RUNOFF ESTIMATION USING HYDROLOGICAL MODELS IN PHEE RIVER BASIN, THAILAND

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**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF ENGINEERING
(ENVIRONMENTAL AND WATER RESOURCES ENGINEERING)
FACULTY OF GRADUATE STUDIES
MAHIDOL UNIVERSITY
2015**

Thesis
entitled

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was submitted to the Faculty of Graduate Studies, Mahidol University
for the degree of Master of Engineering
(Environmental and Water Resources Engineering)
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ACKNOWLEDGEMENTS

The author of this thesis would like to express my gratitude to my major advisor Dr. Kritsanat Surakit, who has given me advice and support throughout the completed thesis research. I would like to convey my sincere appreciation to my co-advisor Dr. Romanee Thongdara for her instructions, advices, care, and support during the thesis research and examination. Not forgetting as well Dr. Thanet Somboon, an outside examiner from the Royal Irrigation Department of Thailand, and Dr. Punpim Puttaraksa Mapiam from the Department of Water resource Engineering, Kasetsart University for their suggestions and recommendations in order to improve the further study during the thesis examination.

I would like to express my genuine gratitude to all lecturers, staffs, and students in the Department of Environmental and Water resource Engineering, Mahidol University, Thailand, Mr. Rapeepong Lertwattanaruk and Mr. Bantad Inchuran in the Department of Water resource Engineering, Kasetsart University, Thailand, and Mr. Asyraf Mustaffa, Nanyang Technological University, Singapore for his knowledge, assistance, cooperation, and support during the master degree study and my thesis research.

Finally, I am also especially thankful to my beloved parents and my lovely friends for their constant support and understanding. I can't thank you enough for your advice, encouragement, and every ounce of support throughout my master degree program and my thesis research.

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ABSTRACT

In predicting future conditions for water resources management, stream flow forecasting could be an option. The aim of this research was to select the right model to simulate the Phee River basin. The performance of three hydrologic models: the Soil and Water Assessments Tool (SWAT), Rainfall-Runoff (NAM), and Unified River Basin Simulator (URBS) models were evaluated for their ability to simulate the hydrology of the 597 sq.km of the Phee River basin, Thailand. This research involved data from 2000 to 2009, and all three models underwent calibration and validation (performance assessment). The key performances of the simulations were investigated by using statistical indicators: EI, RMSE, and r. The models were run daily, but performance was assessed on a daily and monthly basis. The calibration year was chosen for the completeness of the observed data and the representative year was 2001 (wet year). However, while the simple conceptual model is adequate for monthly time periods, the daily simulation results indicate that a more complex model is required for daily predictions.

The results of simulated flows generated by the three models are similar and closely match the observed flow. Daily runoff the simulation by NAM and its daily and monthly results were more accurate than the SWAT or the URBS model. Thus, the NAM is the most suitable to estimate runoff for the Phee River basin, after taking into account various factors such as statistical indicators, economics, efficiency of model, scope of model application on river basins, availability of input data, accessibility of concept, theory, user manual, and source code of the models.

KEY WORDS : HYDROLOGIC MODEL / CALIBRATION / VALIDATION

96 pages

การประเมินปริมาณน้ำท่าโดยใช้แบบจำลองทางอุทกวิทยาในลุ่มน้ำปี้,ประเทศไทย
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บทคัดย่อ

ในการคาดการณ์เหตุการณ์การไหลของน้ำท่าอาจเป็นตัวเลือกหนึ่งที่ใช้ในการพยากรณ์การบริหารจัดการน้ำในอนาคต จุดมุ่งหมายของการวิจัยนี้เพื่อเลือกแบบจำลองที่เหมาะสมที่จะนำมาใช้ในลุ่มน้ำปี้ แบบจำลองอุทกวิทยาที่นำมาการประเมินการไหลของน้ำท่าในลุ่มน้ำปี้นี้คือแบบจำลอง SWAT, NAM และ URBS ซึ่งมีพื้นที่ลุ่มน้ำ 597 ตารางกิโลเมตร ในงานวิจัยนี้ได้เลือกช่วงปีน้ำ พ.ศ. 2543 ถึง พ.ศ. 2552 มาทำการสอบเทียบและตรวจสอบความถูกต้องของแบบจำลองและค่าตัวชี้วัดทางสถิติได้แก่ ดัชนีวัดประสิทธิภาพ, ค่าความคลาดเคลื่อนที่ยอมรับได้และสัมประสิทธิ์สหสัมพันธ์มาเป็นหนึ่งในเกณฑ์การเลือกแบบจำลองที่เหมาะสมที่สุด ทั้งสามแบบจำลองมีข้อมูลด้านเข้าเป็นรายวันและมีการประเมินผลเป็นรายวันและรายเดือน ในการประเมินผลเป็นรายวันได้เลือกปีน้ำ พ.ศ. 2544 เป็นตัวแทนปีน้ำหลาก เพราะมีปริมาณน้ำท่าสูงสุดในช่วงปีที่กำหนด อย่างไรก็ตามการสอบเทียบแบบจำลองรายเดือนยังไม่สามารถให้คำตอบเชิงลึกได้จึงจำเป็นต้องมีการสอบเทียบแบบจำลองรายวันเพื่อคาดเหตุการณ์ที่จะเกิดขึ้น

ผลลัพธ์จากตัวชี้วัดทางสถิติจากการสอบเทียบมีความคล้ายคลึงกับค่าจากการตรวจวัดของสถานี จากผลลัพธ์ดังกล่าวแบบจำลอง NAM มีค่าทางสถิติสูงสุดทั้งการประเมินผลรายวันและรายเดือน ดังนั้นแบบจำลอง NAM จึงเป็นแบบจำลองที่เหมาะสมที่สุดที่ใช้ในการประเมินการไหลของน้ำท่าในลุ่มน้ำปี้ นอกจากตัวชี้วัดทางสถิติแล้วยังมีเรื่องเกณฑ์อื่นที่นำมาวิเคราะห์ครั้งนี้เช่น เศรษฐศาสตร์ การประยุกต์แบบจำลองใช้กับพื้นที่ศึกษาอื่น เป็นต้น

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CHAPTER I
INTRODUCTION

1.1 Problems Statement

This thesis is a study on the hydrologic model for estimating runoff in sub-basin of Yom River basin in the northern part of Thailand as the research conducted at this river is minimal. The Yom River floods regularly and thus requires the estimation of runoff to be conducted in order to prevent flood. There is no major dam in the Yom River, it has 11 sub-basins and all of them have small and medium reservoirs in them. The Phee River basin is relatively small and since it does not have a constructed dam, it is easier to calibrate the hydrological models in such a location. Thus, the results from the study of runoff estimation in Phee River basin will aid in the prevention of flood at other basins in the future using hydrologic models.

1.2 Background Information

Water is a naturally circulating resource that is constantly recharged (Oki & Kanae, 2006). It being a source of ecological balance; vital to humans and all living things, as such, we are very much dependent on water resources. A step to avoiding a water crisis is adopting management techniques which increase accessible water, increase water-use efficiency (short-term) and limiting population growth (long-term). Cooperation and commitment of local, national, and international governments, industries, and other governments are needed for successful active water management (Falkenmark & Widstrand, 1992).

According to Hydro and Agro Informatics Institute (HAII), Yom River basin is the major river in northern Thailand with a catchment area of 24,046.89 square kilometers and an average runoff of 3,683 million cubic meters per year. Yom River consists of mountainous terrain and lower area. There is no major dam in the Yom River basin but small and medium reservoirs of about 77 reservoirs are unevenly distributed throughout the basin (Tingsanchali & Karim, 2010). Phee River basin has a catchment area of 597 square kilometers and is 2.69% of the Yom River basin. When flood and drought occurs in the basin, the amount of water is likely to rise in crisis during the period of February to April every year, especially in the lowlands of the lower north and upper central areas which are annual floodplains. The amount of water from the runoff is affecting the local people. Difficulties in the estimation of the runoff, such as calculating the rainfall data of the lower basin, having no monitoring stations in place, results in discrepancy evaluation.

In order to simulate the hydrologic effects of different management situations, various computer simulation models have been developed. These models include the Soil and Water Assessments Tool Model (SWAT), Rainfall runoff Model (NAM), and Unified River Basin Simulator model (URBS). The performances of these three hydrologic models were evaluated based on their ability to simulate the hydrology of this basin and were investigated by using statistical indicators of: Efficiency Index (EI), Root Mean Square Error (RMSE), and Correlation Coefficient (r). After taking into account factors such as statistical indicators, economical, efficiency of model, width of model application on river basins, availability of input data, accessibility of concept, theory, user manual, and source code of the models, the most suitable model will be selected to simulate the hydrologic processes of Phee River basin. Some of these applications are described in next chapter.

1.3 Objectives

This research was held on these following objectives:

- To study the concept of the hydrologic models: Soil and Water Assessments Tool Model (SWAT), Rainfall-Runoff Model (NAM), and Unified River Basin Simulator model (URBS) in Phee River basin, Thailand.
- To compare the statistical indicators among SWAT, NAM, and URBS model for runoff estimation
- To select the suitable model this can be used for runoff estimation in Phee River basin, Thailand.

1.4 Scopes

- The hydrological models employed for runoff characteristic investigation were selected using the literature review.
- The performance comparison statistical indicators of: Efficiency Index (EI), Root Mean Square Error (RMSE), and Correlation Coefficient (r) using the SWAT, NAM, and URBS in Phee River basin, Thailand.
- The measurement of rainfall and collection of meteorological data at rainfall station of 310002 and 331010 were generated into areal average values using the Thiessen Polygon technique by Royal irrigation Department RID.
- The measurement of rainfall and collection of meteorological data at a station of the study area were generated into areal average values using the Thiessen Polygon technique and Isohyetal technique. The digital elevation model (DEM) for topography was also utilized, before these required data were input into the selected hydrological models.
- The selected hydrologic models were set up to investigate the runoff characteristics in the Phee River basin from 1 April 2000 to 31 March 2010.

CHAPTER II
LITERATURE REVIEW

2.1 Study Area Description

The Yom River basin has 11 sub-basins, a total catchment area of 23,618 square kilometers; total length of 735 kilometers, and an average runoff to 3,650 million cubic meters per year at HAII. The latitude is between 14° 50´N, 18°25´N and longitude is between 99°16´E, 100°40´E at HAII. Yom River originated from Phi Pannam Mountain at Pong district, Phayao province. Basin boundary to the north is connected to Mekong river basin, to the south is Ping River basin, to the east is Nan river basin, and to the west is Wang river basin and Ping River basin. The Yom River flow southwards, and joins to Nan River flow generally south through mountain valleys to the Chao Phraya River in Nakhon Sawan province (Chaibandit & Konyai, 2012), as shown in Figure 2.1.

2.1.1 Location and Geography

Phee River basin, which is located in the northern part of Thailand that covers an area of Chiang Muan district, Phayao province and Ban Luang district, Nan province, as shown in Figure 2.2. The river basin has a total catchment area of 597 square kilometers; total length of river 66 kilometers; and an average runoff of 96 million cubic meters per year, according to Royal Irrigation Department (RID). The latitude and longitude of Hydro and Agro Informatics Institute (HAII) is 18°53´04´´N and 100°17´24´´E respectively. The topography of it shows high mountains terrain and flat narrow range. The area around the Phee River is plain and in some places interrupted by small mountain ranges. The land in close proximity to the Phee River is regularly flooded during the rainy season and alluvial sediment is deposed in this basin. Steep slopes and heavy rainfall especially during the rainy season will lead to increased soil erosion. Phee River is sub-basin of the Yom River basin and flow westwards, joining Yom River.

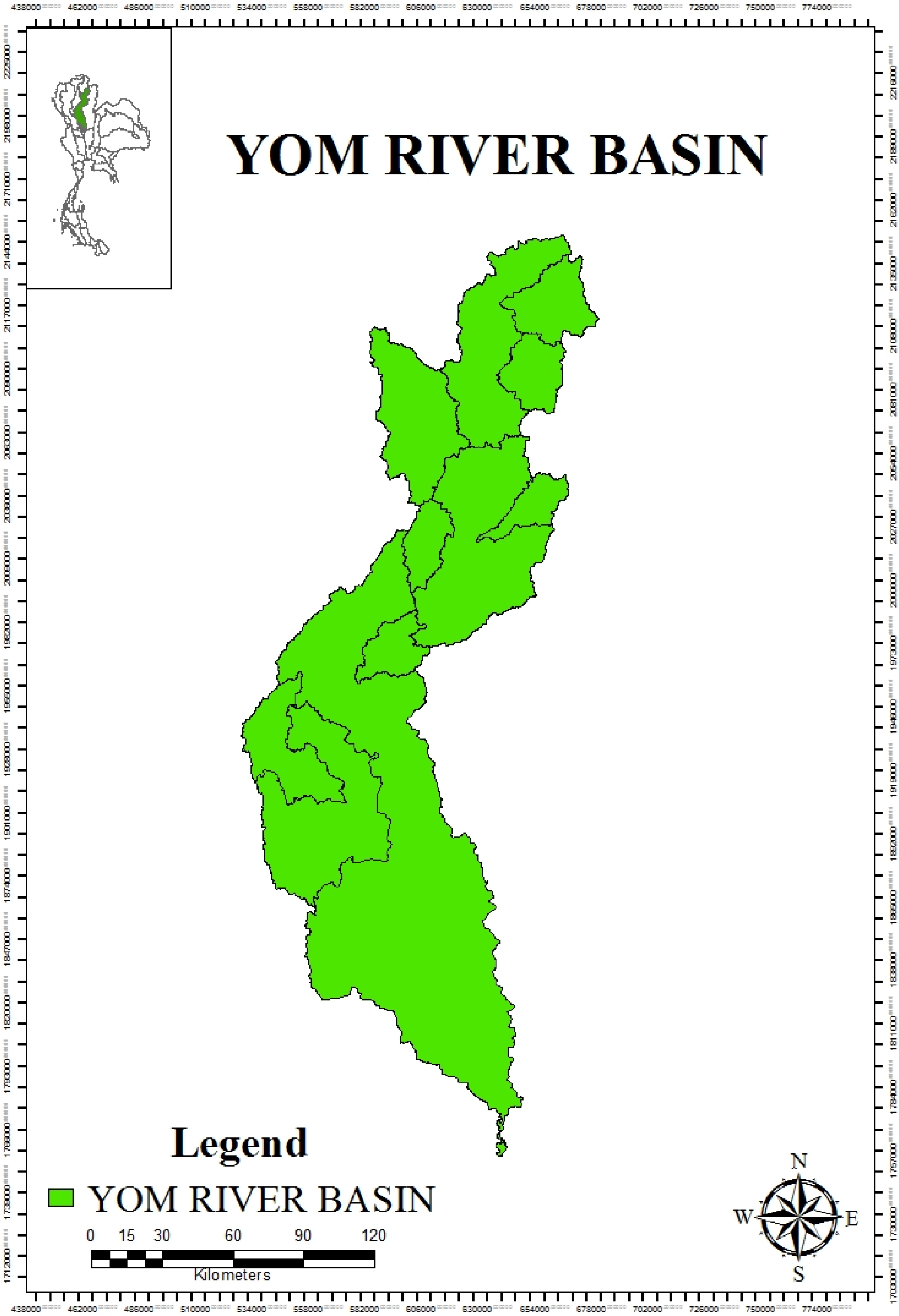

Figure 2.1 The location of Yom River basin

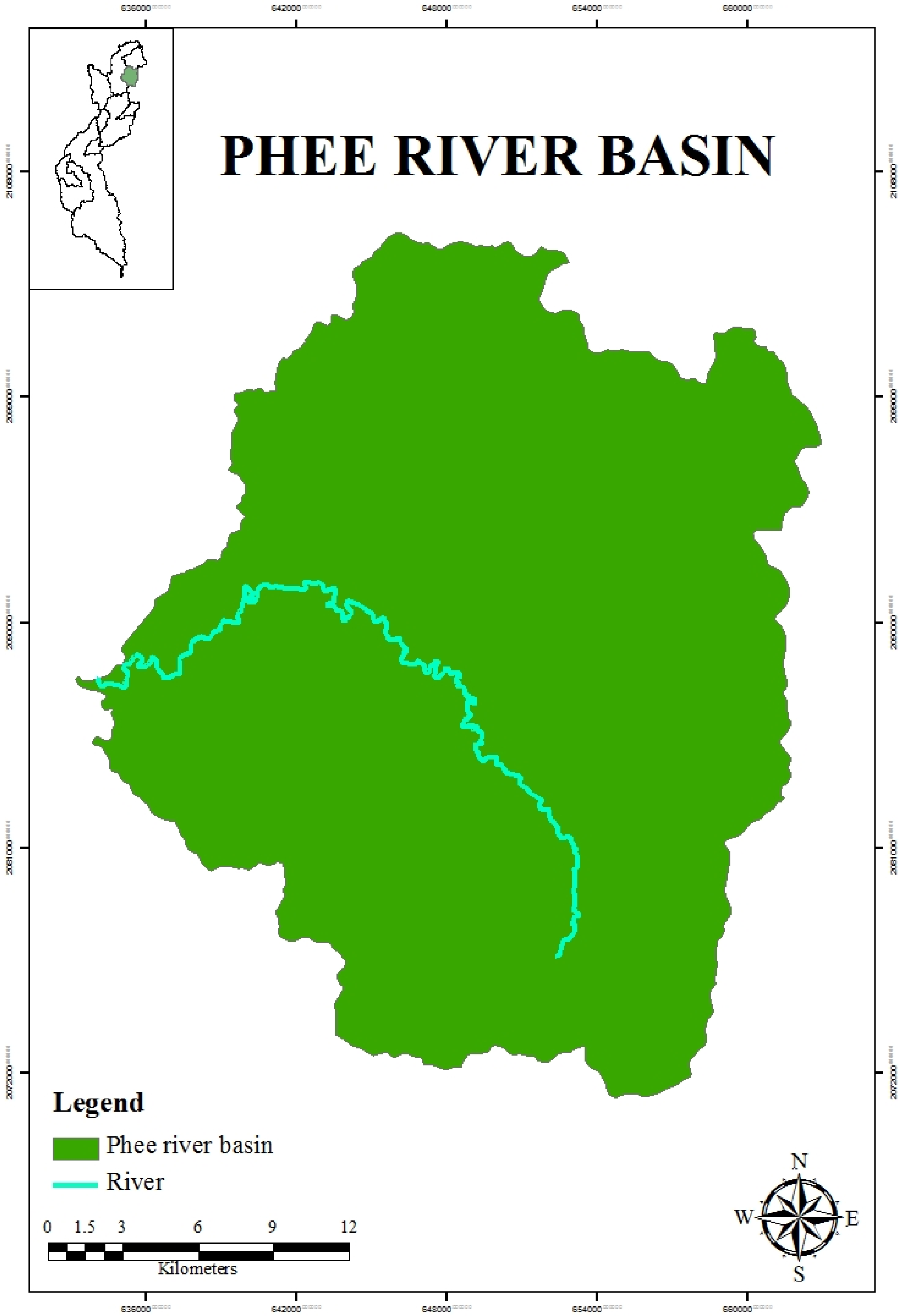

Figure 2.2 The location of Phee River basin

2.1.2 Climatology and Meteorology

The climate of the study area is influenced by two major airstreams – the Northeast and the Southwest monsoon. According to meteorological data from the year 2000 to 2009 the temperature in the study area, relative, and the wind speed shown in Table 2.1.

