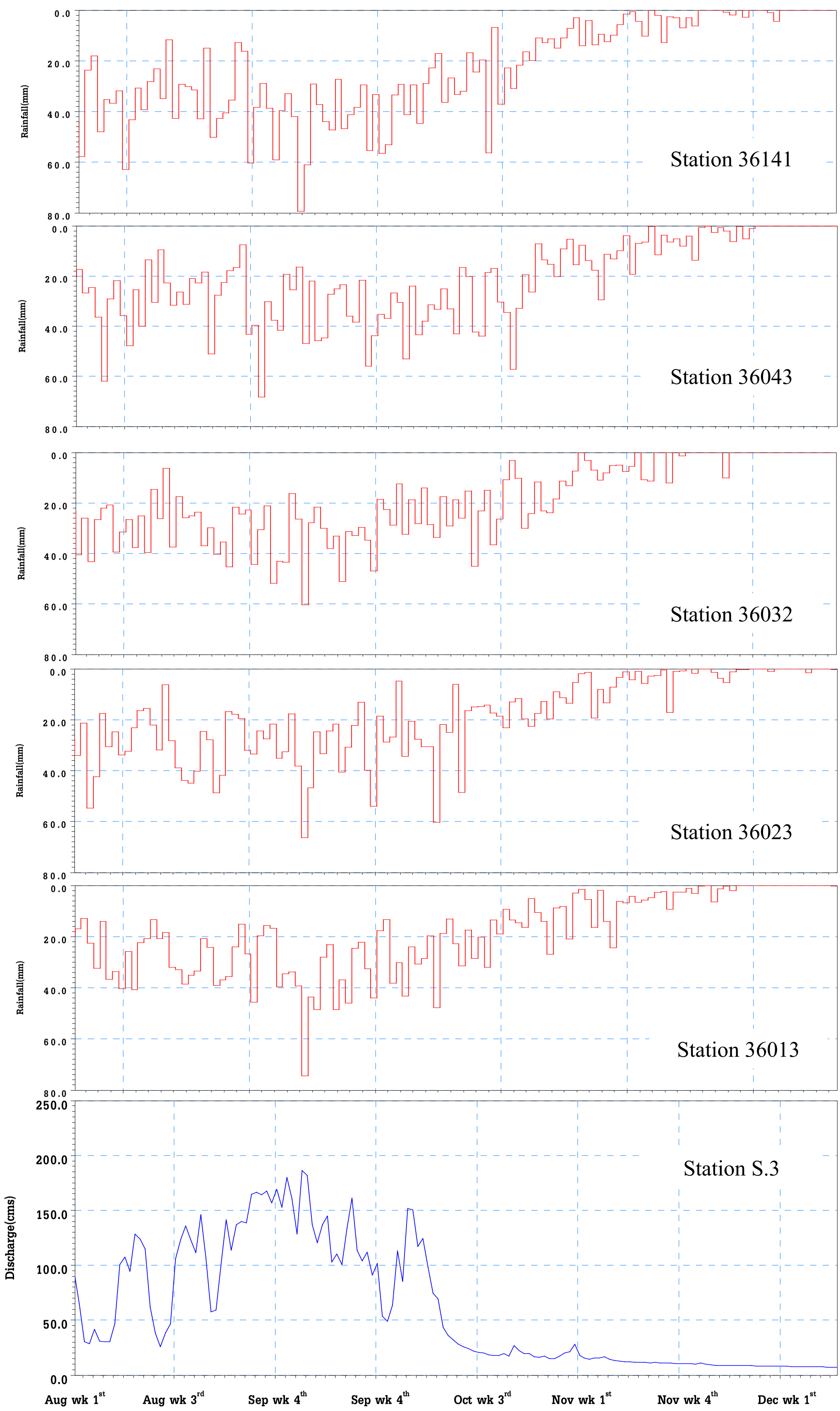


Figure 3.4-10 95th- Percentile Combined Weekly Flood Scenario

Table 3.4-2 shows the maximum 4-day accumulated rain gauge rainfall of each rain gauge station and the peak discharge of the S.3 station at different percentiles. The maximum 4-day accumulated rain gauge rainfall of each rain gauge station at each percentile shown in this table was calculated by; i) calculate time series of rainfall at a considered percentile; ii) calculate the 4-day accumulated rainfall at each day of the time series obtained from (i), for example: 4-day accumulated rainfall of day 4th are the summation of rainfall of day 1st to day 4th; and (iii) the number shown in Table 3.4-2 is the maximum 4-day accumulated rainfall of the time series obtained from (ii).

Table 3.4-2 Maximum 4-day Accumulated Rainfall and Maximum Discharge of The Combined Weekly Flood Scenarios at Different Percentiles.

Station Code	Station Name	Hydrometeorological Condition	Percentiles		
			50	75	95
36013	A. Muang, Phetchaboon	Max 4-day Accumulated rainfall (mm)	11.7	43.1	205.7
36023	A. Lom Sak, Phetchaboon	Max 4-day Accumulated rainfall (mm)	8.9	38.1	175.9
36032	A. Lom Kao, Phetchaboon	Max 4-day Accumulated rainfall (mm)	11.0	49.7	159.5
36043	A. Wichian Buri, Phetchaboon	Max 4-day Accumulated rainfall (mm)	12.9	54.9	181.3
36141	A. Nong Phai, Phetchaboon	Max 4-day Accumulated rainfall (mm)	16.8	77.9	215.3
S.3	A.Lom Sak	Peak discharge (cms)	88.50	141.42	186.03

The different percentiles of combined weekly flood scenarios during August to November as presented in Figures 3.4-8 to 3.4-10 were used as input to the developed flood model for producing weekly flood maps as details are presented in Chapter 5.

3.5 Downstream Boundary Condition

Water level data at the Ban Tha Nam station, A.Wichianburi (S.34) were used as downstream boundary condition of the develop flood modeling. The average 3-hour water level data of this station during September 2005 (normal year) were calculated and used to represent the normal condition of downstream area for all flood scenario studies. Since the S.34 station is located about 10 km downstream of the Muang Phetchaboon district 10 km, using the normal water level at this station as downstream boundary control of the flood modeling will not have any influence on flooding condition at the Muang Phetchaboon district for different flood scenario studies. The average water level of this river gauge station is illustrated in **Figure 3.5-1.**

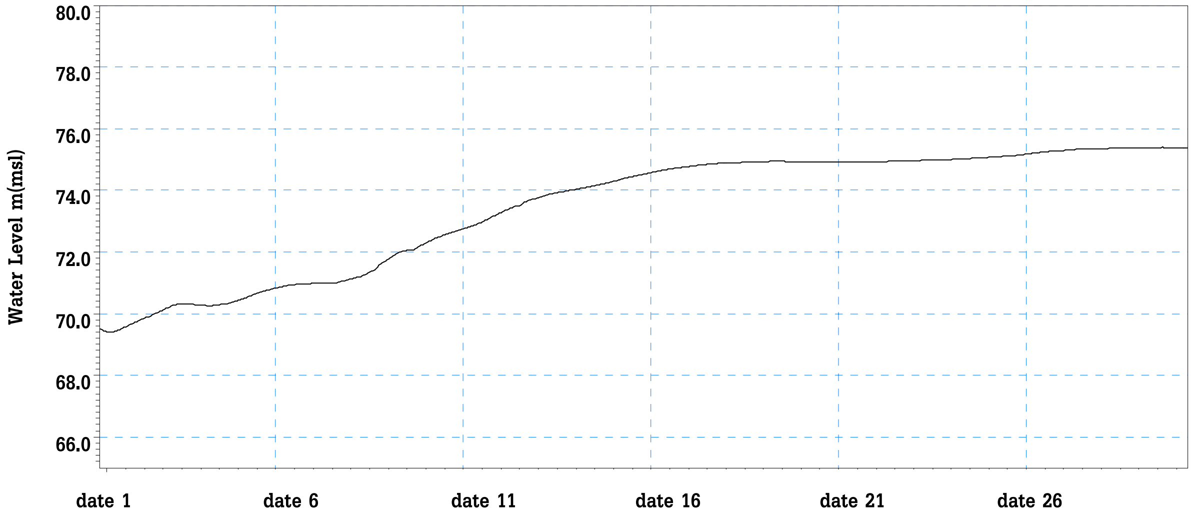


Figure 3.5-1 Average Water Level of S.34 Station during September (Downstream Boundary)

Chapter 4

Flood Modeling Development

Chapter 4

Flood Modeling Development

The Upper Pasak river basin has been modeled using MIKE11 software package. This software package has been developed by the Danish Hydraulic Institute (DHI), Denmark. The objective of developing the flood model is to use the built up flood model to simulate flood characteristics of the study area using different weather scenarios. The developed flood model will be adopted for studying an impact of different probabilities of exceedence of rainfall and flow from the North of the study catchment on flood characteristics of the Muang Phetchaboon district.

4.1 Model Concept and Theory

MIKE11 model provides a versatile and comprehensive approach in river hydrodynamics and environmental river modeling with a wealth of capabilities. The model is an one-dimensional modeling system for river and channels. With the integrated modular structure adopted the user can tailor MIKE11 to match the exact requirements ranging from basic to very advanced solutions. This further enables the user to gradually extend the capabilities as the demand arises. Thereby it provides a very cost-effective solution.

The modules of MIKE11 cover a wide range of applications, ranging from rainfall-runoff module to water quality issues. There are three sub-modules in the MIKE11 software package used in this study which include; i) Rainfall-Runoff module (RR module), ii) Hydrodynamic module (HD module), and iii) Flood Mapping module (MIKE GIS). RR model generates runoff of each sub-catchment according to rainfall input data. Runoff calculated from the RR model is used as an input to the HD model to generate water levels and discharges. The simulated water levels retrieved from HD model are used as input data to MIKE GIS for generating flood map. Details of MIKE11 software package used in this study are presented next.

4.1.1 Rainfall-Runoff Module (RR)

Rainfall and runoff are key issues when modeling river systems. The rainfall-runoff (RR) module contains a number of different models, which can be used to estimate catchment runoff include:

(1) NAM: A lumped, conceptual rainfall-runoff model.
(2) UHM: The Unit Hydrograph Model.
(3) SMAP: A monthly soil moisture accounting model.
(4) Urban: Two different model runoff computation concepts are available: Time/area Method and Non-linear Reservoir (kinematic wave) Method
(5) FEH: Flood Estimation Handbook (flood estimation method in the UK)
(6) DRiFt (Discharge River Forecast): A semi-distributed event model.
(7) Combined: The runoff from a number of catchments will be combined into a single runoff series.

The common and wide-use rainfall-runoff models in Thailand include NAM, UHM and Urban model. The NAM model is applicable for various land use type, while UHM and Urban model is restricted for the urban and industrial area. Due to the study area have varying type of land use such as forest, agricultural and urban area; then the most reasonable method for estimate runoff from rainfall for this study is NAM model. Therefore the below focus only the concept and theory of NAM model.

NAM model simulates the runoff from rural and urban catchments. It is a deterministic, lumped, conceptual rainfall-runoff model, simulating the overland-, inter-flow, and base-flow components as a function of the moisture contents in four storages. Simulated runoff can be transferred directly as lateral inflow to the HD module. The runoff from several (sub) catchments can be calculated simultaneously. NAM makes a continuous account of the moisture content in four interrelated storage. The structure of the model is illustrated in **Figure 4.1-1**. The structure of NAM module is an imitation of the land phase of the hydrological cycle. NAM simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment. These storages are:

- Snow storage
- Surface storage
- Lower or root zone storage
- Groundwater storage

Based on the meteorological input data NAM produces catchment runoff as well as information about other elements of the land phase of the hydrological cycle, such as the temporal variation of the evapotranspiration, soil moisture content, groundwater recharge, and groundwater levels. The Basic modelling components resulting catchment runoff is split conceptually into overland flow, interflow and baseflow components.

