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EFFECTIVENESS OF HYDROLOGIC MODELS FOR STREAMFLOW PREDICTION IN THE NAM SONG RIVER BASIN

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Water Resources Engineering
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แม่น้ำซอง เป็นหนึ่งในแม่น้ำสาขาของแม่น้ำลีก ซึ่งถือว่าเป็นแม่น้ำสายสำคัญที่สร้างมูลค่าด้านการท่องเที่ยวเชิงธรรมชาติของจังหวัดเวียงจันทน์ ประเทศลาว ลุ่มน้ำซองประสบปัญหาน้ำท่วมเป็นประจำเกือบทุกปี และทวีความรุนแรงมากขึ้น โดยมีสาเหตุหลักมาจากรูปแบบและปริมาณฝนที่ตกในพื้นที่มีความผันผวนสูง จึงส่งผลให้การพยากรณ์ปริมาณน้ำท่ามีความซับซ้อนและท้าทายเป็นอย่างมาก นอกเหนือจากนี้ ยังมีข้อจำกัดเกี่ยวกับสถานีวัดข้อมูลอุตุ-อุทกวิทยาในลุ่มน้ำที่มีจำนวนน้อยและกระจายตัวไม่สม่ำเสมอ ซึ่งส่งผลให้ขาดข้อมูลน้ำท่าซึ่งจำเป็นต่อการบริหารจัดการน้ำและภัยพิบัติอย่างมีประสิทธิภาพ แบบจำลองน้ำฝน-น้ำท่าได้ถูกพัฒนาขึ้นและเป็นทางเลือกหนึ่งที่สามารถใช้แก้ไขปัญหาการขาดแคลนข้อมูลน้ำท่าสำหรับลุ่มน้ำที่มีข้อจำกัดด้านข้อมูลได้ การศึกษาครั้งนี้มีวัตถุประสงค์ เพื่อประเมินประสิทธิผลของแบบจำลองน้ำฝน-น้ำท่า ที่มีโครงสร้าง และจำนวนพารามิเตอร์ที่แตกต่างกัน รวมทั้งหมด 3 แบบจำลอง ได้แก่ HEC-HMS, IFAS และ SWAT ในการศึกษาครั้งนี้ใช้ข้อมูลปริมาณน้ำฝนและน้ำท่า 18 ปี (2539-2556) จากสถานีวัดน้ำฝน 4 สถานี และสถานีวัดน้ำท่า 2 สถานี การปรับเทียบแบบจำลอง และวิเคราะห์ความอ่อนไหวของพารามิเตอร์ที่ส่งผลต่อปริมาณน้ำท่าใช้ข้อมูลช่วงปี 2539 – 2547 การสอบทานแบบจำลองใช้ข้อมูลช่วงปี 2548 – 2556 ดัชนีทางสถิติที่ใช้ในการประเมินประสิทธิภาพของแบบจำลองประกอบด้วย ค่าสัมประสิทธิ์สหสัมพันธ์ (Correlation Coefficient, r) และค่าความแม่นยำของแบบจำลอง (Nash Sutcliffe Efficiency, NSE) ผลการวิจัยพบว่า แบบจำลองน้ำฝน-น้ำท่าทั้ง 3 สามารถทำนายปริมาณน้ำท่ารายวันและรายเดือนได้ใกล้เคียงกัน แต่พบความแตกต่างในส่วนของการทำนายปริมาณน้ำท่าสูงสุดที่เป็นพารามิเตอร์ที่แสดงถึงสภาวะน้ำท่วม โดยแบบจำลอง IFAS สามารถทำนายปริมาณน้ำท่าสูงสุดได้ดีกว่าแบบจำลอง HEC-HMS และ SWAT ดังนั้นแบบจำลอง IFAS จึงถูกพิจารณาให้เป็นแบบจำลองที่มีความเหมาะสมที่สุดสำหรับการจำลองในแม่น้ำซองที่มีข้อจำกัดของข้อมูลตรวจวัด การวิจัยนี้สามารถพัฒนาต่อได้โดยการปรับค่าพารามิเตอร์ที่เพิ่มความแม่นยำในการทำนายส่วนอื่นๆ ของชลภาพน้ำท่านอกเหนือจากค่าน้ำท่าสูงสุด

ภาควิชา	วิศวกรรมแหล่งน้ำ	ลายมือชื่อนิสิต ....
สาขาวิชา	วิศวกรรมแหล่งน้ำ	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
ปีการศึกษา	2559	ลายมือชื่อ อ.ที่ปรึกษาร่วม ....

5770521121 : MAJOR WATER RESOURCES ENGINEERING
KEYWORDS: UNGAUGED BASIN / NAM SONG RIVER BASIN / RAINFALL ESTIMATION / RAINFALL-RUNOFF MODEL

BOUNHOME KIMMANY: EFFECTIVENESS OF HYDROLOGIC MODELS FOR STREAMFLOW PREDICTION IN THE NAM SONG RIVER BASIN. ADVISOR: ASST. PROF.ANURAK SRIARIYAWAT, Ph.D., CO-ADVISOR: SUPATTRA VISESSRI, Ph.D., 100 pp.

The Nam Song River is a tributary of the Nam Lik River. Itis one of the most attractive natural tourism places of Vientiane in Lao PDR. The Nam Song River basin has long been affected by natural disasters especially floods. The severity of major floods continues to increase in recent years. This is probably a result of changes in the pattern and amount of rainfall which is highly variable in monsoon regions. While realizing the importance of reliable predictions of streamflow and flood for improved water resources and disaster management in the Nam Song basin, this issue has remained a challenge due to scarce meteorological and hydrological gauges and unequally distributed of the gauges over the basin. To predict streamflow in data scarce basins, a rainfall–runoff modeling technique has been used as an alternative to observed streamflow data. The overall aim of this study is to assess the performance of rainfall-runoff models for streamflow predictions under the data scarcity. Three rainfall-runoff models, i.e. HEC-HMS, IFAS and SWAT, with different complexities were tested. The hydrological data were obtained from four rain gauges and two streamflow gauges. The period of the study was from 1996 to 2013. The training data set was from 1996 to 2004 for parameter calibration and sensitivity analysis. A testing data set was from 2005 to 2013 for validation of the model parameters. The performance of the models was evaluated at two temporal resolutions including daily and monthly scales. The correlation coefficient (r) and Nash-Sutcliffe efficiency (NSE) were used as performance indices. While all the rainfall-runoff models tested in this study performed equally well for predicting daily and monthly streamflow time series, they had different capabilities in prediction high flows that might lead to flooding. These results demonstrated that IFAS outperformed HEC-HMS and SWAT when predicting high flows. Therefore, IFAS was considered to be the most suitable rainfall-runoff model for the case of data scarcity in the Nam Song basin. This study could be improved further by searching for parameter sets that lead to increased accuracy of predicting other components of hydrographs apart from peak flows.

Department:	Water Resources Engineering	Student's Signature	....
Field of Study:	Water Resources Engineering	Advisor's Signature	....
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CHAPTER 1

INTRODUCTION

This chapter introduces the rationale behind the study of predicting streamflow in poorly gauged basin where the problems of hydrological data scarcity exist. Topics presented in this chapter are background, research objectives, scope of study, expected outcome and thesis outline.

1.1 Background

Rainfall and flow are the most important data for hydrological planning and water resources management. Given poor network of hydrological gauges and short historical records in some areas, spatial and temporal variability of rainfall cannot be well captured. Thus, modeling hydrological processes or disasters, such as flood and drought, which rely heavily on good information about rainfall as input is still a challenge.

Most natural disasters especially flooding and drought are caused by weather. Floods are the most frequent natural disasters globally (40%) followed by tropical hurricanes (20%), earthquakes (15%), and drought (15%) (CFE-DMHA, 2014). The natural disasters cause loss of life and property and even causes severe economic setback especially in developing countries. Impacts of natural disasters affecting developing countries are considerably more than those of the developed countries in terms of social and economic and the situation is not likely to change in the foreseeable future (Phommachanh, 2003). Drought is also one of the natural disasters all over the world. Drought has impact on the economy and can affect the largest segment of the society. It has long been accepted as one of the most dangerous of human misery (Thantavong, 2010). The natural of drought with complex phenomenon has multiple effects from a major challenge in planning, monitoring, predicting, assessing impact and offering solution to drought hit area (Mahachaleun, 2011). There are many causes of flood and drought such as abundant or shortage of rainfall, uncertain distribution of the rainfall, and lack of data to be analyzed for water resources planning and management (Manolom, 2016).

The Nam Song basin is one of the worst affected by the natural disaster especially flooding. In the past, Nam Song has been affected by flooding due to tropical storms causing millions in damages. The physical characteristics of the area are mountainous area in the upstream and the wetland covering the area of Vangvieng district, Vientiane Province, Laos (Phommalin, 2014). The Nam Song diversion dam is located at the

Nam Song River to divert water to Nam Ngum dam for generating hydropower and the release flows to the original river for multi-purposes uses. For the dam operation, streamflow data is required for planning and management to reduce natural disaster. The Nam Song basin is an ungauged or poorly gauged basin. Furthermore, some exiting monitoring sites are affected by human influences such as upstream abstraction on river. Consequently, the method with increased accuracy of rainfall prediction in this area is needed as it is expected to lead to an improvement in streamflow prediction (Yoshida, 2016).

There are a number of models which can be applied to a basin for streamflow prediction such as rainfall-runoff model (Mathematical Model), statistical model, and Artificial Neural Network (ANN) model. Each model has the different property, capability and numbers of parameters. The mathematical model uses physical and hydrological characteristics to create the relationship between rainfall and runoff. The multiple regression models applied the principle of statistics including multiple regression analysis and time series analysis. This model is developed for simulating the basin characteristics. The Artificial Neural Network model simulates complex flow behavior with non-linear regression which can be changed by time, but does not consider the basic of physical relationship of variables or statistical analysis. Model selection for flow analysis depends on ability of model and researcher discretion for model application in accordance with the nature of work (Champathangkham, 2012).

According to the information and problems, this study is conducted to predict streamflow in a poorly gauged basin using rainfall-runoff models with different number of parameters. Selected models are HEC-HMS, IFAS, and SWAT models. The performances of the models are measured using r^2 and NSE. This study also investigates the different methods for rainfall estimation that possibly have significant impacts on streamflow prediction. The framework proposed for this study can be applied to other basin for planning and management of water resources at present and for the future.

1.2 Research Objectives

1) To assess the performance of rainfall-runoff models for streamflow prediction under the data scarcity
2) To compare the usage of different rainfall-runoff models for streamflow prediction in the Nam Song Basin.

1.3 Scope of research study

1) The study area is Nam Song Basin in Laos.

2) The hydrological data in Nam Song Basin are obtain from 4 rainfall stations, 1 streamflow station and discharge at the Nam Song Dam.
3) Hydrological and climate data for the period of 18 year (1996-2013) are obtained from the Department of Meteorology and Hydrology of Laos.
4) Land use map and soil type classification of 2010 are from National Agriculture and Forestry Research Institute of Laos.
5) Three Rainfall-Runoff models, i.e. HEC-HMS, IFAS and SWAT models, are used in this study to compare predictability.
6) Thiessen polygon method is used for estimating areal rainfall.
7) The impacts of model principles, structure, limitations, constrains, advantages and disadvantages are discussed.

1.4 Expected outcomes

1) Improved understanding of underlying principles, structures, constrains, advantages and disadvantages of different hydrological models
2) Recommendation towards hydrological modeling for predicting the streamflow on the Nam Song River Basin.
3) Offer guidance in the application of hydrology model for other poorly gauged basins with similar characteristics.

1.5 Research procedures

The procedures of the study are shown in Figure 1.1. The details are as follows:

1) Study the principle and theory of inflow prediction, relationship of rainfall-runoff, relationship between runoff and basin characteristics, review research in the past about hydrological model, compile and study the research and reports about the target basin.
2) Study of the characteristics of the selected basin to understand topography, climate, hydrological characteristics, land use, and soil types. All of them are the basic of studies by compiling data for research such as: hydrological data, digital elevation model (DEM), land use, soil types the check the data and prepare as geographic information.
3) Check and analyze physical and the hydrological data using spatial mapping.
4) Analyze hydrological data and develop simulation of flow by dividing into sub-steps start from defining basin area, land use and soil type characteristic. Climate and rainfall input data are used as meteorological input into rainfall-runoff models. After that, identification of model parameters for model

calibration is performed. The relationship between parameters and physical data is subsequently analyzed. Finally, the models which are considered appropriated for the study basin are used for inflow prediction.

5) Analyze and make the conclusion, then write the thesis.

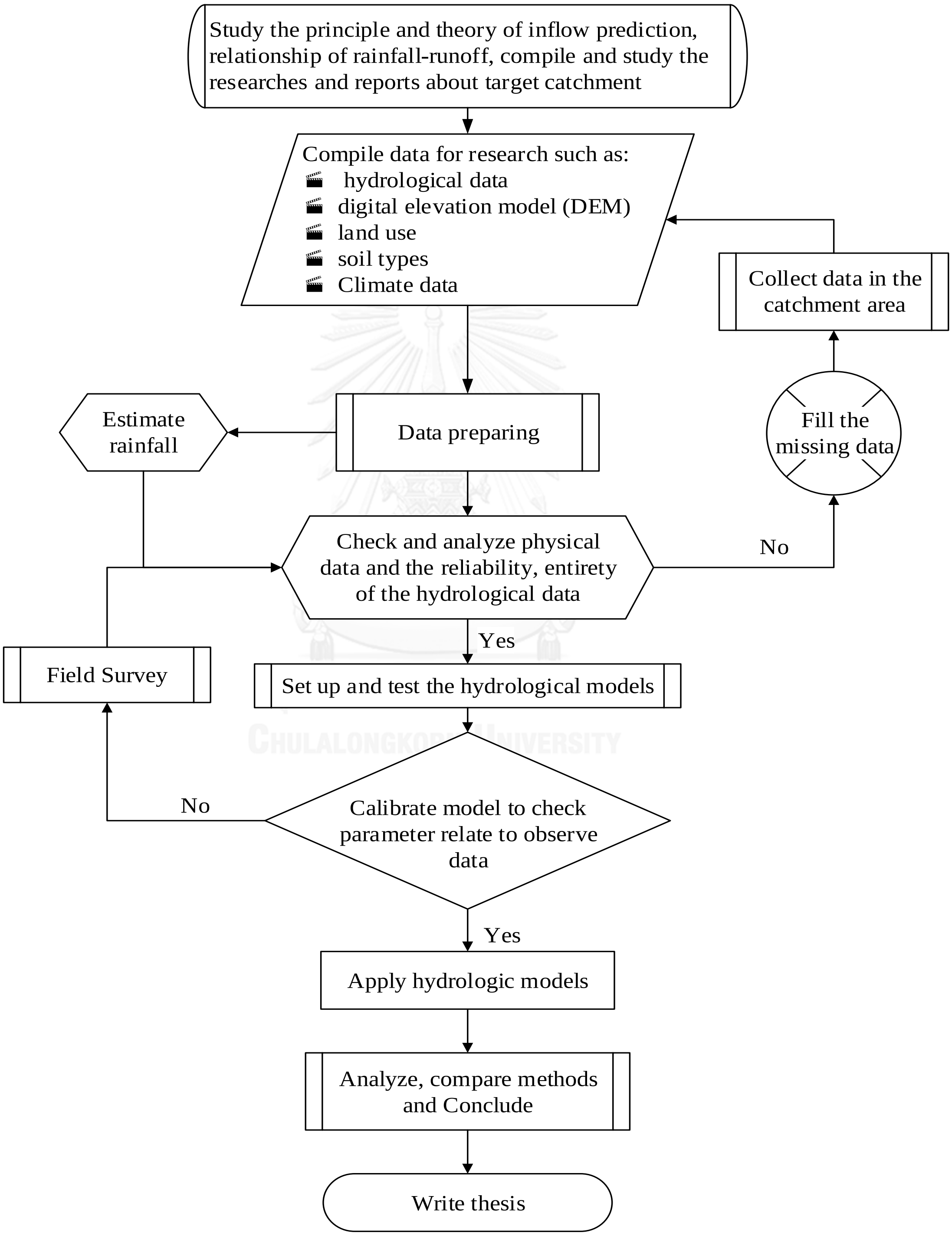


Figure 1.1 The procedures of the study

CHAPTER 2
LITERATURE REVIEW

This chapter introduces and reviews the progression of ideas in the domain of hydrological modeling. In line with the focus of this thesis, the issues of ungauged basins, rainfall-runoff modeling and rainfall estimation are reviewed. Knowledge obtained from this review will be useful as a guideline for predictions of streamflow contributed by upstream basin where rain gauge network is sparse.

2.1 Ungauged basin

A lot of researchers studied and defined about ungauged basin in different ideas. This section can conclude as the ungauged basin can be defined as a basin with insufficient data record of hydrological observations in term of quantity and quality (Webster Gumindoga & Rwasoka, 2016), while Visessri, 2014 defined that ungauged basin is not necessarily to be a basin with no observe station. It can be an ungauged basin, if it is a basin with poorly gauged in term of quantity and quality.

To estimate hydrological variables of interest, several techniques have been used for predictions in ungauged basin. The direct modeling of gauged basin gives way to indirect modeling of target ungauged basins. This involves some forms of information transfer (data or model parameters) from donor (neighboring, nested, downstream or similar) basins to the ungauged basins of interest. Some examples are shown in Figure 2.1.

Model selection i.e. lumped or distributed is one of the issues needs to be explored. Lumped models usually are derived from a distributed form that establishes the link to spatial datasets. Lumped models treat the complete basin as a homogeneous whole, which attempt to calculate flow contribution from separate areas or sub-basins that are treated as homogeneous within themselves (Gayathri, 2015). A distributed model configured using spatial datasets estimates runoff production and flow routing scheme on a grid for area that embraces some gauged sites, providing a natural inference model for forecasting at ungauged sites. A distributed model is divided into elementary unit areas like grid nets and flows are passed from one grid point to another as water drains through the basin (Knapp V. et al., 1991).

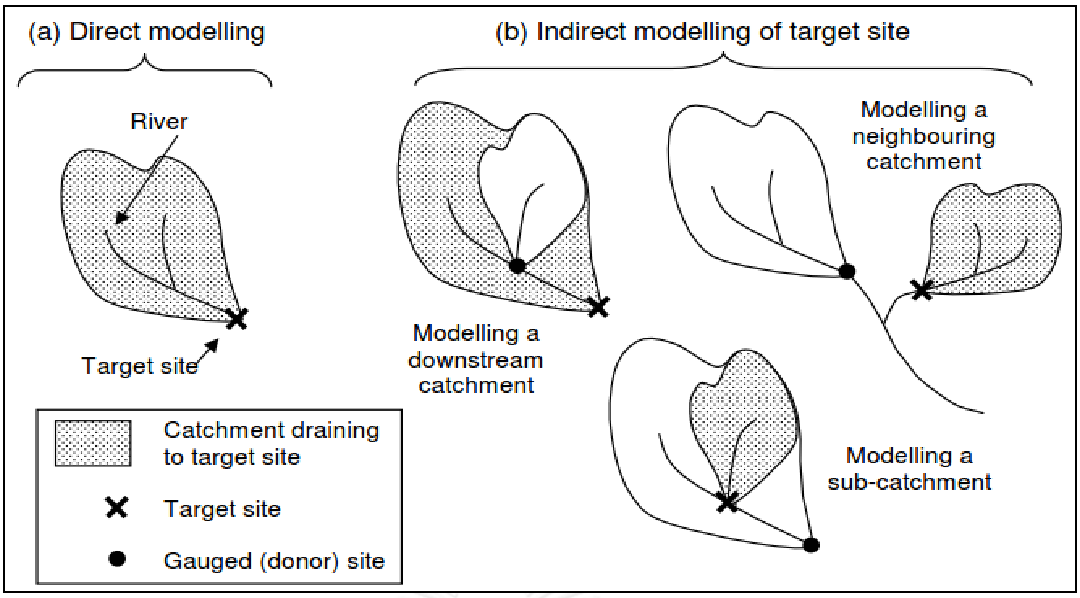


Figure 2. 1 Direct and indirect modeling of a basin, downstream basin, neighboring basin or sub-basin (Y. V. Zhang, 2015).

2.2 Overview of rainfall-runoff modeling

Hydrological systems are extremely complex and difficult to understand in all details of them. Rainfall-runoff models have been used as a tool to improve understanding hydrological behavior and to quantify how much steam flow occurs in a river in response to the given amount of rainfall (Seibert, 1999).

The best of stream flow estimation can be expected from observations at gauge sites where water level is recorded and converted to flow using a stable rating curve. Since water level data are available only for limited number of gauge locations and for limited time period, empirical and statistical method and rainfall-runoff models have been used to estimate flow for ungauged basin (Jai Vaze, 2011).

The most of rainfall-runoff models are completed for research purpose as mean of knowledge about hydrological system. The ultimate aim of prediction using models must be improved the decision-making about the hydrological problem such water resources planning, flood protection, mitigation of pollution (Beven, 2001). The rainfall-runoff model is also standard tool using for hydrological investigation in environment and engineering system. A large number of the models usually combine both linear and non-linear functions, and they were developed into software (Wagener, 2004).

2.2.1 Classification of hydrologic modeling

A rainfall-runoff model is a simplified representation of real-world hydrological processes. Structures of rainfall-runoff models can be classified using various criteria, for example according to spatial resolution (lumped, semi-distributed and distributed), temporal resolution (event-based and continuous), mathematical nature (linear and non-linear) and the modeling approach used as empirical, conceptual and physically-based (Visessri, 2014).

Models are normally classified to help describe and discuss their capabilities, strength and limitation. There is no universal method to characterize rainfall-runoff models, and the models have been classified in several ways depending on the criteria of interest as examples of classifications as shown in Figure 2.2 based on deterministic and stochastic predictions, and in Table 2.1 in term of number of parameter (Chong, 2002; Refsgaard, 2007; Michael et al (1996); and Becker and Serban, 1990 cited by (Gayathri, 2015)).

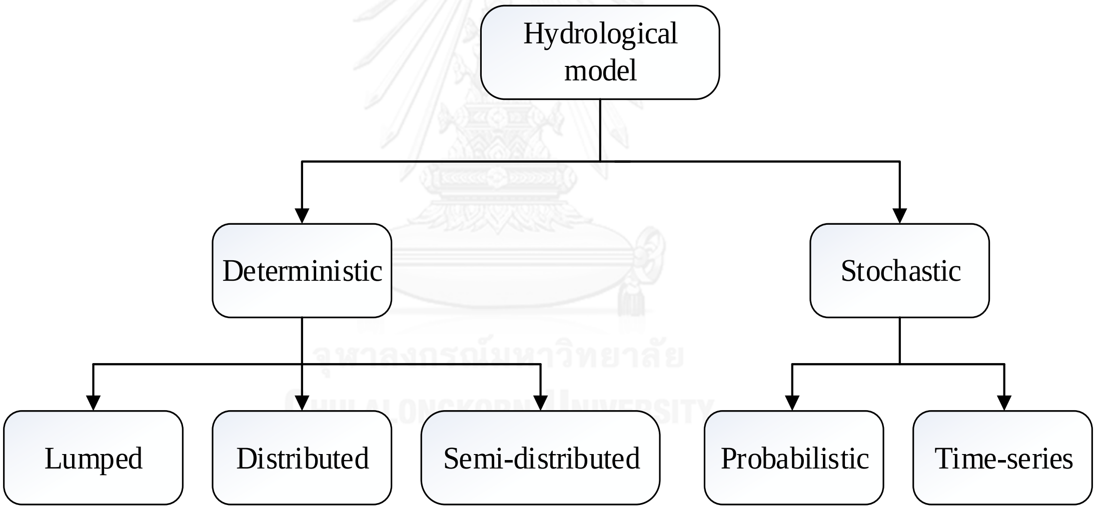


Figure 2.2 Classification of hydrologic model according to process description (Chow V.T., 1988; cited by (Vernon Knapp, 1991))

1) Deterministic model: Michael et al, 1996 gave a definition of deterministic models that it is a system relationships among stages and events without any random variable. Deterministic models, a given input will always produce the same output. In the deterministic models, the outputs of the model are fully determined by the parameter values and the initial condition. The three main groups of the deterministic model as gives below: Empirical, Conceptual, Physical based model.