Table 2.1 Meteorological and hydrological conditions of Phee River basin

Climate variables	Range	Unit
Temperature	25 – 28	degrees Celsius
Humidity	70 – 75	percent
Evaporation	6.8 – 39.7	millimeter
Wind speed	0.8 – 2.3	knots

2.1.3 Rainfall and Runoff

Data collection of the Phee River basin in the 10-year long term period (2000 to 2009) has a rainfall stations by Thai Meteorological Department (TMD) and runoff station by Royal Irrigation Department (RID) record exhibit data as shown in Table 2.2 and Table 2.3 respectively.

Table 2.2 Rainfall station in Phee River basin, Phayao province

Station code	Station name	Longitude	Latitude	Source
330002	Pong, Prayao province	100°16'41"	19°08'32"	TMD
331010	Ban Luang, Nan province	100°45'00"	18°52'00"	TMD

Table 2.3 Station measure of runoff to the Phee River in Phayao province

Runoff Station	Y.24
Name	Phee River basin
Location	Ban Mang, Mang, Chiang Muan, Phayao province

Table 2.3 Station measure of runoff to the Phee River in Phayao province (cont.)

Runoff Station	**Y.24**
Geographical location	Lat. 18° 53' 03" N Long. 100° 17' 25" E
Catchment area	597 sq.km
Length	62.8 km.
Collect data	1 Apr 2000 - 31 Mar 2010
Capacity	185 cms. at 500 m. area 310 cum.

2.1.4 Soil type and Land use

Geographically, the basin is divided into two distinctive areas, the mountainous and agriculture (in the river valleys). Phee River basin has high mountains terrain and flat narrow range. The land used for agriculture was for sorghum, maize, paddy fields, sugarcanes and orchards, including forestry and deforest area. Soil types map, and land use map are shown in, Figure 2.3 and Figure 2.4 respectively, legend of land use are Soils are identified in Appendix A.

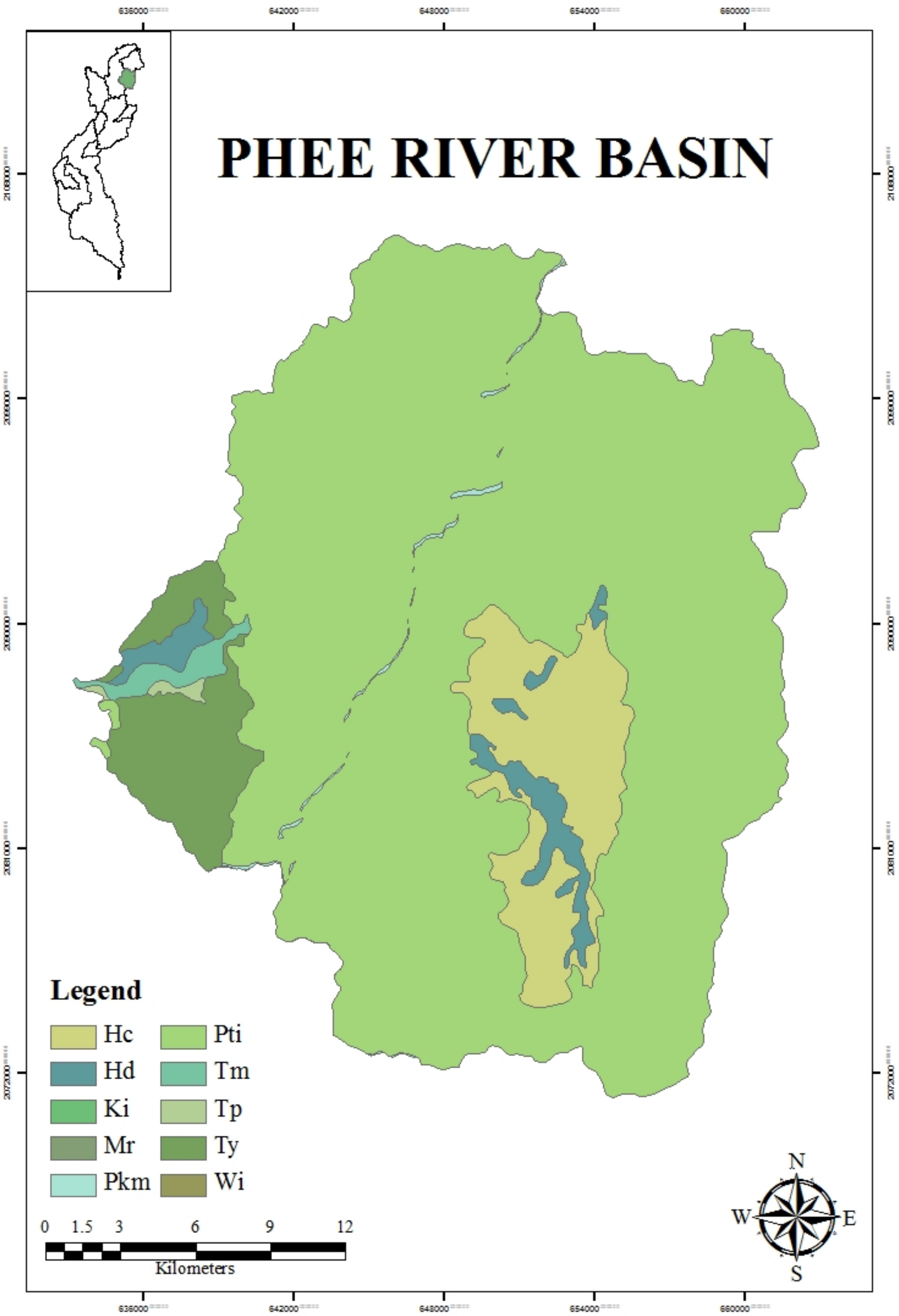

Figure 2.3 Soil type in Phee River basin

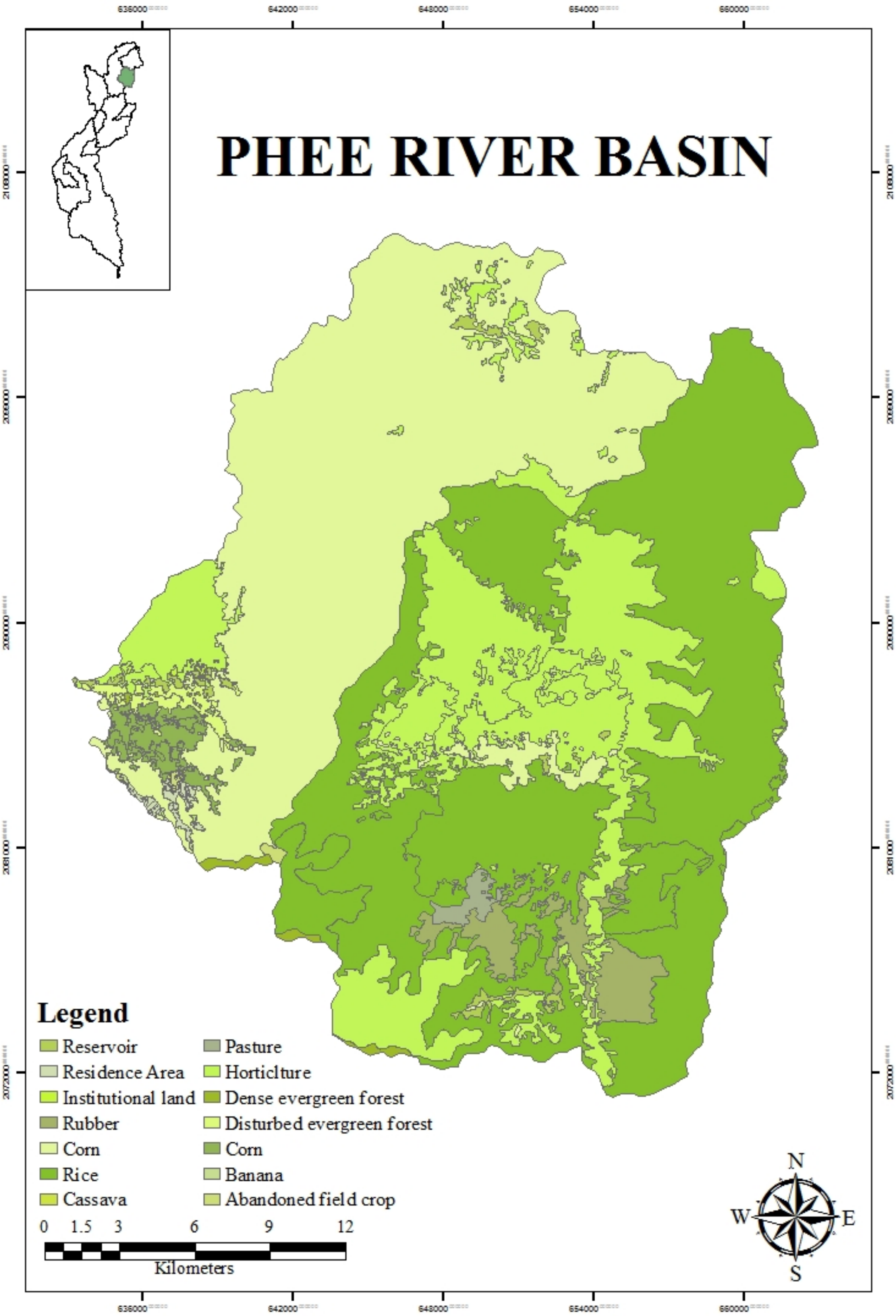

Figure 2.4 Land use in Phee River basin

2.2 Hydrologic model

Hydrological models provide various purposes in water resources projects, inclusive of flow and flood estimation. Such models have been employed to evaluate the characteristics of runoff and developed based on the hydrologic cycle imitation (Carcano, Bartolini, Muselli, & Piroddi, 2008). An empirical model is based on a mathematical relation between an input and output series (for example, rainfall and runoff data) with the catchment considered as a lumped unit, with no physical traits of the basin (Maidment, 1993). The water resource management is not a new concept: the stream flow simulating models become an important research topic, and hydrological models of instrument insurance are directly related for development and future planning of hydrologic cycle (Ghahraman, 2012). Many types of models have been developed to estimate flood hydrographs from excess rainfall. The characteristic that distinguishes the models considered here from unit hydrographs and other transfer function procedures is that the attempt to represent the runoff processes in more detail. Computer programs are available for most models and are required for practical application.

In this study, the models applied for runoff estimation in Phee River basin are the Soil and Water Assessment Tool Model (SWAT), Rainfall-Runoff model (NAM), and Unified River Basin Simulator model (URBS). Their results will be compared, and the most suitable model will be selected for flood estimation in the Phee River basin. The details of the three models are described below.

2.2.1 SWAT

Soil and Water Assessment Tool Model (SWAT) stands for Soil and Water Assessment Tool; a river basin scale, a spatially distributed rainfall-runoff model used for continuous time simulation of river discharge developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) (Arnold & Fohrer, 2005). The SWAT model has been used worldwide and considered as a versatile model that can be utilized to integrate multiple environmental processes, which will then aid in more effective watershed management and the development of better informed policy decisions (Gassman, Reyes, Green, & Arnold, 2007).

2.2.1.1 Features of SWAT

SWAT is a continuous time model, i.e. a long-term yield model and thus it is not designed to simulate detailed, single-event flood routing. It was extended to predict the impact of land management practices on water, sediment and agricultural chemical yield, land use, and management conditions over long periods of time (Neitsch, Arnold, Kiniry, Williams, & King, 2005). To satisfy this objective, the SWAT model

- requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling and more are directly modeled by SWAT using this input data.
- simulates very large basins in order for a variety of management strategies to be performed without excessive investment of time or money.
- enables users to study long-term impacts. Many of the problems currently addressed by users involve the gradual buildup of pollutants and the impact on downstream water bodies. To study these issues, results are needed from runs with output spanning several decades.

2.2.1.2 Modeling method of SWAT

In SWAT, watersheds are divided into sub-basins and each sub-basin is further divided into numbers of Hydrologic Response Units (HRU). The division of the sub-basins is determined by geological location and connection of the streams. The classification of HRU is determined by soil types, land used conditions, and elements related to vegetation and landscape characteristics. Each HRU is spatially independent. Water generated from HURs contributes to reaches through the most upstream end of the main river within the sub-basin. Sub-basins are spatially connected by river reaches. Water contributed to each sub-basin is then conveyed through reaches along the stream network.

SWAT model consists of two main part (Arnold & Fohrer, 2005), Land Phase or Sub-basin Component and Routing Component. A Model fitting analysis of the daily data can be calculated for 100 years consecutively. A model can be classified based on the 3 types of data which are watershed characteristics, climate characteristics, and hydrological characteristics. The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (2.1)$$

Where ;	SW_t	=	Final soil water content (mm)
	SW_0	=	Initial soil water content (mm)
	T	=	time (days)
	R_{day}	=	Precipitation on day i (mm)
	Q_{surf}	=	Surface runoff on day i (mm)
	E_a	=	Evapotranspiration on day i (mm)
	W_{seep}	=	Percolation into soil on day i (mm)
	Q_{gw}	=	Return flow on day i (mm)

2.2.2 NAM

NAM model is an acronym for Nedbor-Afstromings Model that means precipitation-runoff model. It was developed by Hydrological Section of the Institute of Hydrodynamics and Hydraulics Engineering, Technical University of Denmark (ASGER & EGGERT, 1973) which uses semi-empirical equations to describe the behavior during the land phase of the hydrologic cycle. The NAM model is an integrated and conceptual model of runoff-rainfall. NAM model simulates the rainfall-runoff process using the linkage rule between the four reservoirs which are connected together and each represent different physical specifications shown in Figure 2.5 and NAM parameters description shown in Table 2.4.These four reservoirs are: snow storage, surface storage, groundwater storage and root zone storage (Lafdani, Nia, & Pahlavanravi, 2013). The required basic data for NAM model are: model parameters, initial conditions, meteorological data and data for hydrometric calibration; and validation of the model. Basic meteorological data include precipitation, potential evapotranspiration, wherein snowmelt also modeled, temperature and radiation data should also be added. In addition, NAM model has the ability of simulating the changes made by human in hydrologic cycle, meanwhile time series of irrigation and using rate of groundwater aquifers will be required (Taye, Ntegeka, Ogiramoi, & Willems, 2011).

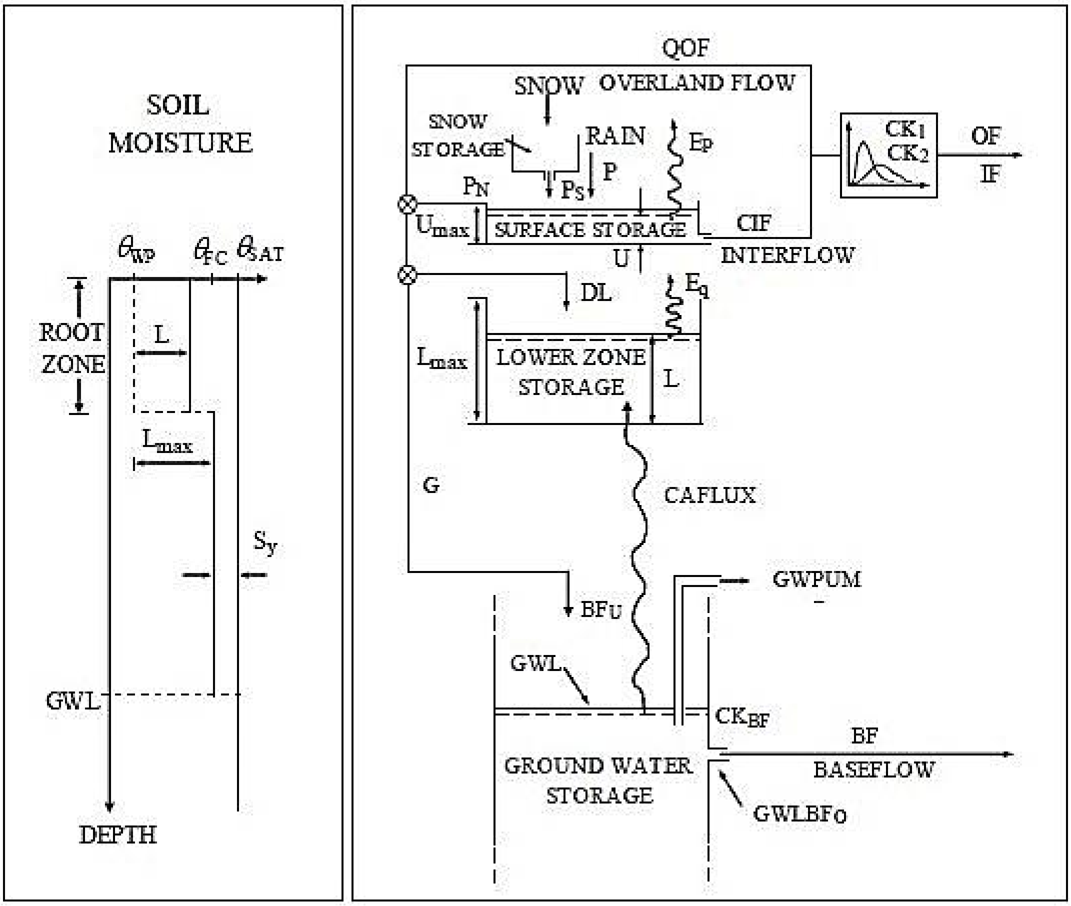

Figure 2.5 Model structure of NAM (DHI, 2008)

Table 2.4 NAM parameters description

Parameter	Description	Unit
U_{max}	Maximum water content in surface storage	mm
L_{max}	Maximum water content in root zone storage	mm
CQOF	Overland flow runoff coefficient	-
CKIF	Time constant for routing interflow	hours
TOF	Root zone threshold value for overland flow	-

Table 2.4 NAM parameters description (cont.)

Parameter	Description	Unit
TIF	Root zone threshold value for interflow	-
TG	Root zone threshold value for groundwater recharge	-
CK1	Time constant for routing overland flow routing 1	hours
CK2	Time constant for routing overland flow routing 2	hours
CKBF	Time constant for routing base flow	hours

A lumped conceptual model of the NAM model treats each sub catchment as a unit. NAM simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment with the following parameters: surface and root zone parameters (maximum water content in surface storage U_{max}, maximum water content in root zone storage L_{max}, overland flow runoff coefficient CQ_{OF}, time constant for interflow CK_{IF}, time constant for routing interflow and overland flow CK_{12}, root zone threshold value for overland flow T_{OF}, root zone threshold value for interflow T_{IF}), groundwater parameters (baseflow time constant CK_{BF}, root zone threshold value for groundwater recharge T_G). Snow module was not considered in this study. Therefore, there are a total of 9 parameters needed to be calibrated and verified in this study and the effects of these parameters on the total runoff volume and on the peak of the runoff.