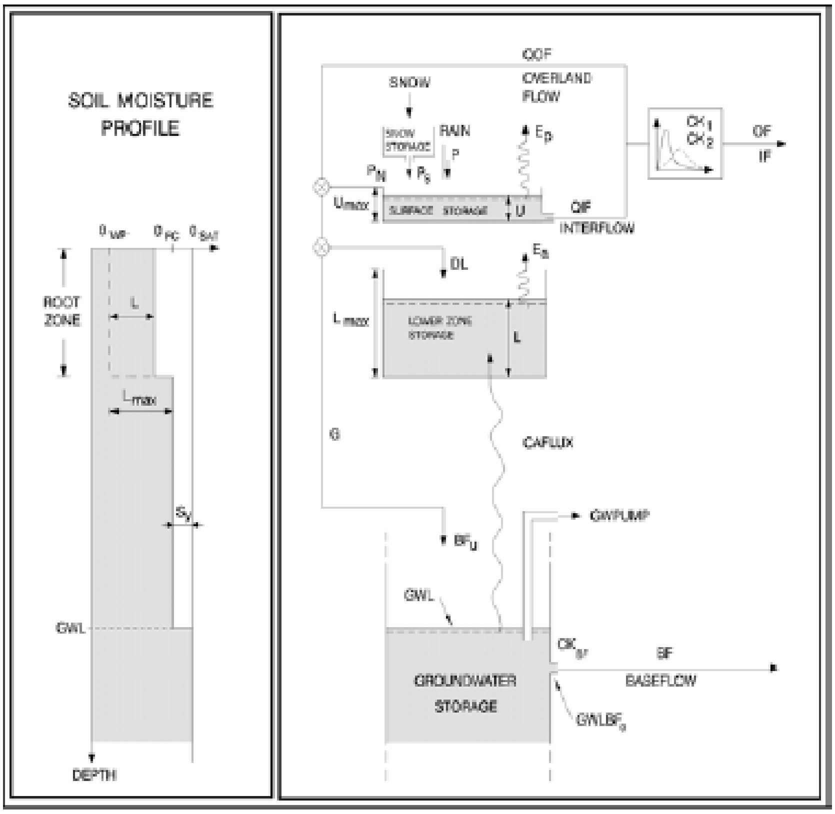


Figure 4.1-1 Structure of NAM module

4.1.2 Hydrodynamic Module (HD)

The hydrodynamic module (HD), which is the core of MIKE11 contains an implicit, finite difference computation of unsteady flows in rivers and estuaries. The formulations can be applied to branched and looped networks and quasi two-dimensional flow simulation on flood plains. The HD editor contains all the hydrodynamic and computational parameters required for the model simulation. The computational parameters relate to the numerical solution of the Saint-Venant equations on which the Mike11 hydrodynamic computation is based. The computational scheme is applicable to vertically homogeneous flow conditions ranging from steep river flows to tidally influenced estuaries. Both subcritical and supercritical flow can be described by means of a numerical scheme, which adapts according to the local flow conditions.

The complete non-linear equations of open channel flow (Saint-Venant) can be solved numerically between all grid points at specified time intervals for given boundary conditions. The solution to the equation is based on the following assumptions:

- The water is incompressible and homogeneous, i.e. negligible variation in density. The bottom-slope is small, thus the cosine of the angle it makes with the horizontal may be taken as 1.
- The wave lengths are large compared to the water depth. This assumes that the flow everywhere can be assumed to flow parallel to the bottom, i.e. vertical accelerations can be neglected and a hydrostatic pressure variation in the vertical direction can be assumed.
- The flow is sub-critical (Super-critical flow is modeled in MIKE11, however more restrictive conditions are applied).

The derivation of the equations of continuity and momentum (used by MIKE11) are given in the MIKE11 HD Reference Manual, Appendix A. Scientific Background. The equations are:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

Momentum :

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2\ AR} = 0$$

Where Q = discharge, (m^3/s) — A = flow area, (m^2)

q = lateral inflow, (m^3/s) — h = stage above datum, (m)

C = Chezy resistance coefficient — R = hydraulic or resistance radius, (m)

The first equation is the continuity equation and the second equation is the momentum equation. The four terms in the momentum equation are local acceleration, convective acceleration, pressure and friction respectively.

4.1.3 Flood Mapping Module (MIKE GIS)

MIKE11 GIS is an advanced tool for the spatial presentation and analysis of one-dimensional (1D) flood model results for use in the flood management planning process. The MIKE11 GIS system integrates the MIKE11 river and floodplain modeling technologies with the spatial analysis capabilities of the ArcView Geographic Information System (GIS). MIKE11 GIS is ideally suited as a decision support tool for river and floodplain management through its enhanced routines that provide precise and efficient means of mapping and quantifying flooding impacts on communities, infrastructure, agriculture, fisheries and on the environment.

The analysis and outputs developed using MIKE11 GIS are important inputs for a range of floodplain management undertakings including flood risk assessment, flood control, flood forecasting, floodplain preservation and restoration, drainage structure projects and project design specifications. The MIKE11 GIS decision support system is designed to transform technical data that are often difficult to interpret into meaningful easily understood formats.

MIKE11 GIS is based on a bi-directional data exchange between MIKE11 and ArcView. It can extracts river networks, cross-section profiles and area - elevation curves from an ArcView GIS developed Digital Elevation Model (DEM) and exports these data into a MIKE11 cross-section database.

MIKE11 GIS imports simulated water levels and discharges from MIKE11 result files. Based on the discrete information from MIKE11, MIKE11 GIS constructs a grid based water surface and compares this data with the developed DEM to produce flood depth and duration mapped surfaces. The MIKE11 results can also be displayed in MIKE11 GIS as time series graphs and long-section profiles using the MIKE11 GIS Graphical User Interface. At its most basic level, MIKE11 GIS requires information from a MIKE11 model (river network), MIKE11 flood simulations and a DEM.

MIKE11 GIS main outputs are inundation maps presented as depth, duration and comparison maps. A flood depth map illustrates the flood depth distribution, while flood duration maps combine critical and actual inundation periods, i.e. parameters that can be used for flood damage assessment, flood risk analysis, planning of urban developments, etc.

Flood comparison maps are maps of the differences between two flood maps. For example, a flood comparison map could illustrate the difference between a 100-year flood as it happens under current state conditions, and the same flood occurring after implementation of a mitigation measure or, on the contrary, after a structure failure. Statistical information on flood or comparison maps can also be output providing a tabular summary of the map. **Figure 4.1-2** summarizes inputs and outputs of MIKE11 GIS.

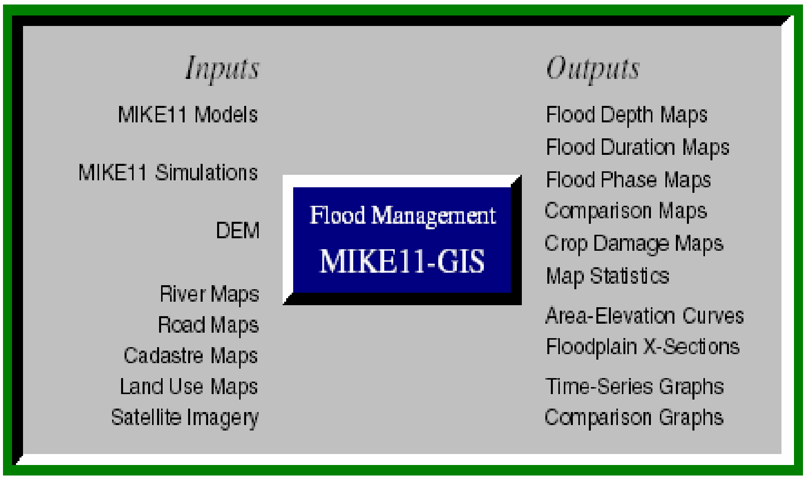


Figure 4.1-2 Input and Output of MIKE11 GIS Module

Details of MIKE11 model set up for the study catchment are presented next.

4.1.4 MIKE11 Literature References

Some pertinent literature references of MIKE11 software package are given below:

- Real-time Flood Forecasting for Gold Coast, Australia (2007) Provision of MIKE 11 forecasting model, development of system interfaces and configuration of MIKE FLOOD WATCH system and web page
- Real-time Optimization of the Orange-Fish Catchment, South Africa (2007) Application of AUTOCAL, MIKE 11 and MIKE FLOOD WATCH for real-time optimisation of dams and diversion weirs
- Chi-Mun Telemetry Project for DWR, Thailand (2006-2007) Provision of real-time flood forecasting system based on MIKE 11 and MIKE FLOOD WATCH. System installation and testing on site and training of staff
- Leie-Bovenschelde Real-time Flood Forecasting System, Belgium (2005-2007) Upgrading of MIKE RR/HD model for forecasting purposes and provision of FLOOD WATCH system

- Hydrological Forecasting in Sydney, Australia (2005-2007) Development of run-time adapters for third party hydrological models to run with MIKE FLOOD WATCH. Setup of on-line system and interface to telemetry. Setup of alarm procedures
- Ping River Basin Flood Forecasting Project, Thailand (2005) Development of a real-time FLOOD WATCH flood forecasting system for Ping River Basin, Thailand
- MIKE FLOOD WATCH SLOVENIA, Slovenia (2005) Development of a froecasting system for Mur River in Slovenia. The Forecasting system is a part of the transboundary forecasting system for Mur River. Automatic Forecasting is performed at the international forecasting centre in Graz, Austria
- Rio Negro Lower Catchment Flood Forecasting (2005) Set-up and Configure the MIKE FLOOD WATCH for the lower basin of the Negro River. This river causes large floodings in the capital city of the Province of El Chaco, Resistencia and neighbouring areas. For this purpose it has been implemented flood protection embankments, several pumpin stations and a control structure (pump and gates) to discharge the water into the Parana River. The end user and who will operate the system is APA - Administracion Provincial del Agua de la Provincia del Chaco
- Ubol Ratana Dam - Flood Watch - (2004-2006) Development of a real time forecasting system for the inflow to Ubol Ratane Dam in Thailand
- Dender, Demer and Grensmas on-line Flood Forecasting Models, Belgium (2004-2005) MIKE FLOOD WATCH, data assimilation, updating, MIKE 11 flood forecasting, training
- Development of a flood forecasting system on Mur, Austria (2004-2005) The primary objective of the project was the establishment of a regional flood forecasting and warning system on Mur river basin in the Southern part of Austria, Slovenia, Croatia and Hungary. The flood forecasting system includes: Real-time monitoring and transmission of hydrologic and hydrometric data. Modelling of mur river and catchments. Preparation of accurate and timely warnings for dissemination
- Chantabury Phase II, Thailand (2004-2005) MIKE 11 DA, FLOOD WATCH, Real-Time Flood Forecasting, Telemetry, GIS
- Bangkok Flood Forecasting, Thailand (2004-2005) Setup and customization of the MIKE 11 hydrological and hydraulic models. Employment of MIKE 11 the

data assimilation module for forecasting purposes. Setup and customisation of MIKE FLOOD WATCH

- Flood Management and Forecasting in Poland, Poland (1998-2000) The 2½ year project has focused on strengthening the capabilities of the polish authorities in the use of MIKE 11 for flood management. The man objectives was: Improved flood modelling cababilities Improved operational flood forecasting capabilities Improved flood control and planning capabilities
- Flood Forecasting for the Middle Yangtze River, China (1995-1998) DHI's well-proven MIKE 11 FF flood forecasting system has been coupled to the advanced meteorological model HIRLAM and successfully used for flood forecasting for the large and heavily populated Middle Yangtze River Basin

4.2 Input Data

Data used for develop flood estimation model of the Upper Pasak river basin have been collected from several government agencies including RID, TMD and the Royal Thai Survey Department (RTSD) and others related agencies. Quality and reliability of the collected data have been checked before using these data in the model. Details of the collected data used in the model are below.

4.2.1 Topographic Map

Twenty-two 1:50,000 topographic maps of RTSD that contain information of contour lines, river network, main roads and railways covering the Upper Pasak river basin have been used for dividing sub-catchments of the study catchment. These sub-catchments will be used for the rainfall runoff model. The twenty-two 1:50,000 topographic maps include 5243II-III, 5242I-IV, 5342IV, 5241I-IV, 5141I-II, 5240I-IV, 5140I-II, 5239I, 5239IV and 5139I. Addition 1:10,000 maps covering the flood risk area of 953 sq.km obtained from "*The installing of a hydrometeorology telemetering system: phase III project*" of TMD has also been used in this study. These additional maps comprise information on sources of water, 1-meter contour lines, slope of the area, roads, habitations, soil types, land use and forestry.