2) Stochastic model: Stochastic model is referred to mathematical model of hydrological events. There are three general principles that are often used for relating or connecting of mathematical probability theory that is to be modeled, they are: 1) the

principle of equally likely outcome, 2) the principle of long run relative frequency and 3) the principle of subjective probability. They are important as guideline for the estimating of probability value in the model (Tarlton & Brown, 2016).

3) Lumped model: Specific rainfall-runoff models are used for multiple purpose including: HEC-HMS model, Thames Basin Model (TCM and available within the Penman Store Modeler PSM), the Midland Basin Runoff Model (MCRM), the PDM (Probability Distributed Model), the Isolate Event Model (IEM), the ISO (Input-Storage-Output) model, forms of Transfer Function (FT) model, and the NAM model (Fionda, 2011).

4) Lumped rainfall-runoff models could be more suitable than others for application to ungauged sites. Some models, such as the Thames Conceptual Model (TCM), appear more complex and have large number of model parameters. However, they can be reduced to simpler forms and a smaller set of parameters. The more complex forms may have closer ties to measurable quantities, and map information, that can support model configuration and calibration and application to ungauged basins (Bell, 2001).

5) Fully distributed hydrological models: Distributed models will be taken to model of basin hydrology. Physical based models are necessarily distributed because the equation is defined generally involve space coordinates (Freeze and Harlan, 1969). Physical based distributed model requires the specification of equation for hydrological process to be considered. The development of distributed modeling of basin hydrology show faltering process. There are numerous papers on modeling individual processes, especially groundwater flow, unsaturated soil water flow and channel routing (Beven, 2001).

6) Beven and O’Connell (1982) considered the role of distributed model in hydrology. They identify four major areas for application of distributed model, these are: forecasting the effect of land-use change, the effect of variable input and output, the movement of pollutant and sediment, and the hydrological response of ungauged basin where no data are available for calibration.

7) Semi-distributed models: A semi-distributed hydrological models are based on subdivision of basin topographical similar area, which is identified a digital elevation model. The semi-distributed hydrological model is capable of reproducing fairly well the measured streamflow when model parameters are calibrated. The distinction of lumped, distributed and semi-distributed models could be explained in Figure 2.3 (Gan, 2001).

Because each grid in distributed model are used lumped process so that, if the grid sizes of in distributed model are very large as same as the size of sub-basin in lumped mode, distributed model will become to lumped model.

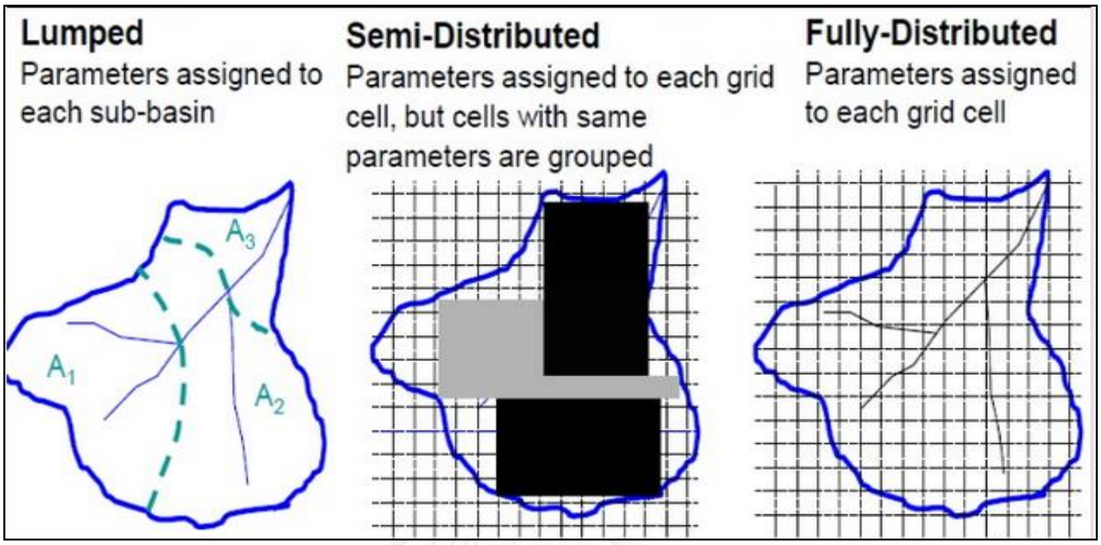


Figure 2.3 Distinction of lumped, distributed and semi-distributed models (Milad Jajarmizadeh, 2012).

Because of the rainfall-runoff model has a lots of various parameters and some models abo to solve multiple purpose so that, the criterion group of parameter in this study (see Table 2.1) is depended on ability or complexity of model and purpose of user.

Table 2. 1 Summary of rainfall-runoff models and its parameters

Parameter range	Author, study year	Rainfall-Runoff Models	Parameter No
1 - 3	Fukami, 2011	Unit Hydrograph (UH)	3
	Servat and Dezetter, 1993	GR3	3
4 - 6	Tekleab et al, 2011	Water Balace Model	4
	Petheram et al, 2012	AWBM	6
	Petheram et al, 2012	SIMHYD	6
	Croke et al, 2004	IHECRES	6
	Piman and Babel, 2013	HEC-HMS	5
	Hong-jun BAO et al, 2010	BTOPMC	5
	Mapiam et al, 2009	NAM	6
7 - 9	Limantana, 2009	IFAS	7
	Servat and Dezetter, 1993	CREC	7
	D.L.E.H. Deckers, 2006	HVB	7
	W. de Hamer et al, 2010	SCS	7
	Hong-jun BAO, 2010	Xinanjiang	7
	Petheram et al, 2012	SMARG	8
	W. Gumindoga et al, 2011	TOPMODEL	8
	Yan Jiang et al, 2015	HIMS	9
	G. P. Zhang et al, 2005	REWASH	9
> 9	Christopher et al, 2015	SCE-UA	11
	Petheram et al, 2012	Sacramento	13
	Alexander et al, 2009	Hysim	14
	Maite Meaurio, 2015	SWAT	21

Castellarin et al. (2013), Parajka et al. (2013), Rosbjerg et al. (2013); cited by (Visessri, 2014).

2.3 Calibration and validation of model

2.3.1 Calibration

Model calibration is a process of optimal adjusting of model parameter values to get a set of parameters which makes the best estimating of the streamflow. All rainfall-runoff models must be calibrated to produce reliable estimating of streamflow. Models should always be calibrated with observed data for describing that the model can produce observed flow with an acceptable level of accuracy. The acceptable level of accuracy is depended on the statistic of flow data to be reproduced, which is determined by the purpose that the model will be apply for (Beven, 1989; cited by (Jai Vaze, 2011)). The calibration performance of the model should be re-tested before it is applied because the purpose for developing model may be different between the earlier and later applications, which may influence the calibration objective. Calibration of hydrological models can use manual or automated methods, or combination of two approaches.

Manual calibration is usually produced as combination of statistical indices and visual inspection of simulated and observed hydrograph. For automated calibration is usually produced by using an objective function. The objective function translates the observed and modeled outputs into a single number. For automated calibration use defined algorithm that can run the model in multiple time and adjusting model parameter values according to strategy that can be intended to improve the value of the objective function (Jai Vaze, 2011).

2.3.2 Validation

Model validation is one of the important steps in rainfall-runoff modeling as the performance of the model calibration. The validation period provides us confidence in the modeling results when the calibrated model is used for predicting streamflow under future climate change.

Model validation can be also defined as a process of using the calibrated model parameter to simulate runoff that over independent period outside to determine suitability of the calibrated model for predicting streamflow over any period outside of the calibration period. If there is not enough data available, the validation may be performance by testing shorter period within the full record (McMillan & Booker, 2016).

2.4 Rainfall-runoff model applications

Gumindoga et al (2016) applied HEC-HMS model to simulate streamflow in ten gauged and ungauged sub-basins Upper Manyame in Zimbabwe. The geometric and hydrologic parameters estimation were determined using Remote sensing and Geographic Information techniques. The Snyder Unit Hydrograph was used for transferring parameter from gauged to ungauged basins. The Marinba and Mukuvisi sub-basins were considered to be the gauged sub-basins while the others are ungauged sub-basins. Before transferring, the model parameters were tested using the Relative Volume Error (RVE) and Nash-Sutcliffe (NSE) criterion. The results presented that the model successfully simulated runoff and peak flow in gauged basin for the calibration with Mukuvisi RVE = -8.9%, NSE = 64%; Marimba RVE = 5.8%, NSE = 68% and validation of Mukuvisi RVE = 9.9%, NSE = 57%; Marimba RVE = 8.1%, NSE = 61%. The result was also demonstrated that in the future, this study has an important contribution for the development of water resources in data-scarce in Upper Manyame basin.

Sengthong (2016) used SWAT model to estimate the mean monthly streamflow in Upper Lam Phra Phloeng River Basin. The analysis was performed using rainfall data at return period 10, 20, 50, and 100 years. The monthly calibration was performed at M. 171 station during 2004-2008 and the result monthly validation during 2009-2010. The results of this study were shown that the mean annual streamflow was increased follow by the rainfall. The volume of streamflow at return period 20, 50, and 100 years were over the capacity of reservoir. Therefore, the capacity of the Lam Phra Phloeng reservoir should be increased to supply the downstream area. Additional, the downstream sub-basin should be dredged to drainage water into the Lam Phra Phloeng reservoir.

Vilaysane et al (2015) applied SWAT model for calibration and uncertainty analysis of hydrological streamflow in the Xedone River Basin, Lao PDR. This research was aimed to test the feasibility and performance of model for streamflow predicting in the Xedone River Basin. The hydrological data used from 1993 to 2008, data was divided into two period for calibration and validation: 1993 to 2000 and 2001 to 2008 respectively. This basin was delineated into 230 hydrological response units (HRUs). The SUFI-2 technique was used for calibration, it gave good results for daily and monthly simulation with the high value of r^2 and NSE higher than 0.80 respectively. The results were also performed that the SUFI-2 technique tool can be used for further analysis of the effect of the land use and climate change, sediment yield and water quality.

Phommalin (2014) analyzed rainfall and streamflow in the Nam Song River Basin using HEC-HMS model. Four rain gauges and one observed streamflow (Outlet station) have been used for calibration and validation. The performance of model was checked by statistic index such Coefficient of Determination (r^2), Nash-Sutcliff Coefficient

(NSE), and Index Agreement (d). The results showed that the model performance was quite well with $r^2 = 0.71$, NSE = 0.70, and d = 0.89. Moreover, this study also found that the streamflow in the Nam Song River Basin was followed by season, which the maximum and minimum flow were appeared on July and November respectively.

Halwatura and Najim (2013) applied the HEC-HMS model to simulate runoff in a tropical basin. The model was calibrated adjusting three different methods, the Soil Conservation Service Curve Number loss method, the Snyder Unit Hydrograph and the Clark Unit Hydrograph methods. The results could be concluded that the HEC-HMS model was reliable to simulate runoff for Attanagalu Oya River Basin; the SCS CN unit hydrograph method could simulate flow more reliable than Snyder method and the Clark unit hydrograph method was not performed well.

Aziz and Tanaka (2011) applied Integrated Flood Analysis System (IFAS) to minimize the losses and damages to the lowest level due to flooding of the Upper-Middle Indus River, Pakistan. The satellite precipitation of GSMap and 3B42RT are used as input data to develop the regional variable the can be used for basin area. The results presented that the flood duration and flood peak that calculated by the satellite GSMap has the best fit with the observed data. The satellite 3B42TR, flood duration is good for most of the case but for the flood peak is a little different. In additional, it is very good for flood forecasting the satellite GSMap and 3B42TR needed to be improved.

Kwanyuen (2003) compared the suitability in the application of HEC-HMS and TOP model for runoff prediction of Lampachi basin. In this study, both of HEC-HMS and TOP model are applied for the case of single event and continuous event. The results showed that the accuracy of single event was higher than continuous event. In case that considered peak flow and time, TOP model was more suitable for application in Lampachi basin than the HEC-HMS model. In addition, for better application of both models, the basin should be divided into sub-basin. Hydrology and meteorology stations should be sufficient to improve parameter value and predict runoff to be more accurate.

Suwanlertcharoen (2001) applied the SWAT model to evaluate runoff and suspended sediment from Mea Phun Watershed. The watershed has no observed runoff and sediment stations installed over the area, so the data of runoff and sediment were collected by weirs and sampling. The results showed that the watershed with large forest land was increased runoff volume in dry period. In other hand; it was decreased runoff volume in wet period. For suspended sediment was decreased in the both of dry and wet period and the amount of soil loss in this study area were also decreased.

2.5 Rainfall estimation

Rainfall estimation is needed as a major input into rainfall-runoff models. Several methods have been used to estimate the amount of precipitation that represents the precipitation that falls over the basin area. Examples of rainfall estimation methods are explained below.

2.5.1 Arithmetic mean method

This method is the simplest compared to other methods for estimating rainfall. Rainfall estimate from this method is obtained from the summation the rainfall data recorded at all rain gauges in the basin area. The form of this method can be shown as:

$$\overline{P} = \frac{1}{n} \; P_1 + P_2 + \ldots + P_n \; = \frac{1}{n}\sum_{i=1}^{n} P_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

Where: $\overline{P}$ is the average depth of rainfall

$P_1 + P_2 + \ldots + P_n$ are the rainfall recorded at station 1, 2, …., n

If the area is plain and the rain gauges are uniformly distributed over the basin area and if the variation of gauge records from the average rainfall is not too large, this method is probably useful as any other method. Even in hilly regions this method will fairly satisfactory result. The advantages of this method are that it allows manual computation (Borges, 2016).

2.5.2 Thiesen polygon

This method endeavors to allow for non-distribution of gauge by providing a weighting factor for every rain gauge station. The stations are plotted on based map, and the nearest stations are connected by straight line. Perpendicular bisectors are down to the straight line joining adjacent stations into form of polygons. Every polygon area is calculated or assumed to be influenced by the rain gauge stations are inside. Gives P_1, P_2, P_3…..P_n are the rainfall at the individual stations, and A_1, A_2, A_3……A_n are the areas of the polygon surrounding these stations. The average depth of rainfall for the entire basin is given by:

$$\overline{P} = \frac{A_1P_1 + A_2P_2 + \ldots\ldots + A_nP_n}{A_1 + A_2 + \ldots\ldots + A_n} = \frac{\sum_{i=1}^{n} A_iP_i}{\sum_{i=1}^{n} A_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

The results of this method are usually more accurate than those obtained by simple arithmetic averaging method, and the gauge should be correctly located over the basin to get regular sharp of polygons.

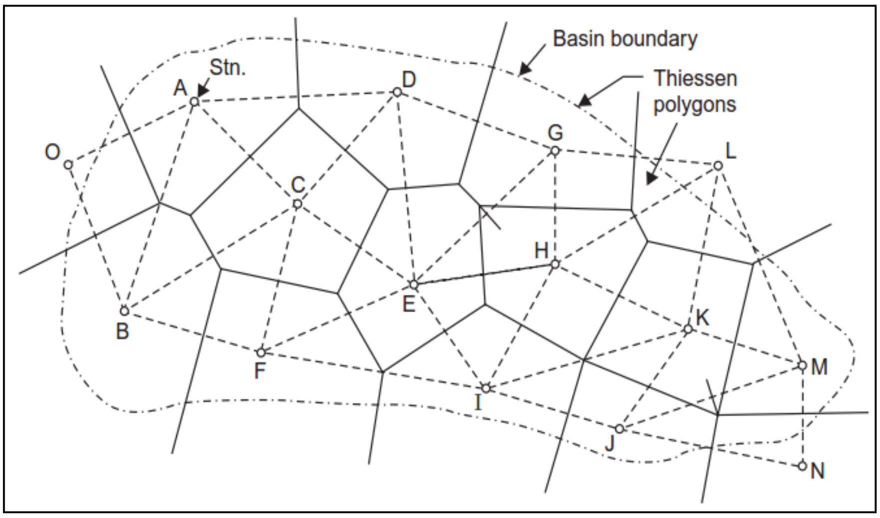


Figure 2.4 Thiesen polygon method (Raghunath, 1985)

2.5.3 Isohyet method

In this method, the point of rainfalls is plotted on a suitable based map and the lines of equal rainfall (isohyets) are drawn giving consideration to orographic effect, morphology, and storm direction. The average rainfall between the successive isohyets is assumed from the average of two isohyet values that weighted with the area between the isohyets, add up and divided by the total area which gives the average depth of rainfall over the basin (Raghunath, 1985).

$$\overline{P} = \frac{A_{1-2}P_{1-2} + A_{2-3}P_{2-3} + ... + A_{n-\ n+1}\ P_{n-\ n+1}}{A_{1-2} + A_{2-3} + ... + A_{n-(n+1)}} = \frac{\sum_{i=1}^{n} A_{i-(i+1)} P_{i-(i+1)}}{\sum_{i=1}^{n} A_{i-(i+1)}} \text{............................}(2.3)$$

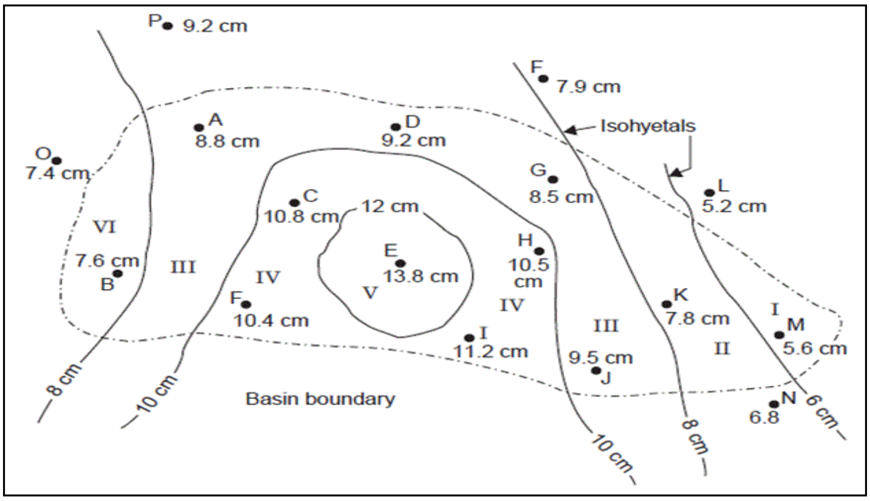


Figure 2.5 Isohyetal method (Raghunath, 1985)

2.5.4 Inverse Distance Weighting

Invert Distance Weighting (IDW) is based on the Tobler's first law (the first law of geography) concept as defined that everything is related to everything else, but the nearest thing is more related than distant thing (Chen, 2012). The IDW was developed by U.S. National Weather Service in 1972, due to the lack data requirements for the statistical calculation. The process of assigning values is to unknown point using value of scattered set of known point. The value at unknown point is a weighted summation of the value of known point (Lima, 2003). The IDW method is used to interpolate spatial data which is based on the concept of distance weighting and is can be used estimate the unknown spatial rainfall data from the area known the data.

$$\overline{R_P} = \sum_{i=1}^{N} w_i R_i \qquad \sum_{i=1}^{n} w_i = 1 \quad \text{.......................................(2.4)}$$

$$w_i = \frac{\frac{1}{d_i^2}}{\sum_{i=1}^{N} \frac{1}{d_i^2}} \qquad \begin{aligned} d_i &= \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \\ d_i^2 &= (x_i - x_0)^2 + (y_i - y_0)^2 \end{aligned} \quad \text{................................(2.5)}$$

Where: $\overline{R_P}$ means of the unknown rainfall data (mm);

R_i means of the rainfall data of known rainfall stations (mm)

N means of the amount of rainfall stations

d_i means of the distance from each rainfall station to the unknown site

w_i weighting factor

Borges et al (2016) compared rainfall interpolation methods in mountainous region. The traditional and geo-statistical interpolation methods, including with Thiesen polygon, Invert distance weighting (IDW), Linear regression, Ordinary kriging (OK), and Simple kriging with varying Simple kriging local means (SKlm), were used to estimate wet and dry season rainfall. The Linear regression and SKlm methods were used to interpolate two types of information: a) elevation extracted from digital elevation model (DEM), and b) distance to regional rainfall maximum. The Thiesen polygon method used to produce the highest error, whereas OK method gave the lowest error. The result indicated that geo-statistical interpolation outperforms traditional methods such the OK method consistently outperformed SKlm method and Linear regression method.

CHAPTER 3

STUDY AREA

This chapter presents an overview of the study area. Hydrological data required for the analysis are also presented. This chapter is expected to offer an understanding of the rainfall-runoff process of the basin and its dominating factor.

3.1 Physical characteristics

Nam Song Basin as presented in Figure 3.1 is a tributary of the Nam Lik River situated in Vangvieng district, Vientiane province, Lao PDR. It is the basin which receives water from the Nam Song River. The Basin area covers six districts in three provinces which are: Vientiane, Luangphabang and Xaysomboon. The maximum and minimum elevations are 1,992 m.a.s.l. (Meter Above Mean Sea Level) and 183 m.a.s.l. respectively. The Nam Song River originates from Phoukeo and flows to the west to Phatang for an approximate distance of 17 km and then flows straight to south of Vangvieng. From the south of Vangvieng to the confluence with Nam Lik at Hineheup, the river meanders along a narrow valley. The basin is located between latitudes 18°55’24”N to 19°16’00”N and longitudes 102°15’00”E to 103°38’00”E covering the total area of 1,258 km^2. The length of the Nam Song River to Vangvieng is about 36 km of the total length of 80 km (Phommalin, 2014).

The Nam Song basin is the most populated basin compared with the surroundings due to rapid development, urbanization and tourist attraction in Vangvieng. Extended industrial area from cement factory is the first and biggest one in Laos. The water law was set up to anticipate population and economic development pressures against limited water supply and to promote conjunctive water management. With rapid growth of population, the problem of water availability becomes crucial during the dry season while in rainy season, the problem of sediment transport becomes dominant. At present there are no serious problems concerning water utilization between upstream and downstream areas. However, competition for water could happen in the future due to rapid development (Bauer & Catalán, 2016).