2.2.2.1 Surface storage

Moisture intercepted on the vegetation as well as water trapped in depressions and in the uppermost, cultivated part of the ground is represented as surface storage. Umax denotes the upper limit of the amount of water in the surface storage. The amount of water, U, in the surface storage is continuously diminished by evaporative consumption as well as by horizontal leakage (interflow). When there is maximum surface storage, some of the excess water, P_N, will enter the streams as overland flow, whereas the remainder is diverted as infiltration into the lower zone and groundwater storage. The overland flow (*QOF*) equation can be shown below.

$$QOF = CQOF \frac{L/L_{max} - TOF}{1 - TOF} P_N \qquad \text{for } L/L_{max} > TOF \qquad (2.2)$$

$$= 0 \qquad \text{for } L/L_{max} \leq TOF$$

Where; $CQOF$ = Overland flow runoff coefficient ($0 \leq CQOF \leq 1$)

TOF = Threshold value for overland flow ($0 \leq TOF \leq 1$)

L/L_{max} = Relative soil moisture content

2.2.2.2 Lower zone or root zone storage

The soil moisture in the root zone, a soil layer below the surface from which the vegetation can draw water for transpiration, is represented as lower zone storage. Lmax denotes the upper limit of the amount of water in this storage. Moisture in the lower zone storage is subject to consumptive loss from transpiration. The moisture content controls the amount of water that enters the groundwater storage as recharge and the interflow and overland flow components. The amount of infiltrating water G recharging the groundwater storage depends on the soil moisture content in the root zone as presented in the equation below.

$$G = (P_n - QOF) \frac{L/L_{max} - TG}{1 - TG} \qquad \text{for } L/L_{max} > TG \qquad (2.3)$$

$$= 0 \qquad \text{for } L/L_{max} \leq TG$$

Where; TG = Root zone threshold value for groundwater recharge ($0 \leq TG \leq 1$)

The amount of water remained in the lower zone storage (DL) are calculated using the following equation.

$$DL = (P_n - QOF) - G \qquad (2.4)$$

The interflow contribution (QIF) is assumed to be proportional to U and to vary linearly with the relative moisture content of the lower zone storage.

$$QIF = CKIF \frac{L/L_{max} - TIF}{1 - TIF} U \quad \text{for } L/L_{max} > TIF \quad (2.5)$$
$$= 0 \quad \text{for } L/L_{max} \leq TIF$$

Where; $CTIF$ = Time constant for interflow

TIF = Root zone threshold value for interflow ($0 \leq TIF \leq 1$)

Evapotranspiration demand is initially met at the potential rate from the surface storage. If moisture content (U), in the surface storage is less than this requirement, the remaining fraction is assumed to be withdrawn by root activity from the lower zone storage at an actual rate, according to:

$$E_a = E_p \frac{L}{L_{max}} \quad (2.6)$$

Where; E_a = Atmospheric concentration of vapor (vapor pressure)

E_p = Evapotranspiration

L, L_{max} = Actual and maximum possible moisture contents

2.2.2.3 Groundwater storage

The water percolated from the lower zone storage will be retained in groundwater storage. Groundwater level (GWL) represents the groundwater table depth measured from ground level. There are 4 essential parameters needed for groundwater level calculation which are a recharge G, capillary flux CAFLUX, net groundwater abstraction GWPUMP, and baseflow BF. The baseflow can be calculated as follows.

$$BF = (GWLBF_0 - GWL) S_Y (CK_{BF})^{-1} \quad \text{for } GWL > GWLBF_0 \quad (2.7)$$
$$= 0 \quad \text{for } GWL \leq GWLBF_0$$

Where; $GWLBF_0$ = Maximum groundwater table depth

S_y = Specific yield of groundwater reservoir

The Capillary Flux is calculated using the equation below.

$$CAFLUX = \left(1 - \frac{L}{L_{max}}\right)^{1/2} \left(\frac{GWL}{GWLFL_1}\right)^{-\propto} \quad (2.8)$$

$$\propto = 1.5 + 0.45 GWLFL_1$$

Where; $GWLFL_1$ = Groundwater table depth at which capillary flux

2.2.2.4 Interflow and overland flow routing

The interflow is routed through two linear reservoirs in series with the same time constant CK1 and CK2. The overland flow routing is also based on the linear reservoir concept but with a variable time constant.

2.2.3 URBS

The Unified River Basin Simulator model (URBS) is a distributed nonlinear rainfall runoff routing model which can take into account the spatial and temporal variation in rainfall (Malone, 1999). It has been applied successfully for real time flood forecasting in a range of catchments from small to very large basins in Australia. For the URBS model, the routing behavior in catchment and channel can be described using either basic or split routing modules. The split module, which is similar to the Watershed Bounded Network Model, was selected for this study because it gives better results than the basic module during model calibration (Carroll, 2004).

2.2.3.1 Runoff-routing network models

URBS is a runoff-routing networked model of sub-catchments. There are two runoff routing models to describe catchment and channel storage routing behaviour. These are the URBS Basic and Split routing model. Details of both sub-models are described as follows.

a) Basic model

The Basic model is similar to a simple RORB model. The assumption of the both models is that the catchment and channel storage for each sub-catchment are lumped together as a single non-linear reservoir. The storage-discharge (S-Q) relationship of conceptual non-linear reservoir can show by the following.

$$S = k_c^1 Q^m \tag{2.9}$$

Where; k_c^1 = Non-linear routing constant for a single reservoir

It is a function of the sub-catchment and channel storage characteristics. When k_c^1 is replaced with these characteristics, the Basic model will be change by the following.

$$S = \left\{\frac{\propto fn(1+F)^2}{\sqrt{S_C}(1+U)^2}\right\} Q^m \tag{2.10}$$

Where; S = Catchment and channel storage (m^3 h/s)

$\propto$ = Storage lag parameter

f = Reach length factor

L = Length of reach (km)

U = Fraction urbanization of subcatchment

F = Fraction of sub-catchment forested

n = Channel roughness or Manning's n

S_C = Channel slope (m/m)

Q = Outflow (m^3/s)

m = Catchment non-linearity parameter

The instability of calculation can be checked by using the subcatchment lag divide by the chosen time interval. The result should close to zero. The criterion of calculation instability can show by the following.

b) Split model

The Split model is a runoff routing model as well as the Basic model, but the catchment and channel routing for each sub-catchment will be separated individually. When the rain fall on a sub-catchment, it is then routed through the catchment storage located at the centroid of the catchment to the channel using the catchment routing component. After that, the outflow of catchment storage which is the inflow of channel storage will be routed along a reach using a non-linear Muskingum method to the next catchment. The catchment and channel routing component can be estimate using the following criteria.

1) Catchment Routing

For catchment routing criteria, the catchment storage represents a non-linear reservoir. Once the rain fall on the ground, it is routed through the non-linear reservoir using the storage-discharge relationship as shown by follows.

$$S_{catch} = \left\{\frac{\beta\sqrt{A}(1+F)^2}{(1+U)^2}\right\} Q^m \qquad (2.11)$$

Where;
Q = Outflow discharge (m^3/s)
β = Catchment lag parameter
A = Area of subcatchment (km^2)
U = Fraction of sub-catchment urbanized
F = Fraction of sub-catchment forested
m = Catchment nonlinearity parameter

2) Channel Routing

Channel routing is based on the non-linear Muskingum model as is given as:

$$S_{chnl} = \propto f \frac{nL}{\sqrt{S_c}} (xQ_n + (1-x)Q_d)^{n_1} \qquad (2.12)$$

Where;
S_{chnl} = Channel storage (m^3h/s)
α = Channel lag parameter
f = Reach length factor
L = Length of reach (km)
S_c = Channel slope (m/m)
Q_u = Inflow at upstream end of reach
Q_d = Outflow at downstream end of the channel reach (m^3/s)

x = Muskingum translation parameter

n_1 = Muskingum non-linearity parameter (exponent)

n = Manning's n or channel roughness

2.2.3.2 Rainfall runoff–loss models

There are two rainfall loss approaches consisting of event based and continuous modeling in URBS model. Details of the two approaches are follows.

a) Event base rainfall loss modelling

This model requires the user to specify the initial loss, which is rainfall loss on the catchment before surface runoff occurrence. There are several loss models provided by the URBS that can be used for rainfall loss estimation. Details of each model are presented as:

1) Impervious loss model

The default of URBS model is that there is no initial loss for impervious area, total rainfall therefore become runoff with 100%. Recent research seems to suggest an initial loss of approximately 1 to 2 mm and a runoff proportion between 90% and 100% to be more appropriate. (Boyd, Bates, Pilgrim, & Cordery, 1987) adopt an effective fraction impervious to represent the directly connected impervious components of the catchment. A value between 0.7 and 0.9 is often used.

2) Pervious loss models

There are three types of pervious loss model composing of:

- Continuing loss model

This model assumes that there is an initial loss of il (mm) before any rainfall becomes effective. After this, a continuing loss rate of cl (mm) per hour is applied to the rainfall.

- Proportional runoff model

This model assumes that there is an initial loss of *il* (mm) before any rainfall becomes effective. After this, a proportional amount of runoff (mm) is applied to the rainfall.

- Manley-phillips loss model

Once the initial loss has been satisfied, Phillips equation is used to calculate rainfall losses. Application of Phillips equation is based on (Manley, 1974) who developed a set of physically based coefficients for Phillip's Equation. The model assumes a loss rate based on the following equation:

$$f_i = \frac{1}{2}(2kP)^{1/2}t^{1/2} + k \qquad (2.13)$$

Where; f_t = Loss rate after time t (mm/h)
t = Time (h)
P = Capillary suction head (mm)
k = Saturated loss rate (mm/h)

3) Including spatial variability effects in loss model parameters

This model has an objective to account the spatial variability of soil loss model parameter by using a statistical distribution approach. The assumption is that when the rainfall infiltrate into the pervious areas that has reach x mm, it can expect that y fraction of the catchment is contributing to runoff. The model assumes a loss rate based on the following equation:

$$f_{\text{eff}} = f_u + \frac{F_t}{F_{max}} \qquad (2.14)$$

Where; f_u = Fraction of the area that is impervious
F_t = Cumulative infiltration into the pervious area after time t
F_{max} = Maximum infiltration capacity of the catchment

Infiltration is the process by which water on the ground surface enters the soil. Excess rainfall (R_t) can be calculated from

$$R_t = f_{eff} C_{imp} R_t^{tot} + (1 - f_{eff}) R_t^{per} \quad (2.15)$$

Where; R_t^{tot} = Total rainfall depth at time t

C_{imp} = Impervious runoff coefficient (the default is 1)

R_t^{per} = Pervious excess rainfall depth

b) Rainfall-runoff models / Continuous loss modelling

There are two methods in the URBS model to be used for continuous rainfall runoff modelling. The first one is recovering initial loss model (RILM), and another one is third party water balance model. Details of both models are presented below:

1) URBS Recovering Initial Loss Models (RILM)

Since the continuing and proportional loss models as mentioned earlier cannot be used for recovering the initial loss. The RILM is an efficiency way developed for recovering the initial loss. There are two sub-models comprising the continuing loss and proportional loss models that can be used in this situation as presented details by the following.

- Manley-Phillips Loss Model

The initial loss is recalculated after every time step using the equation:

$$\begin{aligned} IL_{(i+1)} &= IL_i, \qquad R_i > clr_i \delta t \\ IL_{(i+1)} &= IL_i + f(clr_i \delta t - R_i), \qquad R_i > clr_i \delta t \\ IL_{(i+1)} &= IL_{MAX}, \qquad IL_i > IL_{MAX} \end{aligned} \quad (2.16)$$

Where; R_i = Rainfall series

clr_i = Continuing loss rate series

δt = Model time interval

f = Calibration parameter and represents the fraction of continuing loss deficit that contributes to the initial loss recovery. A value of f should be between 0.1 and 0.5.

- Proportional loss model

The initial loss is recalculated after every time step using the equation:

$$IL_{(i+1)} = IL_i, \qquad prR_i > rlr_i\delta t$$
$$IL_{(i+1)} = IL_i + rlr_i\delta t - R_i, \qquad R_i > rlr_i\delta t \tag{2.17}$$
$$IL_{(i+1)} = IL_{MAX}, \qquad IL_i > IL_{MAX}$$

Where; R_i = Rainfall series

pr = Proportional runoff coefficient

rlr = Recovering loss rate

2) Third party water balance models

The AWBM model is one of a water balance model, which can be used for rainfall loss estimation for a given event (Boughton, 1993). The model generally produces un-routed runoff or rainfall excess to a location of runoff station. The URBS model can access these data and disaggregate the excess for each upstream sub-catchment based on the volume of total rainfall that fell on each sub-catchment. When this loss model is used you should ensure that the parameters for the event based loss models are set so that there is no generated loss.

CHAPTER III
METHODOLOGY

The conceptual framework below describes the methodology of this thesis shown in Figure 3.1. This framework consists of results obtained from three hydrological models; Soil and Water Assessments Tool Model (SWAT), Rainfall runoff Models (NAM), and Unified River Basin Simulator model (URBS) for runoff estimation in Phee River basin.

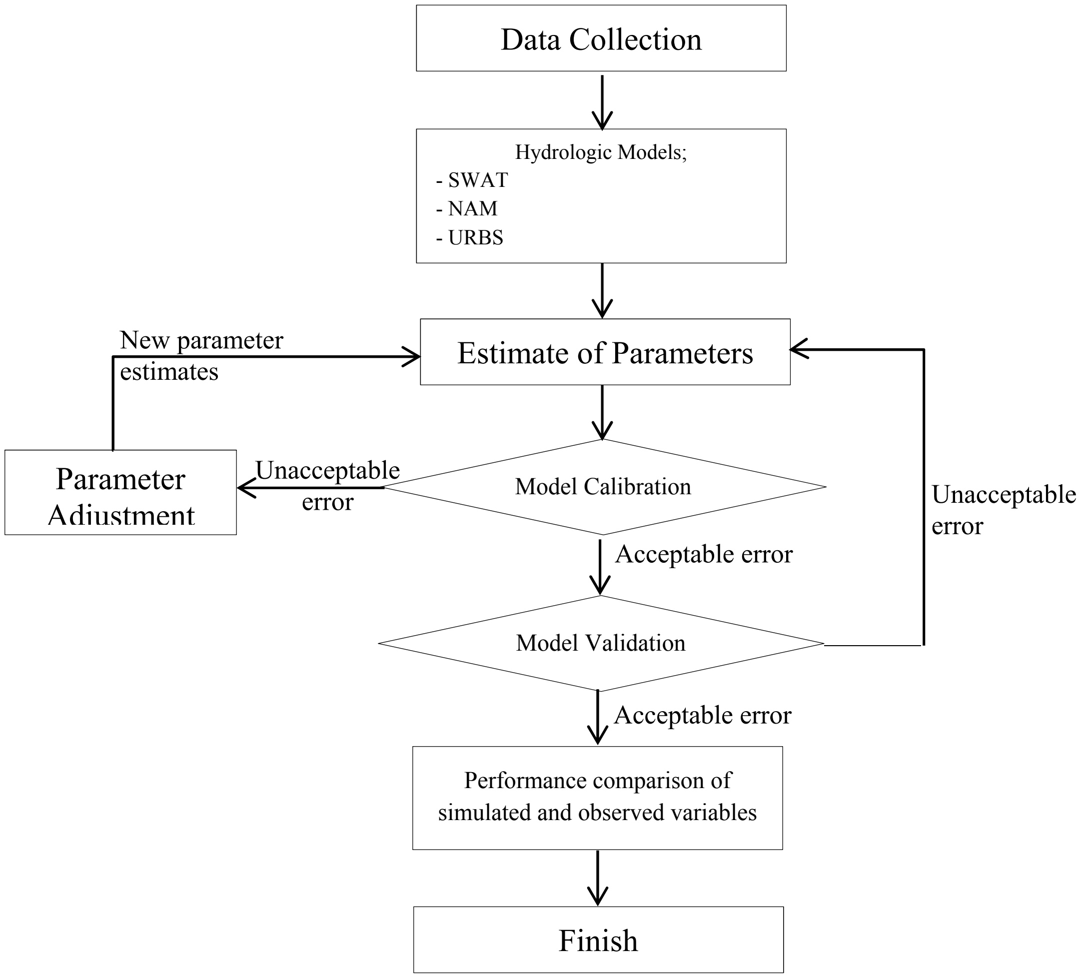

Figure 3.1 Conceptual Framework for this thesis

Following the methodologies used in this thesis, it can be concluded that the performances of these three models require two calibrations; daily and monthly. The monthly calibrations took place from 2000 to 2009 at runoff station Y.24 and the data was used for running calibration and validation processes on the three models. The time period for daily calibration was 2001 as it has the highest runoff data from the 2000 to 2008 period as shown in Figure 3.2 . This calibration year was chosen also because of the completeness of their observed data and the inclusion of a representative year (wet year) (Golmohammadi, Prasher, Madani, & Rudra, 2014). By utilizing a time series analysis, the historical data the historical data was them examined to investigate both missing and abnormal data. The single abnormal data and missing data were corrected by applying necessary mathematical statistics.

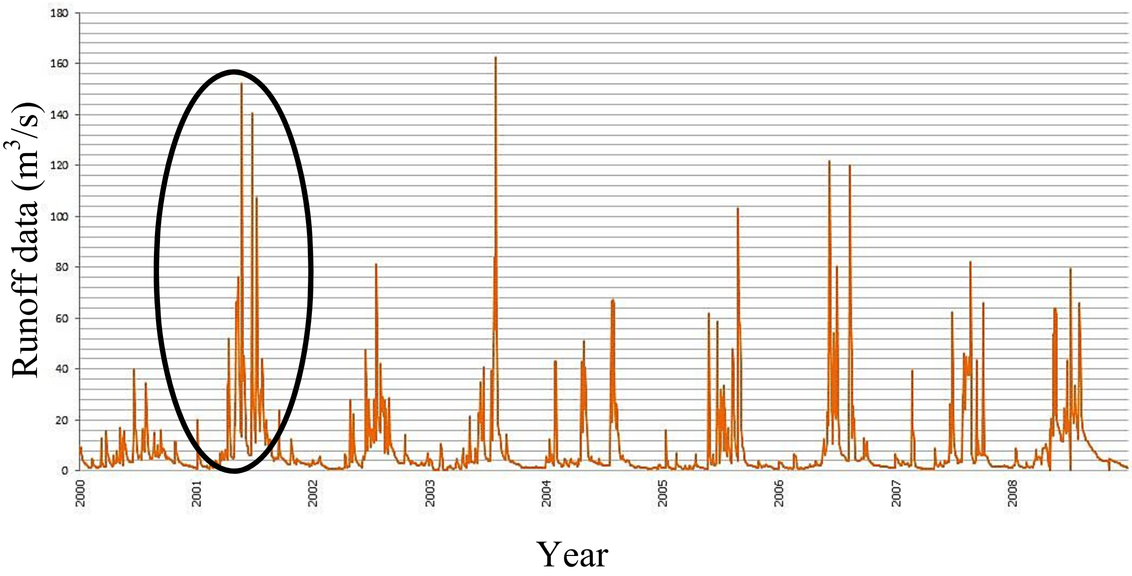

Figure 3.2 Long-term daily runoff data of Phee River basin since 2000-2008

All of these studies classified in three sections due to the objectives that were set. The first section represented the data collection used in this study. The second presents the methodology that was utilized for the setup of the runoff estimation hydrologic model in the Phee river basin. The last section presents the method that is applied to test the selected model performance for flood estimation in the study area. Details of each section are described below.

3.1 Data Collection

Data collected from 3 organizations were Thai meteorological Department (TMD), Royal irrigation Department (RID), and Land Development Department (LDD) for evaluated of their ability to simulate the hydrology in Phee River basin. These three hydrological models have their own data collection and also briefly presented in this Table 3.1.