The topographic information that has been used for generate DEM of the Muang Phetchaboon district by GIS software is illustrated in **Figure 4.2-1**. The water levels calculated from MIKE11 and the generated DEM have been input to MIKE11 GIS to generate flood maps. Details of these are described later.

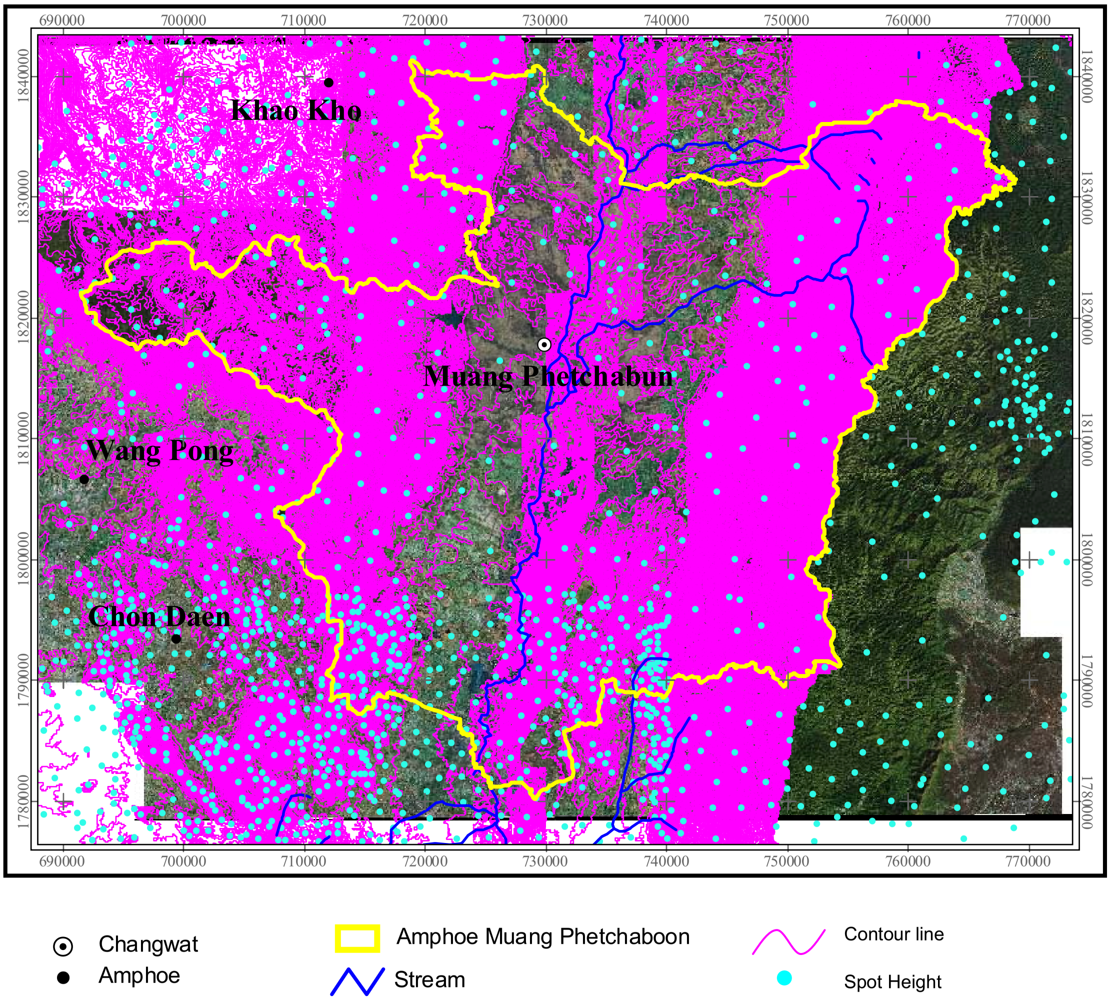


Figure 4.2-1 Topographic Information of Amphoe Muang Phetchaboon

4.2.2 Base Map

Base maps used for developing flood model consist of:

- Catchment and sub-catchment boundaries
- Location of the Phetchaboon city, districts and sub-districts
- Administration boundary at province levels
- Administration boundary at district, sub-district, and tumbol levels
- Location of villages
- Location of meteorological, rain gauge and river gauge stations

4.2.3 Daily Evaporation

Daily evaporation data recorded from the 3 meteorological stations located within the Upper Pasak river basin have been collected for use as an input to the rainfall runoff model. These 3 stations namely Phetchaboon, Lom Sak and Wichianburi stations are owned and operated by TMD. Detail of the stations and mean evaporation data are presented in **Table 4.2-1**. The location of these selected evaporation stations are shown in Figure 2.2-2.

Table 4.2-1 Selected Evaporation Stations of the Upper Pasak River Basin

No	Code	Station Name	Location		Record Available	Mean Annual Evaporation (mm)
			East	North		
1	379201	Phetchaboon	101°- 09' - 00"	16°- 26' - 00"	1951 – 2006	1,564.0
2	379401	Lom Sak	101°- 14' - 48"	16°- 45' - 25"	1970 – 2006	1,638.7
3	379402	Wichianburi	101°- 06' - 30"	15°- 39' - 25"	1970 - 2006	1,545.6

4.2.4 Daily Rainfall

Daily rainfall data recorded from 10 rain gauge stations located within the Upper Pasak river basin have been used for the rainfall RR model. These rain gauge stations have been selected to calculate mean areal rainfall of the study catchment because (i) they record rainfall continuously and cover the flooding periods, (ii) their locations are scattered throughout the study catchment. Locations and details of these stations are presented in Figure 2.2-2 and **Table 4.2-2**, respectively.

Table 4.2-2 Selected Raingauge Stations of the Upper Pasak River Basin

No	Code	Station Name	Province	Location		Record Period	Mean Annual Rainfall (mm)
				East	North		
1	19052	A. Chai Badan	Lopburi	101° 08' 11"	15° 12' 12"	1952 - 2006	1,215.8
2	19113	A. Bua Chum	Lopburi	101° 11' 00"	15° 15' 50"	1969 - 2006	1,114.6
3	36013	A. Muang	Phetchaboon	101° 09' 35"	16° 25' 00"	1952 - 2006	1,120.5
4	36023	A. Lom Sak	Phetchaboon	101° 14' 45"	16° 46' 42"	1952 - 2006	1,091.6
5	36032	A. Lom Kao	Phetchaboon	101° 13' 58"	16° 53' 01"	1952 - 2006	1,061.2
6	36043	A. Wichian Buri	Phetchaboon	101° 06' 37"	15° 39' 20"	1952 - 2006	1,186.6
7	36082	Khok Sa-At School, A. Si Thep	Phetchaboon	101° 04' 00"	15° 28' 20"	1965 - 2006	1,050.4
8	36092	A. Nong Phai	Phetchaboon	101° 03' 53"	15° 59' 13"	1965 - 2006	1,234.2
9	36122	Nam Ron Sub-District, A. Wichian Buri	Phetchaboon	101° 16' 00"	15° 41' 00"	1970 - 2006	1,192.6
10	36141	Ban Wang Thadi (S.12), A. Nong Phai	Phetchaboon	101° 14' 28"	15° 59' 50"	1978 - 2006	1,377.8

4.2.5 Water Level and Discharge

Three-hour and daily water levels and discharges of 8 river gauge stations located in the Upper Pasak river basin have been used for developing of the RR and HD models. All of these stations are owned and operated by RID. Data quality and reliability checking have been performed, and only the reliability data have been used in developing the flood model. Details and locations of the river gauge stations used in this study are presented in **Table 4.2-3** and Figure 2.2-2, respectively.

Table 4.2-3 Selected river gauge Stations of the Upper Pasak River Basin

No.	Code	Stream	At or Near	Amphoe	Changwat	Location East / North	Drainage Area (Sq.Km)	Data Record: Water Level Data	Data Record: Discharge Data
1	S.3	Pasak	Ban Tan Dieo	Lomsak	Phetchabun	101°- 14' - 57" 16°- 46' - 55"	1,047	1950 - 2006	1996 - 2006
2	S.4B	Pasak	Phetchabun	Mueang	Phetchabun	101°- 10' - 13" 16°- 25' - 12"	3,566	1966 - 1991 1992 - 2006	1966 - 1975 1978 - 1983 1995 - 2006
3	S.10	Huai Nam Phung	Ban Hin Hao	Lom Kao	Phetchabun	101°- 13' - 10" 16°- 56' - 50"	268	1965 - 2006	1965 - 1973 1979 - 1990
4	S.17	Huai Nam Chun	Ban Fai Wang Bon	Lom Sak	Phetchabun	101°- 08' - 44" 16°- 45' - 43"	67	1979 - 1995 1996 - 2006	1979 - 1990 1996 - 1997
5	S.28	Pasak	Ban Kaeng Sua Ten	Phatthana--Nikhom	Lop Buri	101°- 04' - 08" 14°- 50' - 21"	8,778	1986 - 1996 1997 - 2006	1996 - 2006
6	S.31	Lam Phaya Klang	Ban Pang Hu Sua	Chai Badan	Lop Buri	101°- 24' - 11" 15°- 06' - 05"	381	1986 - 1998	1987 - 2006
7	S.33	Pasak	Ban Tha Hai Yong	Lom Kao	Phetchabun	101°- 21' - 22" 17°- 00' - 11"	516	1998 - 2006	1998 - 2006
8	S.34	Pasak	Ban Tha Nam	Wichian--Buri	Phetchabun	101°- 06' - 17" 15°- 39' - 13"	6,776	1997 - 2006	1997 - 2006

4.2.6 Cross Section

Due to MIKE11 HD model is a physical base model, river cross section is an important and necessary for model developing. Sixty-six cross sections of the Pasak river and Huai Num Phung obtained from "*The installing of a hydrometeorology telemetering system: phase III project*" of TMD have been used for developing of the MIKE11 HD model. **Figure 4.2-2** illustrates locations of the 66 cross sections along the Pasak river and Huai Num Phung. Details of cross section used for developing of the HD model are presented in **Table 4.2-4**. It is to be noted that surveying of these cross sections was performed every 5-10 meters along Pasak river and Huai Num Phung or every point that has significantly changed. The surveying started from the middle of the river to 100 meters away from the right and the left banks.

Table 4.2-4 Cross Sections Used for Developing of MIKE11 HD Model

no	Stream	River Cross section	
		Amount	Length (km.)
1	Pasak River	51	440
2	Huai Num Pung	15	40

4.2.7 Control Structure

There are 31 control structures that affect on flow characteristics of the Pasak river. Types and locations of these control structures have been input to the HD model. Locations of these control structures are illustrated in **Figure 4.2-2**.