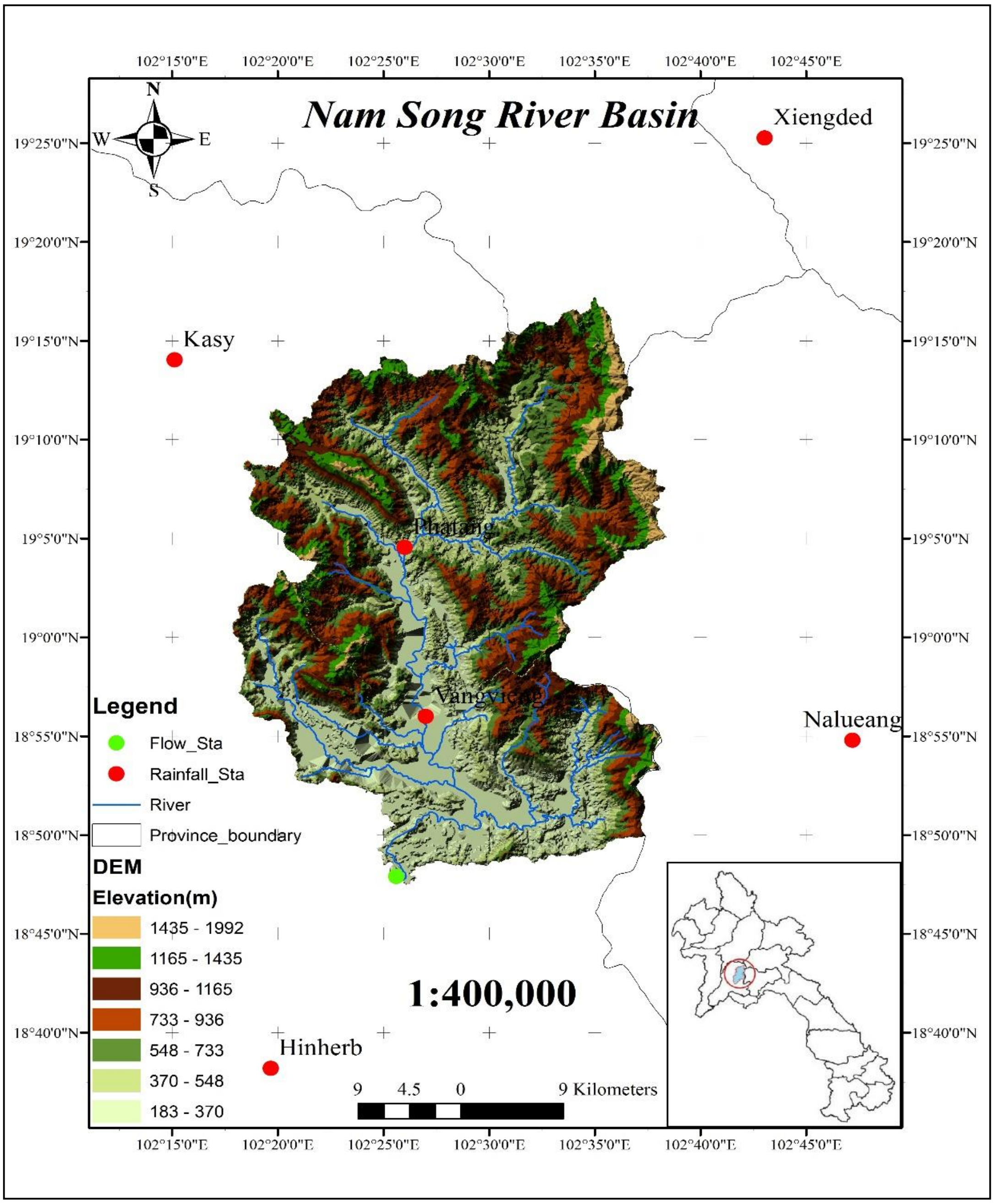


Figure 3.1 Physical characteristics of Nam Song basin

3.2 Geographical characteristics

3.2.1 Topography

Figure 3.1 presented that the Nam Song River basin is divided into two parts by its geology and by the Nam Song diversion dam. Above the dam there are three major tributaries which made up to three main valleys converging below Vangvieng. The Nam Song River flows on to the diversion dam. The flow can be diverted to the Nam Ngum reservoir. South of the dam the Nam Song continues for 27 km to the confluence on the Nam Song and Nam Lik, 3 km upstream from Hinheup village. Major tributaries in this section of the river flowing from the east and include Nam Phat, Nam Ken and Nam Phouset. The northern region of the basin is defined by extreme topography with slopes exceeding more than 30% in some areas. The southern areas from Vangvieng and toward the Nam Lik are rolling hills that support agriculture, rice production and plantation.

3.2.2 Land use

Land use data used in this research is obtained from the National Agriculture and Forestry Research Institute of Laos (2010). It is used for the identification of the land use and land cover types. The major land cover of the Nam song basin approximately 40% is forest. About 25% of the area is used for agriculture, 20% for upland crop, 8% for urban, 1% for lake and river, and 6% for other uses. The distribution and description of land use in the Nam Song basin are shown in Figure 3.2 and Table 3.1.

Table 3.1 Land use description of the Nam Song River basin

No	ID	Brief	Type of land use	Area (km^2)	% Area
1	11	EHCD	Evergreen, high cover density	18.14	1.44
2	12	EMLD	Evergreen, medium-low cover den	131.42	10.45
3	13	EVMS	Evergreen mosaic	38.50	3.06
4	18	MEDM	Mixed (evg&dec) med-low cover de	78.04	6.20
5	19	MXMS	Mixed mosaic	90.72	7.21
6	40	REGR	Regrowth	31.07	2.47
7	41	REGI	Regrowth, inundated	46.24	3.68
8	61	WSEV	Wood- and shrubland-evergreen	723.61	57.52
9	62	GRAS	Grassland	11.21	0.89
10	81	CMCS	Crop mosaic, cropping area <30	15.86	1.26
11	82	CMCL	crop mosaic-cropping area >30	6.37	0.51
12	91	AGRI	Agricultural land - intensive	52.10	4.14
13	93	ROCK	Rocks	2.12	0.17
14	94	URBN	Urban	12.61	1.00
Total				1258	100

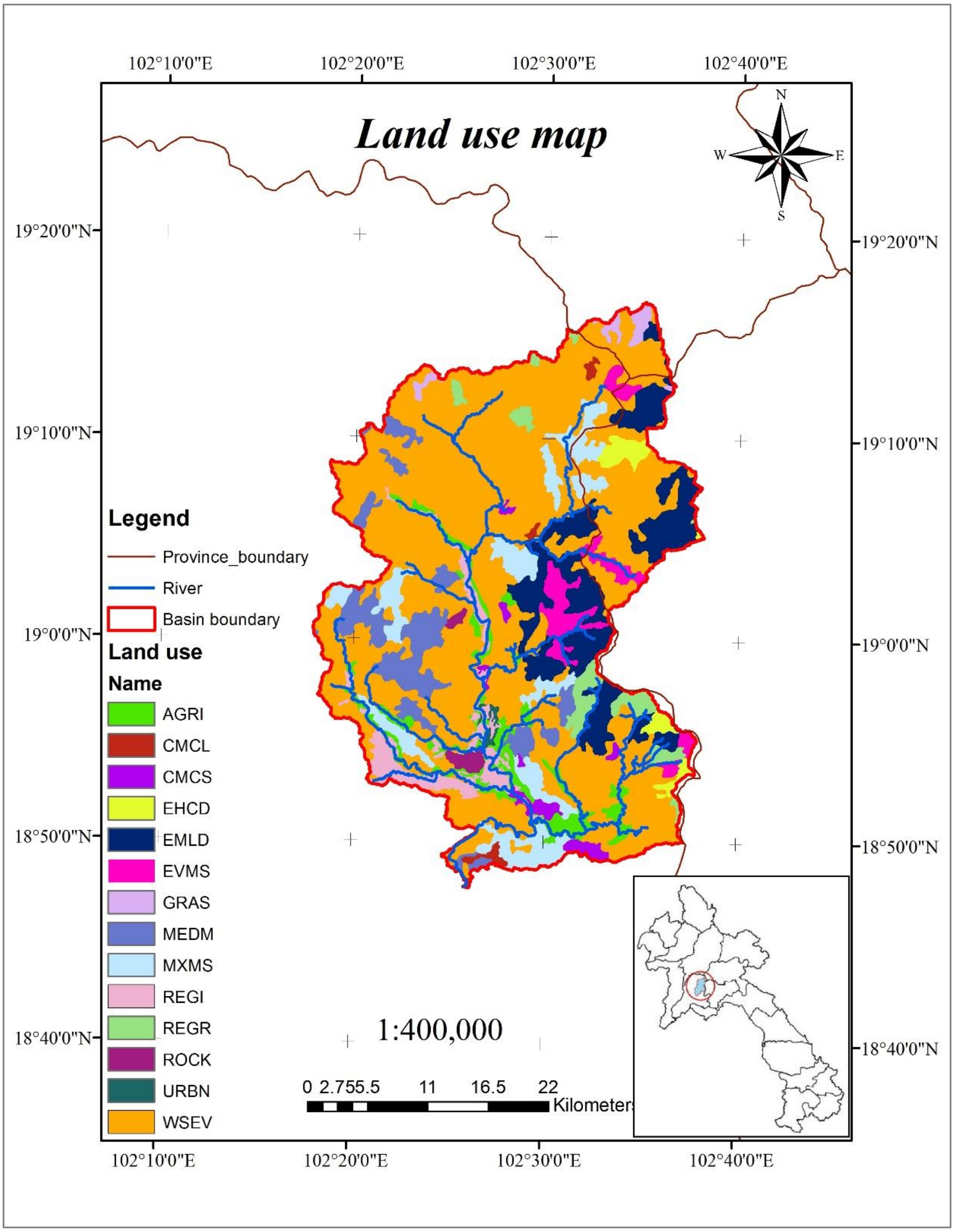


Figure 3.2 Land use types of the Nam Song River Basin

3.2.3 Soil type

Soils data in Nam Song River Basin is obtained from National Agriculture and Forestry Research Institute of Lao PDR (2010). The soil of the study area can be divided into 14 types. The dominant soil type in the upper of basin is sandy loam covering 80.87% of the basin. In the lower area about 11.41% is covered by clay loam and 4.48% is covered by loam. The distribution and description of the soil types in the Nam Song basin are shown in Figure 3.3 and Table 3.2.

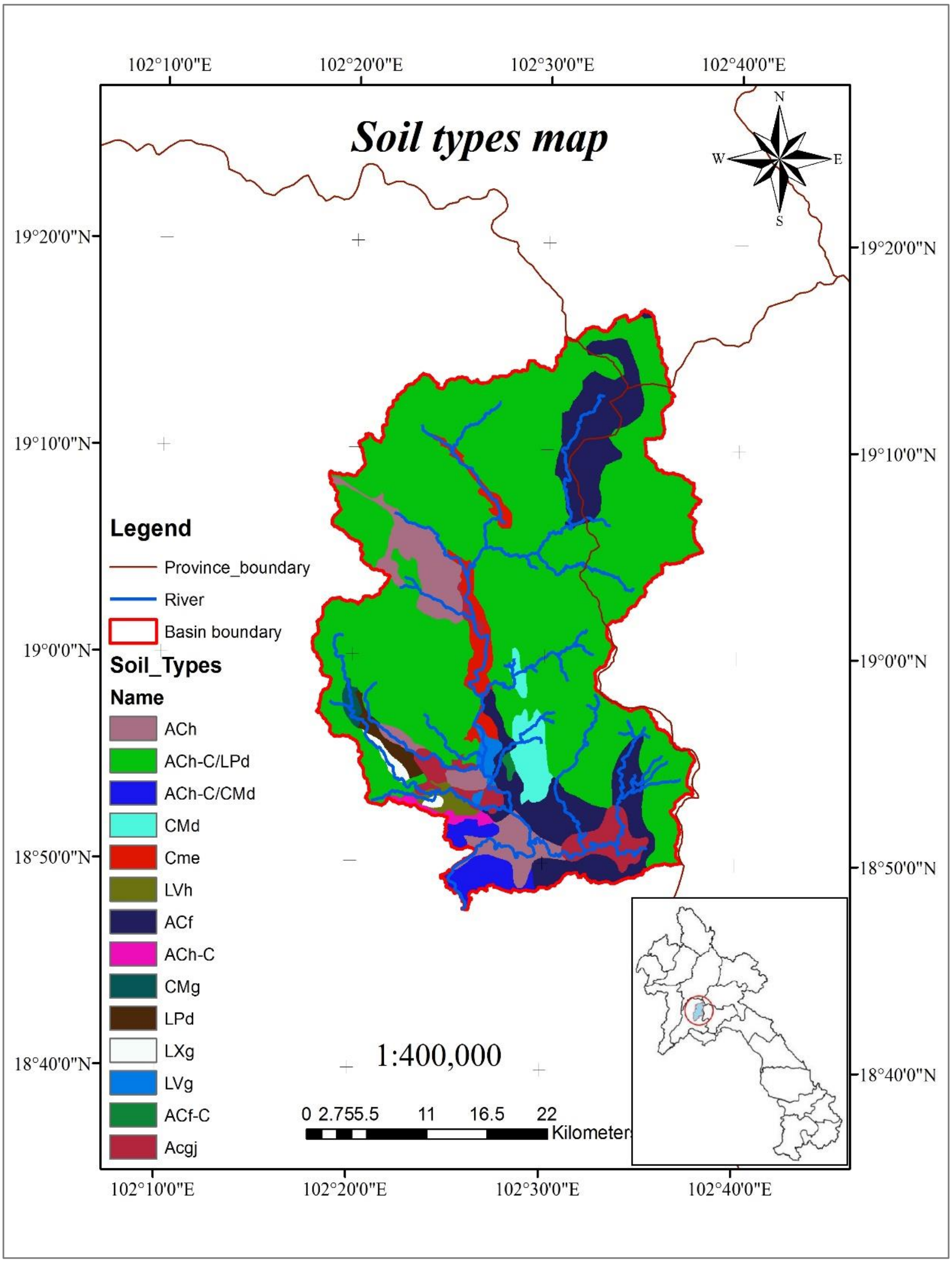


Figure 3.3 Soil types of the Nam Song River Basin

Table 3.2 Soil description of the Nam Song River basin

No	ID	Brief	Soil type	Area (km^2)	% Area
1	0	ACh	HaplicAcrisol	76.99	6.12
2	1	ACh-C/LPd	HaplicAcrisol-skeletic/DystricLeptosol	858.56	68.27
3	2	ACh-/CMd	HaplicAcrisol/DystricLeptosol	26.01	2.07
4	3	CMd	DystricCambisol	26.23	2.09
5	4	Cme	EutricCambisol	31.49	2.50
6	6	LVh	HaplicLuvisol	7.90	0.63
7	10	ACf	Ferric Acrisol	152.07	12.09
8	15	ACh-C	HaplicAcrisol-skeletic	6.16	0.49
9	16	CMg	GleyicCambisol	4.94	0.39
10	30	LPd	DystricLeptosol	9.06	0.72
11	35	LXg	GleyicLixisol	6.42	0.51
12	38	LVg	GleyicLuvisol	7.77	0.62
13	39	ACf-C	Ferric Acrisol-skeletic	1.81	0.14
14	46	Acgj	Stagni-gleyicAcrisol	42.19	3.35
Total				1258	100

Source: National Agriculture and Forestry Research Institute of Laos (2010)

3.3 Hydrological characteristics

The Nam Song River diversion weir was constructed to supply irrigation water to lowland paddy fields. The tributary river systems in this basin are Namnoy, Sanan, Papome, Namkouang, Namka, Nampoh, Namngard, Pooset and Namken River. Hydrological data, i.e. daily rainfall, daily discharge and daily temperatue, in the study area and its vicinity are requested from the Meteorology and Hydrology Department, Lao’PDR. For more detail about location of observed stations are shown in Figure 3.4 and Table 3.3.

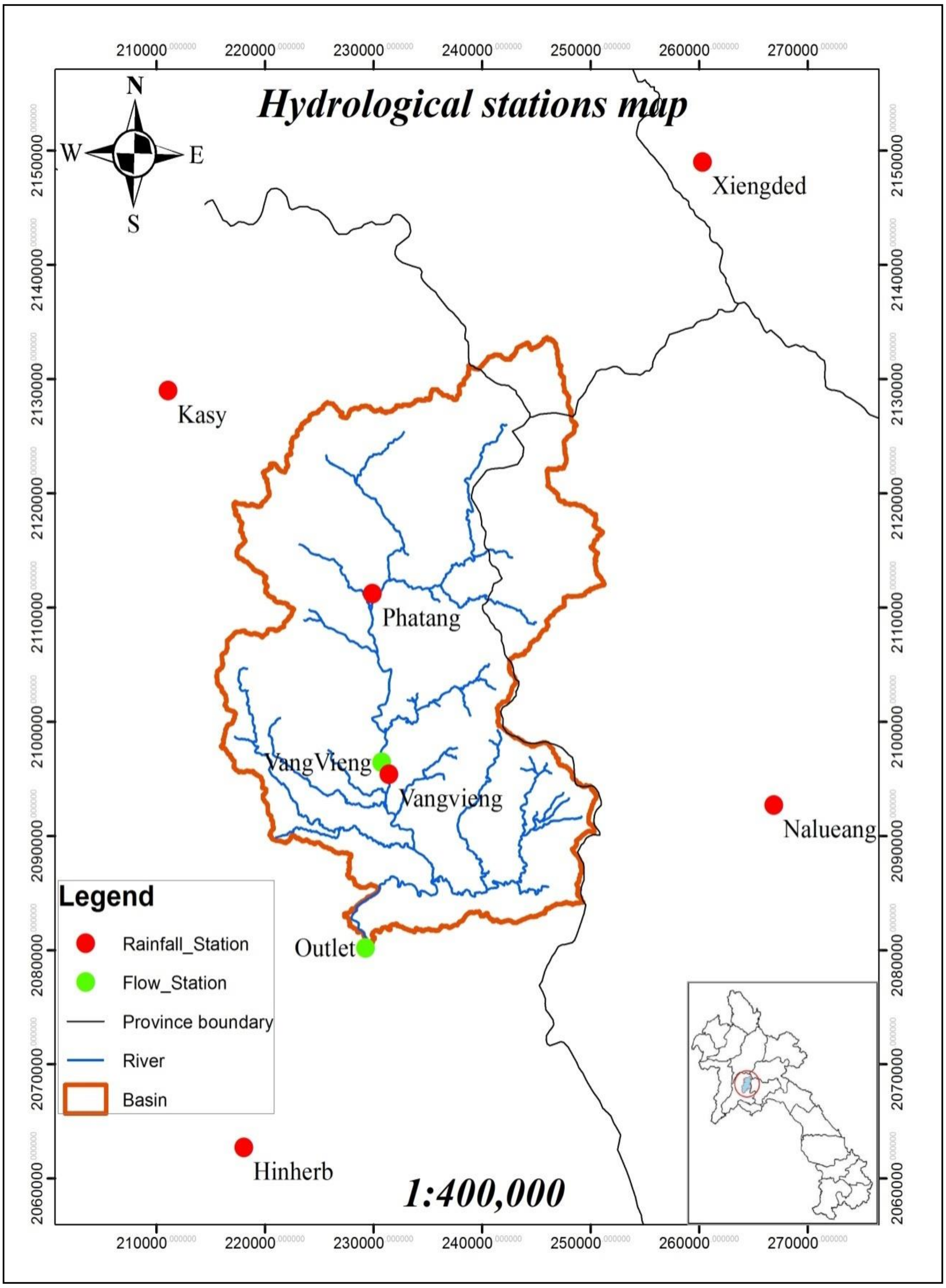


Figure 3.4 Hydrological observed stations

Table 3.3 Hydrological observed stations of Nam Song River basin

Data	Stations	Location		Elevation (m)	Period of time
		Easting	Northing		
Rainfall	Kasy	211,087	2,128,991	216	1996 - 2013
	Phatang	229,914	2,111,195	310	1996 - 2013
	Vangvieng	231,436	2,095,391	215	1996 - 2013
	Hinherb	218,060	2,062,723	195	1996 - 2013
	Nalueang	266,883	2,092,696	290	1991 - 2008
	Xiengded	260,321	2,148,999	720	1996 - 2000
Discharge	Vangvieng	230,773	2,096,474	198	1996 - 2013
	Nam Song Dam	228,770	2,080,482	185	1996 - 2013
Temperature	Vangvieng	231,436	2,095,391	215	1996 - 2013

3.3.1 Precipitation

The rainfall data from six stations are obtained from Meteorology and Hydrology Department, Lao PDR. Among those six stations, two stations are located inside the basin while the other four stations are in the neighboring basins. However, the recording time of Nalueang and Xiengded station are not same with others as shown the details in Figure 3.5 and Table 3.3. The distribution of daily rainfall over the Nam Song River Basin is highly varied. The average daily rainfall was 6.83 mm and maximum rainfall was 263.7 mm occurred in September of 2008 at Vangvieng station. As shown in Figure 3.6, for the time series of monthly average rainfall over the Nam Song basin was ranged from 8.01 mm in to 645.12 mm and the average is 255.30 mm.

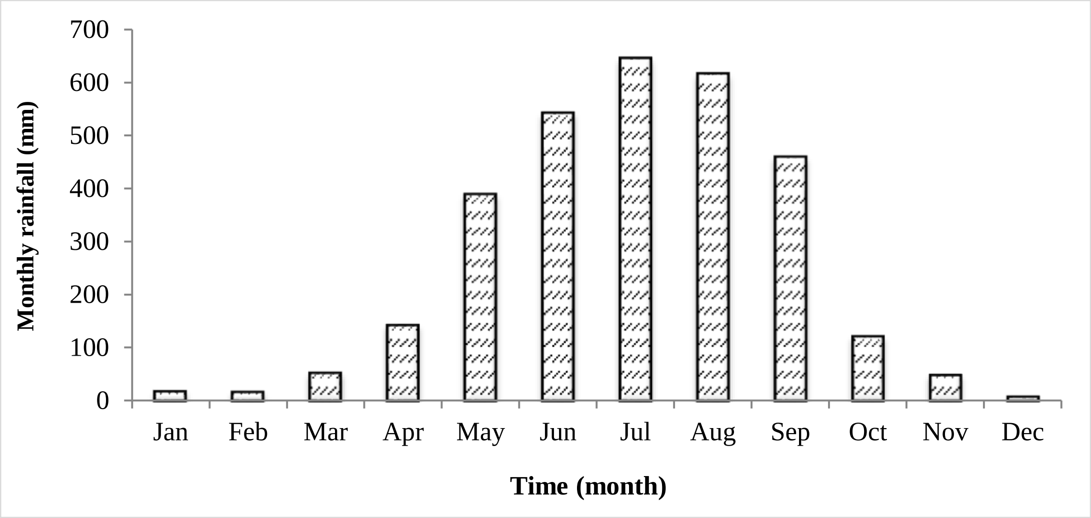


Figure 3.5 Monthly average rainfall (mm) from 1996-2013

1) Precipitation data consistency test

Hydrological data, especially the rainfall data is highly varied in monsoon region. Rainfall data can be recorded using either automatic or manual gage. Generally, long records of rainfall data are preferable than the short ones as they are likely to better represent seasonality and long-term trend. However, the longer record is subjected to a higher number of changes in the physical conditions affecting data consistency. For example, change in the method of the data collection, relocation of the rain gage. The double-mass curve method is used for this study as a tool to assess initial data quality and to ensure data consistency.

Hardison (1960) presented that Double-mass curve is simple, convenient and practical method in the study of the consistency and trend testing of hydrologic data in long term. It is a method used widely in the hydrologic studies. This method plots the regression of accumulated rainfall at the test station against that of the neighboring stations during the same period of time series and examines if any changes in slope can be detected. The rainfall record at the test station is considered consistent if no break in slope is detected. Change in slope indicates data inconsistency which has to be adjusted before performing further analysis. The calculation of the slope of regression line and adjustment of rainfall values is explained below:

$$S_1 = \frac{\Delta Y_1}{\Delta X_1}; \qquad S_2 = \frac{\Delta Y_2}{\Delta X_2} \text{..}(3.1)$$

where: S_1 = Slope of graph of the first period

S_2 = Slope of graph of the second period

If $S_1 = S_2$ the graph is a straight line, that means observed data is consistent

If $S_1 \neq S_2$ the graph has two straight lines, so that difference percentage of slope can be computed:

$$\%Diff = \frac{S_1 - S_2}{S_1} \times 100\% \text{..}(3.2)$$

If %Diff is less than 10% that means observed data is consistent

If %Diff is higher than 10% that means observed data is not consistent and the observed data is needed to be adjusted.

$$\text{Adjust value}(a_1) = \frac{S_2}{S_1} \text{...}(3.3)$$

$$\text{Adjust value}(a_2) = \frac{S_1}{S_2} \text{...}(3.4)$$

For this study, the rainfall consistencies at four rainfall stations (Kasy, Phatan, Hinhueb, and Vangvieng) are tested between 1996-2003. The results indicate small percentages of slope difference (less than 10 %) for almost all stations except only Vangvieng as presented in Table 3.4

Table 3.4 Percentages of slope difference of rainfall data

Station	%Diff	> or < 10%	Adjust value
Hinheub	5.809	<	-
Vangvien	15.359	>	1.352
Phatung	8.966	<	-
Kasy	4.071	<	-

Inconsistency of the record at Vangvieng station is caused by change in gaging instrument in 2004. Adjustment of rainfall record at Vangvieng is performed and shown in Error! Reference source not found..