Table 3.1 Data Collection

Data collection	Source
DEM	LDD
Climatology and Meteorological data	TMD
Rainfall and Runoff data	TMD and RID
Soil type and Land use data	LDD

3.1.1 DEM

The Digital Elevation Model (DEM) is the base which delineates the watershed boundary and stream networks, creating sub-basins. Using the pre-processing module of SWAT enabled us to do this, albeit requiring a so-called minimum threshold area. Topography was defined by a DEM, describing the elevation in a given area at a certain spatial resolution as a digital file. It allowed us to analyze the drainage patterns of the land surface terrain as well. The DEM also allowed us to derive sub-basin parameters such as slope, slope length and width. For this study a DEM of 30m resolution was used having obtained it from ATER GDEM website. A total area of 627 km^2 of DEM data was sourced in the SWAT and latitude 18°53′04′′N and longitude 100°17′24′′E from Hydro and Agro Informatics Institute (HAII). As for the generating map, the DEM was applied with GIS software to generate the floor inundation map by using the calculated maximum water level profile along Phee River.

3.1.2 Climatology and Meteorology Data

Data for the model has to be taken daily either from a measured data set or generated by a weather generator model which include precipitation, max and min air temperature, wind speed, solar radiation and relative humidity. Daily rainfall records were taken from rainfall stations situated within and around the Phee River basin between 2000 and 2009. Meteorological data collected from Thai meteorological Department (TMD), Department of Water Resources (DWR) ad Royal irrigation Department (RID). Consistency of rainfall data was checked and investigated by using the double mass curve technique. Meteorological stations were geo-referenced using latitude, longitude and elevation data. Quality of rainfall data was checked by cross-referencing and relating between stations.

3.1.3 Rainfall and Runoff Data

The weather of the Phee River basin is mainly influenced by the southwest and northeast monsoons and atmospheric depressions from the South China Sea (Sharma, Gupta, & Babel, 2007). In this study, daily rainfall data at 310002 and 331010 rain gauge stations located within and surroundings the Phee River basin during 2000 until 2009 were collected by TMD were entered into the database system to be used as the input data for the three models.

In the Phee River basin, the runoff station in the Phee river basin was available for this thesis at Y.24 operated by RID. The runoff data during 2000 until 2009 therefore the daily runoff data was used for the analysis.

3.1.4 Soil type and Land use Data

Soils in the studied watershed were classified using the revised FAO/UNESCO-ISWC classification system. Soil data was extracted from the 1:250,000 scale soil map. Rudimentary physic-chemical properties of major soil types in the watershed were obtained from the following sources: Phee River basin integrated resources master plan, soil database and digital soil map between year 2000 and 2009; soil and terrain database for northern Thailand. Additionally, some soil properties were also estimated based on available soil parameters.

For the Land Use map, datasets were all gathered from the Land Development Department (LDD). Satellite imagery and field data collected between 2000 and 2009 were also used for this thesis. By reclassifying the Land use map, it could then represent the land use according to the specific land use types and respective crop parameters for the SWAT database. A reference table identifying the SWAT land use code for the numerous categories of land use was done up as well in order to relate the grid values to SWAT land use classes. The land cover/plant growth database contains information needed by SWAT to simulate the growth of a particular land cover. The growth parameters in the plant growth database provides estimated plant growth under ideal conditions and quantify the impact of some stresses on plant growth.

3.2 Structure of Hydrologic model

3.2.1 SWAT

1) SWAT Input

SWAT requires data inputs on DEM, climate, land use, and soil type and these can be obtained from measured and/or generated records. For this study, applicable input parameter values for the model were gathered using several databases. These databases included GIS data and information obtained from both soil type and land use maps. The soil and land use databases were extracted from the provincial soil survey maps of the LDD. Complete data sets for daily rainfall for year 2000 until 2009, derived from the two TMD rain gauge stations were selected, including station 310002 and 331010. For runoff data, it was obtained at runoff station Y.24 which is operated by RID. Other climate data, estimation of Potential Evapotranspiration (PET) was attained using the penman-montheith method (Monteith, 1965), using data from solar radiation, relative humidity and wind speed records.

2) SWAT Setup

a) Watershed delineation

In order to create SWAT model input, the first step was to delineate the watershed from a DEM. Data fed into the SWAT model were organized to have spatial characteristics. Before going in tandem with spatial input data (soil map), Land use map and the DEM were put into a projection called UTM Zone 47 which is a parameter projection for Thailand. The watershed was divided into numerous sub-basins for modeling purposes. Five major steps were included in the watershed delineation process, DEM Setup, stream definition, outlet/inlet definition, watershed outlet selection and definition and calculation of sub-basin parameters. The threshold based stream definition was used to define the minimum size of sub-basins for stream definitions.

b) HRUs

Hydrological Response Units (HRUs) provide load predictions and will be good and accurate if each HRU is considered to obtain the total effect of different land cover/crops and soils. The total runoff depends on the actual hydrologic condition of each land cover/crops and soil present in the watershed. Therefore, the impact of each type of land use is considered in this model to calculate runoff and sediment load in the basin. The distributions of the Hydrological Response Units (HRUs) were determined after the overlay of land-use, soil maps and slope.

3) Model Calibration and Validation

Model calibration is essential for preliminary testing of a model and observed data can afterwards be fine-tuned with it. Without model calibration, it is impossible to have any success in hydrologic and water quality simulations (Shawul, Alamirew, & Dinka, 2013). In this study, Model calibration was conducted for 10 years from 2000 to 2009. The first two years were used for warm up the model. SWAT was calibrated for a five years period (2002-2006) and then validated using three years period (2007-2009) by comparing simulated and observed daily runoff. More detail in appendix B.

3.2.2 NAM

NAM is a rainfall-runoff model that module developed by Department of Water Resources Engineering, Faculty of Engineering, Kasetsart University. The NAM model is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in up to four different storages representing the surface zone, root zone and the ground water storages. The NAM model was prepared with 9 parameters representing four default storages. Description of the parameters and their effects is presented in Table 3.2 and Table3.3. More detail in Chapter 2

Table 3.2 Nam parameter

Parameter	Effects
U_{max}	Overland flow, infiltration, evapotranspiration, interflow
L_{max}	Overland flow, infiltration, evapotranspiration, baseflow
CQOF	Volume of overland flow and infiltration
CKIF	Drainage of surface storage as interflow
TOF	Soil moisture demand that must be satisfied for overland flow to occur
TIF	Soil moisture demand that must be satisfied for interflow to occur
TG	Soil moisture demand that must be satisfied for groundwater recharge to occur
CK1	Routing overland flow along catchment slopes and channels
CK2	Routing interflow along catchment slopes
CKBF	Routing recharge through linear groundwater recharge

Table 3.3 Effects of NAM parameters

NAM Parameter	Change	Effects
U_{max}	Increase	Peak runoff decreased Runoff volume reduced
L_{max}	Increase	Peak runoff decreased Runoff volume reduced

Table 3.3 Effects of NAM parameters (cont.)

NAM Parameter	Change	Effects
CQOF	Increase	Peak runoff decreased
		Runoff volume increased
TOF	Increase	Peak runoff decreased
		Runoff volume reduced
CK1, CK2	Increase	Peak runoff decreased
		The triangular shape expand horizontally
CKBF	Increase	Base flow decreased

1) NAM Input

The NAM model requires rainfall, runoff, and evaporation input data for the period of ten years from 2000 to 2009. For evaporation (ET) is one of the important input in development of NAM model due to its high effect on runoff in the form of evaporation from the surface. The NAM which is based on Penman Monteith Method was used for estimation of ET. The climatological data of TMD was used to estimate ET using the meteorological data like temperature, wind speed, humidity, and sunshine hours. The Thiessen polygon method was used to determine precipitation time series for each sub-basin in Phee River basin by assigning precipitation from a meteorological station to a computed polygon representing that station's data. The comparisons implied that current precipitation observations are spatially adequate in representing precipitation distribution for the sub-basin level that we delineated.

2) NAM Setup

NAM was setup to carry out rainfall-runoff modeling in Phee River basin site having catchment area 597 square kilometers. The input information of daily rainfall, runoff, and evaporation for the period of ten years from 2000 to 2009 was then used for the model development. Model calibration is needed as the parameters of NAM cannot be obtained directly from measurable quantities of basin characteristics. By using the observed rainfall, runoff, and evaporation data of this event as data inputs, the NAM model will automatically estimate the optimal set of parameters that will best match the computed hydrograph with the observed one obtained at the outlet of the Phee River basin.

3) Model Calibration and Validation

Calibration is a procedure to standardize predicted values by using deviations from observed values from a particular area. This is in order to obtain correction factors that can be applied to produce predicted values that are consistent with the observed values. Once the NAM model was set up with the input information, the model was calibrated for a five year period from 2002 to 2006.

Model validation is the observation of the performance of the calibrated model over a period of historical records which has not been used for during the calibration phase. The calibrated NAM model was then validated for the remaining period of three years from 2007 to 2009. During validation, the set of model parameters acquired during the calibration phase was used and the model was then run without auto-calibration mode to simulate runoff. The statistics of the simulated results were analysed and output of the model was verified to compare the simulated and observed runoff. The results were used to verify the capability of calibrated model to simulate the runoff. More detail in appendix C.

3.2.3 URBS

Developed by Carroll in 2004, the URBS model was chosen to simulate runoff hydrographs at gauged and not gauged catchments in the Phee River basin (Sriwongsitanon, 2010). URBS is a semi-distributed nonlinear rainfall-runoff routing model which can explain the spatial and temporal variations in rainfall (Malone, Johnston, Perkins, & Sooriyakumaran, 2003). As the URBS model equations are simplified, there are only 6 model parameters necessary for the application of the model: the channel lag parameter (α), the catchment nonlinearity parameter (m), the catchment lag parameter (β), the initial loss (IL), the proportional amount of runoff (PR), and the maximum infiltration rate (IF). The first four parameters are related to runoff routing behaviour while the last three are related to rainfall loss estimation (Charalambous, 2004; Laurenson & Mein, 1990).

1) URBS Input file

a) Catchment definition file

The Phee River basin has been divided into 9 sub-basins shown in Figure 3.3 presents the details and shape of each sub-basin in Phee River basin respectively. The catchment characteristics of each runoff station comprise of the catchment area (A, km^2), main channel length (L, km), main channel length from the centroid (L_c, km) and details of sub-basin in Phee River basin as shown in Table 3.4.

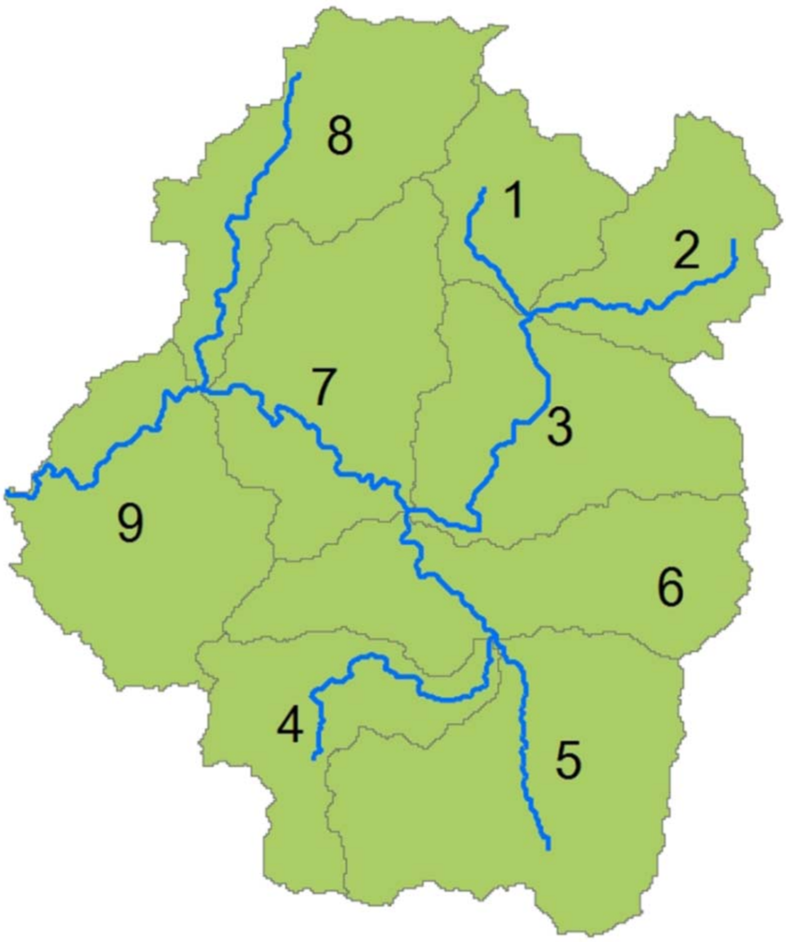

Figure 3.3 Shape of sub-basin in Phee River basin

Table 3.4 Detail of sub-basin in Phee River basin at Y.24

Number of sub-basin	Area (km^2)	River distance (km)	
		L	Lc
1	37.50	0.05	6.17
2	44.90	3.08	7.46
3	75.90	4.45	9.53
4	52.10	1.58	12.70
5	100.50	3.01	6.67
6	79.40	1.40	6.15
7	81.90	7.49	5.87
8	75.10	3.06	12.84
9	79.8	5.82	6.61

b) Rainfall definition file

The method used for the evaluation of rainfall in Phee River basin during 2000 until 2009 is called the Thiessen polygon method. And data was collected at rain stations 310002 and 331010 by TMD.

2) URBS Setup

Setting parameters using the command line interface has the highest precedence the values specified overwrite parameters specified in the 'ini' file, and the catchment definition file or the rainfall definition file. Ini file parameters presented in Appendix D.

a) Catchment definition file

Parameters are specified on the default parameter line as outlined presented in Appendix D. These parameters are overwritten by those specified in the 'ini' file, which are in turn overwritten by those specified on the command line.

b) Rainfall Definition File

The loss parameters and or baseflow are specified in the rainfall definition file as specified presented in Appendix D. These parameters are overwritten by those specified in the 'ini' file, which are in turn overwritten by those specified on the command line.

3) Model Calibration and Validation

The URBS model system was used at the runoff station Y.24 in Phee River basin. This was done to calibrate URBS by determining the most suitable model parameters at station Y.24 to obtain the best fit between calculated and observed hydrographs. To implement the URBS model system for flood estimation, the catchments of runoff station were divided into a number of sub-basins, each having similar size and catchment characteristics. Daily areal rainfall for catchments of runoff stations were calculated using the Thiessen Polygon technique. This basin was simulated using these model parameters as the input data for the URBS 2000 Version 1.1.7.

3.3 Model performance evaluation

In order to define the most suitable set of control parameters for each of the models, model calibration and verification processes were carried out. In these processes, suitability between the observed and calculated discharges was evaluated using three statistical measures: the Efficiency index (EI), Root mean square error (RMSE), and Correlation coefficient (r) as shown by the following formulae (3.1), (3.2), and (3.3).

$$EI = 1 - \frac{\sum_{i=1}^{N}(Q_{mi}-Q_{ci})^2}{\sum_{i=1}^{N}(Q_{mi}-\bar{Q}_m)^2} x\ 100\% \tag{3.1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Q_{mi}-Q_{ci})^2}{N}} \tag{3.2}$$

$$r = \frac{\sum_{i=1}^{N}(Q_{mi}-\overline{Q_m})^2(Q_{ci}-\overline{Q_c})}{\sqrt{(\sum_{i=1}^{N}(Q_{mi}-\overline{Q_m})^2)(\sum_{i=1}^{N}(Q_{ci}-Q_c)^2)}} \tag{3.3}$$

Where, Q_{mi} = Daily observed discharge at time *i*

$\bar{Q}_m$ = Average value of observed discharge

Q_{ci} = Calculated discharge at time *i*

$\bar{Q}_c$ = Average value of calculated discharge

N = Number of data points

The best fit between the calculated and observed discharges using these parameters occur when the efficiency index (*EI*) approaches 100 percent, the root mean square error (*RMSE*) approaches zero, and the correlation coefficient (r) approaches 1 (Santhi et al., 2001) (Van Liew, Arnold, & Garbrecht, 2003).

3.4 Hydrologic model selection

In this section, the most suitable hydrologic model for runoff estimation in the Phee River basin will be selected after careful deliberation of both the theory and the concepts of the three hydrologic models (SWAT, NAM, and URBS models) as presented in the literature review.

3.4.1 Model selection criteria

To select a suitable hydrologic model for runoff estimation in Phee River basin, the selection criteria is necessary to be established. The methodology for hydrologic model selection is shown below.

1) Statistical indicators
2) Economics
3) Efficiency of model input and output facilities
4) Width of application of model on river basins
5) Availability of input data from Thailand river basins
6) Accessibility of concept, theory, user manual and source code of the models

Since there are six selection criteria ranked according to importance, the rated score of each selection criterion are presented in Table 3.5 to Table 3.10 respectively.

Table 3.5 Range score of statistical indicators

Statistical indicator	**Range of score**				
	Very low (0.00)	Low (0.25)	Medium (0.50)	High (0.75)	Very high (1.00)
EI (%)	≤59	60-69	70-79	80-89	90-100
RMSE (m^3/s)	≥15.01	15.00-10.01	10.00-5.01	5.00-0.01	0.00
r	≤0.59	0.60-0.69	0.70-0.79	0.80-0.89	0.90-1.00

Table 3.6 Range score of economic

Selection criteria	**Range of score**				
	Very low (0.00)	Low (0.25)	Medium (0.50)	High (0.75)	Very high (1.00)
Economic (baht)	≥ 100,001	10,001-100,000	1,001-10,000	1-1,000	Free

Table 3.7 Range score of efficiency of model input and output facilities

Selection criteria	**Range of score**				
	Very low (0.00)	Low (0.25)	Medium (0.50)	High (0.75)	Very high (1.00)
Input	Difficult	-	Medium	-	Easy
Output	Difficult	-	Medium	-	Easy

<u>Remark:</u>

Easy: Input and output data can be completed by the graphic user or text file, which is user friendly.

Medium: Input and output data is prepared in the form of text files.

Difficult: No user interface available for preparing input data.

Table 3.8 Range score of width of application of model on river basins

Selection criteria	Range of score				
	Very low (0.00)	Low (0.25)	Medium (0.50)	High (0.75)	Very high (1.00)
Width of application	Not Applicable	-	-	-	Applicable

Remark:

Not Applicable: Can be applied for any general river basin.

Applicable: Cannot be applied for any general river basin.

Table 3.9 Range score of availability of input data from Thailand river basins

Selection criteria	Range of score				
	Very low (0.00)	Low (0.25)	Medium (0.50)	High (0.75)	Very high (1.00)
Availability of input data	Less	-	Medium	-	Well

Remark:

Well: Input data needed for model applications are available in Thailand river basins.

Medium: The abnormal data and missing data were corrected by applying necessary mathematical statistics.

Less: Input data needed for model applications are unavailable in Thailand river basins.

Table 3.10 Range score of accessibility of concept, theory, user manual and source code of the models

Selection criteria	Range of score				
	Very low (0.00)	Low (0.25)	Medium (0.50)	High (0.75)	Very high (1.00)
Accessibility of models	Less	-	Medium	-	Well

Remark:

Well: All necessary information is available via Internet.

Medium: Theory and concept of the model are presented in the user manual but not the source code.

Less: Inaccessibility of concept, theory, user manual and source code of the models.