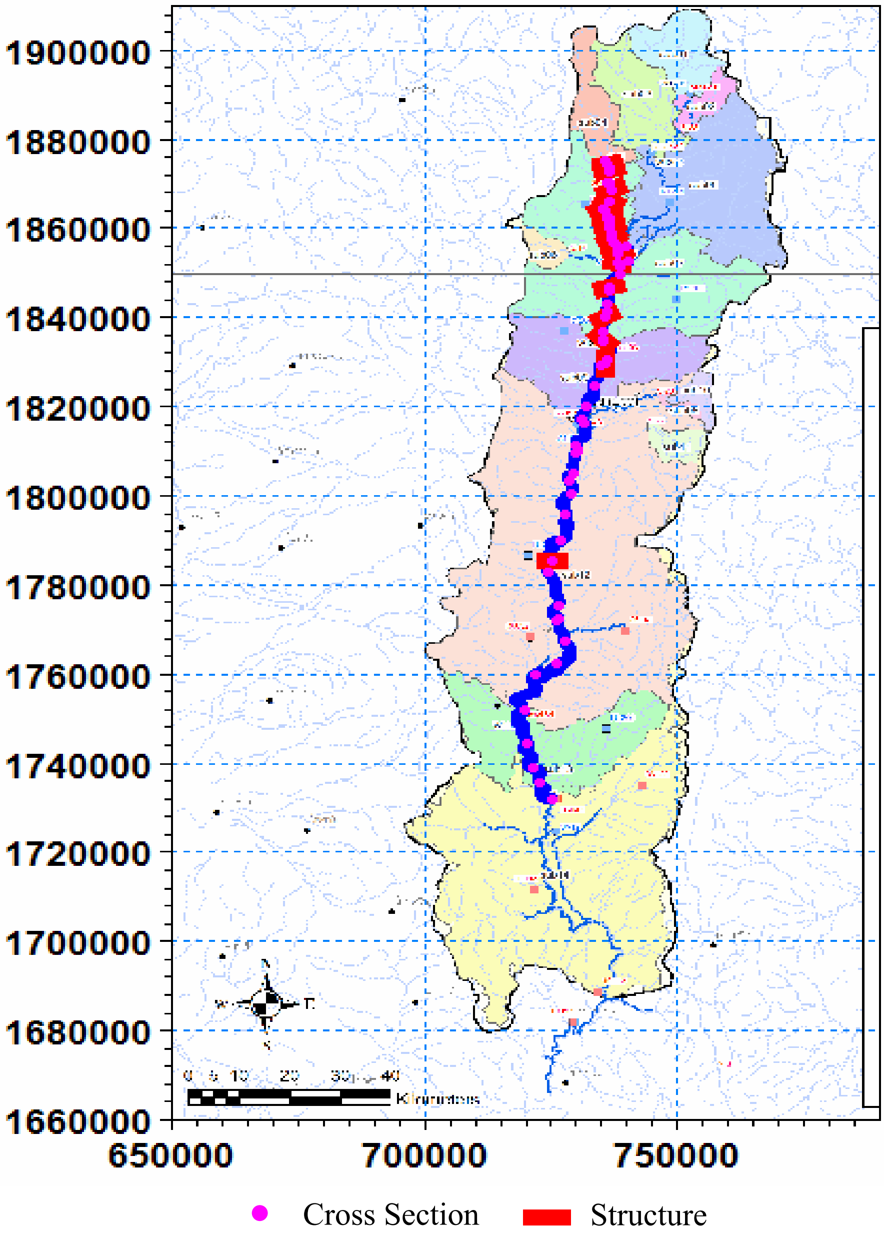


Figure 4.2-2 Location of Cross Sections and Control Structures of the Upper Pasak River Basin

4.3 Study Period

Recent data should be used for calibration of flood model because the catchment characteristics and river conditions in the past and the present times might be different. Flood model developed based on the data in the previous times might not be able to represent flood characteristics of the present or future times. Therefore, in this study we consider to use the water level data at the Muang Phetchaboon station (S.4B) back to 7 years (2000 – 2006) as indicator for selection of the study period. **Figure 4.3-1** shows plot of water depths at S. 4B station during 2000 - 2006. From hydrological study presented in section 3.2, it has been found that the critical water depth that causes overflow from the Pasak river is about 9.00 m. Based on this critical water depth, Figure 4.3-1 is evident that flood event occurred in year 2000 only. However, the data gained from the field investigation indicate that floods occurred in the study area in years 2000, 2001, 2002, 2003, 2006 and 2007. Especially, the severe flood occurred in year 2002 which corresponded to the satellite imagery during September 2002. By considering the momentary peak of gauge height as presented in **Table A-17** and the plot of water depth shown in Figure 4.3-1, it is reasonable that flood events occurred in 2000, 2001, 2003 and 2006. The water depths of 2002 shown in Figure 4.3-1 does not conform to the field inspection and the satellite imagery. Therefore, we assume that the historical water depths at the S.4B station records during the 2002 flooding period are not reliable. Hence, the model parameters will not be adjusted based on these data. Note that the water depths of year 2005 are below to the critical water depth and the water depths of year 2004 are significantly below the critical water depth. Thus, in this study we consider that years 2005 and 2004 can be represent as normal and dry year, respectively.

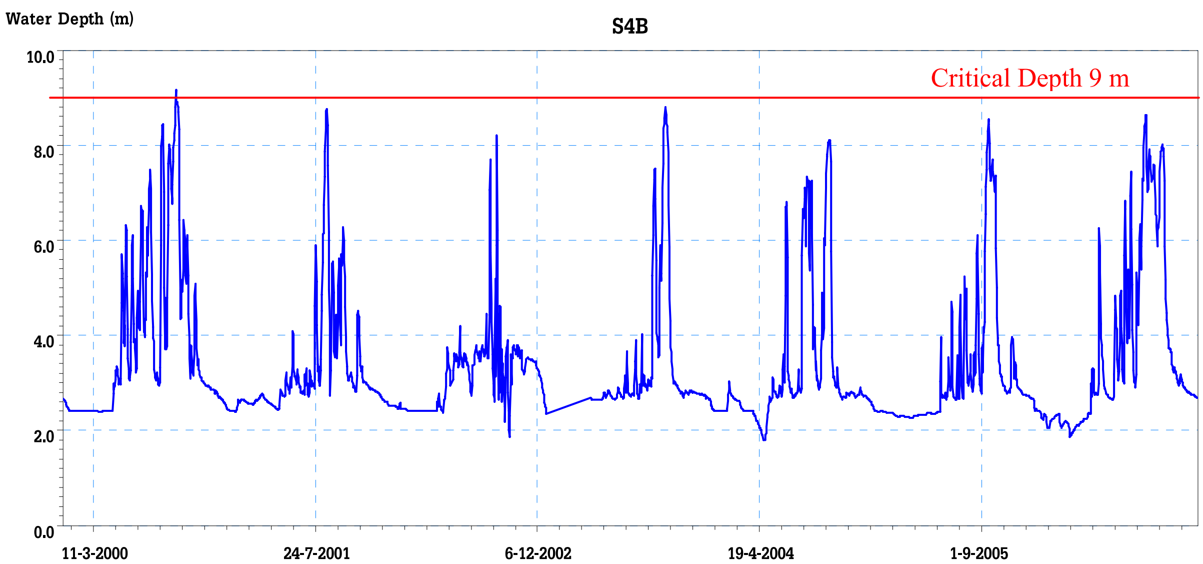


Figure 4.3-1 Observed Water Depth at the Muang Phetchaboon District Station (S.4B)

A good rainfall runoff model should be able to give an accurate simulated runoff for both wet and dry years. For this reason, it is necessary to calibrate and verify the developed RR and HD models using the data covering both wet and dry years to derive model parameters that are able to be represent hydrological and flow characteristics of the catchment for all cases. From the above analysis, we consider to use the data during 2000 – 2006 for model developing. These data are cover wet and dry years of the study area. However, discharge data are required for model calibration and verification, but only the discharge of years 2000 to 2005 are available, therefore the RR and HD models developed in this study have been built up based on these data only. The 2000-2001 data were used for model calibration and the recent data in years 2003-2005 were used for model verification.

The MIKE11 GIS model will be used to transform the results obtained from the RR and HD models into meaningful easily understood flood map. Since there are only three satellite imageries available in this study which are the images of 2002, 2006 and 2007 flood events. The satellite imagery of 2002 will be used for calibration of the generated flood map while the 2006 and 2007 satellite images will be used for verification. Once satisfy, the developed flood model will be adopted to simulate flood maps for different flood scenarios.

4.4 Rainfall-Runoff Model Development

Steps to develop the Rainfall-Runoff model (NAM module) to imitate rainfall-runoff process of the catchment consist of; (i) Sub-catchment dividing, (ii) model calibration, (iii) model verification, and (iv) model application. Details of these are presented below:

4.4.1 Sub-catchment Dividing

In this study, we selected 3 river gauge stations located within the Upper Pasak river basin namely S.3, S.4B and S.34 for use in developing the RR model. The recorded discharge data of these stations are long enough for use in model calibration and verification. The catchment has been divided into 3 sub-catchments that correspond to the locations of the 3 river gauge stations as illustrated in **Figures 4.4-1 to 4.4-3**. It is to be noted that the sub-catchment dividing has been performed by considering of the 1:50,000 topographic maps, river network, roads and railways.

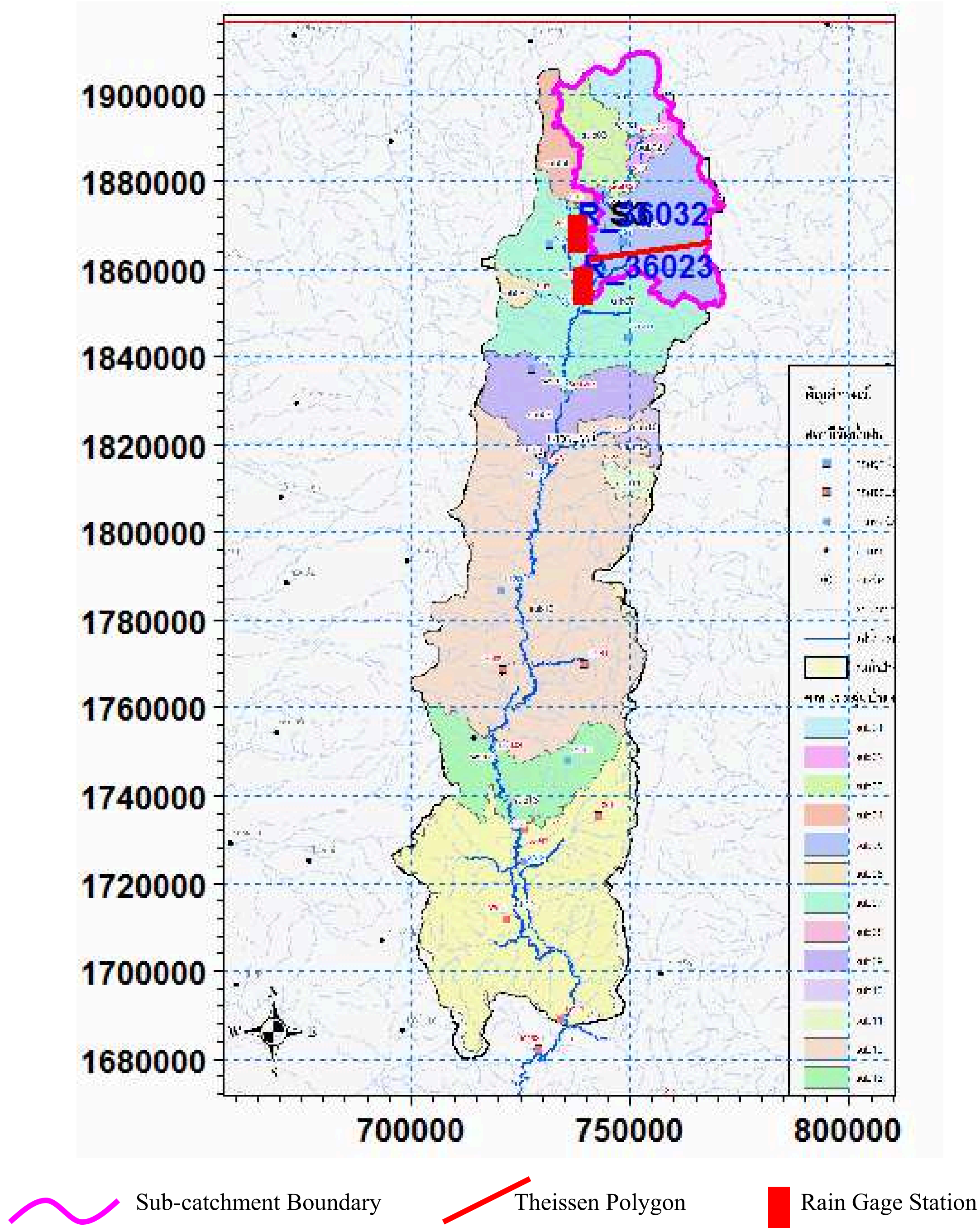


Figure 4.4-1 Sub-catchment “S.3” and Thiessen Polygon for the NAM Model Development