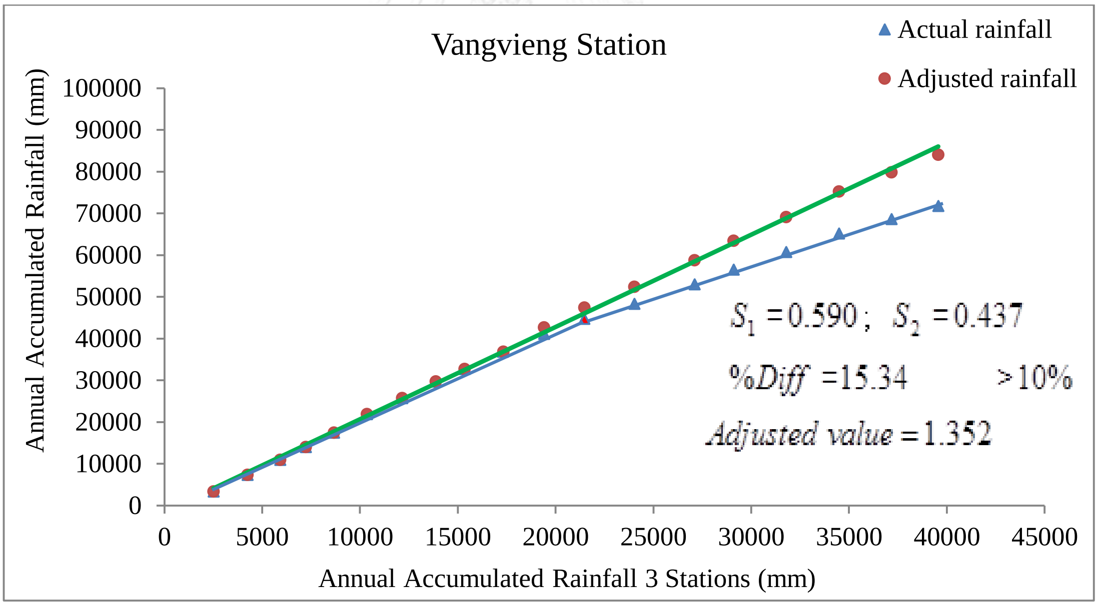


Figure 3.6 Double-mass curve of precipitation data

2) Rainfall interpolation

Rainfall data used for this study are from 1996 to 2013 from a network of six gauge stations that located in and around Nam Song River basin. This point rainfall data was used for estimating the average rainfall over the Nam Song River Basin by using Arithmetic mean and Thiesen polygon methods. Phommalin L. (2014) also estimated the average rainfall over the Nam Song River Basin by using Isohyet and

Invert Distance Weighting (IDW) methods. Table 3.5 presented that whole of methods could estimate in similarity results, but Thiesen polygon method estimated by weighting area and it could be more appropriated, so that average rainfall over the Nam Song River Basin for this study was estimated using Thiesen polygon method. The polygons were created using ArcGIS software. The results found that the basin rainfall is influenced by five rain gauged stations included station outside the basin which are Kasy, Phatang, Vangvieng, Xiengded and Nalueng. Influential areas from each polygon are show in Figure 3.7 and Table 3.5.

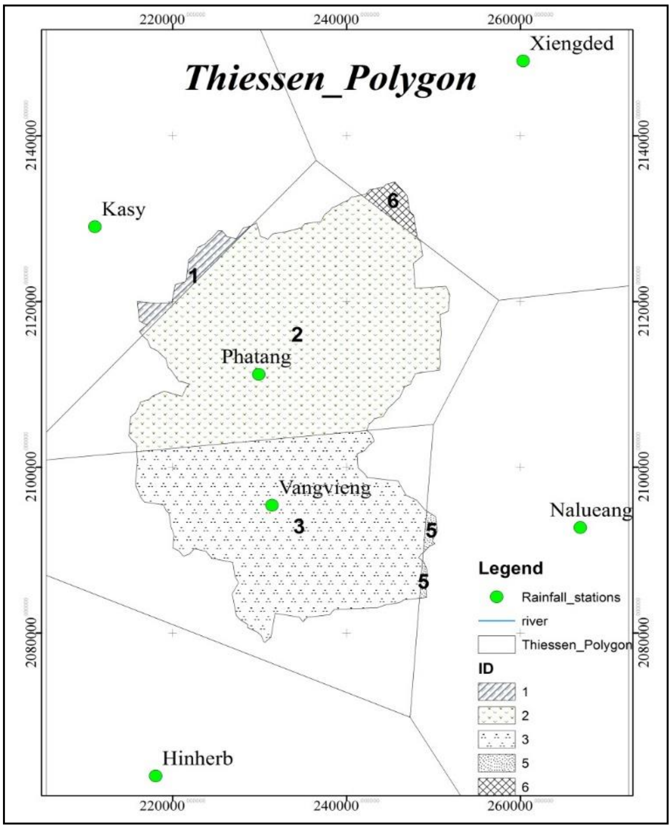


Figure 3.7 Rainfall gauge stations influential basin area

Table 3.5 Rainfall stations area coverage

Method	Average rainfall (mm)	Remark
Thiessen polygon	2444.27	
Arithmetic mean	2464.39	
Isohyetal	2432.83	Phommalin L. (2014)
IDW	2440.78	Phommalin L. (2014)

It can be seen from Fig.3.8 that the areas covered by Kasy, Xiengded and Nalueng stations are small. As a result, the areal rainfall was calculated using the records from Phatang and Vangvieng stations and the values are summarized in Figure 3.8.

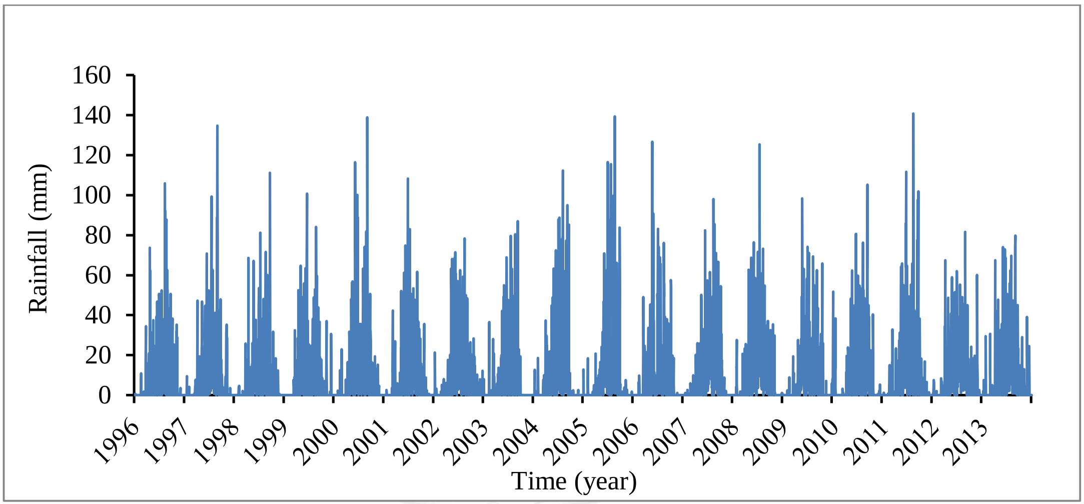


Figure 3.8 Daily average rainfall estimated by Thiesen polygon method

3.3.2 Streamflow

Data from two flow gauge stations from 1996 – 2013 are used for this study. One of the gauges was installed at Vangvieng district and another at the dam (outlet) as shown in Figure 3.4 and Table 3.3. Monthly average discharge at the Vangvieng station was 1,620.33 m^3while maximum and minimum are 4,525.68 m^3 and 258.07 m^3 respectively, see Error! Reference source not found. for more details. The daily average discharge is 48.53 m^3/s while the maximum of 799 m^3/s and minimum is 4 m^3/s.

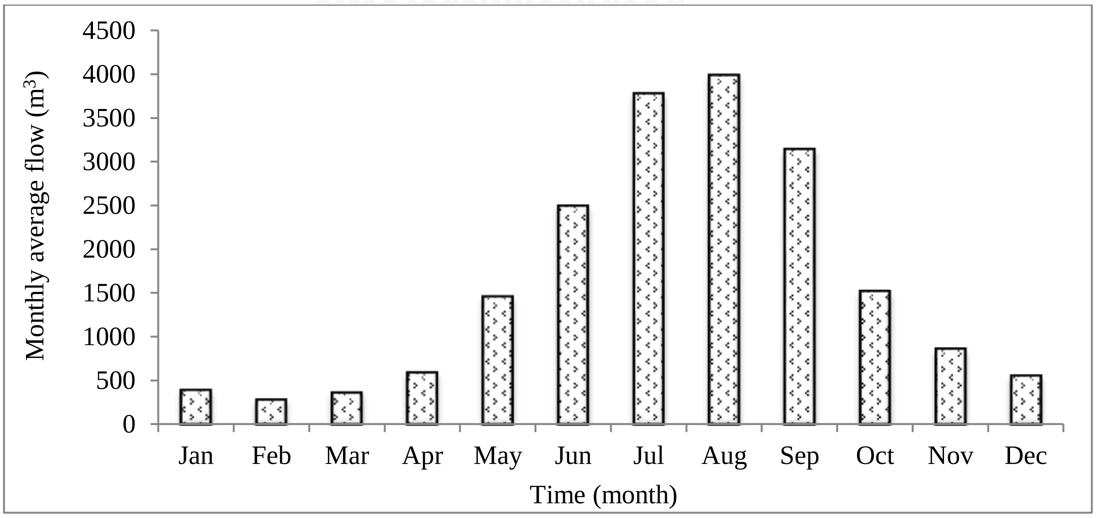


Figure 3.9 Monthly average flow at Vangvieng station (1996-2013)

Flow station at Nam Song Dam will be used for this study. The discharge at the Nam Song dam shows similar pattern to the discharge at the Vangvieng station. The discharge was increased from May until August. The monthly average discharge at the Dam station was 5003 m^3 while maximum and minimum are 13,839 m^3 and 589 m^3 respectively (Error! Reference source not found.). The daily average discharge is 102.4 m^3/s while the maximum of 942.7 m^3/s and minimum is 5.6 m^3/s.

The capacity of this flow rate is sufficient for approximately 200 ha of irrigated area. A private company constructed the weir in 1997. It is about 50 m long and 4.5 m high from the bed of the stream giving a flooding storage level of about 5.0 m. The weir cost was about 30 million Kips of which 30% came from contributions by the 4 neighboring villages while the rest was a government subsidy. The operation of weir is very simple, because the gate made from wood. During the dry season the gate is replaced by wood pieces to keep the water level at the require height, and the rainy season they are removed to increase discharge capacity (Keochan, 2014).

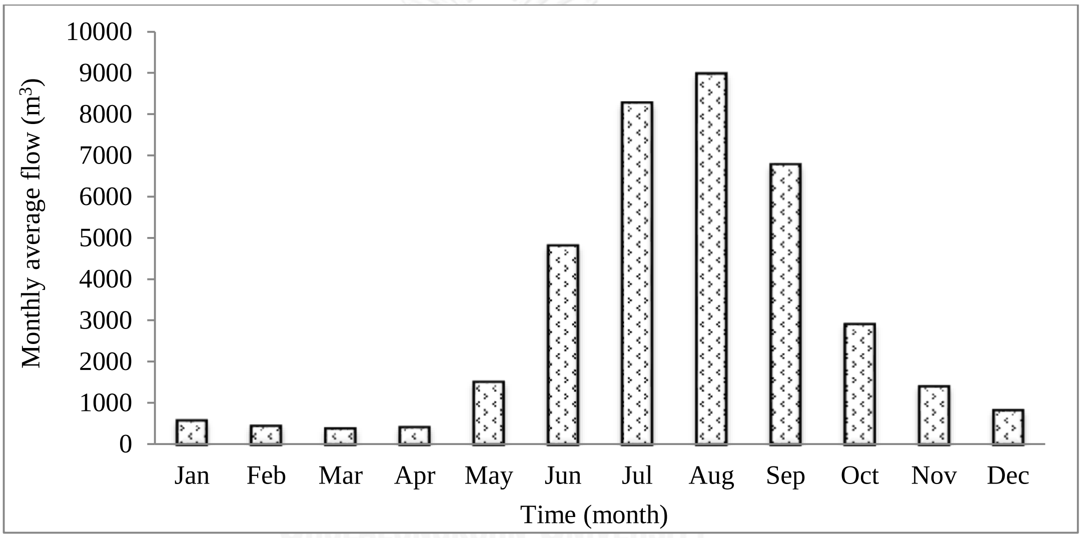


Figure 3.10 Monthly average flow at Outlet station (1996-2013)

3.3.3 Temperature

According to the temperature measurement of Department of Meteorology and Hydrology at Vangvieng station (1996-2013), it is indicated that daily maximum of temperature was 40 ºC (May, 2003) while the minimum 4.5 ºC (December, 1999) and the average 26 ºC. For the monthly average temperature as shown in Figure 3.11, the variability between maximum and minimum ranged from 5.87 to 12.78 °C. The largest fluctuation was occurred in March, while the smallest fluctuation was occurred in July (Katus & Suhardiman, 2016).

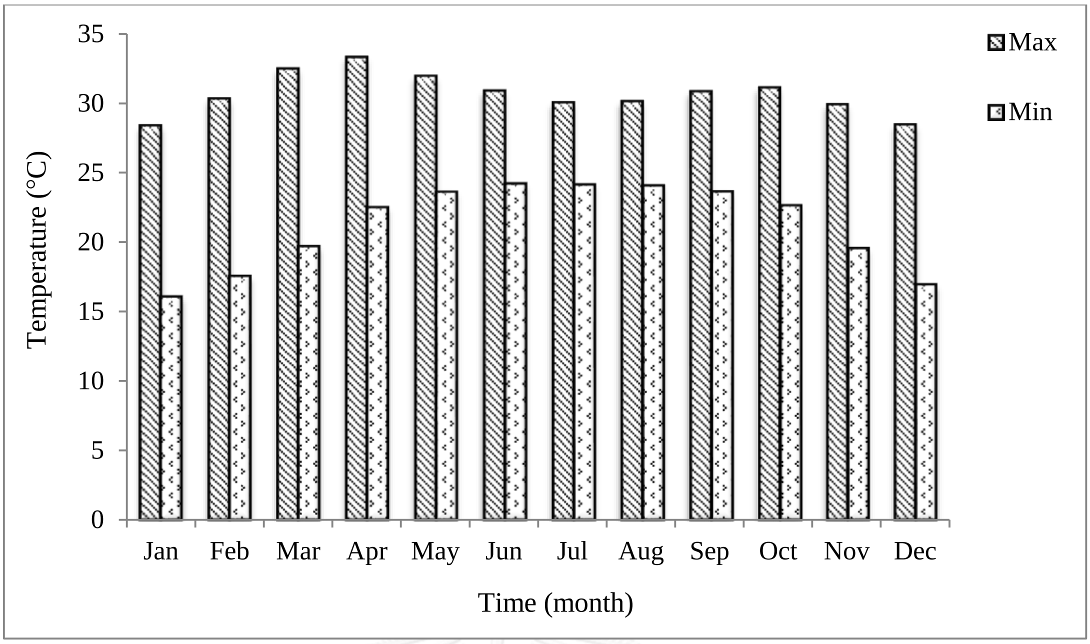


Figure 3.11 Monthly average temperature (1996 – 2013)

CHAPTER 4
METHODOLOGY

To achieve the desired objectives mentioned in the earlier session, research methodology is set as flowchart in Error! Reference source not found.. The first step is data collection followed by the testing of rainfall estimation methods. Next is rainfall-runoff modeling which includes parameters calibration and validation to evaluate the effectiveness of the model for streamflow prediction. The final step is to analyze and discuss the model results. Detail of each step is explained in the following part of this chapter.

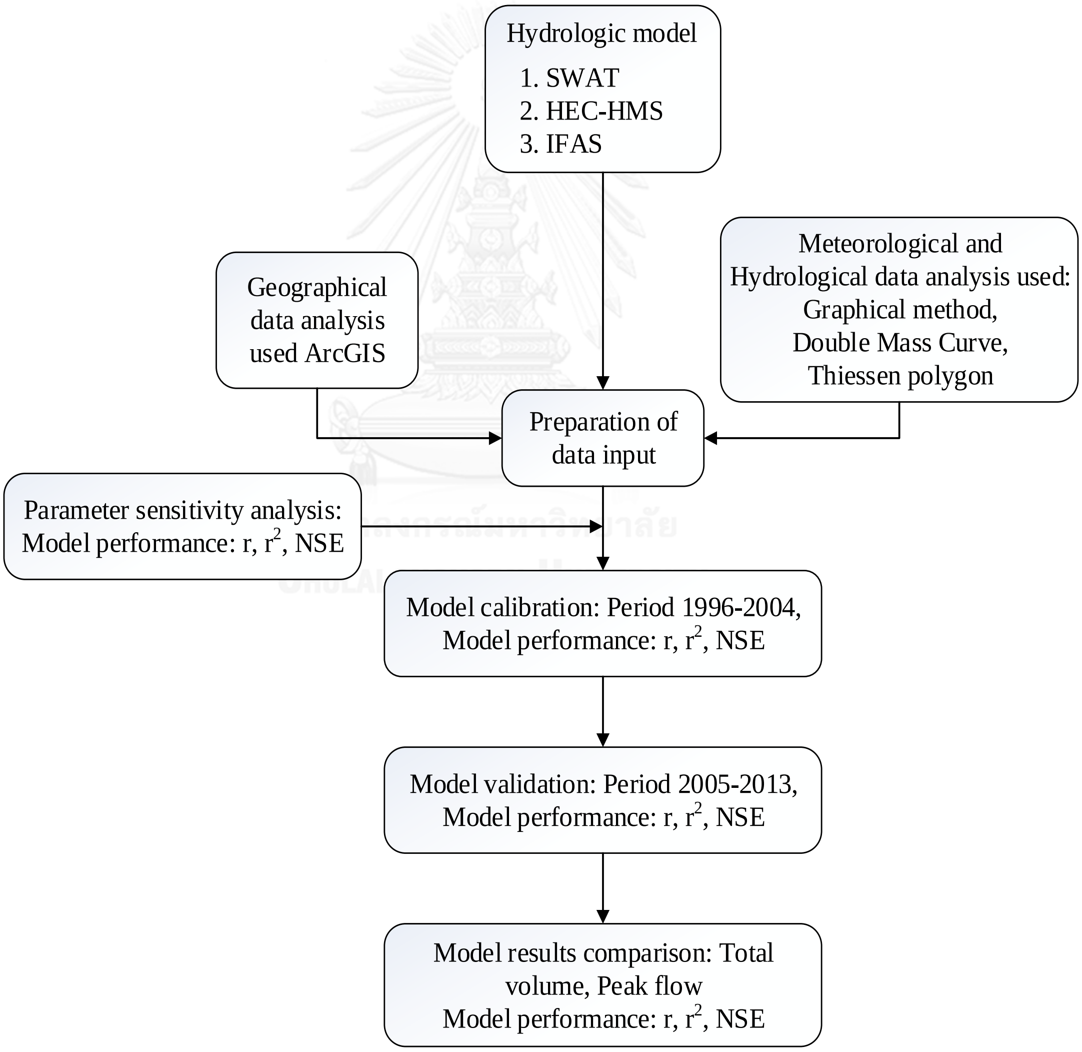


Figure 4.1 Research method

4.1 Model selection

Suitable rainfall-runoff model selection for streamflow simulation is based on the understanding of the objectives and the system being modeled. The principle in choosing a model, it should not have more parameters requirement or greater level than the available data that modeler can support (Kadane & A., 2004). There are numerous criteria which can be used for choosing a suitable hydrologic model. Some criteria are user dependent such as the personal preference for graphical user interface, computer operation system, input-output management and structure, fundamental selection. The following possible factors and criteria are required when selecting a model (Jai Vaze, 2011).

1) Ability to served desired objectives; e.g. hydrological forecasting, assessing human influence on natural hydrological regime or climate change impact assessment.
2) The types of system to be modeled such as small basin, river reach, reservoir or large river basin.
3) Hydrological elements to be model; e.g. flood, daily and monthly average discharge, water quality, amongst others.
4) Climate and physiographic characteristics of the system to be modeled.
5) Data availability with regard to type, length and quality of data and data requirements for model calibration and operation.
6) Model simplicity, as far as hydrological complexity and ease for application are concerned.
7) Possible transposition of model parameter value from smaller sub-basin of the overall basin or from neighboring basin.
8) The ability of the model to be updated conveniently on the basic current hydro-meteorological conditions.

The simple method for the runoff estimation could be Modified rational method, but the rational method is appropriate for estimating peak discharge for small drainage areas of up to 25 km^2 or smaller with no significant flood storage (Chow V.T., 1988). In additional, the Nam Song basin is large than 25 km^2, therefore, this study is need to select others model to apply for the Nam Song basin.

There are a large number of rainfall-runoff models found to give satisfactory results for simulating daily, monthly or seasonal streamflow, and usually for forecasting and estimating long-term runoff-volume such as NAM model (Doulgeris, 2011), SWAT model (Keochan, 2014), TOPMODEL (Bancha Kwanyuen, 2003; W. Gumindoga, Rwasoka, & Murwira, 2011), MIKESHE (Sandu, 2015), HEC-HMS model (Phommalin, 2014), IFAS mode (Jamila Rajabi, 2015; Wathanakarn, 2010), HBV model (Grillakis, Tsanis, & Koutroulis, 2010) and VIC mode (Tatsumi, 2015). They can be classified as lumped, semi-distributed and fully distributed model based on the model parameters as a function of space and time and deterministic and stochastic models based on the other criteria. The lumped method averages the total rainfall, its distribution over space, soil characteristics, overland flow conditions, etc. Fully distributed parameters describe the both of geographical variation of parameters and identify between changes in the hydrologic processes that occur on the basin. Parameters assigned to each grid cell while parameters of semi-distributed assigned to each grid cell, but cells with same parameters are grouped (see Chapter 2 section 2.2.1) (Vernon Knapp, 1991).

The rainfall-runoff models selection for this study are based on the categories and number of parameters in the model. The SWAT, HEC-HMS and IFAS models are chosen to apply in this research. Because, SWAT and HEC-HMS rainfall-runoff models are popularly using for predicting streamflow in Lao PDR, but they just Lumped (HEC-HMS) and semi-distributed (SWAT) models so that, one more Fully-distributed model (IFAS) is added (see Table 2.1).

4.2.1 HEC-HMS model

HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) model was developed by the US Army Corps of Engineers (Feldman, 2000) that could be used for many hydrological simulations. HEC (Hydrologic Engineering Center) has led object-oriented programming on HEC-1 and developed a window mode. HEC-1 evolved into HEC-HMS. The program is generalized modeling system capable of representation in many different basins. The model of watershed is constructed by separating hydrologic cycle manageable pieces and the boundary around the basin of interest is constructed also. The mathematic model is used the mass and energy flux in the hydrologic cycle, each mathematic model is included into the program for using in different environments and under different conditions. Many methods are included for transforming excess precipitation into surface runoff that are Unit hydrograph method included the Clark, Snyder and SCS techniques.

HEC-HMS model is a lumped model that designed to simulate both event and continuous simulation. HEC-HMS is comprised of a graphical user interface, integrated hydrological analysis components, data storage and management capabilities, and graphic and reporting facilities (Bell, 2001).

The HEC-HMS model contains four main components: 1) An analytical model to calculate overland flow runoff as well as channel routing, 2) an advanced graphical user interface illustrating hydrologic system components with interactive features, 3) a system for storing and managing data, specifically large, time variable data sets, and 4) a means for displaying and reporting model outputs (Tim, 2002). The flow characteristics in the HEC-HMS model is classified in the lumped hydrological model (Fionda, 2011) due to the large basin area is divided into sub-basins, each sub-basin comprises of Hydrologic Response Units (HRUs). Flow routing process of each HRU is Lumped processes (Oleyiblo, 2010).