3.4.2 Model selection

From Table 3.11, it can be seen that these three models have their own advantages and disadvantages in each selection criteria. To ensure that the most appropriate model for this study is selected, scores need to be given for individual criterion of each model (Mapiam, 2009). The model which obtains the maximum score will be chosen for further investigation.

1) Since there are six selection criteria ranked according to importance, weighing factors 3.0, 2.0, 2.0, 1.0, 1.0, and 1.0 are given to the selection orders 1, 2, 3, 4, 5, and 6, respectively.

2) For each selection criterion, the rated score for each model is shown Table 3.12.

Table3.11 Suitability of Model based on Criterion

Selection criterion	SWAT	NAM	URBS
1) Statistical indicators	Medium performance	Medium performance	Medium performance
2) Economics	Approximately 200,000 baht	Approximately 200,000 baht	Approximately 30,000 baht
3) Efficiency of model input and output facilities	- Input and output data is prepared in the form of text files. - Able to link to the ArcView GIS software using the extension AVSWAT-2000 to arrange input and output data.	- Friendly graphic user interface for easy usage. - All input data can be completed by the graphic user or text file, which is user friendly - Output can also be exported as text file for further analysis.	- No user interface available for preparing input data - All input data needs to be in the form of text file. - Locations of input data are specified via user interface or batch file, which is ready to be executed. - Output data is displayed as time series plot and table via user interface.

Table 3.11 Suitability of Model based on Criterion (cont.)

Selection criterion	SWAT	NAM	URBS
4) Width of application of model on river basins	- CN value is the main parameter used - User can change parameters to suit various study areas. - Land use and soil type are needed for model application and these data are not easily measured	- Can be applied for any general river basin - Ranges of the suitable parameters are provided in the user manual but model parameters may not be among recommended ranges.	- Can be applied for any general river basin - Ranges of the suitable parameters are provided in the user manual but model parameters may not be among recommended ranges. - Can be simplified and reduce model parameters to ease model application.
5) Availability of input data from Thailand river basins	- Data needed for model applications are available in Thailand river basins.	- Data needed for model applications are available in Thailand river basins.	- Data needed for model applications are available in Thailand river basins.

Table 3.11 Suitability of Model based on Criterion (cont.)

Selection criterion	**SWAT**	**NAM**	**URBS**
6) Accessibility of concept, theory, user manual and source code of the models	- All necessary information is available via Internet.	- Theory and concept of the model are presented in the user manual but not the source code	- Theory and concept of the model are presented in the user manual but not the source code

Table3.12 Rated score for each selection criteria model

Selection criterion number	Range of score					Weighing factor
	Very low (0.00)	**Low (0.25)**	**Medium (0.50)**	**High (0.75)**	**Very high (1.00)**	
1)	Detail from table 3.5					3.0
2)	≥ 100,001	10,001-100,000	1,001-10,000	1-1,000	Free	2.0
3)	Difficult	-	Medium	-	Easy	2.0
4)	Not Applicable	-	-	-	Applicable	1.0
5)	Less	-	Medium	-	Well	1.0
6)	Less	-	Medium	-	Well	1.0
Total						10.0

CHAPTER IV
RESULTS AND DISCUSSION

According to the objectives of this thesis, the results and discussion of the study corresponding to the methodologies described above can be summarized below.

This research took data from 2000 to 2009 to run calibration and validation processes of the three hydrologic models (SWAT, NAM, and URBS) in Phee River basin. All three models underwent a five-year calibration and their three-year validation performances were assessed with a range of statistics. There models were run daily but performance was assessed on both a monthly and daily basis by aggregating daily model runoff and conducting monthly observations. The calibration year was chosen for the completeness of their observed data and the inclusion of representative year was during 2001 (wet year). However, while the simple conceptual model is sufficient for monthly time periods, the daily simulation results indicate that a slightly more complex model is required for daily predictions in these dry catchments.

4.1 Results of Hydrologic Model

Initially, consider the calibration performance of the three models with respect to daily data. For catchment the 10-year period of record was split into calibration and validation periods are presented in Figure 4.1 and Figure 4.2 respectively. Figure 4.3 and Figure 4.4 presents the observed and simulated from the daily calibration and validation. Based on Figure 4.1 and Figure 4.3, it can be concluded that with respect to the mean observed discharge assessed under calibration conditions, the models yielded comparable results.

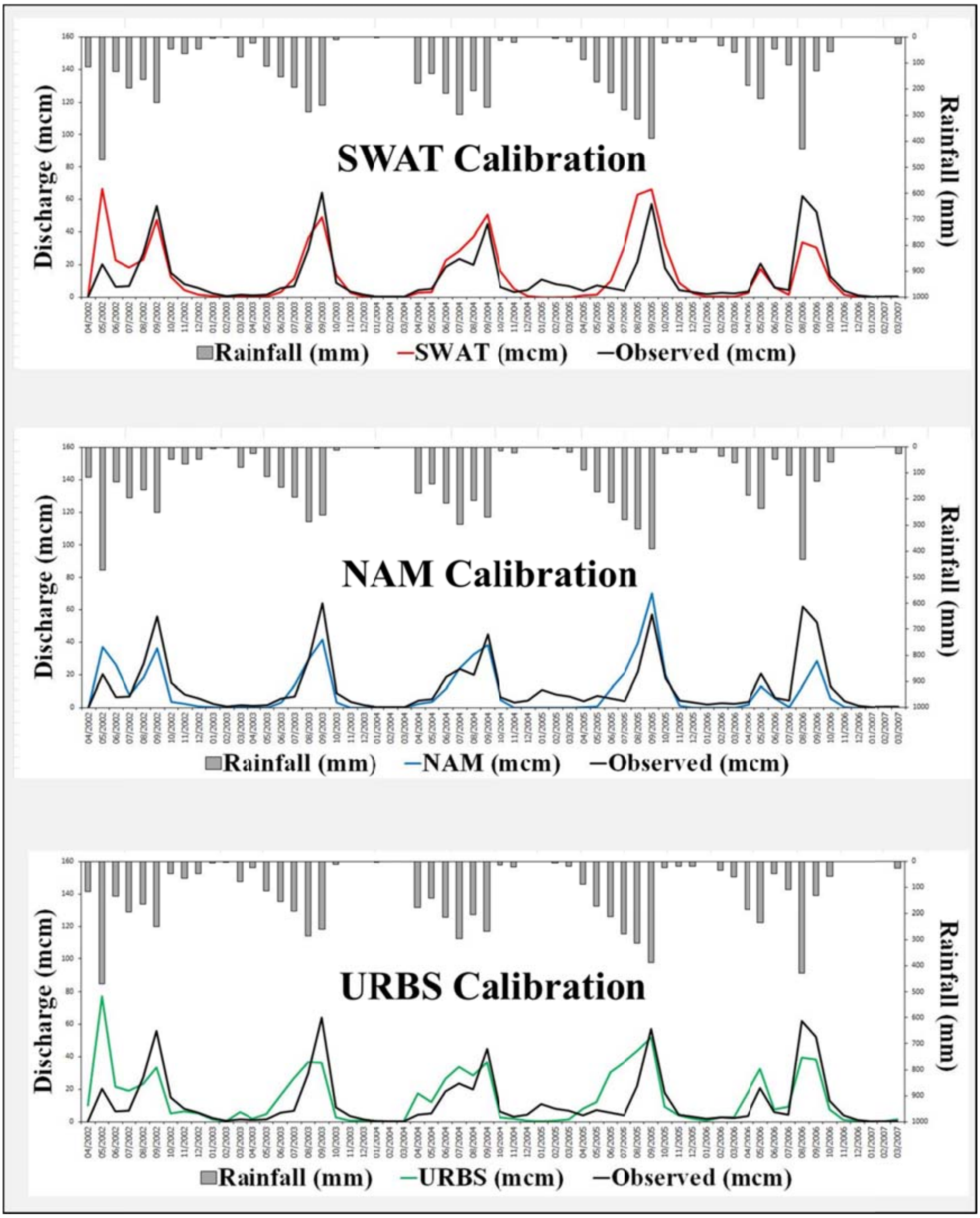

Figure 4.1 Observed and simulated daily runoff using SWAT, NAM, and URBS for the monthly calibration period (water year 2002-2006)

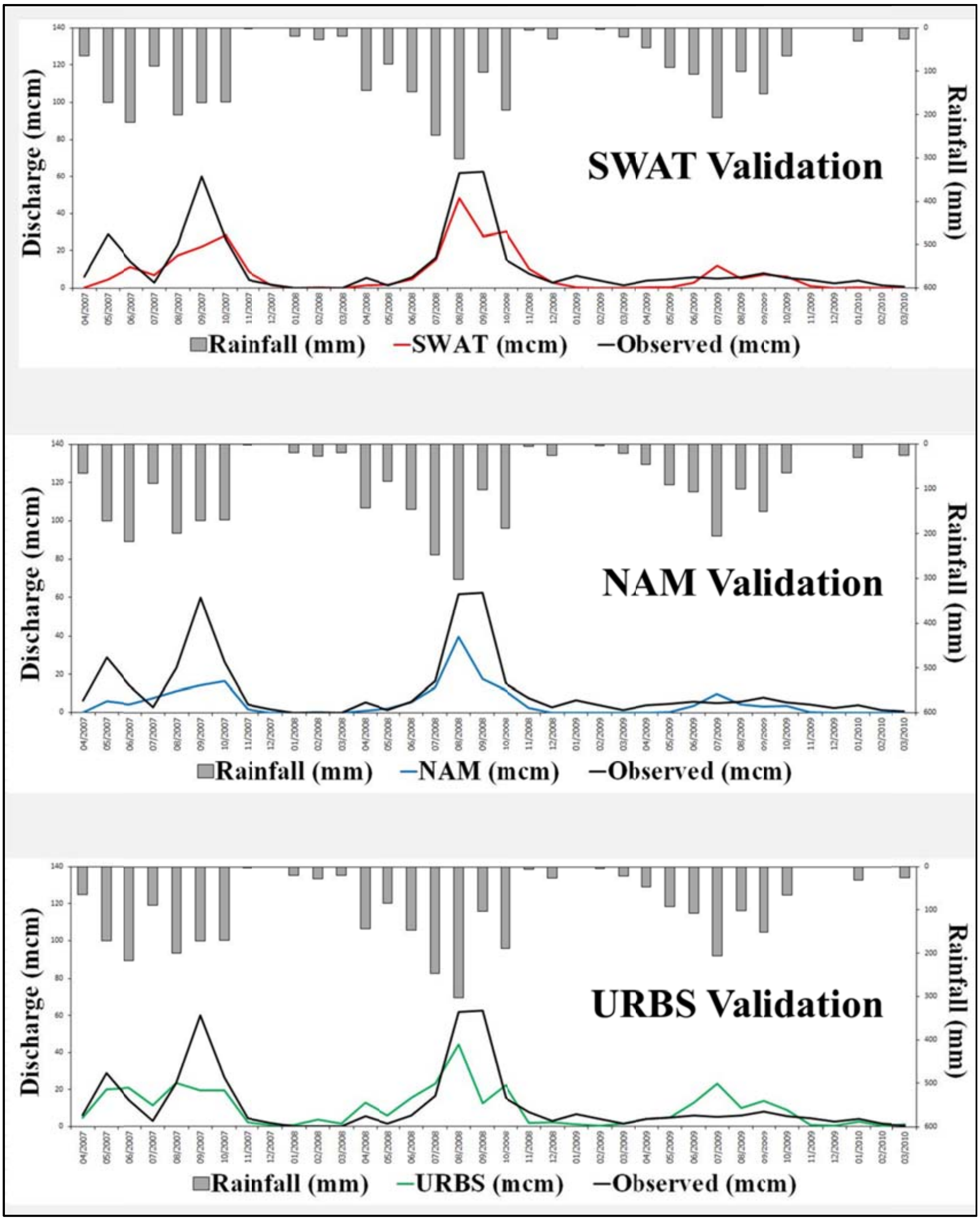

Figure 4.2 Observed and simulated daily runoff using SWAT, NAM, and URBS for the monthly validation period (water year 2002-2006)

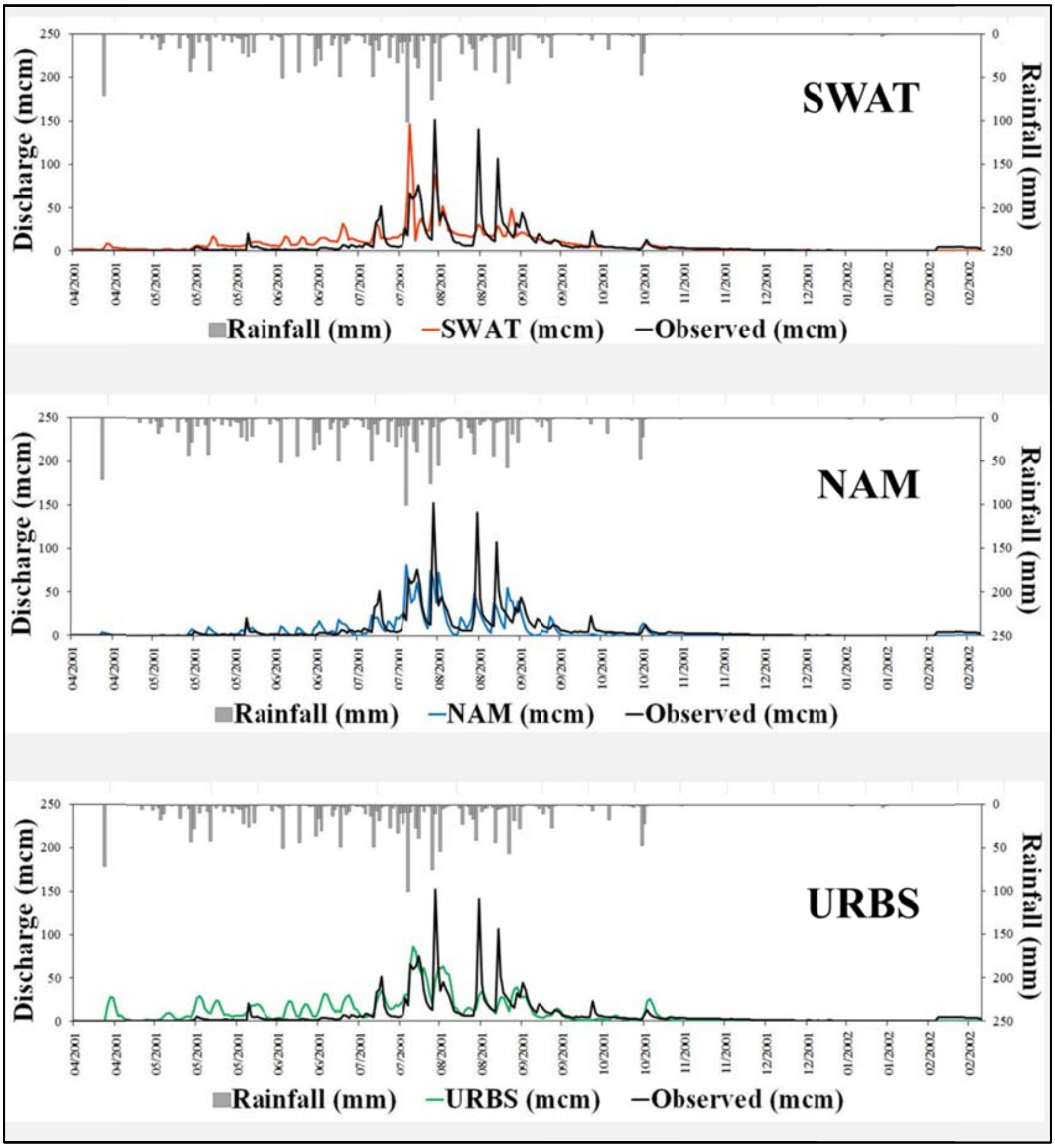

Figure 4.3 Observed and simulated daily runoff using SWAT, NAM and URBS for daily calibration period (water year 2001)

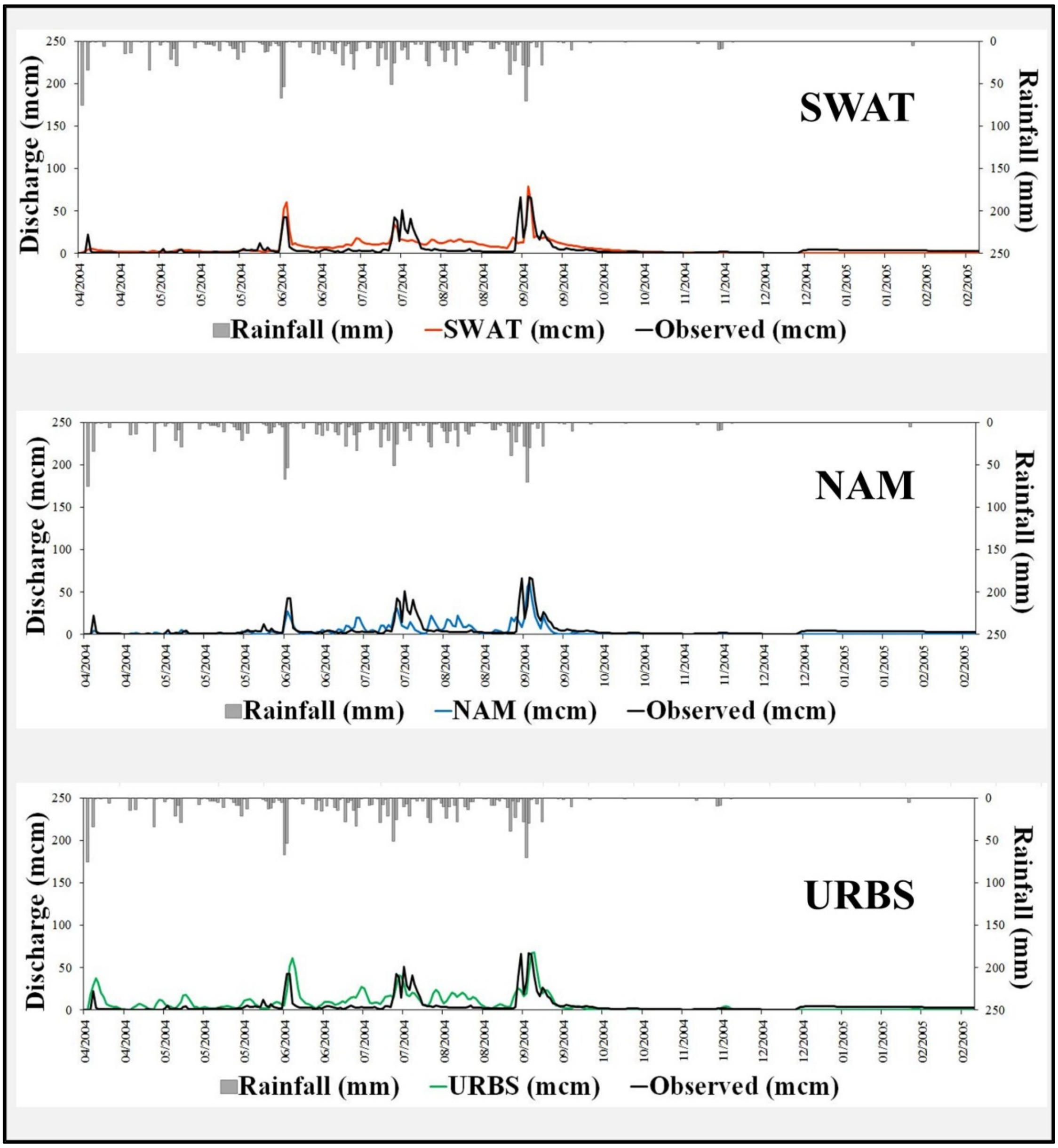

Figure 4.4 Observed and simulated daily runoff using SWAT, NAM and URBS for daily validation period (water year 2004)

The calibration parameters of the three models with respect to daily data. For monthly and daily calibration of record were split into SWAT, NAM and URBS parameters are presented in Table 4.1, Table 4.2, and Table 4.3, respectively.