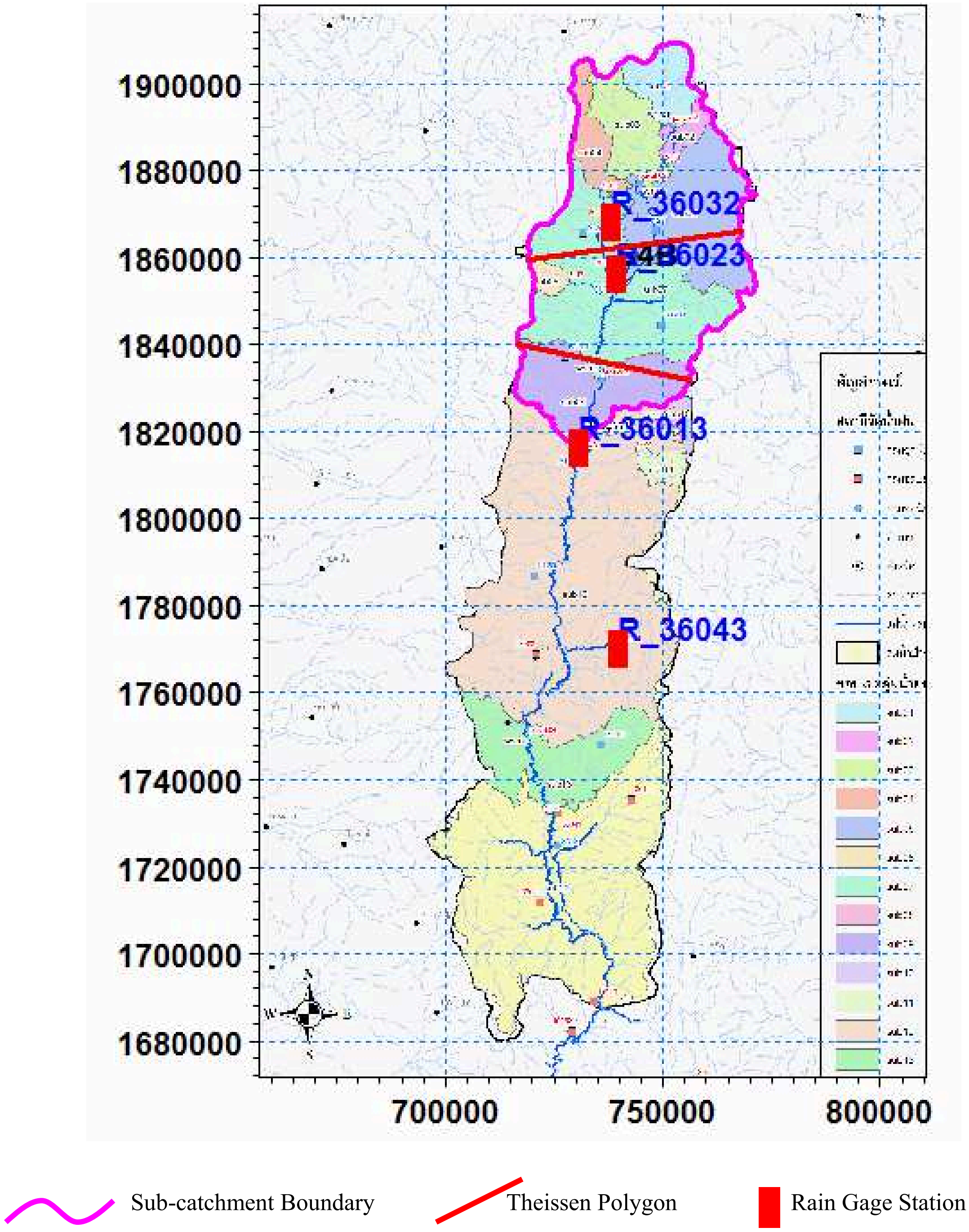


Figure 4.4-2 Sub-catchment “S.4B” and Thiessen Polygon for the NAM Model Development

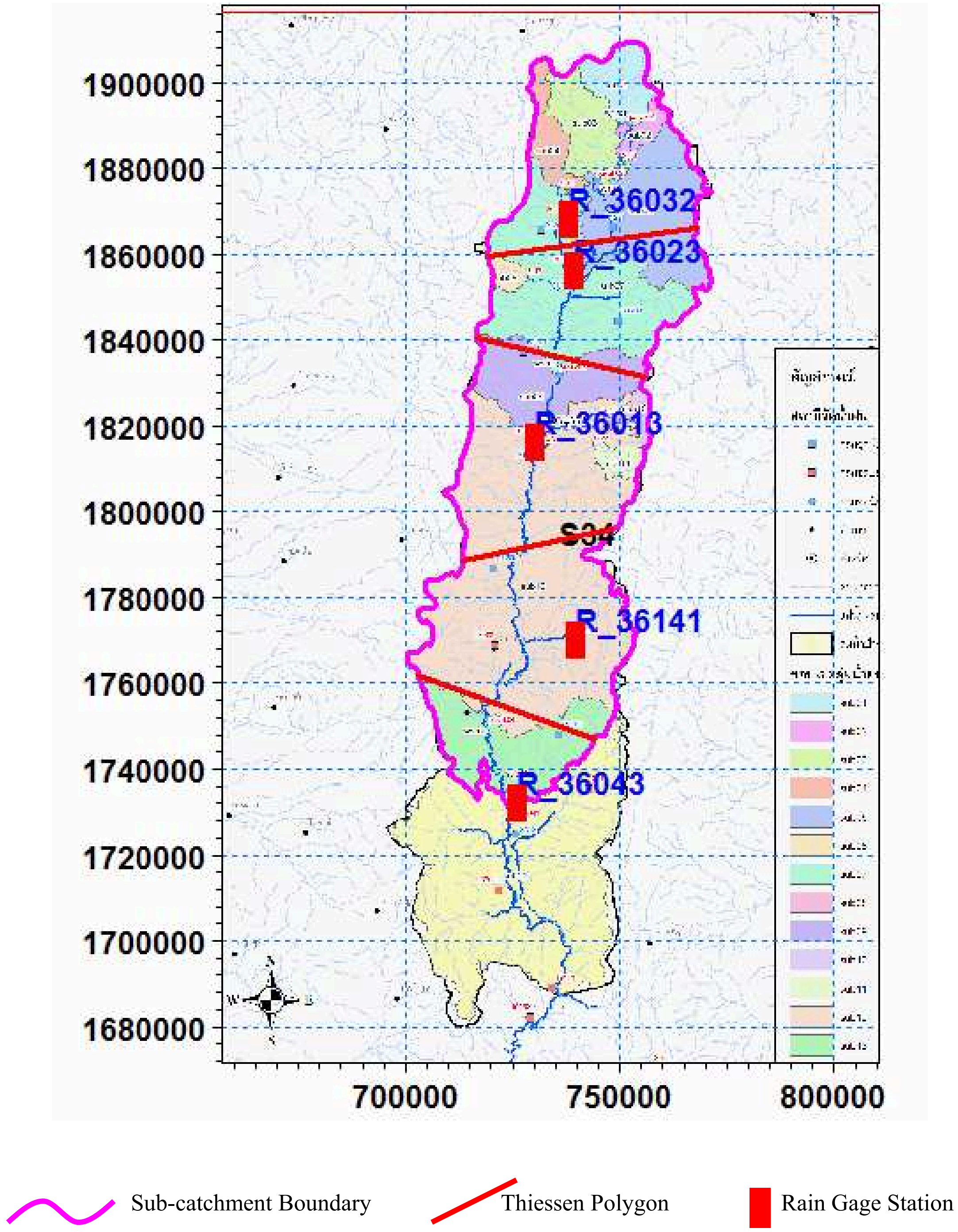


Figure 4.4-3 Sub-catchment "S.34" and Thiessen Polygon for the NAM Model Development

4.4.2 NAM Module Calibration

Calibration of NAM model was performed by comparing the calculated discharges obtained from the developed RR model with the observed discharges of the 3 river gauge stations. Daily rainfall data of 5 rain gauge stations recorded from 2000 – 2002 were used for model calibration. Mean areal rainfall of the catchment is required to be input into the model. Mean areal rainfall of the Upper Pasak river basin was analyzed from these rain gauge stations using Thiessen polygons method. Thiessen Polygon of each sub-catchment are illustrated in Figures 4.4-1 to Figure 4.4-3, respectively. The Thiessen polygon weighting factors based on these 5 rain gauge stations are presented in **Table 4.4-1**. Daily evaporation data of the Phetchaboon (379201), Lom Sak (379401) and Wichianburi (379402) meteorological stations recorded during the calibration period were used. Model parameters of the rainfall runoff model were adjusted to minimize differences between the calculated and observed discharges.

After the daily rainfall and daily evaporation were input into the model, runoff of each sub-catchment was calculated by MIKE11 NAM model using default parameter values. Thereafter, the parameters of each sub-catchment were adjusted by starting from the sub-catchment located at the upper stream then moved downward to the sub-catchment located at the downstream, respectively. The parameters of each sub-catchment were adjusted until the calculated discharges correspond to the observed discharges in terms of peak, time to peak and accumulated runoff. Parameters adjustment can be summarized below:

- L_{max}, U_{max} are adjusted when the estimated and observed accumulated runoff of are different.
- CQOF, TOF, CK1 and CK2 are adjusted when the estimated runoff during flooding period is different from the observed.
- CQOF, TG and CFBF are adjusted when the estimated runoff during dry period is different from the observed.

The calculated and observed discharges of each sub-catchment were compared as shown in **Figures 4.4-4 to 4.4-6**. Model parameters derived from the calibration are established in **Table 4.4-2**.

Table 4.4-1 Thiessen Polygon Weighting Factor of each Sub-Catchment

Sub-catchment	Drainage Area (sq.km.)	Rain Gauge Station				
		36023	36032	36013	36043	36141
S.3	1047	0.195	0.805	-	-	-
S.4B	3566	0.382	0.474	0.144	-	-
S.34	6478	0.183	0.227	0.257	0.0895	0.243

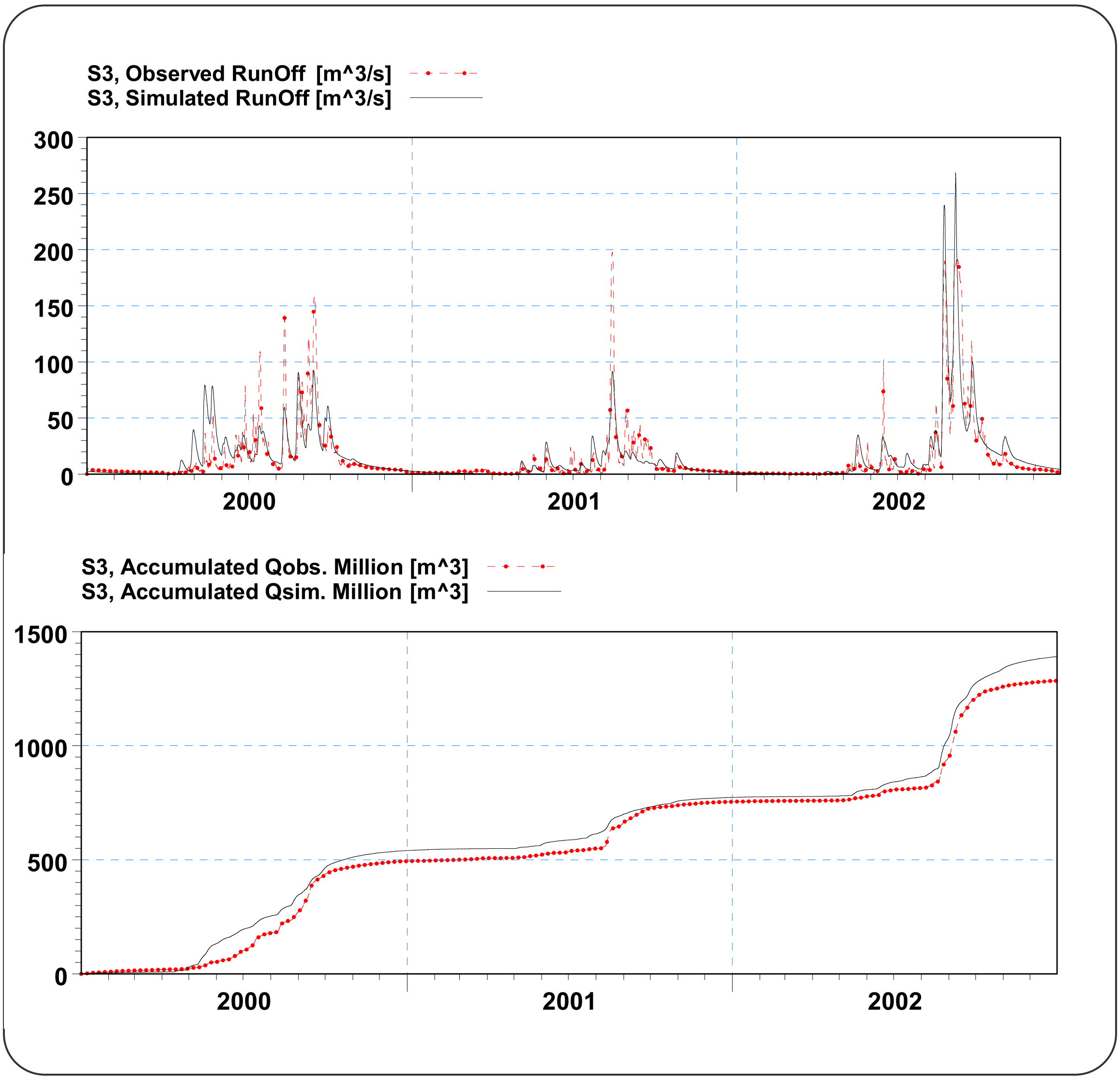


Figure 4.4-4 Comparison between Estimated and Observed Discharges of Ban-TalDeaw (S.3) Sub-catchment (MIKE11 NAM: Calibration)