A sub-basin is an element that has no inflow and only one outflow. The outflow is computed from meteorological data by three main methods such losses, transforming excess rainfall, and baseflow. The user can add a canopy component to represent interception and evapotranspiration. It is also optimal to add a surface component to represent water caught in surface depression storage (Feldman, 2000).

1) Canopy method

Canopy is one of the components can be included in the sub-basin element. It is intended to represent the plant in the landscape. Plants intercept precipitation, reducing the amount of precipitation that arrives at the ground surface. Plant also extracts water from the soil in a process called transpiration. There are two methods in canopy method. First method is called dynamic canopy and another is gridded simple canopy.

2) Surface method

The surface method is intended to represent the ground surface where the water may accumulate in surface depression storage. Surface runoff will begin when the precipitation rate exceeds than the infiltration rate, and the surface storage is filled. The precipitation in the surface storage can infiltrate after precipitation stop. The surface method is generally used for continuous simulation application.

3) Loss method

While the basin element represents infiltration, surface runoff, and subsurface together, the actual infiltration calculation is perform by loss method. There are a lot of different loss method are provided. Some of the methods are designed for continuous simulating while others are intended for events simulation. All of methods are the summary of infiltration and precipitation on the surface that equal to total incoming precipitation (Phommalin, 2014). Event modeling is included exponential, Green Ampt, and Smith Parlange. The SCS curve number and one-layer deficit constant methods can be used for continuous modeling. The three-layer soil moisture accounting method can be used for complex infiltration of continuous modeling. The SCS curve number method is widely used in rainfall- runoff field and it is also used in this study. For the detail of SCS curve number method is shown in section 4.3.1.

4) Transform method

Transform method is one of the actual surface runoff calculation within the sub-basin that is included the infiltration. Transforming excess precipitation into the surface runoff can choose in seven methods. Unit hydrograph methods include the Clark, Snyder, and SCS techniques. User-specified unit hydrograph or s-graph can also be used. Modified Clark method is a linear quasi-distributed unit hydrograph method that can be used with gridded meteorology data. Kinematic wave method with multiple planes and channels is also included. The Snyder method is used in his study. It is a synthetic unit hydrograph method. The original data is only supported computing the peak flow as the result of a unit precipitation. Later on, it was developed to calculate the time base of hydrograph (Chow, 1988). Snyder defied a standard unit hydrograph as one of rainfall duration related to the basin lag.

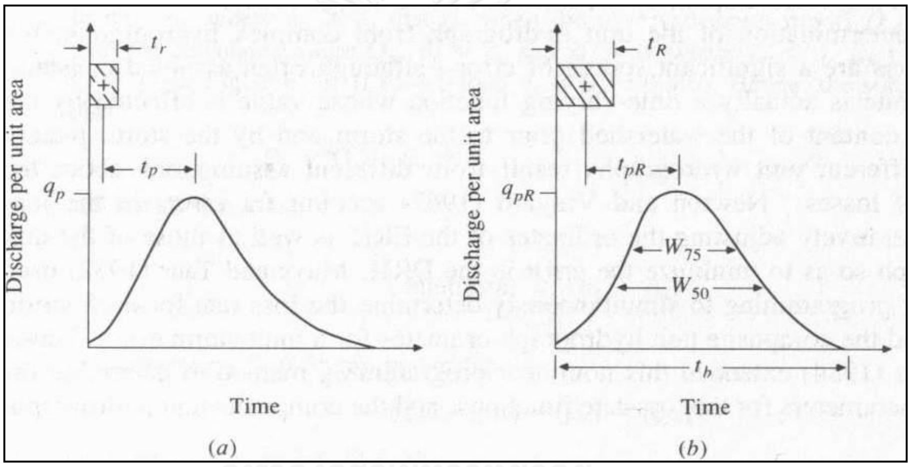


Figure 4.2 Snyder’s synthetic unit hydrograph (Chow, 1988)

5) Baseflow method

Baseflow method is one of components in the sub-basin element. While a sub-basin element represents infiltration, surface runoff, and subsurface together, the subsurface computation are performed by baseflow method. A total of five different baseflow methods are used for sub-basin outflow. Several methods are used for designing of primary simulating events, for the others designed for continuous simulation. The recession method gives an exponentially decreasing baseflow from a single or multiple events. The constant monthly method is well for continuous simulation. The linear reservoir method computes mass by routing infiltrated precipitation to the channel. The last method is nonlinear Boussinesq, this method provided a response similar to the recession method.

4.2.2 IFAS model

Integrated Flood Analysis System (IFAS) was developed by a collaborative research team of International Centre for Water Hazard and Risk Management (ICHARM), the Public Works Research Institute (PWRI) (ICHARM, 2009). IFAS is a succinct tool with a Graphic User Interface (GUI) for building analysis distributed rainfall-runoff model. The model comprise of distributed hydrological model based on the tank model and routing model and also based on kinematic wave hydraulic model. The hydrological analysis model is Public Work Research Institute Distributed Hydrological model (PWRI-DHM) and has developed in the 1990th in Japan. Therefore, the preparing user-friendly graphic interface for data input and output, model constructing module, parameter setting function and rainfall-runoff analysis can be possible even in poorly gauged basin (ICHARM, 2011)

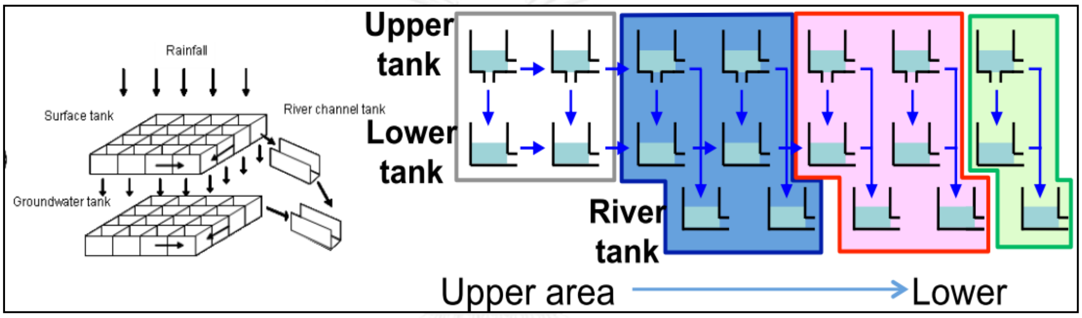


Figure 4.3 Schematic figure of distributed hydrological model (ICHARM, 2011)

There are several issues of flood predicting system installation in poorly gauged basins such as poor of implement and maintenance of hydrological observation gauges, including rain gauge and river discharge gauge. Lack of the data for creation of streamflow forecasting model such as coordination, land use, land cover, and river channel network, these are needed for a streamflow simulation system installation, and also insufficient of framework to enhance technical capabilities.

To simulate streamflow process, IFAS uses the theoretical of tank model, Manning's law, Darcy's law and kinematic wave methods. Parameters can be estimated by using grid-based global data set on topography, soil classes, and land use. When the actual flood event is reproduce by storage function method. Flood reproducibility is not enough in medium/small size floods, because the storage function method is non-linear and one layer tank. For numerical calculation, approximation function was used to solve time integral equation. For the discharge calculating in the river course tank is solved by Kinematic Wave equation (Jamila Rajabi, 2015).

IFAS model Version 1 contains three layers included surface tank, unsaturated tank and groundwater tank. According to the results from users, the unsaturated tank does not need for this model so that, Version 2 contains configuration of two tanks on vertical direction. Direction flow is routed from upstream to downstream area by the surface and aquifer tank as shown in the Figure 4.3. For the river channel tank distribution is set according to four cell types and only starts in cell with a defined number of upstream cells. To set the cell type value for estimating the number of upstream cell, the default value of cell type can be defined. Type 0 is 1-2 cell, type 1 is 3-4 cells, type 2 is 5-64 cells, and for type 3 are 65 or more. The characteristics of each cell type are shown in Table 4.1 (ICHARM, 2009). Different cell type is the way to estimate the different flow process and how different tank are used. Assume that the upstream is the area near the end of the drainage course of each river tributary.

Table 4. 1 Cell type characteristics

Cell type	Characteristics
Cell type 0	The cell which water flows only into surface tank and aquifer tank, without river channel tank
Cell type 1	The cell which water flows into aquifer tank and river channel tank from surface tank
Cell type 2	The cell which water flows from aquifer tank into river channel tank
Cell type 3	The cell of river tank, which executes channel routing based on kinematic wave method.

The horizontal and vertical flows in IFAS can be divided into three types of model including Surface tank, Groundwater tank, and River tank, the characteristic of each model can be described by follows (Jamila Rajabi, 2015).

1) Surface tank model

The surface model in IFAS is used to calculate the rainfall to runoff, rapid intermediate, and ground infiltration flow. The surface outflow is estimated as a fraction of storage capacity based on the Manning law while the ground infiltration is based on Darcy Law.

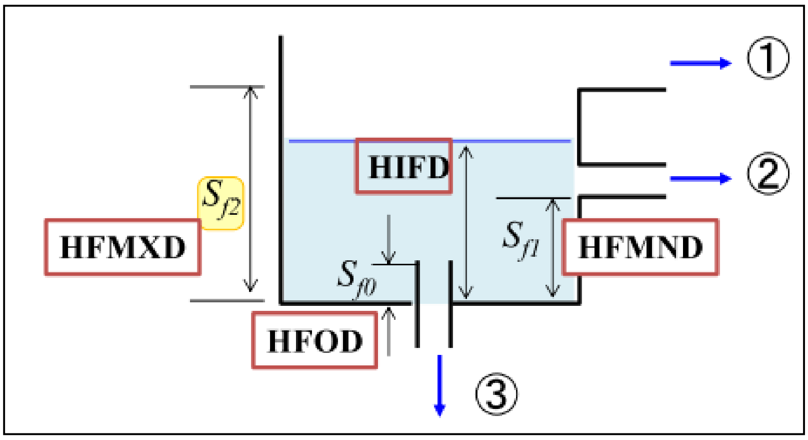


Figure 4.4 Surface layer tank (ICHARM, 2009)

- Surface flow $$L\frac{1}{N}\ h-S_{f_2}\ ^{5\!/\!3}\sqrt{i}\text{...}(4.1)$$
- Subsurface flow $$\alpha_n A_{f_0}\frac{h-S_{f_1}}{S_{f_2}-S_{f_1}}\text{...}(4.2)$$
- Infiltration $$A_{f_0}\frac{h-S_{f_0}}{S_{f_2}-S_{f_0}}\text{...}(4.3)$$

where: f_0 = vertical hydraulic conductivity
S_{f_0} = height where the ground infiltration occurs
S_{f_1} = height from which rapid unsaturated subsurface flow occurs
S_{f_2} = height from which surface flow occurs
N = ground surface roughness coefficient
L = mesh length
i = slope with the adjacent cell
α_n = rapid unsaturated subsurface flow regulation coefficient
h = water height for the tank

2) Groundwater tank model

The groundwater model configuration is shown in Figure 4.5. The top right and bottom right orifices represent the confined and unconfined groundwater flow, respectively. Groundwater outflow is considered by a fraction of confined aquifer to h, and unconfined aquifer to h^2.

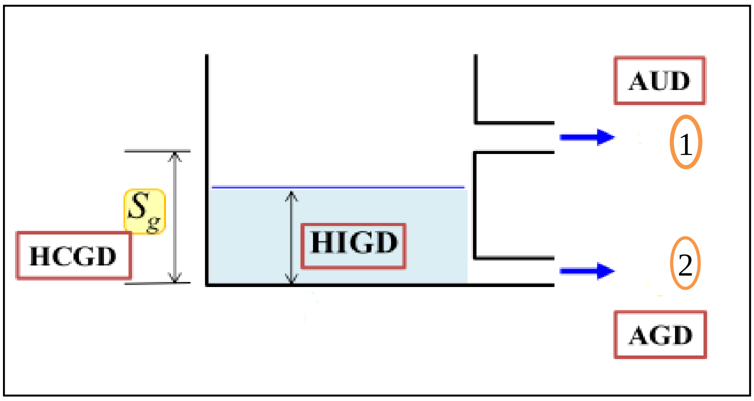


Figure 4.5 Groundwater tank

- Unconfined groundwater flow $A_u^2 \times \ h - S_g \ ^2 \times A$.....................................(4.4)
- Confined groundwater flow $A_g \times h \times A$..(4.5)

where: A_u = slow saturated subsurface flow coefficient
A_g = base flow coefficient
S_g = height where slow saturated subsurface flow occurs

3) River channel tank model

The river channel model configuration is shown in Error! Reference source not found.. The discharge in the river course tank is based on the cell type. For cell type 1 and 2, the outflow from river channel tank is based on Manning equation while the cell type 3 is based on kinematic wave method.

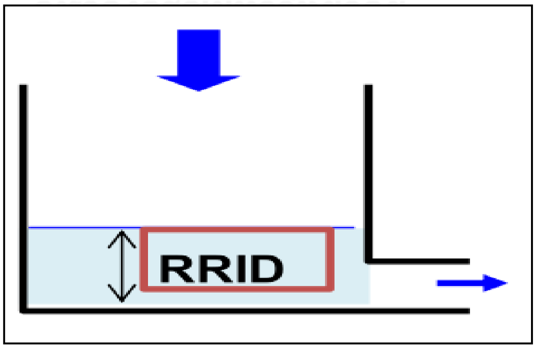


Figure 4.6 River channel tank model

Manning equation: $B\frac{1}{n}h^{5/3}\sqrt{i}$..(4.6)

where: B = breadth of river course
i = slope of river course
h = water height for the tank
n = roughness coefficient of river course

4.2.3 SWAT model

Soil and Water Assessment Tool (SWAT) model was developed by the Backland Research Center (BRC), United State Department of Agriculture - Agriculture Research Service (USDA-ARS) and Texas Agriculture Experiment Station (TAES) (Koonto, 2012). SWAT model was developed to predict the impact of land management on water resources, sediment chemical yield from agricultural practices in the large-complex watershed with varying of soil, land use and management over the long period of time. The model can simulate physical systems occurred over basin by dividing the large basin into sub-basins of similar land use characteristics. In each sub-basin has at least a HRU, a main channel, a tributary channel or reach (Suwanlertcharoen, 2011).

Hydrologic response units are a part of a sub-basin that process land use and soil attributes. To capture the diversity of land use and soil classes, the method is needed to distribute the complexity of land use and soil classes within the boundary of sub-basin. An HRU is the total area in the sub-basin with particular land use and soil classes, HRUs with similar land use and soil classes are lumped together into a single response unit (S.L. Neitsch, 2011). The benefit of HRUs is to increase the accuracy and give a much better physical description of the basin. The growth and development of plants can differ greatly among species. When the diversity of plant cover within a sub-basin is accounted, the runoff in the main channel from the sub-basin will be more accurate (Navarathna, 2005).

There are two options in determining the HRU distribution including a single HRU and multiple HRUs. The single HRU option is determined by the dominant land use category and soil classes within each sub-basin. This option will allow creating only one HRU for each sub-basin. The multiple HRUs option may specify sensitivities for land use and soil class data that will be used to determine the number and kind of HRUs in each sub-basin. For this option will allow creating multiple HRUs within each sub-basin (Kalcic, 2015). Multiple Hydrologic Response Units is defining of sub-basin boundary into HRUs to conform to land use percentages over sub-basin area, soil class percentages over land use area, and slope class percentages over soil class area. This study set those thresholds at 10%, 10%, and 5% respectively (Keochan, 2014).

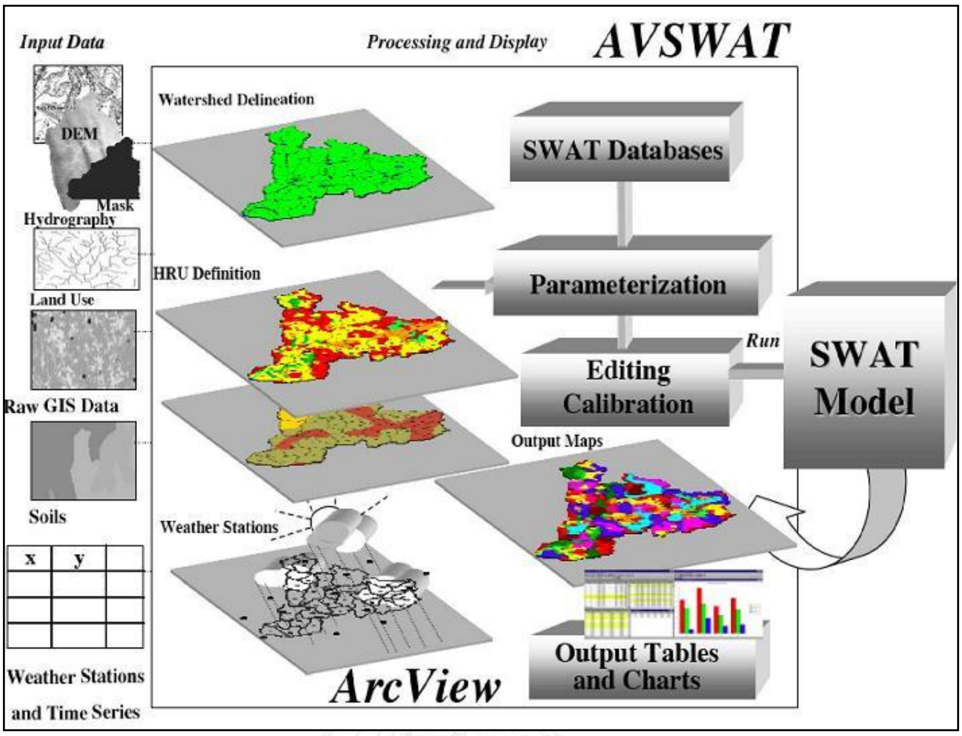


Figure 4.7 Processing of SWAT model (Dile, 2016)

The model offers two options for analysis of hydrological basin they are: 1) Land phase is to study hydrologic cycle for flow estimation, sediment and chemicals from agricultural practices before flowing to the main rivers of each sub-basin, the sub-basin can be subdivided into 8 parts such as hydrology, climate conditions, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agriculture management; 2) River Routing phase is to calculate the water routing, sediment and etc. The hydrologic cycle in SWAT model is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \quad \text{..(4.7)}$$

where: SW_t = final soil water content
SW_0 = initial soil water content on day i
t = time (day)
R_{day} = amount precipitation on da i
Q_{surf} = amount of surface runoff on day i
E_a = amount of evapotranspiration on day i
w_{seep} = amount of water entering the vadose zone from soil profile on day i
Q_{gw} = amount of return flow on day i

This equation takes into account several different processes precipitation, surface runoff, evapotranspiration, recharge, and soil water storage.

1) Surface runoff

Surface runoff is computed by using a modification of SCS curve number method or Green and Ampt infiltration method. In the curve number method, the curve number varies non-linearly with the soil moisture content. The curve number decreases as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation (Chow, 1988).

$$P_e = \frac{{P - I_a}^{\;2}}{P - I_a + S} \text{...} (4.8)$$

This is the basic equation for computing the depth of excess rainfall or direct runoff from a storm by using SCS method. By the results of study from many small experimental watersheds, an empirical relation was developed.

$$I_a = 0.2S \text{...} (4.9)$$

$$P_e = \frac{{P - 0.2S}^{\;2}}{P + 0.8S} \text{...} (4.10)$$

The curve number and S values are related by:

$$S = \frac{1000}{CN} - 10 \text{...} (4.11)$$

where *S* is in inches. The curve numbers have been listed by the Soil Conservation Service on the basic of soil type and land use. The soil can be defined into four groups.

Group A: Deep sand, deep loess, aggregated silts. They have a high rate of water transmission. The soils have a high infiltration rate even when thoroughly wetted.

Group B: Shallow loess, sandy loam. The soils have a moderate infiltration rate even when thoroughly wetted.

Group C: Clay loams, shallow sandy loam, soil low in organic content, and soil usually high clay. The soils have a slow infiltration rate even when thoroughly wetted.

Group D: Soil that swell significantly when wet, heavy plastic clays and certain saline soils.

The curve number values for various on these land use on these soil types are given in Appendix (A1). The curve number values made up from Nam Song Sub-basins for using in this study can be calculated (Wathanakarn, 2010).

2) Peak runoff rate

SWAT calculates the peak runoff rate by using a modified rational method. The rational method is widely used in the design of canals, channels and storm water control system. The rational method is based on the assumption that if rainfall intensity begins at time (zero) and continues indefinitely, the rate of runoff will increase until the time of concentration. The rational formula can be defined:

$$q_{peak} = \frac{C \times i \times Area}{3.6} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.12)$$

where: q_{peak} = peak runoff rate (m^3/s)
C = runoff coefficient
i = rainfall intensity (mm/hr)
$Area$ = sub-basin area (km^2)
3.6 = unit conversion factor

3) Lateral Subsurface Flow

Lateral subsurface flow in SWAT is calculated with kinematic storage model and developed by Sloan and Moore (1984). This model is based on the mass continuity equation, or mass water balance. Estimation of saturated subsurface or lateral flow assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of the bed. Lateral subsurface flow is calculated by equation:

$$Q_{lat} = 0.024\left(\frac{2 \times SW_{ly,excess} \times K_{sat} \times slp}{\varphi_d \times L_{hill}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.13)$$

where: Q_{lat} = water discharge from hillslope outlet (mm/day)
$SW_{ly,excess}$ = drainable of water volume in saturated zone of hillslope (mm)
K_{sat} = saturated hydraulic conductivity (mm/hr)
slp = slope of the bed
ϕ_d = drainable porosity of the soil layer (mm/mm)
L_{hill} = hill slope length (m)

4) Groundwater flow

Groundwater flow in SWAT is calculated two aquifers in each sub-basin. The shallow aquifer is an unconfined aquifer that contributes to flow in the main channel or reach of sub-basin. The deep aquifer is a confined aquifer. Water that enters the deep aquifer contributes to streamflow somewhere outside of watershed. The water balance for the shallow aquifer can be defined by:

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg,sh} - Q_{gw} - w_{revap} - w_{pump,sh} \text{..} (4.14)$$

where: $aq_{sh,i}$ = amount of water in the shallow aquifer on day *i* (mm)
$aq_{sh,i-1}$ = amount of water in the shallow aquifer on day *i*-1 (mm)
$w_{rchrg,sh}$ = amount of recharge inter the shallow aquifer on day *i* (mm)
Q_{gw} = groundwater or base flow into the main channel on day *i* (mm)
w_{revap} = amount of water moving into the soil on day *i* (mm)
$w_{pump,sh}$ = amount of water moving from shallow by pumping on day *i* (mm)

The water balance for the shallow aquifer can be defined by:

$$aq_{dp,i} = aq_{dp,i-1} + w_{deep} - w_{pump,dp} \text{...} (4.15)$$

where: $aq_{dp,i}$ = amount of water in the deep aquifer on day *i* (mm)
$aq_{dp,i-1}$ = amount of water in the deep aquifer on day *i*-1 (mm)
w_{deep} = amount of water from shallow aquifer into the deep aquifer day *i* (mm)
$w_{pump,dp}$ = amount of water moving from deep aquifer by pumping day *i* (mm)

Water in the deep aquifer is not considered water budget calculation in the future and it can be considered to be lost from system.

5) Evapotranspiration

In SWAT model has three methods for calculating the evapotranspiration. The Penman-Monteith method requires solar radiation, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiation, air temperature and relative humidity. The Hargreaves method requires only air temperature.