Table 4.1 Final monthly and daily calibration values of performance by SWAT

	Parameter	Default value	Calibration value
		Monthly calibration	
.MGT	CN2 RNGE/Pti	79	49
	CN2 RICE/Pti	81	51
	CN2 ORCD/Pti	77	47
	CN2 ORCD/Hc	66	46
	CN2 RNGE/Ty	69	49
	CN2 CORN/Ty	77	47
.HRU	SLSUBBSN	15.244	40.244
	HRU_SLP	0.204	0.064
.GW	GW_DELAY	31	51
	ALPHA_BF	0.048	0.05
	GW_REVAP	0.02	0.2
	REVAPMN	1	0
	RCHRG_DP	0.05	0.95
.SOL	SOL_AWC	0.2	0.4
	ESCO	0.95	0.1
		Daily calibration	
.MGT	CN2 RNGE/Pti	79	49
	CN2 RICE/Pti	81	51
	CN2 ORCD/Pti	77	47
	CN2 ORCD/Hc	66	36
	CN2 RNGE/Ty	69	39
	CN2 CORN/Ty	77	47
.HRU	SLSUBBSN	15.244	40.244
	HRU_SLP	0.204	0.104

Table 4.1 Final monthly and daily calibration values of performance by SWAT (cont.)

	Parameter	Default value	Calibration value
.GW	SHALLST	0.5	900
	GW_DELAY	31	250
	GWQMN	0	50
	RCHRG_DP	0.05	0.95
.SOL	SOL_AWC/Pti	0.2	0.4
	SOL_AWC/Hc	0.14	0.34
	SOL_AWC/Ty	0.33	0.13

Table 4.2 Final monthly and daily calibration values of performance by NAM

Parameter	Default value	Monthly calibration	Daily calibration
Umax (mm)	5-35	1	1
Lmax (mm)	50-350	50	50
CQOF (-)	0.01-0.99	0.05	0.05
CKIF (hr)	500-1,000	560	700
TOF (-)	0-0.09	12	12
TIF (-)	0-0.09	0.2	0.2
TG (-)	0-0.09	12	12
CK1 (hr)	3-72	104	24
CK2 (hr)	3-72	104	24
CKBF (hr)	500-5,000	500	500

Table 4.3 Final monthly and daily calibration values of performance by URBS

Parameter	Monthly calibration	Daily calibration
α	1.2	1.2
IL	25	10
PR	0.10	0.12
IF	900	800
β	6	6
m	1	0.6

The performance of the models with respect to simulated river discharge was further examined using statistical criteria, applied to the calibration and validation periods. Model calibration and validation statistics, which are used to compare both observed and simulated flows for daily and monthly time intervals, are presented in Table 4.4 and Table 4.5. Better model performances are attained if the values of efficiency index (EI) are closer to 100%, the root mean square error (RMSE) is closer to 0 and correlation coefficient (r) is closer to 1.

Table 4.4 Monthly calibration and validation statistics for SWAT, NAM and URBS

Statistical indices	Calibration			Validation		
	SWAT	NAM	URBS	SWAT	NAM	URBS
EI	51.21	60.09	38.35	60.27	41.51	44.39
RMSE	11.47	10.37	12.89	10.46	12.70	12.38
r	0.79	0.80	0.70	0.82	0.84	0.68

Table 4.5 Daily calibration and validation statistics for SWAT, NAM and URBS

Statistical indices	Calibration			Validation		
	SWAT	NAM	URBS	SWAT	NAM	URBS
EI	45.93	46.78	41.08	45.93	45.78	22.82
RMSE	11.99	11.89	12.52	6.45	6.99	8.34

Table 4.5 Daily calibration and validation statistics for SWAT, NAM and URBS (cont.)

Statistical indices	Calibration			Validation		
	SWAT	NAM	URBS	SWAT	NAM	URBS
r	0.69	0.69	0.71	0.70	0.70	0.67

From Table 4.4 the statistical coefficients showed that the fully distributed physically-based NAM model performed better than the SWAT and URBS during calibration phase. However, with regards to the validation phase, SWAT performed better than the NAM and URBS from the statistical coefficients of EI and REMSE but not the statistical coefficients of r in which NAM is proven better. The daily calibration statistical coefficients in Table 4.5 show that the statistical coefficients of EI, RMSE, and r in NAM performed slightly better than both SWAT and URBS.

Based on EI, RMSE and r values, SWAT and NAM performed better for monthly calibration comparisons than daily calibration but URBS performed better for daily calibration comparisons than monthly calibration. This shows that although the NAM prediction follows trends in the observed data, the deviation of the results from the average is high. For daily predictions, all statistical parameters show that all three models performances obtained acceptable results.

4.2 Hydrologic model selection

According to the results of hydrologic model selection as presented in the section on the methodology for model selection is presented in Table 4.6 and Table 4.7.

Table 4.6 Score for each model and selection criterion

Selection criterion number		Score		
		SWAT	NAM	URBS
1)	EI (%)	0.00	0.25	0.00
	RMSE (m^3/s)	0.25	0.25	0.25
	r	0.50	0.75	0.50
2)		0.00	0.00	0.25
3)	Input	0.50	0.50	0.00
	Output	0.50	1.00	0.50
4)		0.00	1.00	0.00
5)		0.50	0.50	0.50
6)		1.00	0.50	0.50

Table 4.7 Final score for each model and selection criterion

Selection criterion number	Weight factor	SWAT	NAM	URBS
1)	3.0	0.75	1.25	0.75
2)	2.0	0.0	0.0	0.5
3)	2.0	1.0	1.5	0.5
4)	1.0	0.00	1.00	0.00
5)	1.0	0.50	0.50	0.50
6)	1.0	1.00	0.50	0.50
Total	**10.0**	**3.25**	**4.75**	**2.75**

These criteria assign scores to each model and the model with the highest score will be chosen for runoff estimation. From Table 4.7, NAM is most appropriate hydrologic model for runoff estimation under conditions of this research selection criterion in Phee River basin, Thailand are statistical indicators, efficiency of model input and output facilities, and width of application of model on river basins. The highest scores for selection criterion of SWAT and URBS are accessibility of concept, theory, user manual, source code of the models and economics, respectively.

4.3 Discussion

The hydrologic models (SWAT, NAM, and URBS) have become increasingly popular in estimating runoff characteristics for drainage sub-basin for water resources. The calibration of these hydrologic models needs to incorporate both theory and knowledge in several fields, which includes computer science, and GIS technology. However, the calibration of some previous applications was based on older hydrologic models theory and computer science, and not based on recent theories and technologies.

CHAPTER V
CONCLUSION

The conclusion and recommendation for the study on “Runoff estimation using hydrological models in Phee River basin, Thailand” are as stated below.

5.1 Conclusion

The objectives of this paper are to evaluate the statistical indicators between the SWAT, NAM, and URBS models for runoff estimation and select the most suitable hydrologic model for Phee River basin. The observed mean daily discharge was utilized to examine the performance of the fully distributed SWAT, NAM and URBS. All three models require a fair amount of input and model parameters. For their advantages and limitations to be understood, these widely used watershed management models were analyzed using the same flow data obtained from a gauging station at the outlet of the Phee River basin in Prayao and Nan provinces, Thailand. The performance of the three models was tested using both qualitative (graphical) and quantitative (statistical) methods.

To compare the three models, the data from the discharge monitored at the Y.24 station, located at the outlet of Phee River basin, for the period of 2000-2009 was used. One year of data was used to initialize the models, while from the ten-year record of daily discharge values, five years were used for calibration of the models and the remaining three years to validate them.

All three models are able to simulate the hydrology of the watershed adequately. The calibration results for the three models were comparable, though the concept and spatial distribution in the models were dissimilar. Notwithstanding their similarity in modeling capabilities, a comparative analysis showed the NAM to be slightly better at predicting the overall variation in streamflow under conditions of this research selection criterion in Phee River basin, Thailand are statistical indicators, efficiency of model input and output facilities, and width of application of model on river basins. The second suitable model was SWAT; its performance only differed from that of NAM in the validation period. URBS performance in predicting daily mean streamflow was not as effective as that of the other models. Therefore, it can be concluded that the NAM is the most suitable model to estimate runoff, after taking into account factors such as statistical indicators, efficiency of model input and output facilities, width of application of model on river basins, and availability of input data from Thailand river basins. The SWAT and URBS are suitable models under conditions of accessibility of concept, theory, user manual, source code of the models and economical, respectively. And all three models good in availability of input data from Thailand river basins.

5.1.1 Strengths

In this paper, three models are used to construct the rainfall-runoff model. The fully supervised learning calibration is presented for the parametric estimation of Phee River basin. Based on the data obtained from this study, the results show that the SWAT, NAM, and URBS can be successfully applied to attain runoff estimation in Phee River basin. The values from the statistical indicators, as well as economic comparisons, suitability, and limitations also provide future forecasts for suitable development.

5.1.2 Limitations

This study has also considered the ability of rainfall-runoff models to simulate daily and monthly runoff in Phee River basin. The limitations of NAM and URBS are that they are lumped conceptual models, and their disadvantages include the ability to only calibration basins of small size. On the other hand, SWAT is a semi-distributed conceptual model, and it is advantageous in the sense that it was applied in the region for which it was specifically developed. However, the SWAT model requires more input data for it to be accurate. The objective of this paper is not to determine which of these models is superior. Rather, the purpose was to ascertain how well these three models fare in Phee River basin based on various selection criteria, inclusive of statistical indicators, economical, efficiency of model input and output facilities, width of application of model on river basins, availability of input data from Thailand river basins, and accessibility of concept, theory, user manual and source code of the models.

5.2 Recommendation

1) The literature on Accessibility of concept, theory, user manual and source code of the models of hydrologic models are also relatively few. An increase in this field will aid future studies.

2) The literature of Phee River basin in runoff estimation is limited and an improvement in the area will be of benefit.

3) In future work, for other research can set the other weight factor under condition with fits to runoff estimation of study area.

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APPENDICES

APPENDIX A
RAW DATA OF PHEE RIVER BASIN

Table A.1 Land use in Phee River basin

Land use categories	Area (km^2)	Land use categories	Area (km^2)
Dense deciduous forest	181.00	Upland rice	0.36
Dense forest Plantation	121.00	Mixed orchard	0.34
Dense evergreen forest	55.00	Rain tree	0.26
Corn(Swidden cultivation)	48.20	Mango	0.23
Corn	43.01	Pasture	0.20
Rice paddy	28.63	Eucalyptus	0.15
Disturbed deciduous forest	26.62	Disturbed evergreen forest	0.14
Tamarind	13.27	Orange	0.12
Bush fallow/Disturbed deciduous fo	11.01	Grass	0.10
Longan	8.38	Mango/Tamarind	0.09
Bush fallow	6.72	Mulberry	0.03
Corn/Upland rice	5.23	Banana	0.03
Teak	3.74	Dragon fruit	0.03
Scrub	2.84	Health center	0.02
Para rubber	2.31	Cassava	0.02
Bush fallow/Corn(Swidden cultivati	1.29	Tamarind/Pomelo	0.02
Corn/Truck crop	1.26	Para rubber/Agalloch	0.02
Marsh and Swamp+Corn	0.94	Bamboo	0.02
Abandoned field crop/Corn	0.70	Tamarind/Teak	0.01
Litchi	0.38	Papaya	0.01

Table A.2 Agricultural Land Use (Land Development Department, 2008)

Land use Code	Land use types
AGRL	Cassava
AGRR	Eucalyptus Eucalyptus
BANA	Banana
CORN	Corn
FLAX	Cotton
FRSD	Deciduous waiting rejuvenating
FRSE	Completely deciduous
FRST	Completely evergreen
ORCD	Mixed fruit
PAST	Pasture
PEPR	Pepper
PINE	Mixed perennials
PNUT	Peanuts
RICE	Paddy
RNGE	Meadow
RUBR	Rubber tree
SGHY	Sorghum
SUGC	Cane
UCOM	Downtown and commercial district
UIDU	Industrial factory
UINS	Government and Institutions
URBN	Village
URLD	Recreation facilities
UTRN	Road
WATR	Water
WETF	Coppice wood
WETL	Lowland
WETN	Reclamation area

Table A.3 Monthly runoff at Y.24

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual runoff (mcm)	Average annual runoff (cum/s)
2000	4.08	17.03	7.97	11.32	24.62	24.71	18.27	6.77	1.73	0.79	0.23	2.90	120.40	3.82
2001	0.87	3.49	7.03	24.10	100.28	56.97	15.24	8.18	3.33	1.81	0.25	0.00	221.53	7.02
2002	0.22	20.17	6.30	6.76	26.90	55.99	15.14	8.00	5.65	2.14	0.86	1.32	149.45	4.74
2003	1.27	1.38	5.80	6.64	29.65	64.17	8.79	3.52	1.40	0.40	0.37	0.13	123.50	3.92
2004	4.21	5.05	18.76	23.70	20.03	44.88	6.52	3.25	4.34	11.10	7.93	6.86	156.63	4.97
2005	3.86	7.38	5.70	4.00	22.10	57.10	18.02	4.17	3.15	1.90	2.67	2.18	132.22	4.19
2006	3.60	20.65	5.84	4.31	62.10	52.33	12.92	4.08	1.06	0.32	0.27	0.28	167.77	5.32
2007	6.12	28.92	14.11	3.04	23.53	59.90	26.22	4.42	1.74	0.08	0.10	0.15	168.32	5.34
2008	5.64	1.47	5.79	16.46	61.76	62.51	15.34	7.60	2.91	6.45	4.18	1.48	191.60	6.08
2009	4.19	4.59	5.69	5.08	5.92	8.22	5.65	4.51	2.68	4.04	1.57	0.73	52.88	1.68

APPENDIX B
SWAT

Table B.1 SWAT input files list

Level	File type	Descriptions
Watershed	file.cio	Master watershed file. This required file contains the names of watershed level files and parameters related to printing.
	.fig	Watershed configuration file. This required file defines the routing network in the watershed and listed input file names for different objects in the watershed
	.pcp	Basin input file. This required file defines values or options used to model physical processes uniformly over the entire watershed.
	.tem	Temperature input file. This optional file contains daily measured max and min temperature for a measuring gage. Up to 18 precipitation files may be used in each simulation and each file can hold data for up to 150 stations.
	.slr	Solar radiation input file. This optional file contains daily solar radiation for a measuring gage. The solar radiation file can hold data for up to 300 stations.
	.wnd	Wind speed input file. This optional file contains daily average wind speed for a measuring gage. The wind speed file can hold data for up to 30 stations.
	.hum	Relative humidity input file. This optional file contains daily relative humidity values for a measuring gage. This file can hold up to 300 stations

Table B.1 SWAT input files list (cont.)

Level	File type	Descriptions
Watershed	.pet	Potential evapotranspiration input file. This optional file contains daily PET values for the watershed.
	.cst	Weather forecast input file. Optional
	.cal	Auto-calibration input file. Optional
	crop.dat	Land cover/plant growth database file. This required file contains plant growth parameters for all land covers simulated in the watershed.
	till.dat	Tillage database file. This required file contains information on the amount and depth of mixing caused by tillage operations simulated in the watershed
	pest.dat	Pesticide database file. This required file contains information on mobility and degradation for all pesticides simulated in the watershed.
	fert.dat	Fertilizer database file. This required file contains information on the nutrient content of all fertilizers and manures simulated in the watershed.
	urban.dat	Urban database file. This required file contains information on the building-up/ wash-off of solids in urban areas simulated in the watershed.
Sub-basin	.sub	Sub-basin input file. This required file for each sub-basin defines climatic inputs, tributary channel attributes, and the number and types of HURs in the sub-basin.
	.wgn	Weather generator input file. This required file contains the statistical data needed to generate representative daily climatic data for a sub-basin.
	.pnd	Pond/wetland input file. Optional
	.rte	Main channel input file. This required file contains parameters governing water and sediment movement in the main channel of a subbasin

Table B.1 SWAT input files list (cont.)

Level	File type	Descriptions
Sub-basin	.wus	Water use input file. Optional
	.wwq	Watershed water quality input file. Optional
	.swq	Stream water quality input file. Optional
	.hur	HRU input file. Required file for HUR level parameters. Catch-all file.
HRU	.hru	HRU input file. Required file for HUR level parameters. Catch-all file.
	.mgt	Management input file. This required file contains management scenario and specifies the land cover simulated in the HRU.
	.sol	Soil input file. This required file contains information about initial nutrient and pesticide levels of the soil in the HRU.
	.chm	Soil chemical in put file. Optional
	.gw	Groundwater input file. This required file contains information about the shallow and deep aquifer in the sub-basin.
	.res	Reservoir input file. Optional
	.lwq	Lake water quality input file. Optional

Table B.2 SWAT parameters description in Phee River basin

File Type	Variable Name	Definition
.Hru	SLSUBBSN	Average slope length (m). This is the distance that sheet flow is the dominant surface runoff flow process. Slope length should be measured to the point that flow begins to concentrate. This length is easily observable after a heavy rain on a fallow field when the rills are well developed. In this situation, the slope length is the distance from the

Table B.2 SWAT parameters description in Phee River basin (cont.)

File Type	Variable Name	Definition
.Hru	SLSUBBSN	microwatershed divide to the origin of the rill. This value can also be determined from topographic maps. Terraces divide the slope of the hill into segments equal to the horizontal terrace interval. With terracing, the slope length is the terrace interval. For broadbase terraces, the horizontal terrace interval is the distance from the center of the ridge to the center of the channel for the terrace below. The horizontal terrace interval for steep backslope terraces is the distance from the point where cultivation begins at the base of the ridge to the base of the frontslope of the terrace below.
	HRU_SLP	Average slope steepness (m/m). The GIS interfaces will assign the same value to this variable for all HRUs within a sub-basin. However, some users like to vary this value by soil type and land cover.
.Mgt	CN2	Initial SCS runoff curve number for moisture condition II. The SCS curve number is a function of the soil’s permeability, land use and antecedent soil water conditions. Typical curve numbers for moisture condition II are listed in the following tables for various land covers and soil types. These values are appropriate for a 5% slope. The curve number may be updated in plant, tillage, and harvest kill operations. If CNOP is never

Table B.2 SWAT parameters description in Phee River basin (cont.)

File Type	Variable Name	Definition
.Mgt	CN2	defined for these operations, the value set for CN2 will be used throughout the simulation. If CNOP is defined for an operation, the value for CN2 is used until the time of the operation containing the first CNOP value. From that point on, the model only uses operation CNOP values to define the curve number for moisture condition II. Values for CN2 and CNOP should be entered for pervious conditions. In HRUs with urban areas, the model will adjust the curve number to reflect the impact of the impervious areas.
.Gw	SHALLST	Initial depth of water in the shallow aquifer (mm H_2O). We recommend using a 1 year equilibration period for the model where the watershed simulation is set to start 1 year prior to the period of interest. This allows the model to get the water cycling properly before any comparisons between measured and simulated data are made. When an equilibration period is incorporated, the value for SHALLST is not that important.
	GW_DELAY	Groundwater delay time (days). Water that moves past the lowest depth of the soil profile by percolation or bypass flow enters and flows through the vadose zone before becoming shallow aquifer recharge. The lag between the time that water exits the soil profile and enters

Table B.2 SWAT parameters description in Phee River basin (cont.)