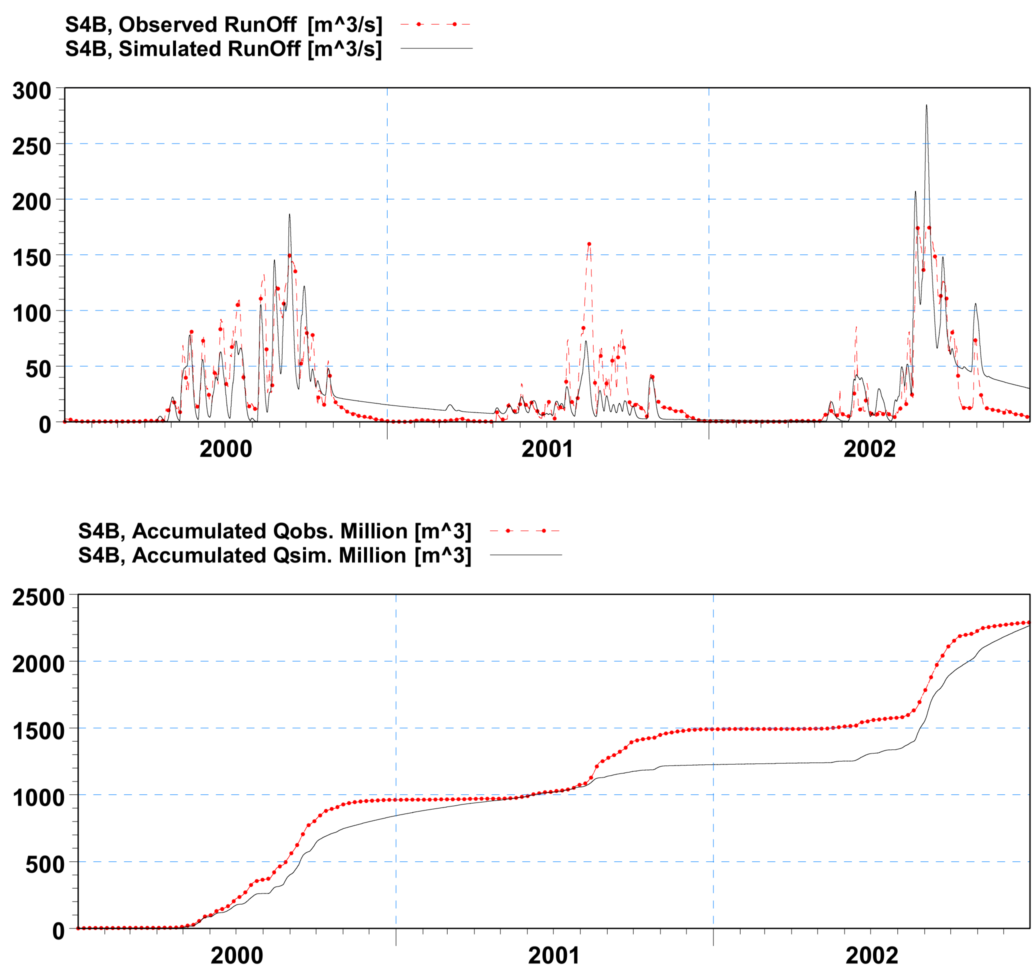


Figure 4.4-5 Comparison between Estimated and Observed Discharges of the Muang Phetchaboon District (S.4B) Sub-catchment (MIKE11 NAM: Calibration)

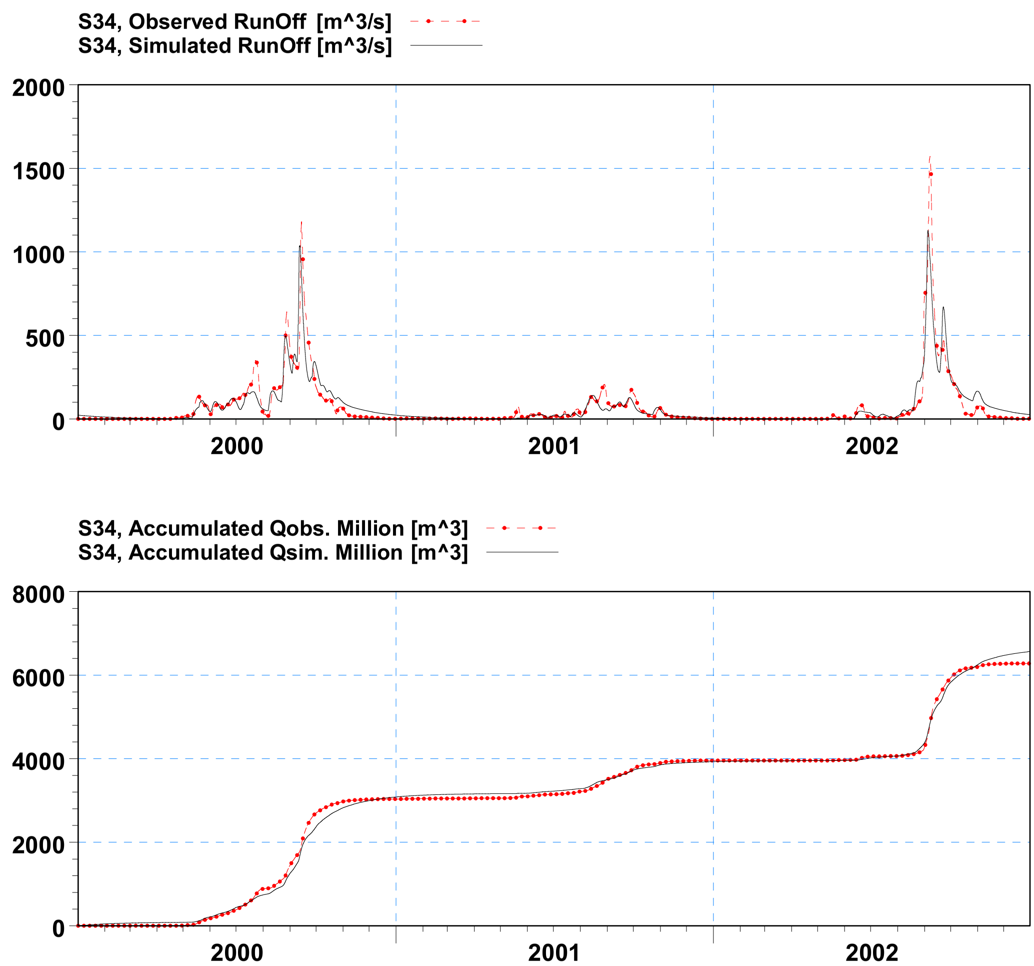


Figure 4.4-6 Comparison between Estimated and Observed Discharges of Ban ThaNam (S.34) Sub-catchment (MIKE11 NAM: Calibration)

Table 4.4-2 Calibrated Parameter of MIKE11 NAM Model of the Upper Pasak River Basin

Sub-Catchment	Drainage Area (sq.km)	MIKE11 NAM Model Parameters								
		Surface-Rootzone							Groundwater	
		U_{max}	L_{max}	CQOF	CKIF	CK1,2	TOF	TIF	TG	CKBF
S3	1047	10	108	0.57	238	47	0.1	0.1	0.05	1040
S4B	3566	18	250	0.14	220	46	0.14	0.17	0.87	3680
S34	6478	18	242	0.65	218	48	0.8	0.28	0.38	1060

The calibration results shown in Figures 4.4-3 to 4.4-5 are evident that discharges and accumulated discharges estimated from the developed model correspond to the measured data for all sub-catchments. Errors estimation between the simulated and measured observed was also performed and the results are presented in **Table 4.4-3**.

Table 4.4-3 Errors Estimation of the MIKE11 NAM Model Calibration

Sub-catchment	Drainage Area (sq.km.)	Statistical Comparison		
		Peak Error (%)	Volume Error (%)	Correlation Coefficient, R^2
S3	1,047	35.68	8.39	0.722
S4B	3,566	62.73	-0.99	0.727
S34	6,478	-29.01	4.66	0.825
Average		42.47	4.02	0.758

From Table 4.4-3, a percentage of the average peak error is quite large which is about 42%. This is possible due to only few rain gauge stations located in the study basin. These few rain gauge stations might not be able to represent mean areal rainfall of the catchment correctly, especially when heavy rainfall occurs. It is to be noted that the recorded streamflow data of S.4B station (Muang Phetchaboon district) during the 2002 flooding period are lower than the actual data as mentioned in section 4.3. The simulated flood peak at this station during the 2002 flooding period is higher than the observed data. The simulated peak discharge is about 260 cms while the observed peak discharge is only 170 cms. The simulated peak discharge is much higher than the capacity of S.4B station which is about 175 cms. Based on the simulated peak discharge of this station, flood will occur at the Muang Phetchaboon district which corresponds to the satellite imagery of the 2002 flooding period. Moreover, the percentage error of the accumulated discharge is only about 4% and the R^2 values are between 0.722 – 0.825, with the average value of 0.758. These two errors measurement indexes are in an acceptable range. Based on the above reasons, we consider that the developed model is appropriate to be representing rainfall-runoff process of the study catchment.

4.4.3 NAM Module Verification

To test an appropriate of the parameters obtained from the calibration whether they can be applied to use for simulating runoff at different time periods, another data set that had not been used in the calibration were used for verification. The recent data during 2003-2005 were selected to use for verification purpose. Using the most recent available data for validation can confirm the ability of the model that it is able to represent rainfall-runoff process of the study catchment at the present and the future times. The develop MIKE11 NAM model was used to simulate runoff of the 2003 to 2005 using the same parameters that were derived from the calibration. The verification results shown in **Figures 4.4-7 to 4.4-9** are evident that on average the discharges and accumulated discharges estimated from the developed model correspond to the measured data for all sub-catchments. Errors estimation between the simulated and measured discharges was performed and the results were presented in **Table 4.4-4**.