The Penman-Monteith equation combined component of energy that need to maintain evaporation. The mechanism strength is required to remove the water vapor and aerodynamic and surface resistant term. The Penman-Monteith equation can be written:

$$\lambda E_t = \frac{\Delta \cdot (H_{net} - G) + \left[\gamma \times K_1 \times (0.622 \times \lambda \times \rho_{air} / P)\right] \times (e_z^o - e_z) / r_a}{\Delta + \gamma \cdot (1 + r_c / r_a)} \text{..........} (4.16)$$

where: λ = latent heat of vaporization (MJ/kg)
E_t = maximum transpiration rate (mm/day)
K_1 = dimension coefficient (8.64×10^4)
P = atmospheric pressure (kPa)
Δ = slope of the saturation vapor pressure-temperature curve (kPa/ $°C$)
H_{net} = net radiation (MJ/m^2/day)
G = heat flux density to the ground (MJ/m^2/day)

ρ_{air} = air density (kg/m^3)
e_z^o = saturation vapor pressure of air at height z (kPa)
e_z = water vapor pressure of air at height z (kPa)
r_c = plant canopy resistance (m/s)
r_a = diffusion resistance of air layer (m/s)
γ = psychometric constant (kPa/$°C$)

Routing phase of hydrologic cycle, SWAT routes the water, sediment, nutrients and pesticides through the stream network of the watershed to the main channel. The routing phase can be divided into two components such routing in the main channel or reach and routing through the reservoir. Manning's equation is used in SWAT to define the rate and velocity of flow. Water is routed through channel network by using the variable storage or Muskingum river routing method. Both of them are variation of the kinematic wave model (Chow, 1988). Muskingum routing method was used in this study. This method simulates the storage volume in the channel as a combination of the wedge and prism storages as show in Figure 4.8.

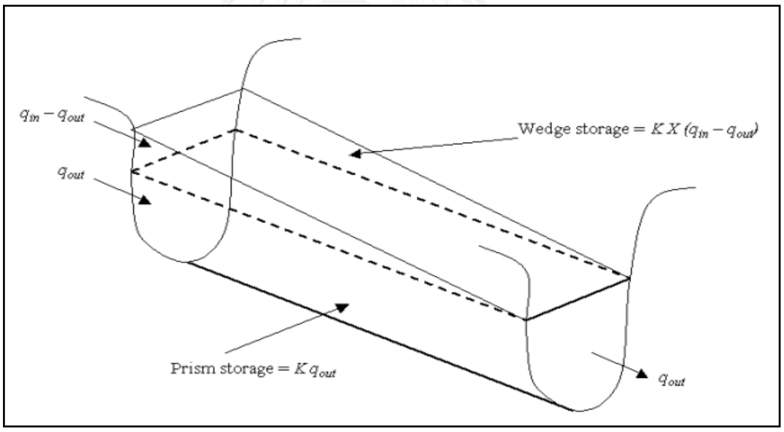


Figure 4.8 Wedge and prism storages in a channel (Chow, 1988).

The cross-sectional area of flow is assumed to be directly to calculate the discharge. The volume of prism storage can be computed by function of $K \times q_{out}$, where K is the ratio of storage to discharge and dimension of time. The volume of the wedge storage can be computed by $K \times X \times \ q_{in} - q_{out}$, where X is weighting factor of inflow and outflow. This term gives a value for total storage.

$$V_{stored} = K \times q_{out} + K \times X \times \ q_{in} - q_{out} \quad \text{..}(4.17)$$

4.2.4 Parameter sensitivity

Sensitivity analysis is evaluated the impact of model parameters on the model outputs, and it is also a tool to assess model behavior and particularly the importance of parameterizations within the model. Generally, sensitivity analysis is widely used in the model calibration process and attempts to identify the most important parameters for hydrologic model calibration (Vilaysane, 2015). Some hydrological change indexes are used for sensitivity analysis, such as discharge total volume, and peak flow (Shrestha, 2016). The criteria of parameter sensitivity in Table 4.2 has been defined into three groups which are high, medium and low (Maharjan & S., 2015; Ram-indra, 2015).

Table 4.2 Parameter sensitivity criteria

Level of change	Correlation coefficient change (%)	Nash-Sutcliffe Efficiency change (%)
Low	< 0.01	< 0.01
Middle	0.01 - 10	0.01 - 10
High	> 10	> 10

The initial simulation to determine the sensitivity of the model was performed using default parameter values. The parameter values were varied within upper and lower limits established according to the characteristic of each parameter. In generally method, the parameter adjusting to analyze the sensitivity of model can start by increasing or decreasing the value of single parameter in the same proportion (Bancha Kwanyuen, 2003). Sensitivity analysis was used in many researches as presents bellow:

Table 4.3 Parameter sensitivity analysis appeared in SWAT application by (Vilaysane, 2015)

No	Parameter Names	Max	Min	Fitted
1	CN2.mgt	0.691	0.583	0.684
2	ALPHA_BF.gw	-0.037	-0.051	-0.047
3	GW_DELAY.gw	208.32	196.11	205.95
4	GWQMN.gw	2.619	0.154	2.546
5	GW_REVAP.gw	0.156	0.147	0.154
6	ESCO.hru	0.96	0.92	0.94
7	CH_N2.rte	0.672	0.598	0.634
8	CH_K2.rte	127.02	125.13	126.31
9	GW_REVAP.gw	0.727	0.676	0.648
10	SOL_AWC .sol	0.17	0.15	0.16
11	SOL_K .sol	0.75	0.68	0.73
12	SOL_BD .sol	0.4	0.07	0.17

Table 4.4 Parameter sensitivity analysis appeared in SWAT application by (Lin, 2015)

No	Parameter Names	Max	Min	Fitted
1	SOL_AWC	0	1	0.25
2	RCHRG_DP	0	1	0.3
3	CH_N2	35	98	58
4	GWQMN	0	500	30
5	ESCO	0	1	0.68
6	SOL_K	0	2000	49
7	CANMX	0	100	5

Table 4.5 Parameter sensitivity analysis appeared in HEC-HMS application by (Phommalin, 2014)

Parameters model	Definition	Parameter fitted
Loss	Curve Number	65.2
Routing	Muskingum K (hr)	17.76
	Muskingum X	0.4
Baseflow	initial Discharge (m3/s)	8.1
	Recession Constance	0.70
Transform	Lag Time (min)	654
Canopy	Max storage (mm)	2
	Crop coefficient	1

4.2.5 Model calibration

Model calibration is one criterion of model structure. It is the requirement of model that some of its parameters must be estimated through calibration against observed system output. The model can be calibrated by adjusting parameter that contain in the model. In each model contained the different calibration method such manual calibration method and automated calibration method. The hydrological data used in this study were obtained from four rainfall gauges and two streamflow gauges. The period of data for the study was from 1996 to 2013. The training data set was from 1996 to 2004 for parameter estimation and sensitivity analysis.

The calibration was made for the average daily streamflow and was performed by trial and error by changing one parameter at a time and then analyzing the results. In generally method, the parameter adjusting to analyze the sensitivity of model can start by +20% increasing or -20% decreasing the value of single parameter in the same proportion, this criteria was presented by (Ercan, 2014). This study used the same criteria, because the study has been used the same model and the area is also mountainous as similar as with my area. Parameters were calibrated through the adjustment values until a good agreement between the observed and simulated hydrographs were achieved.

HEC-HMS and IFAS models calibrate parameter by trial and error method. Two methods are in SWAT model, SWAT-CUP model is used as automated calibration method. SWAT-CUP is an interface that was developed for SWAT based on the deterministic and stochastic. A set of parameter value is selected to be initial value for flow calibration from model and simulation results are compared with observed flow.

4.2.6 Model validation

Validation will be performed by applying calibrated parameters to predict streamflow time series for the period that was not used for calibration. A testing data set was from 2005 to 2013 for validation of the model. Graphical comparisons and statistical test methods are used for evaluating the relationship between the observed and simulated flows.

4.2 Data input

The period of 1998-2013 is selected for this study due to data availability and quality. Hydrological input data to hydrologic models are obtained from the Department of Meteorology and Hydrology, Lao PDR. Geographical and geological data are requested from National Agriculture and Forestry Research Institute of Laos (2010). Lists of required data are as follows:

Table 4.6 Data requirement for rainfall-runoff models

Hydrologic and Meteorological data (1996 - 2013)		
Data	Frequency	Source
Rainfall	daily	Department of Meteorology and Hydrology, Lao PDR
Streamflow	daily	Department of Meteorology and Hydrology, Lao PDR
Temperature	daily	Department of Meteorology and Hydrology, Lao PDR
Physical data of basin		
Data	Resolution	Source
Elevation(DEM)	30 x 30 m	Department of Geology and Minerals, Lao PDR
Stream network	2010	Department of Geology and Minerals, Lao PDR
Land use	2010	National Agriculture and Forestry Research Institute, Lao PDR
Soil class	2010	National Agriculture and Forestry Research Institute, Lao PDR

Detail descriptions of the data in Table 4.6 were explained in Section 3.1-3.3. Most of various data requirements for running of selected models are presented in Table 4.7

Table 4.7 Minimum input data requirement

Model	Data type	Data
SWAT	Local data[1]	DEM, land use/land cover, soils, daily precipitation, max. and min. temperature, daily discharge
	Default data[2]	Solar radiation, relative humidity, wind speed
HEC-HMS	Local data	Soil information, land use, daily precipitation, and daily observed runoff data, basin boundary
IFAS	Local data	Daily precipitation, daily discharge
	Global[3]	DEM, land use/land cover, soils

Note: [1] Local data is data observed by some units in target area

[2] Default data is the exited data in data base of SWAT model

[3] Global is the data downloads from particular website defined by IFAS model developer

4.3 Model evaluation

Several quantitative variables are used to measure model performance. Most of the quantitative variables are based on the comparison of two variables which are observed and simulated flows. Choice of quantitative variables could be different depending on a number of factors such as the purpose of modeling, the preference of the modeler. For this study, the performance of the model in calibration and validation periods is assessed based on statistical measures such as correlation coefficient (r), Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (r-square).

4.3.1 Coefficient of determination (r^2)

The coefficient of determination (r^2) is a measure of how well the regression line represents the data. If the regression line passes exactly though every point on the scatter plots, it would be able to explain all of the variation. The coefficient of determination ranges from 0 to 1. Determination coefficient (r^2) can be measured using formulas:

$$r^2 = \left(\frac{n\sum xy - \sum x \sum y}{\sqrt{n \sum x^2 - {\sum x}^{2}}\sqrt{n \sum y^2 - {\sum y}^{2}}} \right)^2 \quad \text{..........(4.18)}$$

The determination coefficient (r^2) is chosen in this study because it gives the proportion of the fluctuation of one variable that is predicable from the other variable.

The determination coefficient (r^2) represents the percent of the data that is the closest to the line of best fit.

4.3.2 Correlation coefficient (r)

Correlation coefficient is indicated that strength and direction of a linear relationship between two variables. Correlation coefficient is also called Pearson's correlation coefficient. It is a statistical measure of the linear relationship between pair data. If we have a series n observations and n model values, then the Pearson product-moment correlation coefficient can be used to estimate the correlation between model and observations (Maharjan & S., 2015).

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \text{...}(4.19)$$

where: x_i is observed value and y_i is modeled value at time, the value of r is such that $-1 \leq r \leq +1$. The + and – signs are used for positive linear correlations and negative linear correlations, respectively.

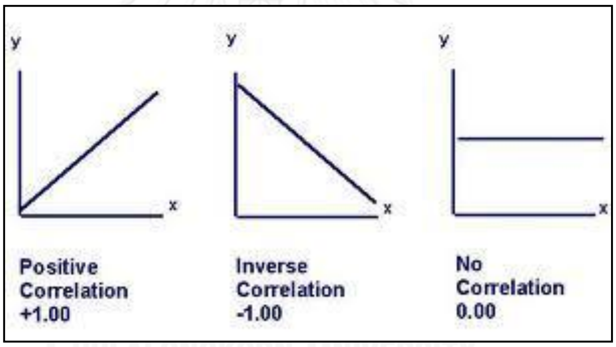


Figure 4.9 linear correlation coefficient (Maharjan & S., 2015)

Positive correlation: When *x* and *y* have a strong positive linear correlation, *r* value is close to +1. Positive value indicates that a relationship between *x* and *y* variable as value of *x* increases, value of *y* also increases.

Negative correlation: When *x* and *y* have a strong Negative linear correlation, *r* value is close to -1. Negative value indicates that a relationship between *x* and *y* variable as value of *x* increases, value of *y* also decreases.

No correlation: When there is no linear correlation or weak linear correlation, *r* value is close to 0. A value near zero means that there is a nonlinear relationship between two variables.

4.3.3 Nash-Sutcliffe Efficiency coefficient (NSE)

The Nash-Sutcliffe model Efficiency coefficient (NSE) is used to assess the predictive power of hydrological discharge models and the accuracy of model can be measured by using NSE. However, it can also be used to quantitatively describe the accuracy of model outputs for other things than discharge (J.E. Nash, J.V. Sutcliffe, 1970). It is defined as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_{obs} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs} - \overline{X}_{obs})^2} \quad \text{...(4.20)}$$

where: X_{obs} is observed values and X_{model} is modeled values at time *i*.

4.4 Analysis and conclusion

This section is to analyze the results of the research, to conclude and to offer guidance for further study. The streamflow, total volume, and peak flow time series are analyzed by graphical comparison and statistical test methods.

CHAPTER 5

RESULT ANALYSIS AND DISCUSSION

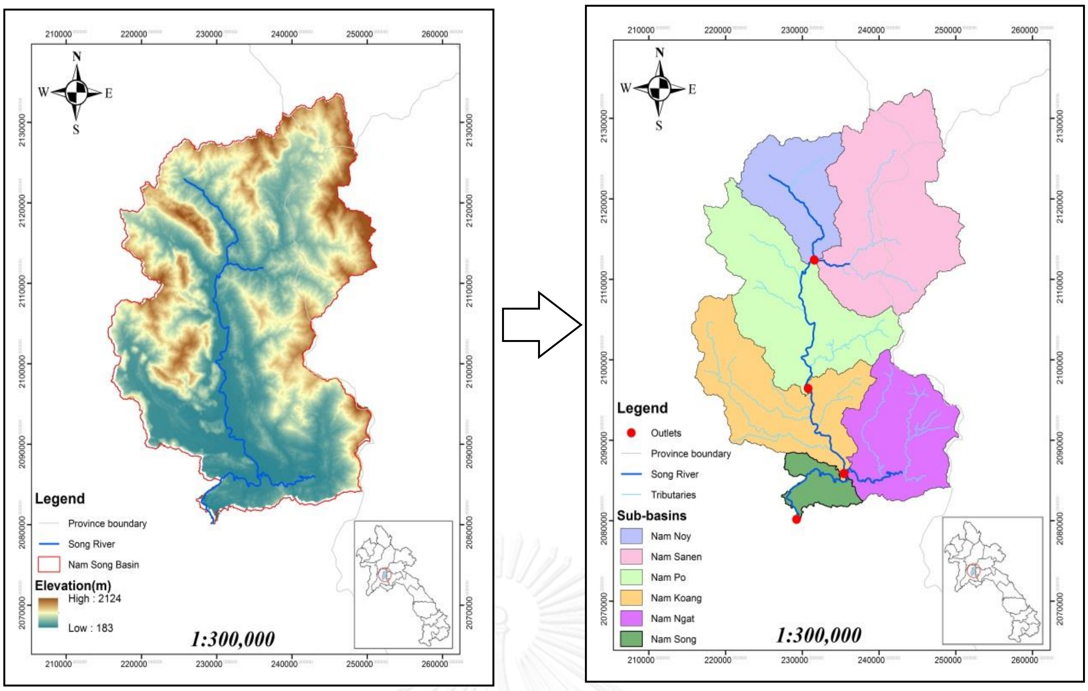
In this chapter, there are two main parts from hydrologic modeling development in the Nam Song River basin. The first part is the result of physical condition of the basin. The second part is the result of streamflow generated from hydrologic models with different complexity. Flow station at the outlet was used to be a representative for calibration and validation. The result can be shown about relationship between rainfall and runoff, including the linkage with physical condition of area. However, the results from the models are accurate or reliable; the calculation results of model must be checked with observed data in study area. In addition, for the good model calibration to get reliable value, parameter sensitivity should be analyzed.

5.1 Results of SWAT model

5.1.1 Physical condition of the basin

Dividing of basin boundary into sub-basins according to their spatial distribution of physical conditions is an important step for developing a physical model for a basin. Dividing the entire basin into sub-basins involves key steps which are identifying flow direction, calculating flow accumulation, creating river network, and slope of basin using Digital Elevation Model (DEM) data. The resolution of the DEM is a factor affecting how well the sub-basins and river network fitted with natural sub-basin (P. L. Zhang, 2014). In this study, the resolution of the DEM used was 30 m x 30 m, the threshold area 1,000 hectares (10 km^2), this threshold area is also presented (Keochan, 2014; P. L. Zhang, 2014). The basin was divided into sub-basin using six points at the outlets as show in Figure 5.1 with details provided in Table 5.1.

From Figure 5.1 and Table 5.1, it can be seen that the Nam Song Sub-basins have high slope ranging from 24.61% to 45.08%, and elevation from 183 to 1992 meter above mean sea level (m.s.l.). The average elevation of the upper part of the river basin is higher and more complex than the lower part due to mountains.



a) b)

Figure 5.1 a) Digital Elevation Map b) Sub-basins of Nam Song River Basin

a) b)

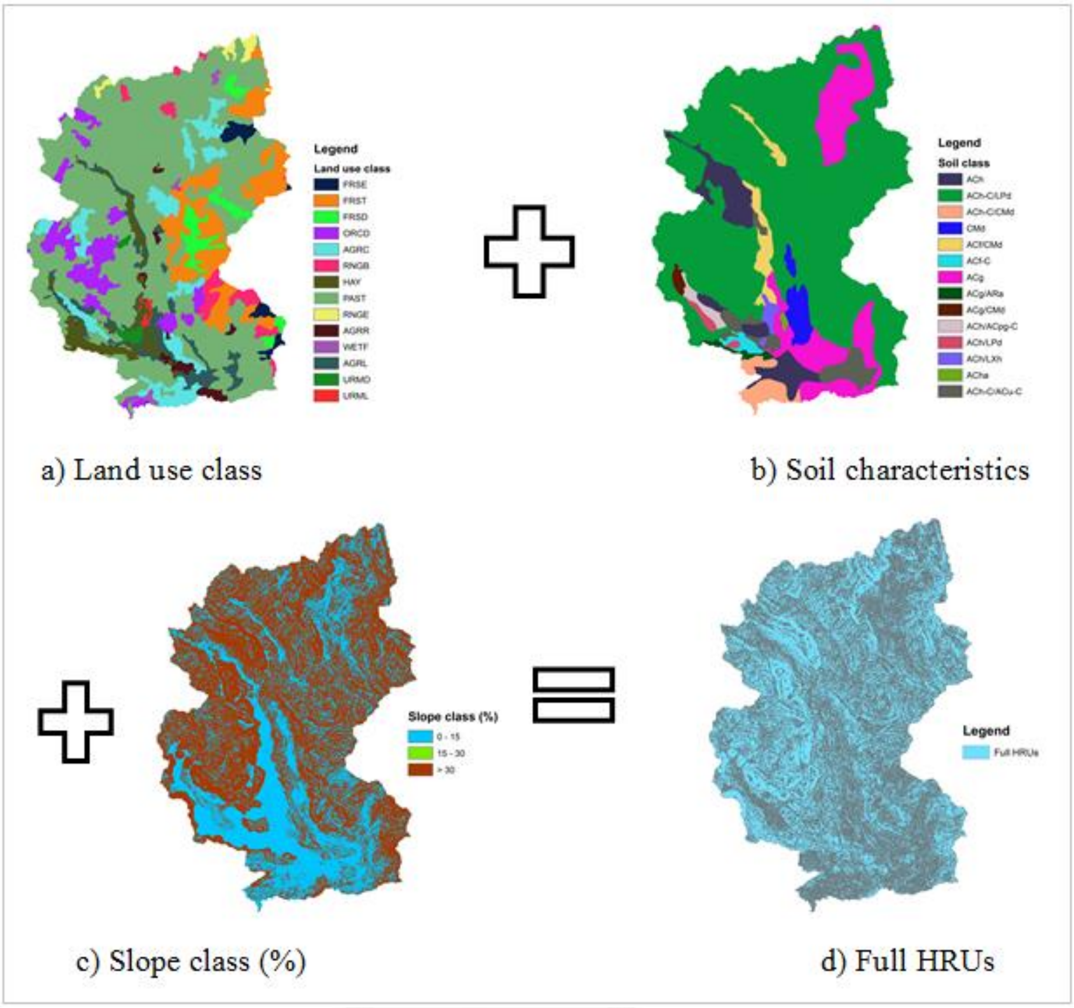
Figure 5.2 a) Nam Song River condition and b) Nam Song Basin condition (Secretariat, 2011)

Table 5.1 Physical characteristic of sub-basins

Sub-basin	Area(km^2)	Sub-basin Slope (%)	Elevation Min (m)	Elevation Max (m)	Main river length(m)	Main river slope (%)
Nam Noy	140.395	45.08	262	1795	15933.19	0.138
Nam Sanen	353.993	40.52	270	2124	5495.88	0.873
Nam Po	291.44	43.40	197	1793	22531.16	0.706
Nam Koang	237.331	35.02	185	1558	15167.64	0.086
Nam Ngat	188.568	31.54	185	1864	12927.93	0.093
Nam Song	45.7596	24.61	183	726	17360.94	0.219

5.1.2 Hydrologic Response Units distribution (HRUs)

According to the subdivision of the watershed as appears in the Figure 5.1 and Table 5.1, the SWAT further divide each sub-basin into Hydrologic Response Units (HRUs). HRUs are lumped spatial unit of the land area within the sub-basin that is comprised of unique land cover, soil classes, and management combinations. To divide the sub-basin into HRUs, Multiple HRUs option was chosen for this study. The results of HRUs distribution showed that the whole Nam Song River basin was covered by 81 HRUs as shown in Figure 5.3.



a) Land use class

b) Soil characteristics

c) Slope class (%)

d) Full HRUs

Figure 5.3 Hydrologic Response Units distribution

5.1.3 Parameter sensitivity analysis

The parameters used for the flow were selected based on what were suggested in the literatures and SWAT documentation. The initial simulation to determine the sensitivity of the model was performed using default parameter values. The parameter values were varied within upper and lower limits established according to the characteristic of each parameter. In generally method, the parameter adjusting to analyze the sensitivity of model can start by increasing or decreasing the value of single parameter in the same proportion (Ercan, 2014). The results of sensitivity analyses of parameters influences on the flow are described in Table 5.2. This parameter set will be used in calibration and validation processing.