File Type	Variable Name	Definition
.Gw	GW_DELAY	the shallow aquifer will depend on the depth to the water table and the hydraulic properties of the geologic formations in the vadose and groundwater zones. The delay time, δ_{gw}, cannot be directly measured. It can be estimated by simulating aquifer recharge using different values for δ_{gw} and comparing the simulated variations in water table level with observed values.
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O). Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than GWQMN
	RCHRG_DP	The fraction of percolation from the root zone which recharges the deep aquifer. The value for RCHRG_DP should be between 0.0 and 1.0.
.Sol	SOL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil). The plant available water, also referred to as the available water capacity, is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity, $AWC = FC - WP$ where AWC is the plant available water field capacity,

Table B.2 SWAT parameters description in Phee River basin (cont.)

File Type	Variable Name	Definition
.Sol	SOL_AWC	and *WP* is the water content at permanent wilting point. Available water capacity is estimated by determining the amount of water released between in situ field capacity and the permanent wilting.
	ESCO	Soil evaporation compensation factor. This coefficient has been incorporated to allow the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks. ESCO must be between 0.01 and 1.0. As the value for ESCO is reduced, the model is able to extract more of the evaporative demand from lower levels. If no value for ESCO is entered, the model will set ESCO = 0.95. The value for ESCO may be set at the watershed or HRU level

Table B.3 and Table B.4 shown lists all the default plant species and all the generic land covers included in the database respectively. When adding a new plant/land cover to the database, a review of existing literature should provide adequate parameter values needed to simulate plant growth. For users that plan to collect the data directly, the following sections explain the methods used to obtain the plant growth parameters needed by SWAT briefly.

Table B.3 Plants included in plant growth database (User Manual of SWAT)

Common Name	Plant Code	Taxonomic Name	Plant type
Corn	CORN	Zea mays L.	warm season annual
Corn silage	CSIL	Zea mays L.	warm season annual
Sweet corn	SCRN	Zea mays L. saccharata	warm season annual
Eastern gamagrass	EGAM	Tripsacum dactyloides (L.) L.	perennial
Grain sorghum	GRSG	Sorghum bicolor L. (Moench)	warm season annual
Sorghum hay	SGHY	Sorghum bicolor L. (Moench)	warm season annual
Johnsongrass	JHGR	Sorghum halepense (L.) Pers.	perennial
Sugarcane	SUGC	Saccharum officinarum L.	perennial
Spring wheat	SWHT	Triticum aestivum L.	cool season annual
Winter wheat	WWHT	Triticum aestivum L.	cool season annual
Durum wheat	DWHT	Triticum durum Desf.	cool season annual
Rye	RYE	Secale cereale L.	cool season annual
Spring barley	BARL	Hordeum vulgare L.	cool season annual
Oats	OATS	Avena sativa L.	cool season annual
Rice	RICE	Oryza sativa L.	warm season annual
Pearl millet	PMIL	Pennisetum glaucum L.	warm season annual
Timothy	TIMO	Phleum pratense L.	perennial
Smooth bromegrass	BROS	Bromus inermis Leysser	perennial
Meadow bromegrass	BROM	Bromus biebersteinii Roemer & Schultes	perennial
Tall fescue	FESC	Festuca arundinacea	perennial
Kentucky bluegrass	BLUG	Poa pratensis	perennial
Bermudagrass	BERM	Cynodon dactylon	perennial
Crested wheatgrass	CWGR	Agropyron cristatum (L.) Gaertner	perennial

Table B.3 Plants included in plant growth database (User Manual of SWAT) (cont.)

Common Name	Plant Code	Taxonomic Name	Plant type
Western wheatgrass	WWGR	Agropyron smithii (Rydb.) Gould	perennial
Slender wheatgrass	SWGR	Agropyron trachycaulum Malte	perennial
Italian (annual) ryegrass	RYEG	Lolium multiflorum Lam.	cool season annual
Russian wildrye	RYER	Psathyrostachys juncea (Fisch.) Nevski	perennial
Altai wildrye	RYEA	Leymus angustus (Trin.) Pilger	perennial
Sideoats grama	SIDE	Bouteloua curtipendula (Michaux) Torrey	perennial
Big bluestem	BBLS	Andropogon gerardii Vitman	perennial
Little bluestem	LBLS	Schizachyrium scoparium (Michaux) Nash	perennial
Alamo switchgrass	SWCH	Panicum virgatum L.	perennial
Indiangrass	INDN	Sorghastrum nutans (L.) Nash	perennial
Alfalfa	ALFA	Medicago sativa L.	perennial legume
Sweetclover	CLVS	Melilotus alba Med.	perennial legume
Red clover	CLVR	Trifolium pratense L.	cool season annual legume
Alsike clover	CLVA	Trifolium hybridum L.	perennial legume
Soybean	SOYB	Glycine max L., Merr.	warm season annual legume
Cowpeas	CWPS	Vigna sinensis	warm season annual legume
Mung bean	MUNG	Phaseolus aureus Roxb.	warm season annual legume
Lima beans	LIMA	Phaseolus lunatus L.	warm season annual legume
Lentils	LENT	Lens esculenta Moench J.	warm season annual legume
Peanut	PNUT	Arachis hypogaea L.	warm season annual legume

Table B.3 Plants included in plant growth database (User Manual of SWAT) (cont.)

Common Name	Plant Code	Taxonomic Name	Plant type
Field peas	FPEA	Pisum arvense L.	cool season annual legume
Garden or canning peas	PEAS	Pisum sativum L. ssp. sativum	cool season annual legume
Sesbania	SESB	Sesbania macrocarpa Muhl [exaltata]	warm season annual legume
Flax	FLAX	Linum usitatissum L.	cool season annual
Tobacco	TOBC	Nicotiana tabacum L.	warm season annual
Sugarbeet	SGBT	Beta vulgaris (saccharifera) L.	warm season annual
Upland cotton (harvested with stripper)	COTS	Gossypium hirsutum L.	warm season annual
Upland cotton (harvested with picker)	COTP	Gossypium hirsutum L.	warm season annual
Potato	POTA	Solanum tuberosum L.	cool season annual
Sweetpotato	SPOT	Ipomoea batatas Lam.	warm season annual
Carrot	CRRT	Daucus carota L. subsp. sativus (Hoffm.) Arcang.	cool season annual
Onion	ONIO	Allium cepa L. var cepa	cool season annual
Sunflower	SUNF	Helianthus annuus L.	warm season annual
Spring canola-Polish	CANP	Brassica campestris	cool season annual
Spring canola-Argentine	CANA	Brassica napus	cool season annual
Asparagus	ASPR	Asparagus officinalis L.	perennial
Broccoli	BROC	Brassica oleracea L. var italica Plenck.	cool season annual

Table B.3 Plants included in plant growth database (User Manual of SWAT) (cont.)

Common Name	Plant Code	Taxonomic Name	Plant type
Cabbage	CABG	Brassica oleracea L. var capitata L.	perennial
Cauliflower	CAUF	Brassica oleracea L. var botrytis L.	cool season annual
Celery	CELR	Apium graveolens L. var dulce (Mill.) Pers.	perennial
Head lettuce	LETT	Lactuca sativa L. var capitata L.	cool season annual
Spinach	SPIN	Spinacia oleracea L.	cool season annual
Green beans	GRBN	Phaseolus vulgaris	warm season annual legum
Cucumber	CUCM	Cucumis sativus L.	cool season annual
Eggplant	EGGP	Solanum melongena L.	warm season annual
Cantaloupe	CANT	Cucumis melo L. Cantaloupensis group	warm season annual
Honeydew melon	HMEL	Cucumis melo L. Inodorus group	warm season annual
Apple	APPL	Malus domestica Borkh.	trees
Watermelon	WMEL	Citrullus lanatus (Thunb.) Matsum and Nakai	warm season annual
Bell pepper	PEPR	Capsicum annuum L. Grossum group	warm season annual
Strawberry	STRW	Fragaria X Ananassa Duchesne.	perennial
Tomato	TOMA	Lycopersicon esculentum Mill.	warm season annual
Pine	PINE	Pinus	trees
Oak	OAK	Quercus	trees
Poplar	POPL	Populus	trees

Table B.4 Generic Land covers included in database

Name	Plant Code	Origin of Plant Growth Values	Plant type
Agricultural Land-Generic	AGRL	use values for Grain Sorghum	warm season annual
Agricultural Land-Row Crops	AGRR	use values for Corn	warm season annual
Agricultual Land-Close-grown	AGRC	use values for Winter Wheat	cool season annual
Orchard	ORCD	use values for Apples	trees
Hay	HAY	use values for Bermudagrass	perennial
Forest-mixed	FRST	use values for Oak	trees
Forest-deciduous	FRSD	use values for Oak	trees
Forest-evergreen	FRSE	use values for Pine	trees
Wetlands	WETL	use values for Alamo Switchgrass	perennial
Wetlands-nonforested	WETN	use values for Alamo Switchgrass	perennial
Wetlands-forested	WETF	use values for Oak	trees
Pasture	PAST	use values for Bermudagrass	perennial
Summer pasture	SPAS	use values for Bermudagrass	perennial
Winter pasture	WPAS	use values for Fescue	perennial
Range-grasses	RNGE	use values for Little Bluestem (LAImax=2.5)	perennial

Table B.4 Generic Land covers included in database (cont.)

Name	Plant Code	Origin of Plant Growth Values	Plant type
Range-brush	RNGB	use values for Little Bluestem (*LAImax*=2.0)	perennial
Range-southwestern US	SWRN	use values for Little Bluestem (*LAImax*=1.5)	perennial
Water	WATR		not applicable

For catchment the long-term period the observed and simulated daily runoff in Phee River basin using SWAT for the monthly and daily calibration periods, respectively are presented in Figure B.1 and Figure B.2

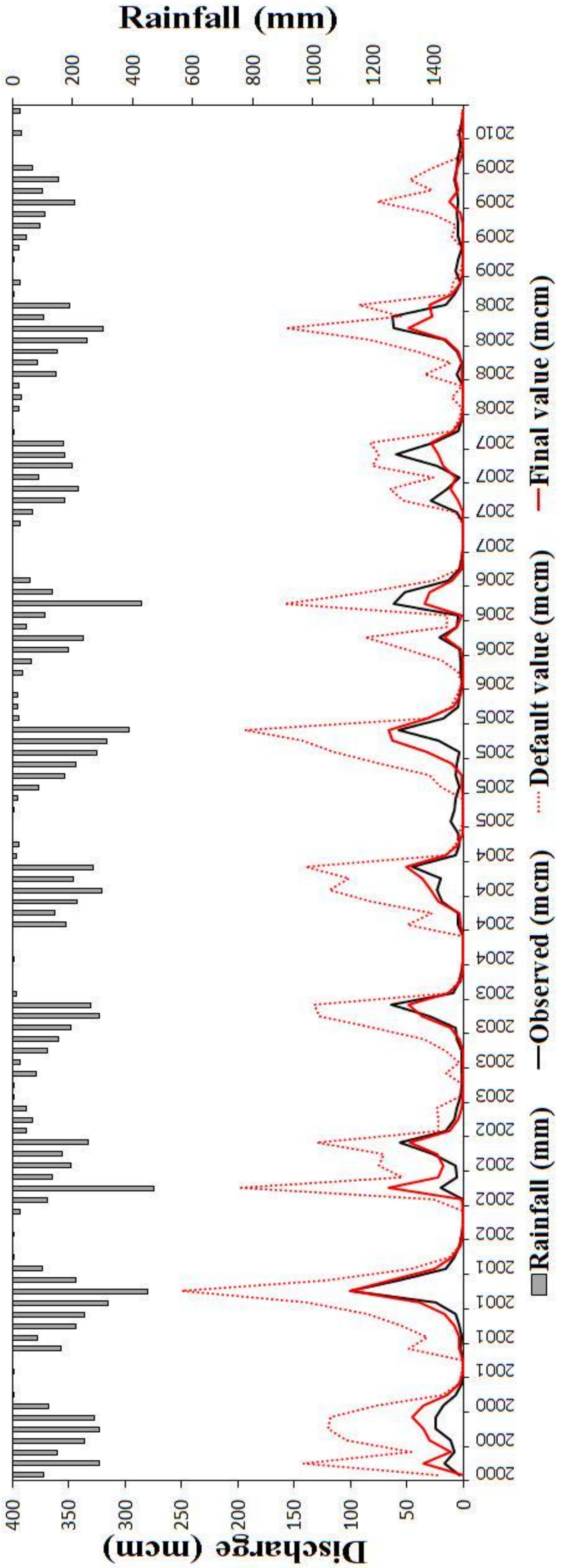

Figure B.1 Observed and simulated daily runoff using SWAT for the monthly calibration period (year 2000-2009)

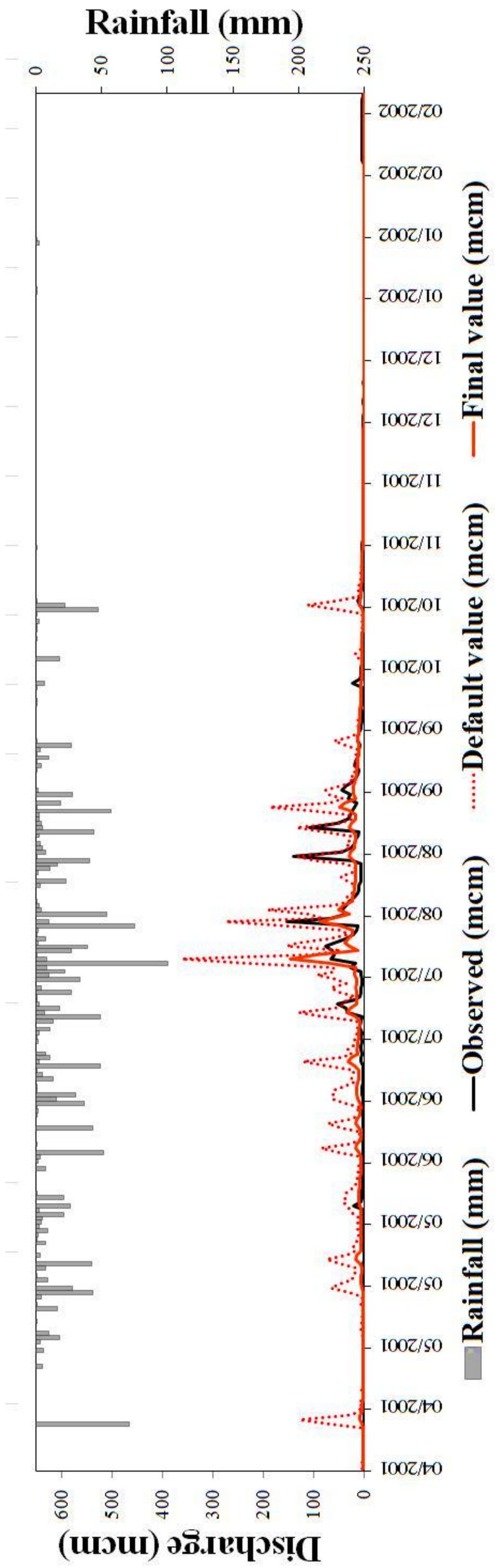

Figure B.2 Observed and simulated daily runoff using SWAT for the daily calibration using period (year 2001)

APPENDIX C
NAM

Figure C.1 and Figure C.2 presented the final value the simulated daily runoff in Phee River basin using NAM for the monthly and daily calibration periods, respectively.

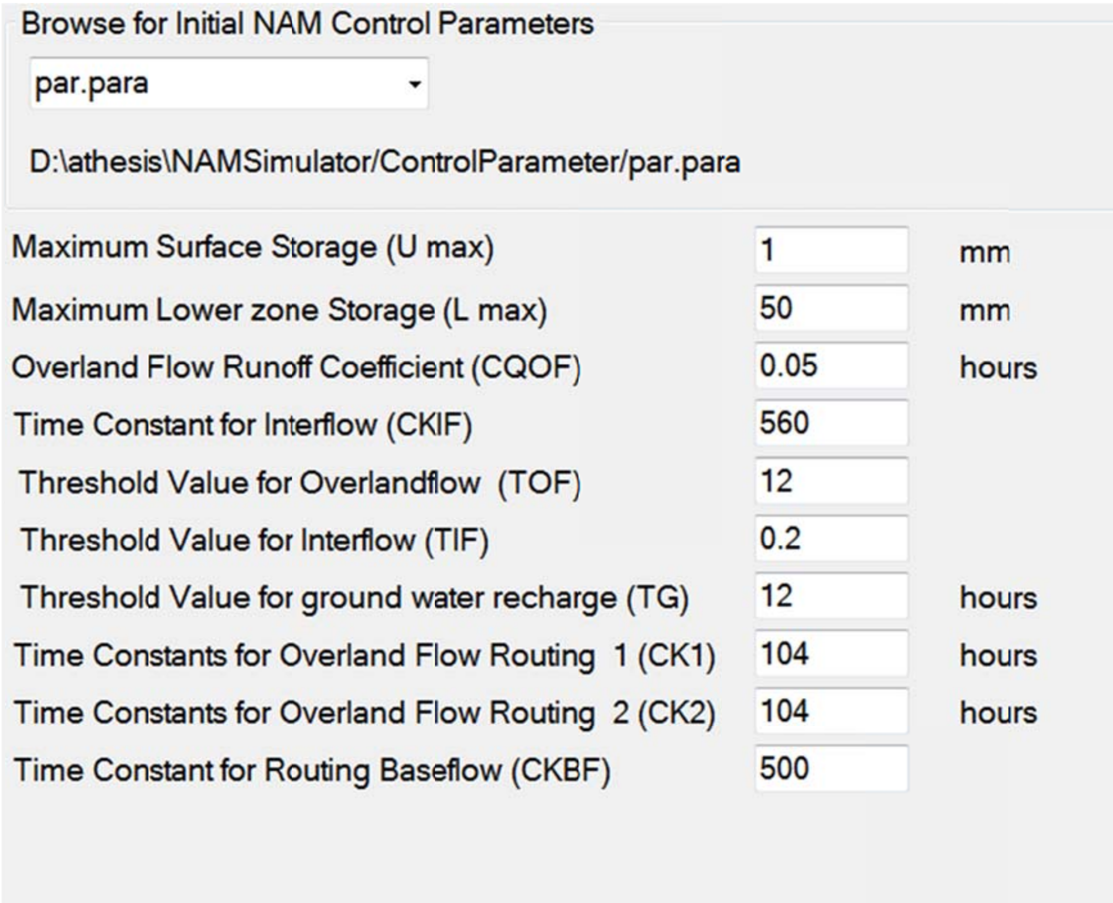

Figure C.1 Final value the simulated daily runoff in Phee River basin using NAM for the monthly calibration period (year 2002-2006)

Maximum Surface Storage (U max)	1	mm
Maximum Lower zone Storage (L max)	50	mm
Overland Flow Runoff Coefficient (CQOF)	0.05	hours
Time Constant for Interflow (CKIF)	700	
Threshold Value for Overlandflow (TOF)	12	
Threshold Value for Interflow (TIF)	0.2	
Threshold Value for ground water recharge (TG)	12	hours
Time Constants for Overland Flow Routing 1 (CK1)	24	hours
Time Constants for Overland Flow Routing 2 (CK2)	24	hours
Time Constant for Routing Baseflow (CKBF)	500	

Figure C.2 Final value the simulated daily runoff in Phee River basin using NAM for the daily calibration period (2001)

Figure C.3 and Figure C.4 presented the long-term period the observed and simulated daily runoff in Phee River basin using NAM for the monthly and daily calibration periods, respectively.