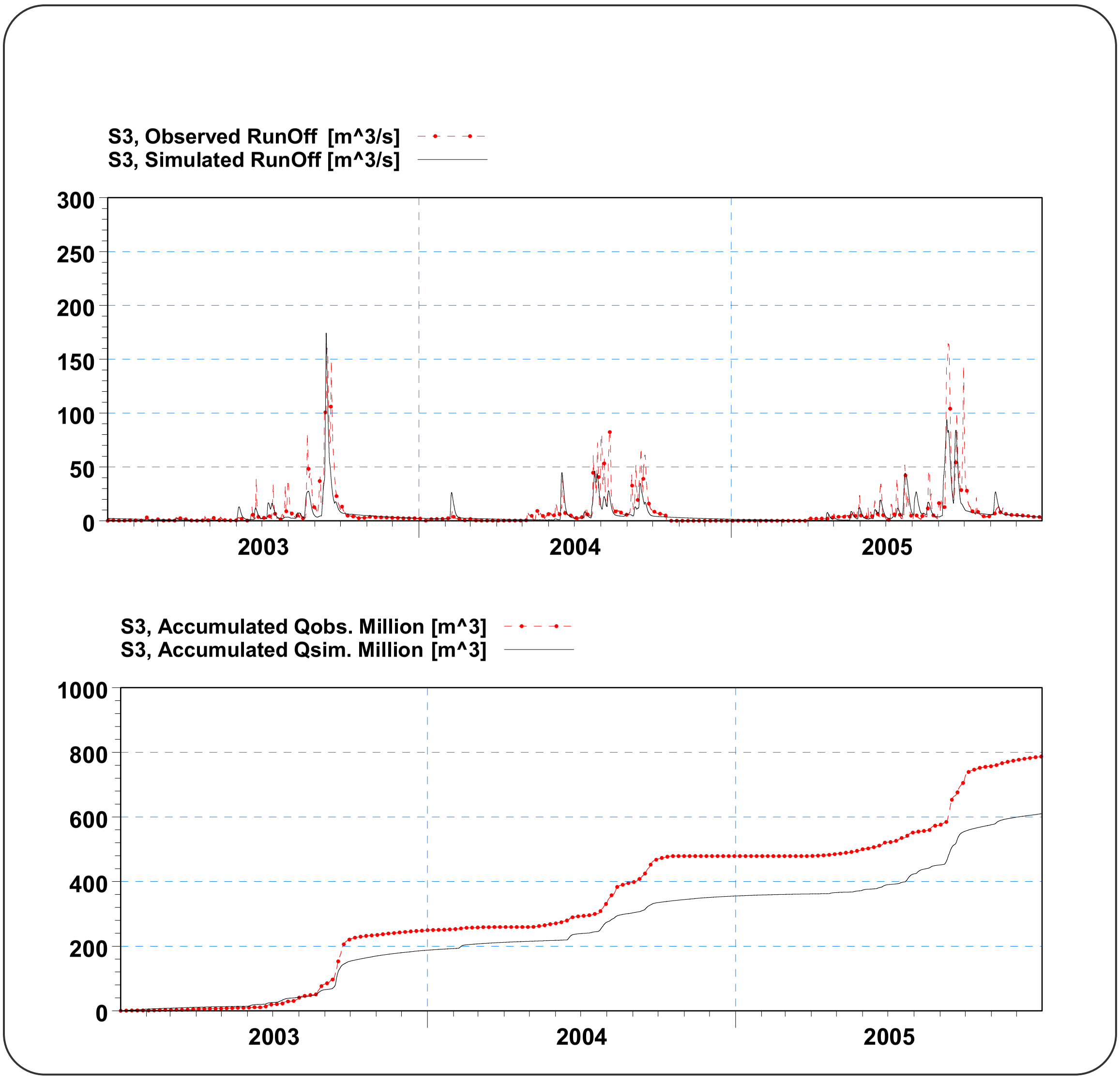


Figure 4.4-7 Comparison between Estimated and Observed Discharges of Ban-TalDeaw (S.3) Sub-catchment (MIKE11 NAM: Verification)

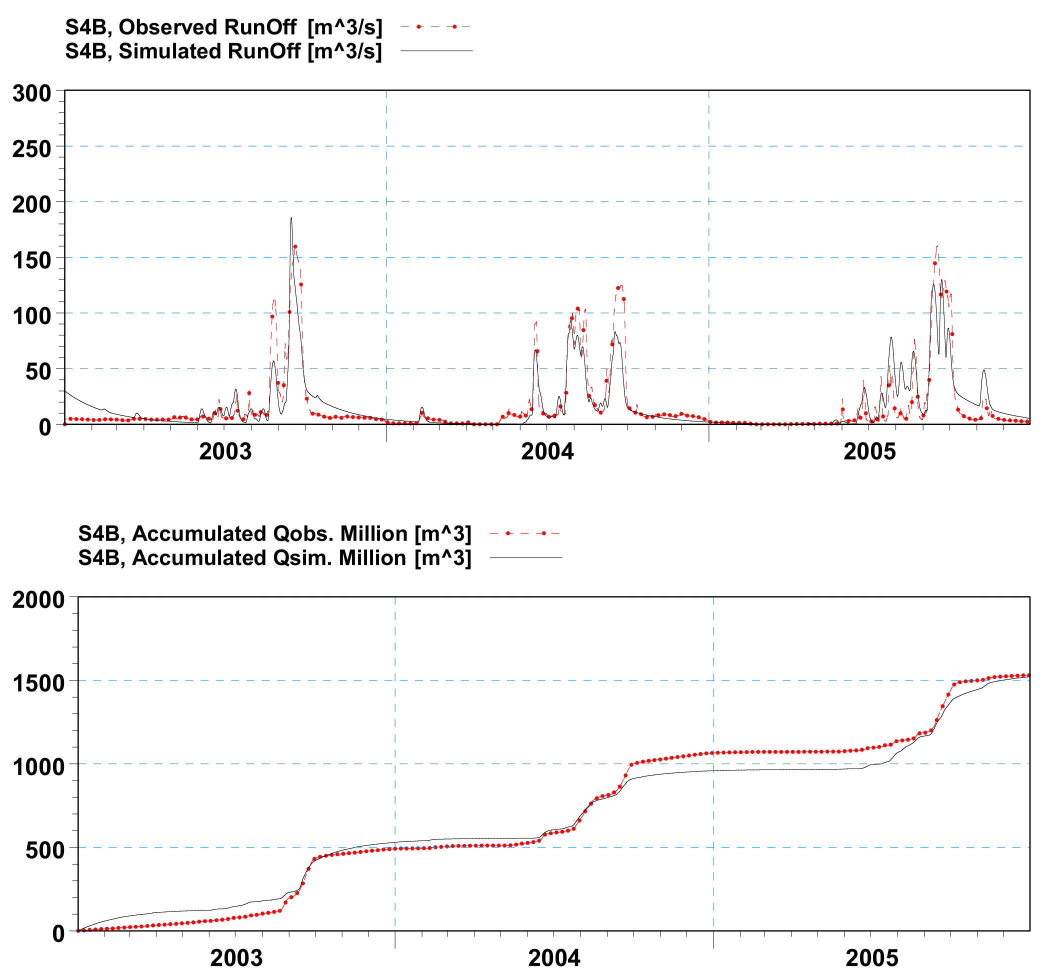


Figure 4.4-8 Comparison between Estimated and Observed Discharges of Muang Phetchaboon District (S.4B) (MIKE11 NAM: Verification)

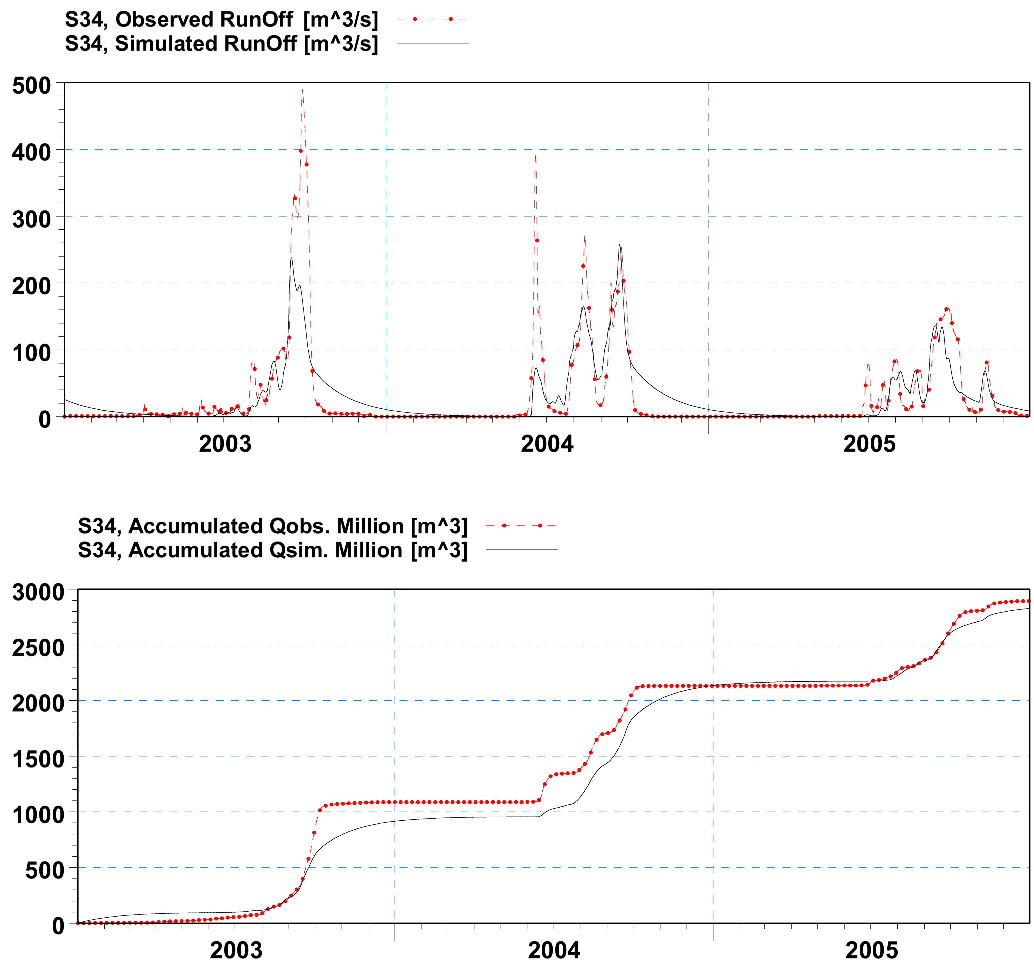


Figure 4.4-9 Comparison between Estimated and Observed Discharges of Ban ThaNam (S.34) Sub-catchment (MIKE11 NAM: Verification)

Table 4.4-4 Errors Estimation of the MIKE11 NAM Model Verification

Sub-catchment	Drainage Area (sq.km.)	Statistical Comparison		
		Peak Error (%)	Volume Error (%)	Correlation Coefficient, R^2
S3	1,047	5.82	-22.36	0.634
S4B	3,566	15.89	-0.59	0.746
S34	6,478	-47.59	-2.23	0.664
Average		23.10	- 8.39	0.681

As expected, on average the percentage of volume error and the R^2 value of the verification period are lower and higher than the calibration period, respectively. The average peak error of the verification is lower than the calibration. This possible due to the observed flood peak of the verification data is much lower than the calibration data, leading to less flood peak error of the verification period. However, on average we consider that the developed RR model can be used to simulate runoff of the study basin.

4.4.4 Application of Rainfall Runoff Module

Since the results of the calibration and verification of the developed RR model are satisfied as presented in the above sections, the next step is to apply the developed model to use with MIKE11 HD model. Runoff of each sub catchment generated from the developed RR model were input to the MIKE11 HD model. Details of developing MIKE11 HD model for the study basin are presented next.

4.5 Hydrodynamic Module Development (MIKE11 HD Module)

The Pasak river is the main river of the Upper Pasak catchment. It passes the area of the Muang Phetchaboon district. Floods in this area are frequently due to overflow from this river. To simulate flooding conditions of the Muang Phetchaboon district, flow characteristics of the Pasak river have to be imitated. In this the study, the hydrodynamic module of MIKE11 software package has been used to simulate flow characteristics of the Pasak river and Huai Num Phung. Additionally, the MIKE11 HD module has been used to imitate flood plain of the Upper Pasak river basin. Details of setting up the HD module are explained next.

4.5.1 Defining of Model Boundary

The MIKE11 HD model of the Upper Pasak river basin has been built up. The river network modeling consists of the Pasak river and Huai Num Pung. Flow schematic of the developed HD model of the Upper Pasak river basin is illustrated in **Figure 4.5-1**. Model boundaries have been defined as details below.

- **Upstream boundary** are runoff of sub-catchment located upstream of Pasak river and Huai Nam Phung. These runoff were obtained from the observed data of S.3 and S.10 stations, respectively.
- **Lateral sideflow** are runoff of sub-catchments located at the side of main river and tributary. These runoff data were calculated from the MIKE11 NAM model.
- **Downstream boundary** are an 3-hour water levels at Ban ThaNam station (S.34). This station located in A.Wichianburi which is about 10 km upstream of the meeting point of Lum Sonthi and the Pasak river.

The flow network of the Upper Pasak river and Huai Num Phung have been modeled using 66 cross sections of these waterways as mentioned in section 4.2.6.