From the Table 5.2 and Table 4.3, it can be summarized that the highest sensitive parameters on flow are SCS runoff curve number (CN2), Baseflow alpha factor (ALPHA_BF), and Available water capacity of the soil layer (SOL_ACW). For the middle influence parameters for flow are Saturated hydraulic conductivity

(SOL_K), Manning's "n" value for the main channel (CH_N2), and Depth of water in the shallow aquifer required for return flow (GWQMN). For the parameters such Soil evaporation compensation factor (ESCO), and Surface runoff lag time (SURLAG) are the lowest influenced for flow. Parameter sensitivity analysis is shown in the following table and paragraphs:

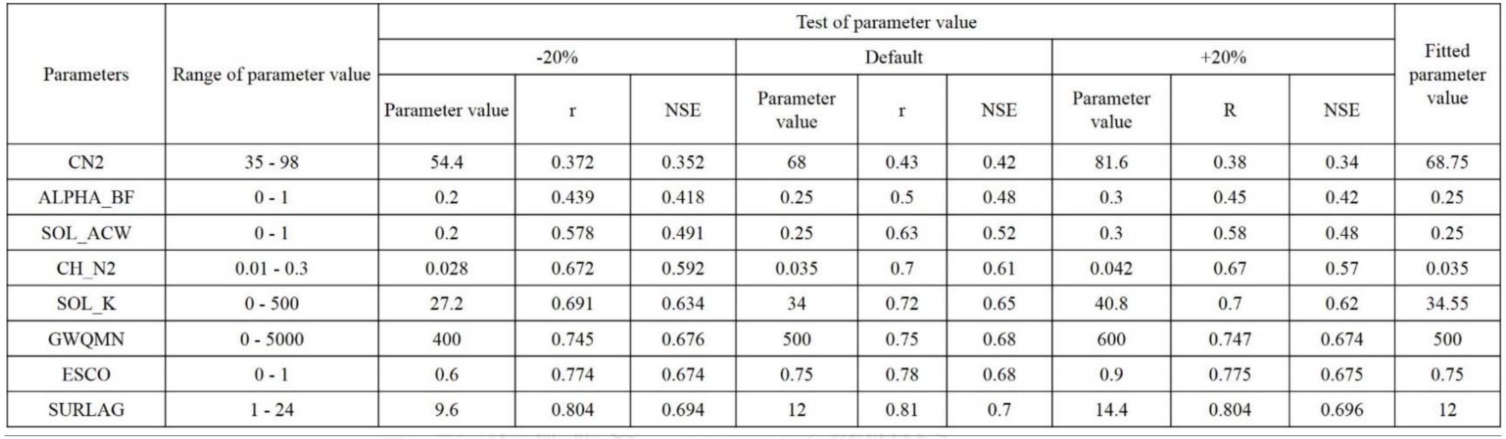
1) Influence of change in Curve Number (CN): the total volume increased when increases the Curved Number value and the base flow decreased when increases the Curved Number value, that means if soil and land use data has changed the flow simulation was easy to change. It can also describe that flow simulation from based on the rainfall indicates relationship of physical area, especially soil and land use with flow. So that the soil and land use data should be checked and focused for hydrologic model development.

2) Influence of change in Available water capacity (ACW): this parameter relates to soil property, when this value of parameter increases the flow decreases. But decreasing of flow was not decreased in the same rate. The flow rate increased in dry season more than rainy season, this may causes of the difference of available water capacity of soil layer.

3) Influence of change in Manning's "n" value for the main channel (CH_N2): this parameter is also one of the important parameters that influences to flow in the channel. It was affected to water routing such the time period of flow and relationship of flow rate. If Manning's "n" value increases, the surface flow will decrease and the water routing flows slowly.

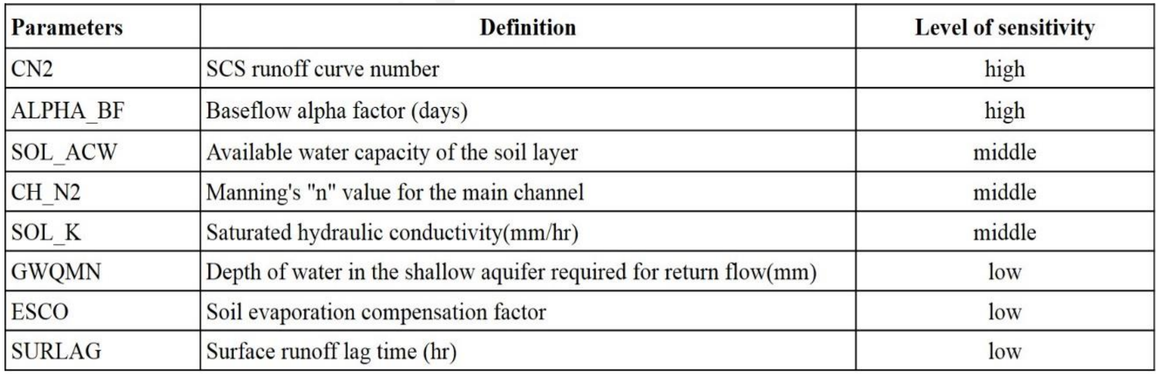
4) Influence of change in Saturated hydraulic conductivity (SOL_K): this parameter was related to the soil property, it affected to the surface flow and base flow. It is hydraulic conductivity value of main channel in each sub-basin and controlled the water losing of surface area. The flow will decrease when the hydraulic conductivity increase.

Table 5.3 Parameters influences flow of SWAT model



Parameters	Range of parameter value	Test of parameter value									Fitted parameter value
		-20%			Default			+20%			
		Parameter value	r	NSE	Parameter value	r	NSE	Parameter value	R	NSE	
CN2	35 - 98	54.4	0.372	0.352	68	0.43	0.42	81.6	0.38	0.34	68.75
ALPHA_BF	0 - 1	0.2	0.439	0.418	0.25	0.5	0.48	0.3	0.45	0.42	0.25
SOL_ACW	0 - 1	0.2	0.578	0.491	0.25	0.63	0.52	0.3	0.58	0.48	0.25
CH_N2	0.01 - 0.3	0.028	0.672	0.592	0.035	0.7	0.61	0.042	0.67	0.57	0.035
SOL_K	0 - 500	27.2	0.691	0.634	34	0.72	0.65	40.8	0.7	0.62	34.55
GWQMN	0 - 5000	400	0.745	0.676	500	0.75	0.68	600	0.747	0.674	500
ESCO	0 - 1	0.6	0.774	0.674	0.75	0.78	0.68	0.9	0.775	0.675	0.75
SURLAG	1 - 24	9.6	0.804	0.694	12	0.81	0.7	14.4	0.804	0.696	12

Table 5.2 Parameters influences flow of SWAT model



Parameters	**Definition**	**Level of sensitivity**
CN2	SCS runoff curve number	high
ALPHA_BF	Baseflow alpha factor (days)	high
SOL_ACW	Available water capacity of the soil layer	middle
CH_N2	Manning's "n" value for the main channel	middle
SOL_K	Saturated hydraulic conductivity(mm/hr)	middle
GWQMN	Depth of water in the shallow aquifer required for return flow(mm)	low
ESCO	Soil evaporation compensation factor	low
SURLAG	Surface runoff lag time (hr)	low

5) Parameters influence to groundwater: several parameters that affected to groundwater flow such as depth of water in the shallow aquifer required for return flow (GWQMN). If the depth of water in the shallow aquifer is very low, a lot of water will be stored in the shallow aquifer and the flow for returning to channel is decreased. It can also indicate that the flow will decrease when increases the value of GWQMN.

5.1.4 Model calibration results

Ten parameters are chosen for model calibration according to initial parameter sensitivity. The period of data for the study was from 1996 to 2013. The training data set was from 1/1/1996 to 31/12/2004 (9 years) for parameter estimation and sensitivity analysis. The flow observed station at Nam Song Dam (outlet) and four rain gauges are used. The results of model calibration indicated that the simulated and measured daily streamflow values are well fitted as demonstrated in Figure 5.4. In additional, the results of model calibration can be checked by statistical indexes such Correlation coefficient (r) and Nash-Sutcliffe coefficient (NSE). The results were shown that Correlation coefficient (r) = 0.81 and Nash-Sutcliffe coefficient (NSE) = 0.70, they are in acceptable value ranged criteria (Ref. with similar statistical performance values). Correlation coefficient indicated that relationship of simulated daily flow was likely to be in line with the measured daily streamflow while Nash-Sutcliffe coefficient indicated that the most of daily peak flow was underestimated as presented in Figure 5.4 and scatter plots in Figure 5.5. By comparing observed and simulated flows at the outlet station during the calibration period, SWAT model was found to under-predict peak flows as shown in Figure 5.6.

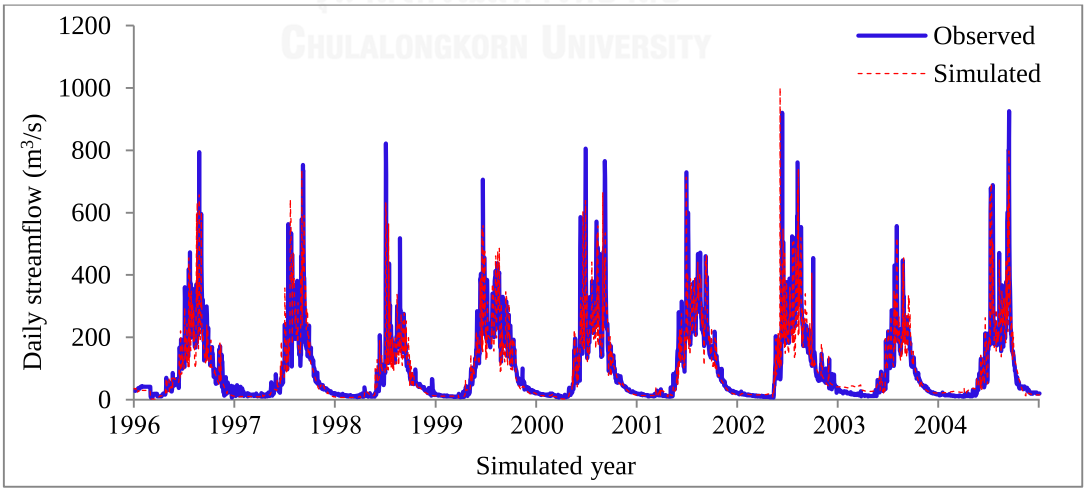


Figure 5.4 Comparison of measured hydrograph with SWAT simulated time series for the calibration period

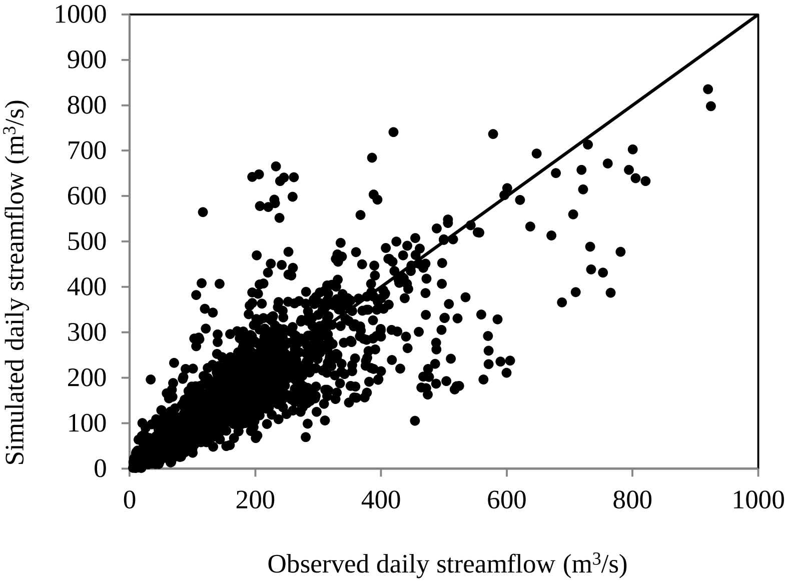


Figure 5.5 Scatter plots of observed and simulated daily streamflow time series for the calibration period

The high peak flow values were presented in Figure 5.6, except on 2002 the peak flow of simulation was high. High monsoon rainfall was reported during October, 2002. For the results of total volume (Figure 5.7) are similar with the trend of peak flow, except on 2003 the simulated volume higher than observed. The high monsoon rainfall was reported during October, 2002 that causes to increase baseflow in 2003.

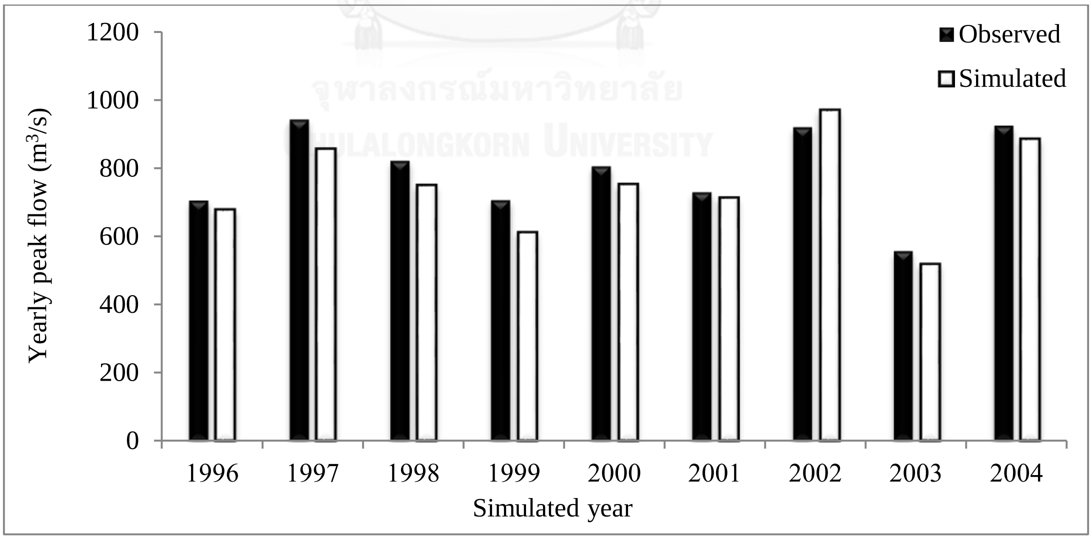


Figure 5.6 Comparison of measured with simulated yearly peak flow for the calibration period

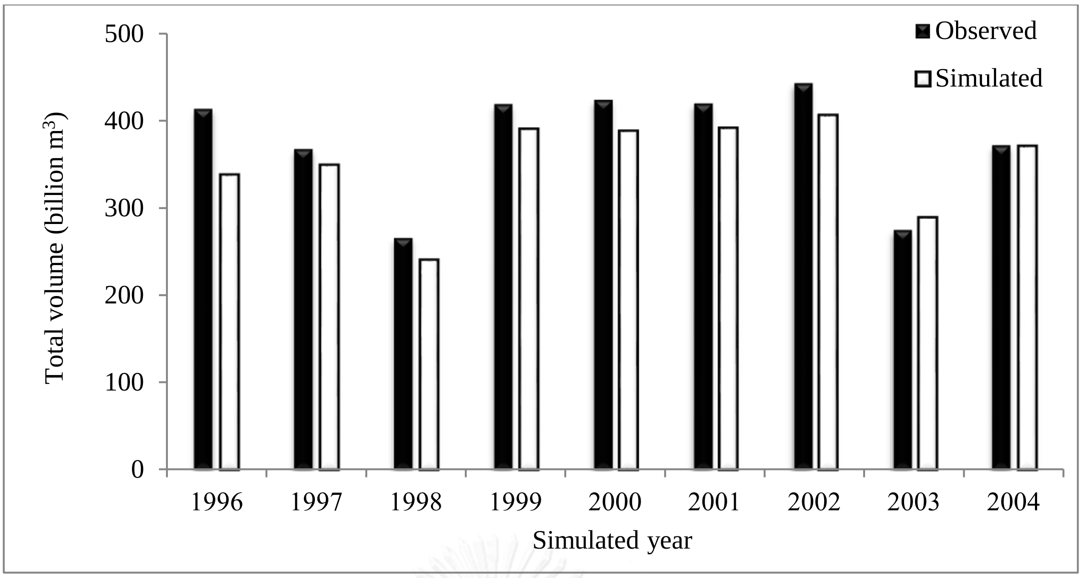


Figure 5.7 Comparison of measured with simulated yearly total volume for the calibration period

5.1.5 Model validation results

The validation is process of streamflow simulation by using a set of parameters from model calibration and parameter sensitivity. The period of data for the study was from 1996 to 2013 (9 years). The training data set was from 1/1/2005 to 31/12/2013 for model validation analysis. The flow observed station at Nam Song Dam (outlet) and four rain gauges are used, for more details were in section 4.2.4. The validation phase, daily and monthly streamflow time series, peak flow, and total volume from model simulation were compared with observed flows. The simulated daily flow matches the observed values for the validation period with Correlation coefficient (r) = 0.77 and Nash-Sutcliffe coefficient (NSE) = 0.68, they are in acceptable value ranged criteria. Correlation coefficient indicated that relationship of simulated daily flow was likely to be in line with the measured daily streamflow while Nash-Sutcliffe coefficient indicated that the most of daily peak flows were underestimated as presented in Figure 5.8 and scatter plots in Figure 5.9.

Figure 5.10 show the comparison of the monthly observed and simulated flow hydrograph at the outlet station during the validation period, SWAT model results indicated under-predicts the high peak flow values, except on 2005, 2008, and 2011 the peak flow of simulation was high. High monsoon rainfall was reported during October, 2005, 2008, and 2011. The performance of the observed and simulated monthly streamflow time series for the calibration period was considered very well with r = 0.87, and NSE = 0.82. For the results of total volume are similar with the trend of peak flow, except on 2006, 2009, and 2012 the simulated volume higher than observed. The high monsoon rainfall was reported during 2005, 2008, and 2011 that causes to increase baseflow in 2006, 2009, and 2012.

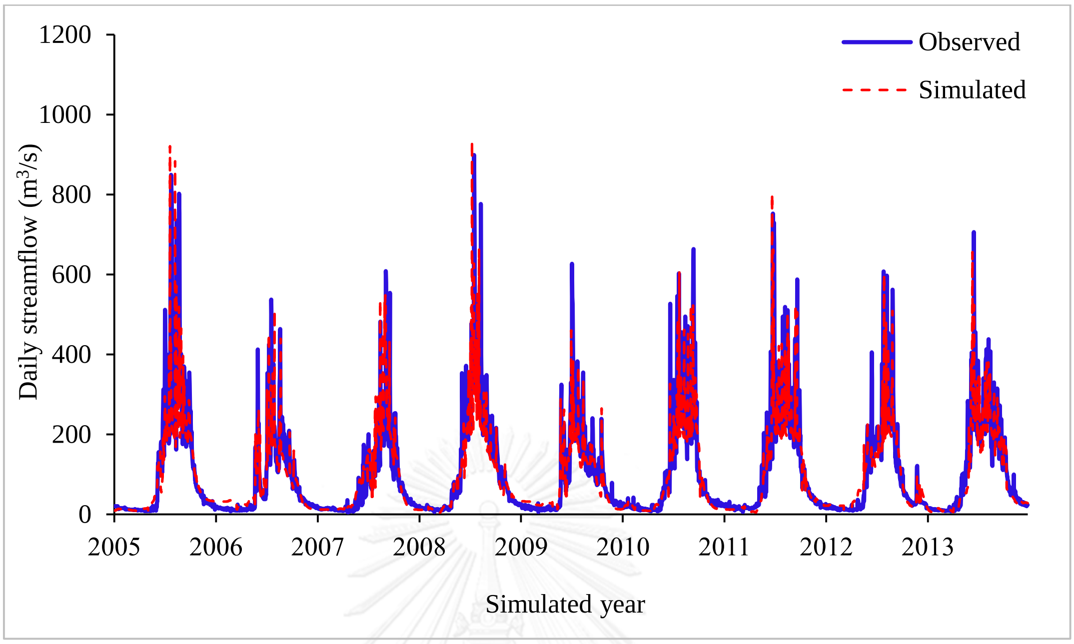


Figure 5.8 Comparison of measured hydrograph with SWAT simulated time series for the validation period

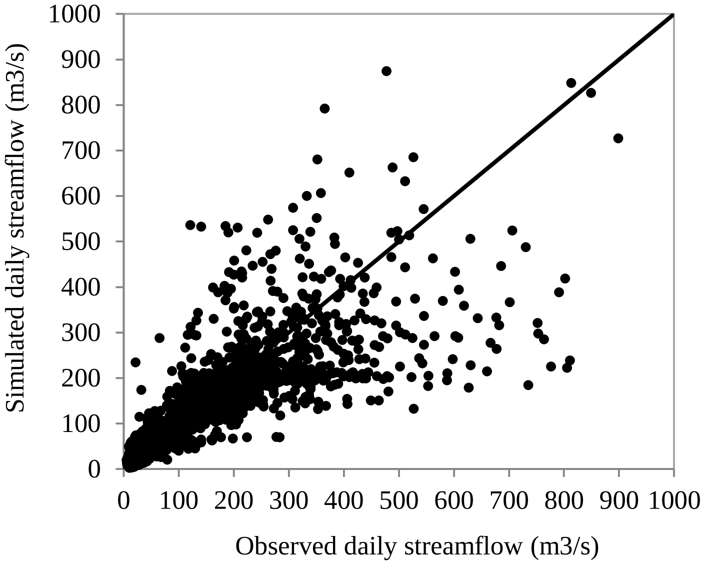


Figure 5.9 Scatter plots of observed and simulated daily streamflow time series for the validation period

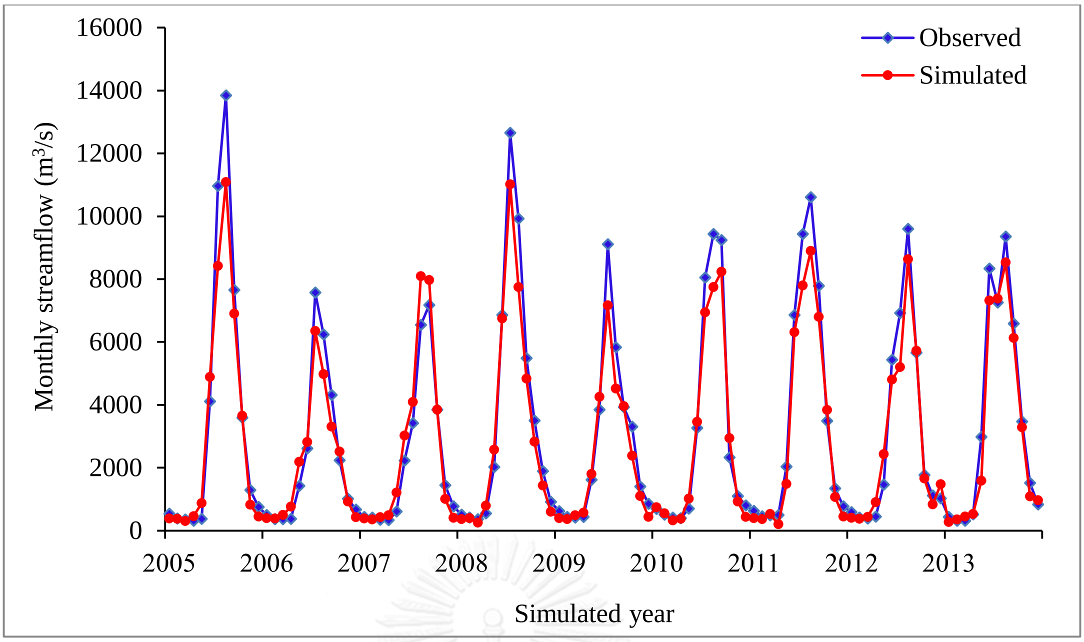


Figure 5.10 Comparison of measured with SWAT simulated monthly streamflow time series for the validation period

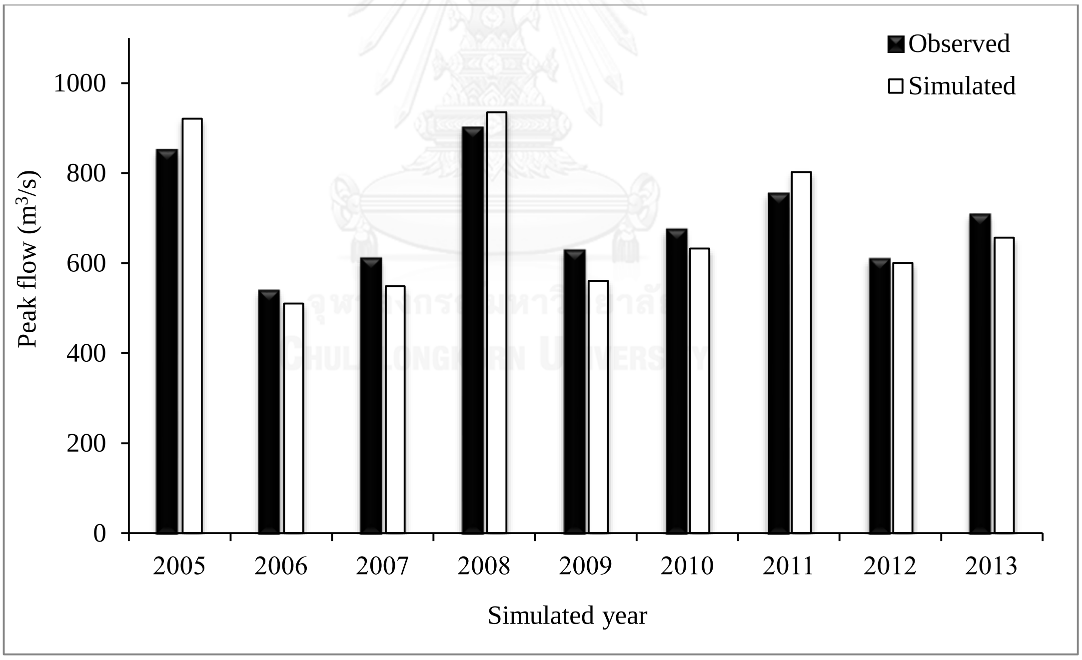


Figure 5.11 Comparison of measured with simulated yearly peak flow for the validation period