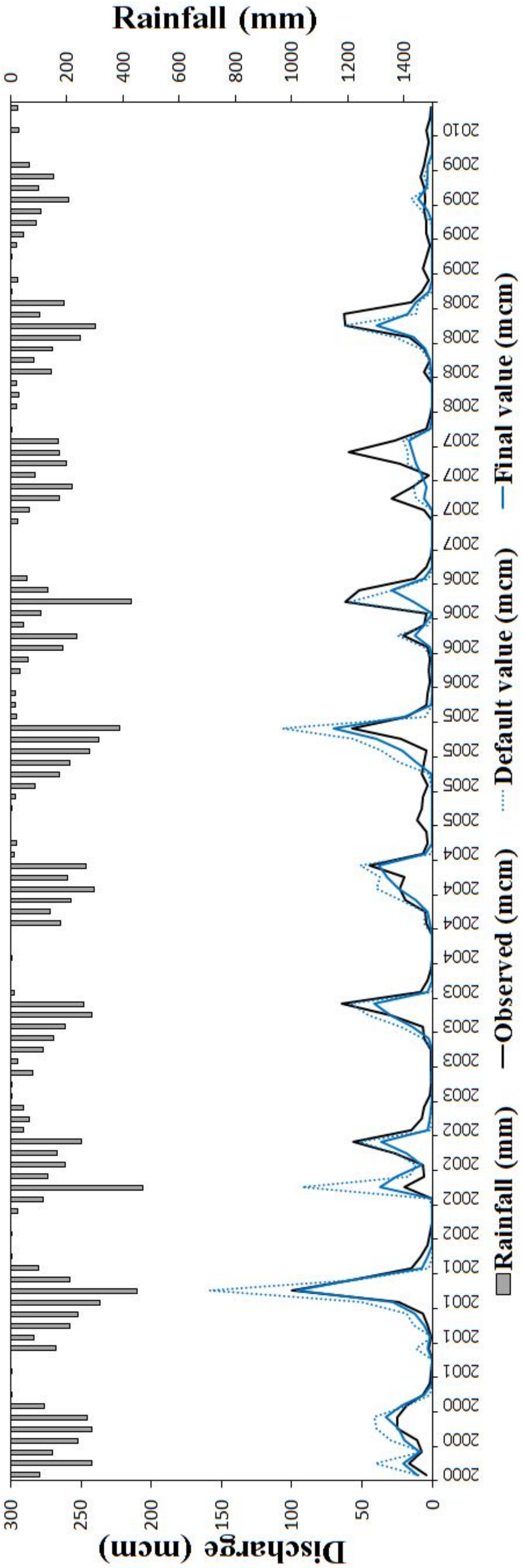

Figure C.3 Observed and simulated daily runoff using NAM for the monthly calibration period (year 2000-2009)

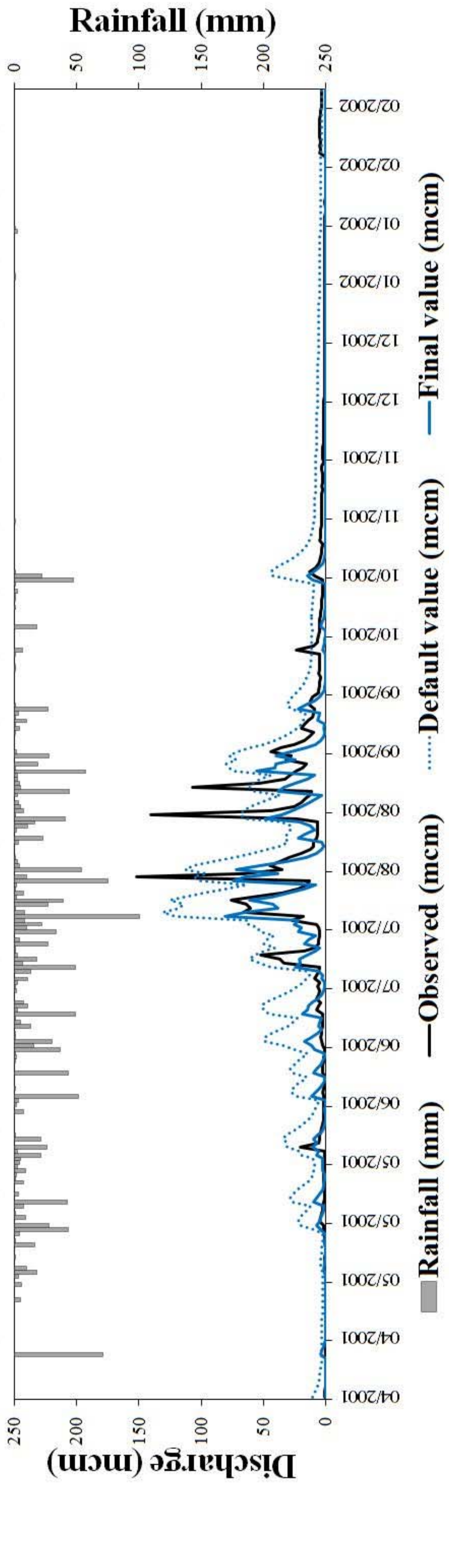

Figure C.4 Observed and simulated daily runoff using NAM for the daily calibration using period (year 2001)

APPENDIX D
URBS

Input file of Phee River basin using URBS at Y.24, the catchment definition file will be based on the parameters specified on the default parameters line as described below.

Phee River Basin at Y.24 (2000)
MODEL: SPLIT
USES: L
DEFAULT PARAMETERS: alpha = 0.2 m = 0.8 beta = 5 x = 0.3 n = 1
DEFAULT PARAMETERS: if = 300 k = 0.9
DEFAULT PARAMETERS: BR = 0.985 BC = 0.001 BM = 1

9 SUBAREAS OF AREA:
37.5 44.9 75.9 52.1 100.5 79.4 81.9 75.1 79.8
{**}
RAIN #1 L = 6.17
STORE.
RAIN #2 L = 7.46
GET.
ROUTE L = 4.45
ADD RAIN #3 L = 9.53
STORE.
RAIN #4 L = 12.70
STORE.
RAIN #5 L = 6.67
GET.
ROUTE L = 1.40
ADD RAIN #6 L = 6.15

```
GET.
ROUTE              L = 7.49
ADD RAIN    #7     L = 5.87
STORE.
RAIN        #8     L = 12.84
GET.
ROUTE              L = 5.82
ADD RAIN    #9     L = 6.61
PRINT. Y24
END OF CATCHMENT DATA.

9 PLUVIOGRAPHS:
LOCATION. RY24-1
  1 SUBAREAS:
  1
LOCATION. RY24-2
  1 SUBAREAS:
  2
LOCATION. RY24-3
  1 SUBAREAS:
  3
LOCATION. RY24-4
  1 SUBAREAS:
  4
LOCATION. RY24-5
  1 SUBAREAS:
  5
LOCATION. RY24-6
  1 SUBAREAS:
  6
LOCATION. RY24-7
  1 SUBAREAS:
```

7
LOCATION. RY24-8
1 SUBAREAS:
8
LOCATION. RY24-9
1 SUBAREAS:
9
END OF PLUVIOGRAPH DATA.

1 GAUGING STATION:
LOCATION. Y24
END OF GAUGING STATIONS DATA.

The Rainfall definition file will include a range of evaluation, file name, and rainfall station as described below.

Phee River Basin at Y.24 (2000)
CALIBRATION RUN
TIME INCREMENT: 24.0 HOURS
RUN DURATION: 87648.0 HOURS
PLUVIOGRAPH. RY24-1
PLUVIOGRAPH. RY24-2
PLUVIOGRAPH. RY24-3
PLUVIOGRAPH. RY24-4
PLUVIOGRAPH. RY24-5
PLUVIOGRAPH. RY24-6
PLUVIOGRAPH. RY24-7
PLUVIOGRAPH. RY24-8
PLUVIOGRAPH. RY24-9
LOSS: UNIFORM PROPORTIONAL

The 'ini' file is a parameter file that contains environment variable settings as well as parameter specifications. Parameters set the in the ini file override those specified in the catchment definition and rainfall definition file, but are overwritten by command line parameters. The parameters that can specified in the ini file are identical to those that can be set using the alpha mode for the command line mode, with the exception of the hot start file specification. However, the names of the parameters are different to reflect the names of other environment variables that can be specified in the ini file - ie the names are preceded with URBS. The list of ini file variable names are given in Table D.1.

Table D.1 Parameter Specification Methods

Parameter	Cmd line - Numeric (1)	Command Line – alpha (1)	INI FILE (2)	Default (3)	Affects	Typical Range
Alpha	4th parm	Alpha=n.n	URBS_ALPHA	Alpha=n.n (CDF)	Channel|Catchment routing	0.03 – 0.2
N	N/A	N=n.n	URBS_N	N=n.n (CDF)	Channel routing exp 1/(km/h)	0.8 - 1
M	5th parm	M=n.n	URBS_M	M=n.n (CDF)	Catchment routing exponent	0.6-1
Beta	6th parm	Beta=n.n	URBS_BETA	Beta=n.n (CDF)	Catchment Routing	1 – 9
Il	7Th parm	IL=n.n	URBS_IL	Il=n.n (RDF)	Initial Loss mm	0-100
IlMax	N/A	ILmax=n.n	URBS_ILMX	N/A	Maximum Initial Loss mm	0-100
Cl	8th parm	Cl=n.n | lp=n.n	URBS_CL	Cl=n.n (RDF)	Continuing loss mm/hr	0-5
Rf	9th parm	Rf= n.n	URBS_RF	Rf= n.n (RDF)	Recovery Factor	0-1
If	N/A	IF= n.n	URBS_IF	IF= n.n (CDF)	Infiltration Capacity (mm)	0-500
X Factor	N/A	XF=n.n	URBS_XF	N/A	Muskingum x scaling factor	> 0
Bf	N/A	Bf=n.n	URBS_BF	Bf=n.n (C|RDF)	Baseflow scaling factor	> 0
Kd	N/A	Kd=n.n	URBS_IFRF	Kd=n.n (CDF)	Daily Infiltration Recovery factor	0.5-1
TL	N/A	Tf = n.n | Tl = n.n	URBS_TRLS	Tl = n.c (CDF)	Transmission Loss ML/km	Varies
hotStartFile	N/A	HotStartFile=<filename>	N/A	Basename.hst	Hot Start File	N/A

Note:

- Hierarchy (highest to lowest): Command->ini file -> default parameters
- Parameters are case insensitive
- Either the numeric or the alpha command line mode can be used – they cannot be mixed
- In the alpha command mode, parameters and values must be separated by =. Spaces are allowed. Any order is permitted.
- n.n denotes a value. N/A denotes not available. | means either specification is allowed,
- CDF catchment definition file, RDF rainfall definition file

URBS can access nine different input files besides the necessary catchment definition and rainfall definition files. A summary of the file types is shown in Table D.2. The base name of these files is specified in the catchment or rainfall definition file.

Table D.2 Input file types

EXTENSION	FILE CONTENTS
.rat	Rating Curve
.r	Pluviograph Information
.g	Gauging Station Recorded Flows or Heights
.i	Inflow Hydrograph
.rrf	Rainfall-Runoff Station Data
.cdf	Catchment data file
.sq	Storage Discharge File
.dam	Storage Elevation File
.sgf	Sediment Grading Curve data

Table D.3 Output File Types

EXTENSION	FILE CONTENTS
.a	Average Rainfall per Period on Catchment
.b	Binary File for Program PLOTU
.cc	Catchment Characteristics results
.csv	All the results for spreadsheet import
.e	Average Excess Rainfall per Period on Catchment
.h	Table of Calculated & Recorded Heights
.hst	Hot start file contain model results at a specified date
.hc	Hydraulic connectivity file
.log	Run log file
.o	Discharge Hydrograph at PRINT Location
_cal.o	Modelled Storage Results
.osd	Results of OSD analysis

Table D.3 Output File Types (cont.)

EXTENSION	FILE CONTENTS
.p	Table of Calculated Peak Discharges & Heights
.prm	File listing parameters used in the run
.q	Table of Calculated & Recorded Discharges
.s	Sediment Wash-off and Deposition results
.t	Traffic Disruption Costs results
.vbf	File containing air space data for storages

Figure D.1 and Figure D.2 presented the long-term period the observed and simulated daily runoff in Phee River basin using URBS for the monthly and daily calibration periods, respectively.

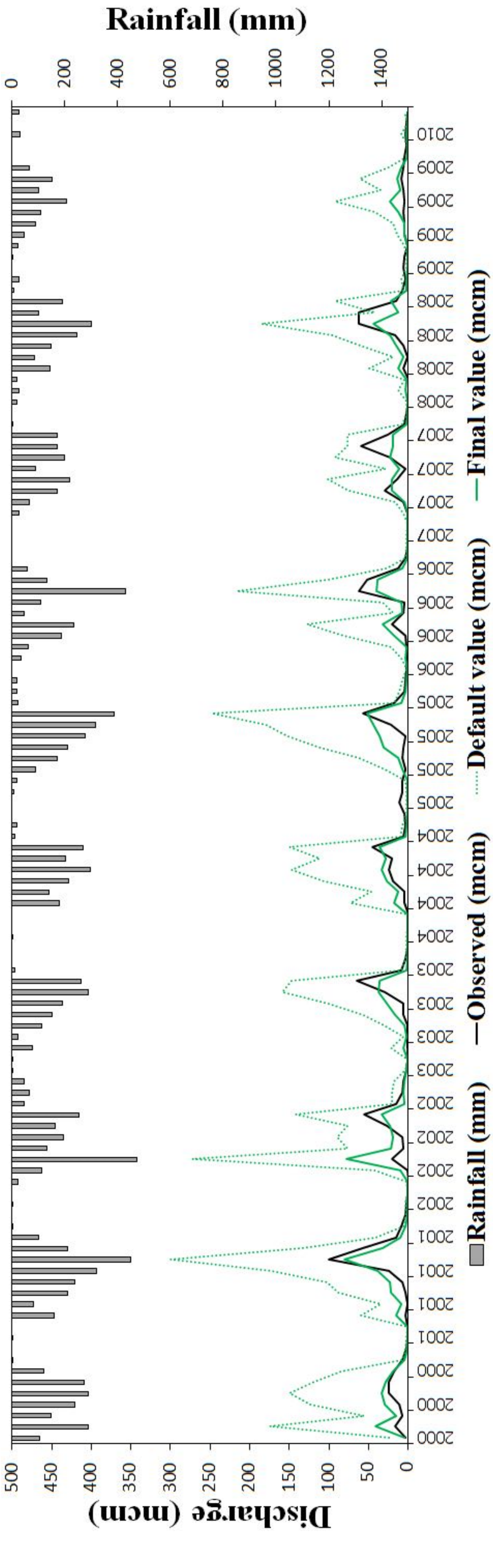

Figure D.1 Observed and simulated daily runoff using URBS for the monthly calibration period (year 2000-2009)

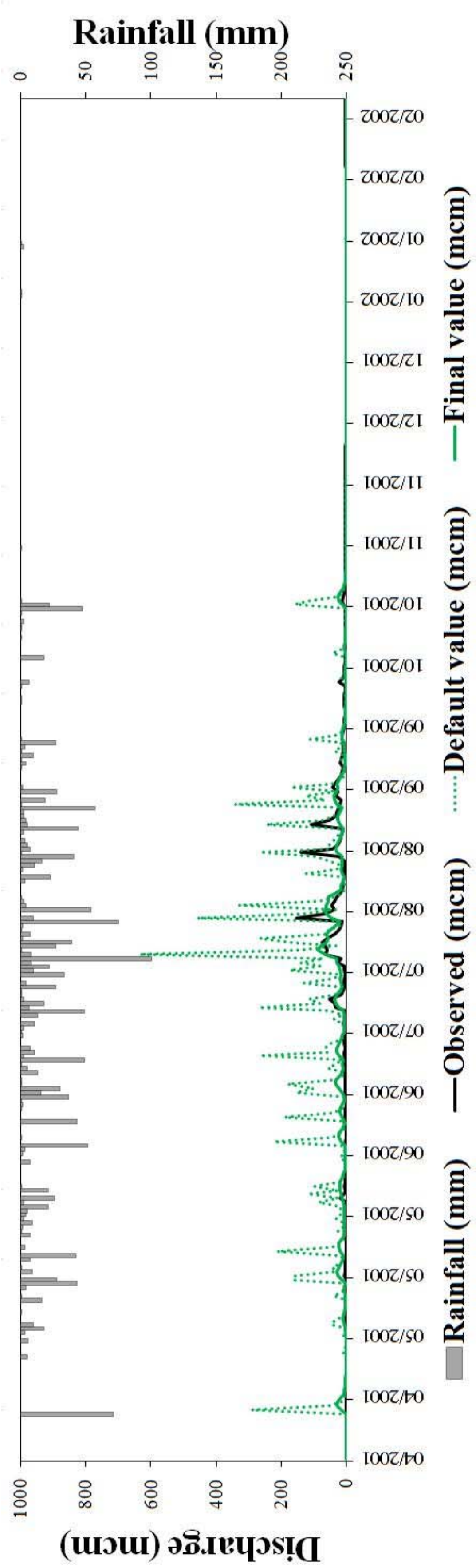

Figure D.2 Observed and simulated daily runoff using URBS for the daily calibration using period (year 2001)

APPENDIX E
UNIT IN PHEE RIVER BASIN

This Table E.1 gives lists of conversion factors for each of a number of physical quantities, which are listed in the index. For each physical quantity, a number of different units are shown and expressed in terms of the corresponding SI unit.

Table E.1 SI unit in Phee River basin

Name of unit	Symbol	Definition	Relation to SI units
		AREA	
square kilometre	km^2	1 km x 1 km	10^6 m^2
square metre	m^2	1 m x 1 m	1 m^2
		VOLUME	
cubic metre	m^3	1 m x 1 m x 1 m	1 m^3
		TIME	
minute	min	60 s	60 s
hour	h	60 min	3,600 s
day	d	24 h	1,440 min = 86,400 s
week	wk	7 d	168 h = 10, 080 min = 604,800 s
year	y or yr	365 d	31,536,000 s
		FLOW	
Cubic metre per second	m^3/s	1 m^3/s	m^3/s
		PRESSURE	
atmosphere	atm		101,324 Pa
pascal	Pa	$km/(m \cdot s^2)$	1 Pa

Table E.1 SI unit in Phee River basin (cont.)

Name of unit	Symbol	Definition	Relation to SI units
		KINEMATIC VISCOSITY	
square metre per second	m^2/s	1 m^2/s	m^2/s
		TEMPERATURE	
Degree Celsius	°C	°C ≡ K-273.15	[K] ≡ [°C]+273.15

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