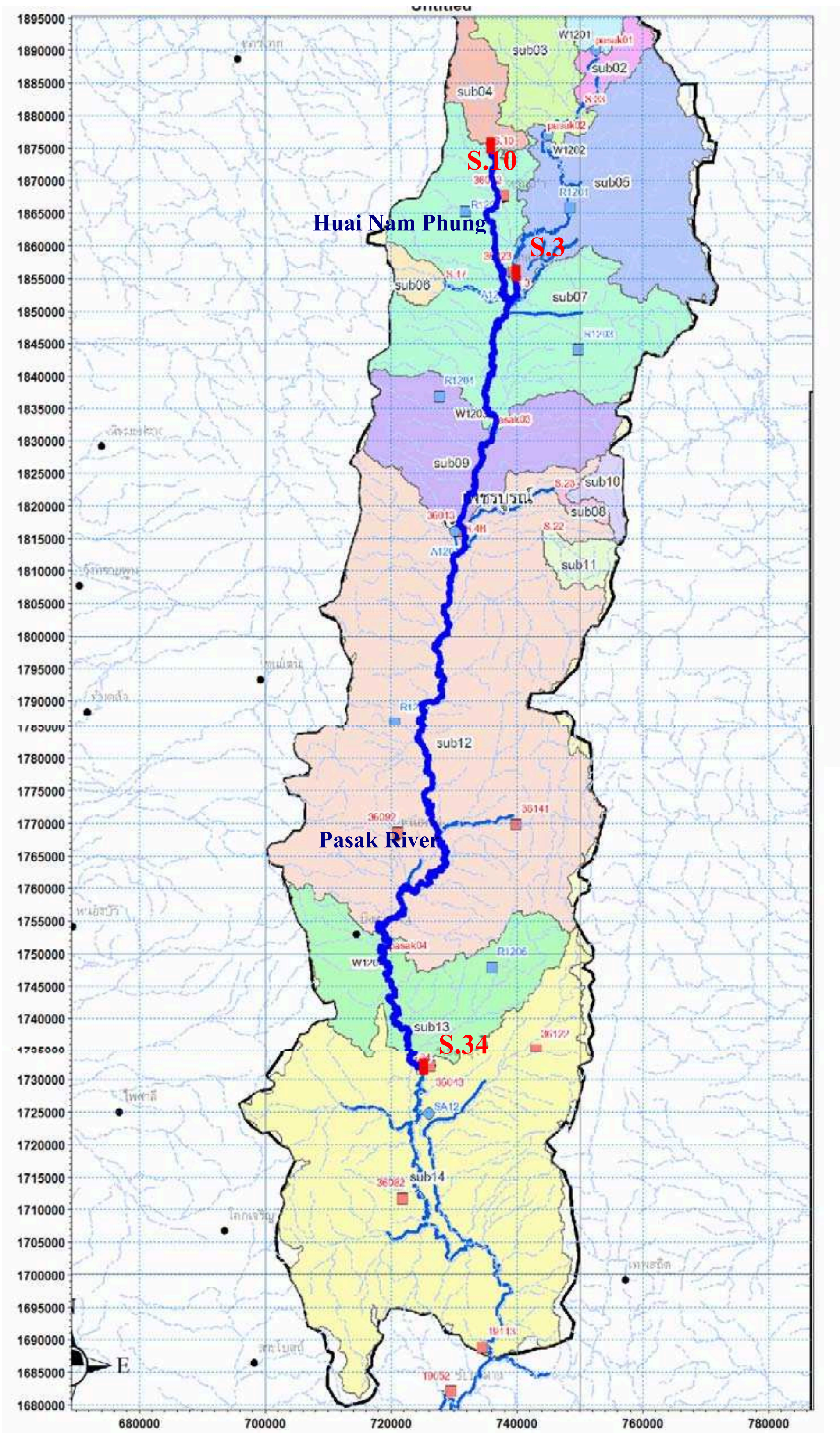


Figure 4.5-1 Upper Pasak River Basin Flow Network for MIKE11 HD Model

4.5.2 Calibration of HD Model

Water level data recorded from the S.4B river gauge station of the Pasak river were used to calibrate parameters of the developed HD model. Model parameters were adjusted to minimize differences between the estimated and observed water levels at this station. An important parameter of the HD model that affects on water level and discharge of the river system is a roughness coefficient in river and flood plain (Manning's n). From the calibration results, the Manning's n coefficient of the Pasak river and Huai Num Phung are summarized in **Table 4.5-1**

Table 4.5-1 Calibrated Manning's n Roughness Coefficient

Stream	Reach	Manning's Coefficient 'n'
Pasak River	km.12+850 to 185+750	0.08 - 0.06
	km.185+750 to 440+000	0.06 - 0.045
Huai Num Phung	km.0+000 to 39+895	0.075 - 0.07

Comparisons between the estimated and observed water levels of the S.4B stations are shown in **Figures 4.5-2**. This figure shows that the simulated water levels during dry periods are higher than the observed. This is because river flow has been taken out for agriculture and consumption uses which has not been considered in the develop HD model, since we only focus on the wet period. The simulated water levels during 2002 are much higher from the observed as the same reason that has been given before. However, on average, the water levels calculated from the developed HD model are close to the observed data for both time and magnitude. Correlation coefficient, R^2 between the estimated and observed water levels were calculated and presented in **Table 4.5-2**. The average R^2 of the calibration period is about 0.531 which is in an acceptable range. Therefore, we consider that the calibrated HD model is able to use to simulate water level and discharge of the main river system of the Upper Pasak river basin.

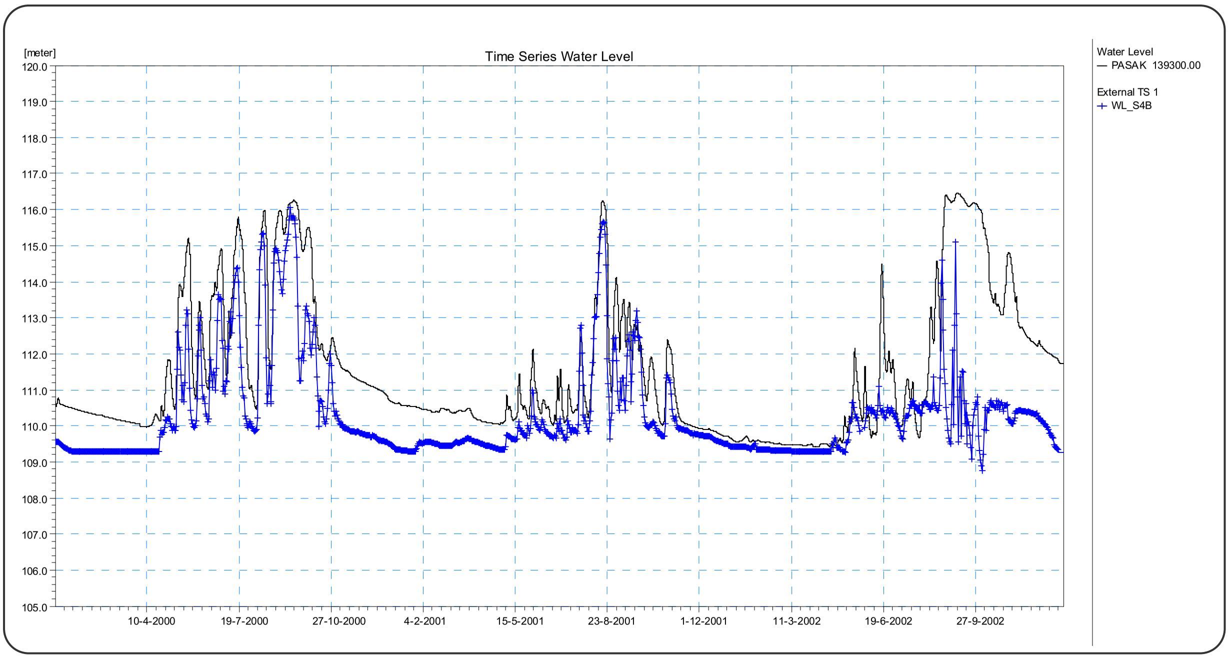


Figure 4.5-2 Comparison between Estimated and Observed Water Level of A. Muang Phetchaboon (S.4B) Sub-catchment (MIKE11 HD: Calibration)

Table 4.5-2 Errors Estimation of the MIKE11 HD Model Calibration

Period	Duration (days)	Statistical Comparison				
		Peak			Volume Error (%)	Correlation Coefficient, R^2
		observed	modeled	Error (%)		
1/5/2000 - 31/10/2000	183	116.06	116.255	0.168	1.323	0.683
1/5/2001 - 31/10/2001	183	115.66	116.248	0.508	0.707	0.831
1/5/2002 - 31/10/2002	183	115.10*	116.465	1.186	2.085	0.035
1/1/2000 - 31/12/2002	1,095	116.06	116.465	0.349	1.106	0.531

Note that : the observed data might not be reliable (as the reason has been given in section 4.3)

4.5.3 Verification of HD Model

The same dataset during 2003 to 2005 that were used for verification of MIKE11 NAM model were used to verify the MIKE11 HD model. The develop MIKE11 HD model was used to simulate water levels of the 2003 to 2005 verification periods using the parameters derived from the calibration period. The verification results show in **Figure 4.5-3** are evident that the simulated water levels of the S.4B station correspond to the observed data. Errors estimation between the simulated and observed water levels were also performed and the results were presented in **Table 4.5-3**.

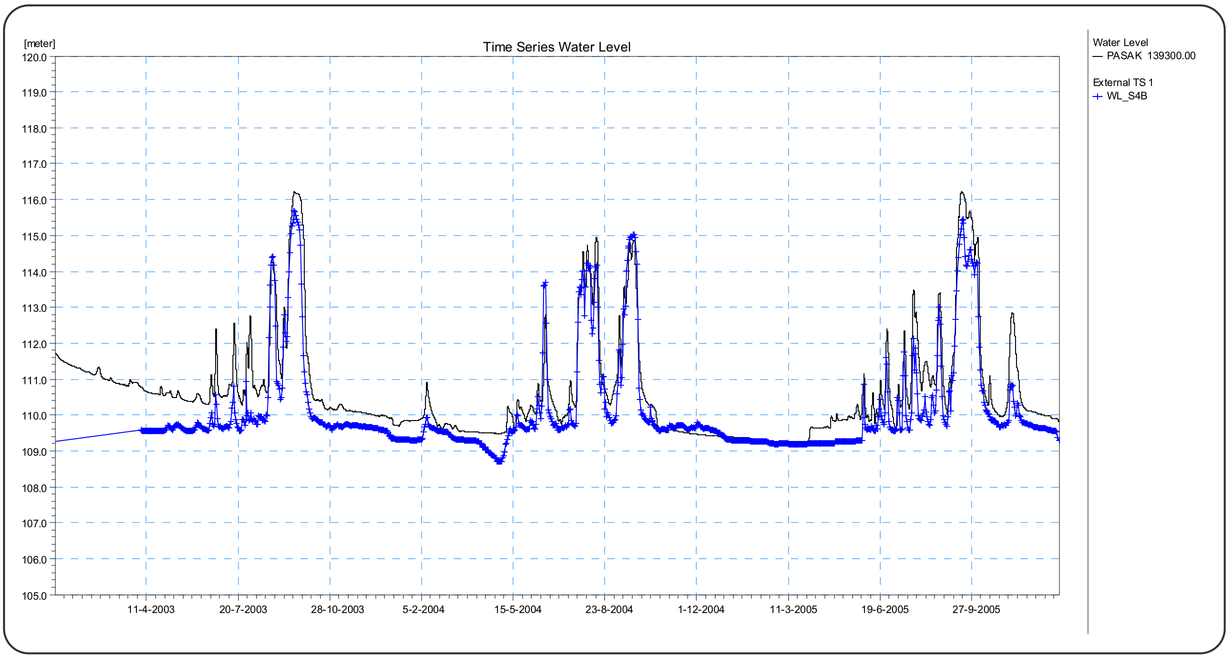


Figure 4.5-3 Comparison between Estimated and Observed Water Level of A. Muang Phetchaboon (S.4B) Sub-catchment (MIKE11 HD: Verification)

Table 4.5-3 Errors Estimation of the MIKE11 HD Model Verification

Period	Duration (days)	Statistical Comparison				
		Peak			Volume Error (%)	Correlation Coefficient, R^2
		observed	modeled	Error (%)		
1/5/2003 - 31/10/2003	183	115.69	116.204	0.445	0.757	0.884
1/5/2004 - 31/10/2004	183	115.01	114.94	-0.061	0.276	0.925
1/5/2005 - 31/10/2005	183	115.45	116.215	0.662	0.603	0.945
1/1/2003 - 31/12/2005	1,095	115.69	116.215	0.454	0.439	0.891