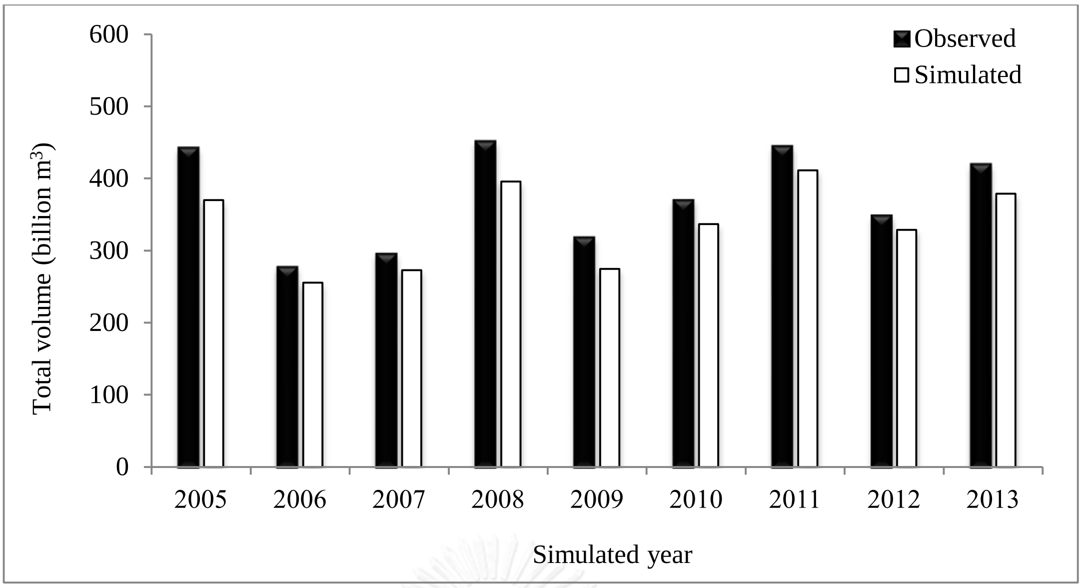


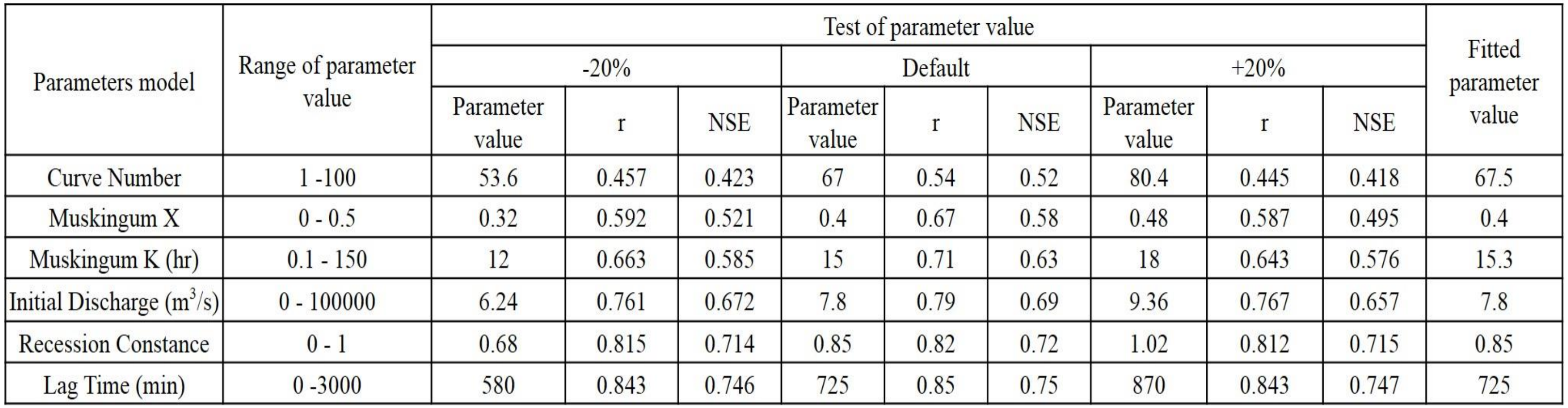
Figure 5.12 Comparison of measured with simulated yearly volume for the validation period

5.2 Result from HEC-HMS model

5.2.1 Parameter sensitivity analysis

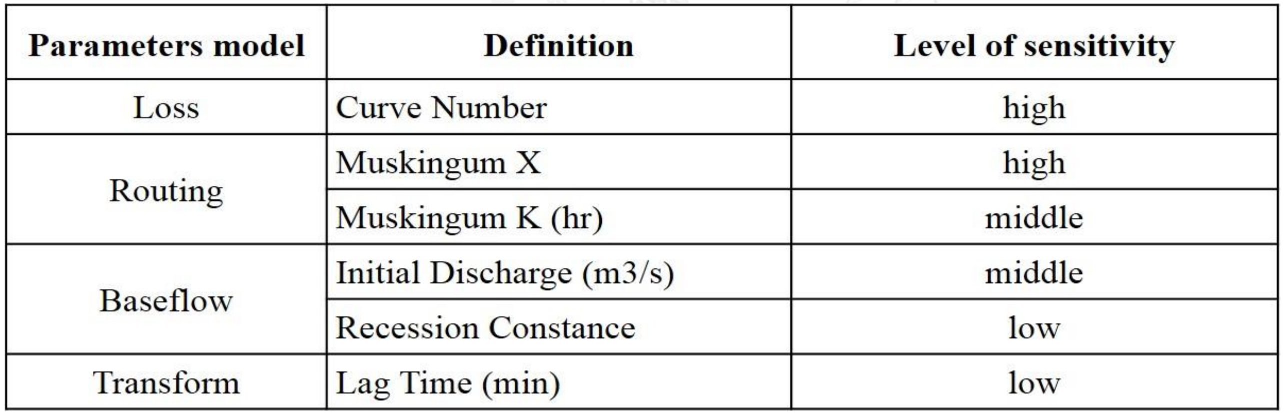
The HEC-HMS model has been calibrated by manual method to optimize the best possible parameter. SCS Curve Number Loss, SCS Unit Hydrograph Transform and Recession Base flow methods are used. The parameters used for the flow were selected based on the literatures and HEC-HMS documentation. The initial simulation to determine the sensitivity of the model was performed using default parameter values. The parameter values were varied within upper and lower limits established according to the characteristic of each parameter. The results of sensitivity analyses of parameters influences the flow (Table 5.4 and Table 5.5) found that the highest sensitive parameter was Curve Number (CN) and Time to peak (Tp). Curve Number (CN) affected to the peak flow while Time to peak (Tp) affected to the time of peak flow occurring. The Time to peak (Tp) is related to physical characteristics of basin such river length, river and area slope, and shape of basin. For the Curve Number (CN) is related to the basin land cover and soil properties. The middle sensitive parameter was baseflow parameter such Initial Discharge and Recession Constance. This parameter set will be used in calibration and validation processing.

Table 5.4 Parameters sensitive to streamflow in HEC-HMS model



Parameters model	Range of parameter value	Test of parameter value									Fitted parameter value
		-20%			Default			+20%			
		Parameter value	r	NSE	Parameter value	r	NSE	Parameter value	r	NSE	
Curve Number	1 -100	53.6	0.457	0.423	67	0.54	0.52	80.4	0.445	0.418	67.5
Muskingum X	0 - 0.5	0.32	0.592	0.521	0.4	0.67	0.58	0.48	0.587	0.495	0.4
Muskingum K (hr)	0.1 - 150	12	0.663	0.585	15	0.71	0.63	18	0.643	0.576	15.3
Initial Discharge (m^3/s)	0 - 100000	6.24	0.761	0.672	7.8	0.79	0.69	9.36	0.767	0.657	7.8
Recession Constance	0 - 1	0.68	0.815	0.714	0.85	0.82	0.72	1.02	0.812	0.715	0.85
Lag Time (min)	0 -3000	580	0.843	0.746	725	0.85	0.75	870	0.843	0.747	725

Table 5.5 Summarize of the parameters sensitive level to streamflow of HEC-HMS



Parameters model	**Definition**	**Level of sensitivity**
Loss	Curve Number	high
Routing	Muskingum X	high
	Muskingum K (hr)	middle
Baseflow	Initial Discharge (m3/s)	middle
	Recession Constance	low
Transform	Lag Time (min)	low

5.2.2 Model calibration results

The calibration simulated results indicated that the simulated and measured daily streamflow values are well fitting as demonstrated in Figure 5.13. The fit of the streamflow simulated by the HEC-HMS model compared to those observed with some underestimates in the peak flow and overestimates in the recession period of the hydrograph. A good fit was found for the minimum streamflow simulation, this also found by (Webster Gumindoga & Rwasoka, 2016). In additional, the results of model calibration can be checked by statistical indexes such Correlation coefficient (r) and Nash-Sutcliffe coefficient (NSE). The results (Figure 5.13) were shown that Correlation coefficient (r) = 0.85 and Nash-Sutcliffe coefficient (NSE) = 0.72. Correlation coefficient indicated that relationship of simulated daily flow was likely to be in line with the measured daily streamflow while Nash-Sutcliffe coefficient indicated that the most of daily peak flow was underestimated, except the several low flow years as presented in Figure 5.13 and scatter plots in Figure 5.14.

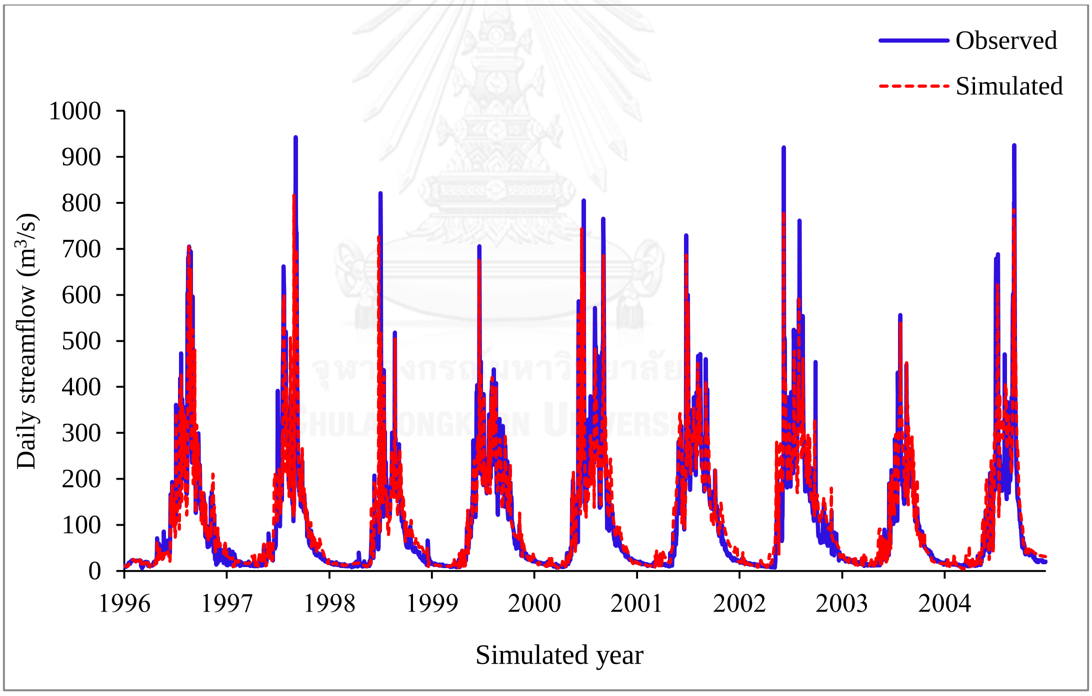


Figure 5.13 Comparison of measured hydrograph with HEC-HMS simulated time series for the calibration period

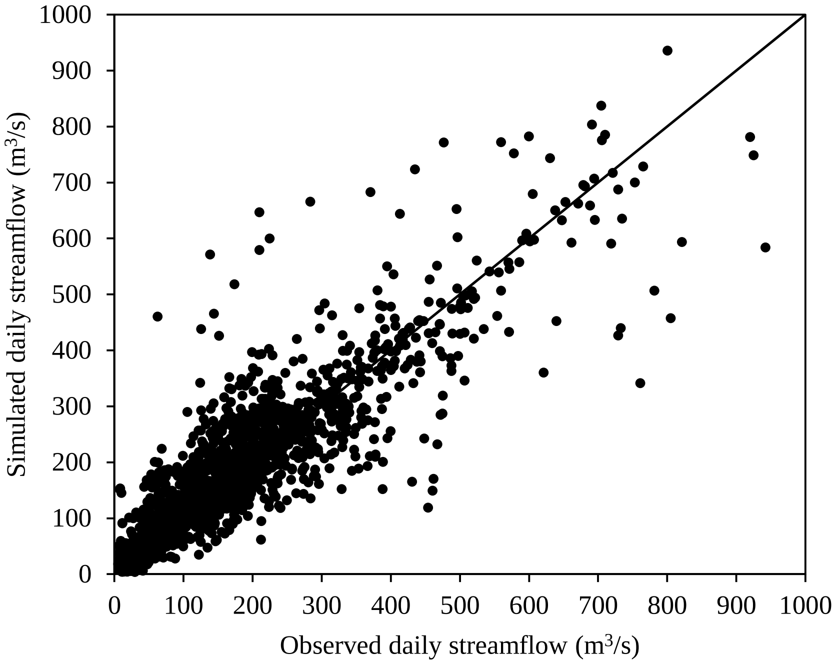


Figure 5.14 Scatter plots of observed and HEC-HMS simulated daily streamflow time series for the calibration period

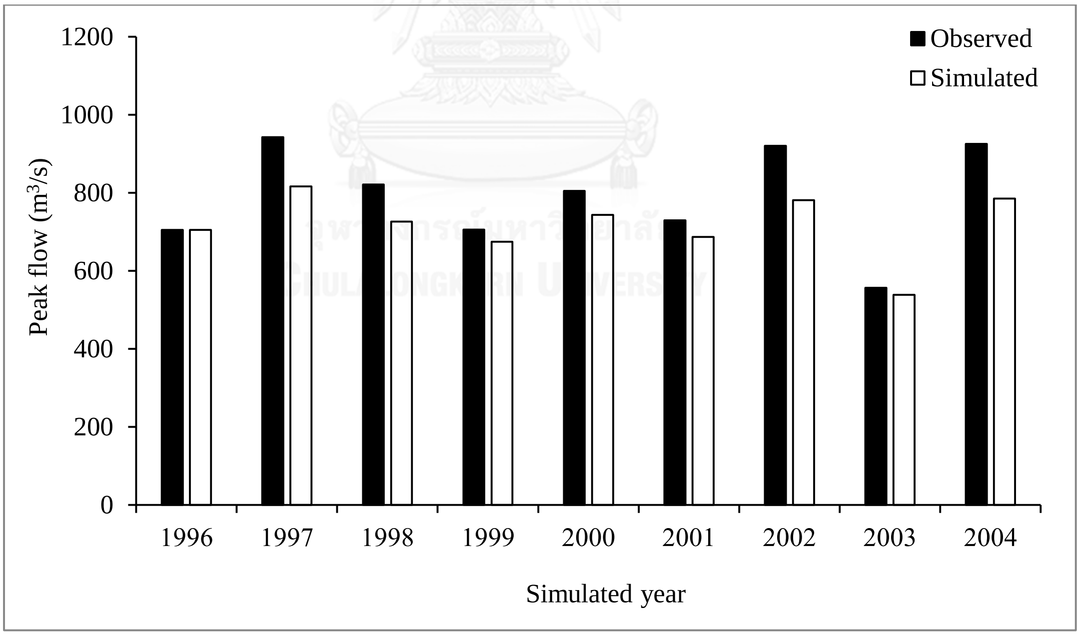


Figure 5.15 Comparison of measured with HEC-HMS simulated yearly peak flow for the validation period

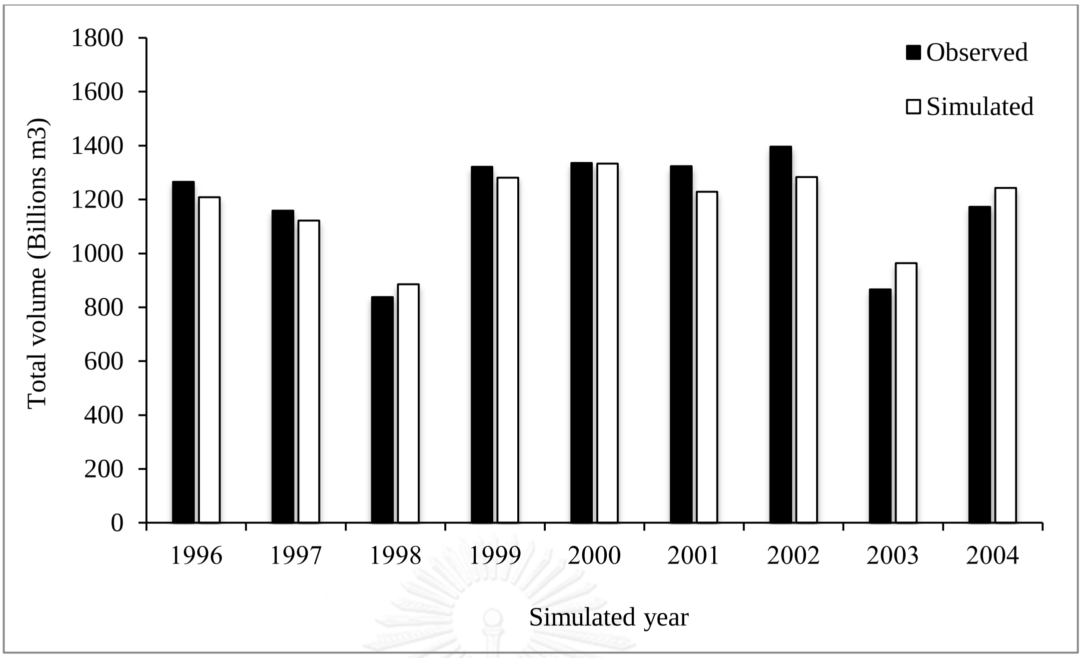


Figure 5.16 Comparison of measured with HEC-HMS simulated yearly total volume for the validation period

5.2.3 Model validation results

The validation results show that the comparison between the simulated daily stream flow and the observed data is well for the minimum streamflow simulation (Figure 5.17). The simulated daily flow matches the observed values for the validation period with Correlation coefficient (r) = 0.81 and Nash-Sutcliffe coefficient (NSE) = 0.72, they are in acceptable value ranged criteria. Correlation coefficient indicated that relationship of simulated daily flow was likely to be in line with the measured daily streamflow while Nash-Sutcliffe coefficient indicated that the most of daily peak flow was underestimated as presented in Figure 5.17 and scatter plots in Figure 5.18. However, the daily simulation in some years was slightly underestimated in the high flow years and overestimates in the recession period of the hydrograph as appeared in calibration period. Figure 5.20 and Figure 5.21 show that the average percentage difference in the simulated volume of runoff and peak flow was – 7.71 % and + 9.17% respectively. Figure 5.19were presented that comparing of the monthly observed and simulated flow hydrograph at the Outlet station during the validation period, HEC-HMS model results indicated under-predicts the high peak flow values, except the low flow years such 2006, 2007, and 209 the peak flow of simulation was good.

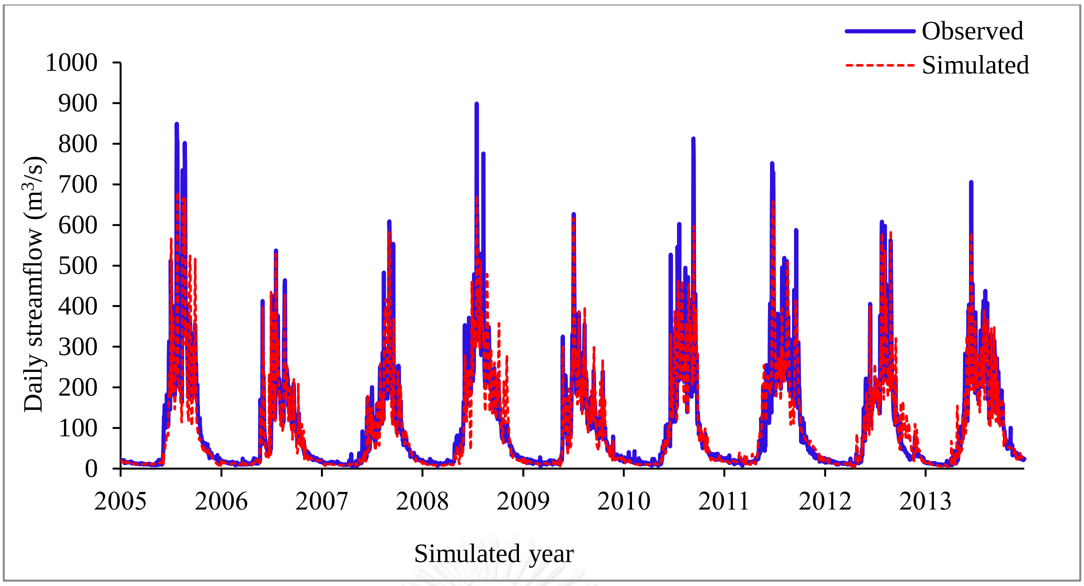


Figure 5.17 Comparison of measured hydrograph with HEC-HMS simulated time series for the validation period

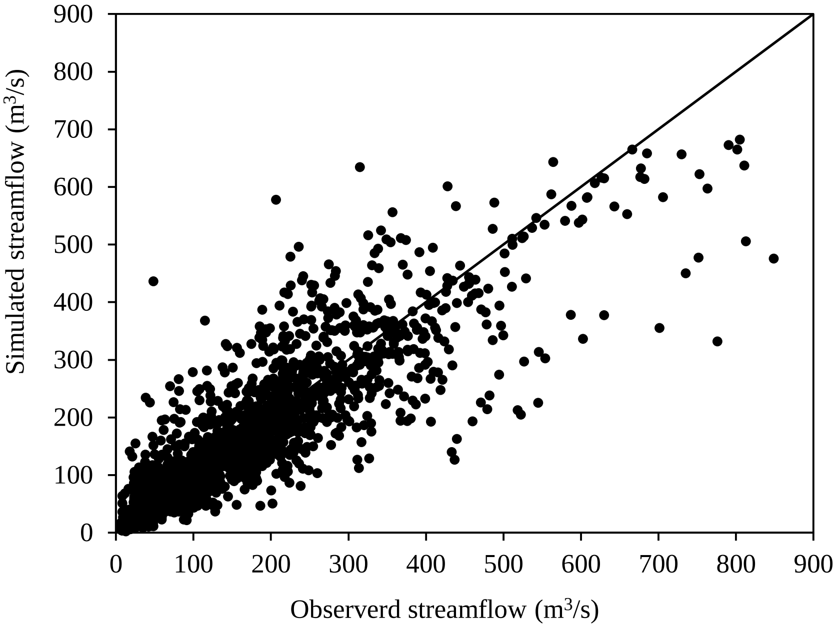


Figure 5.18 Scatter plots of observed and HEC-HMS simulated daily streamflow time series for the validation period

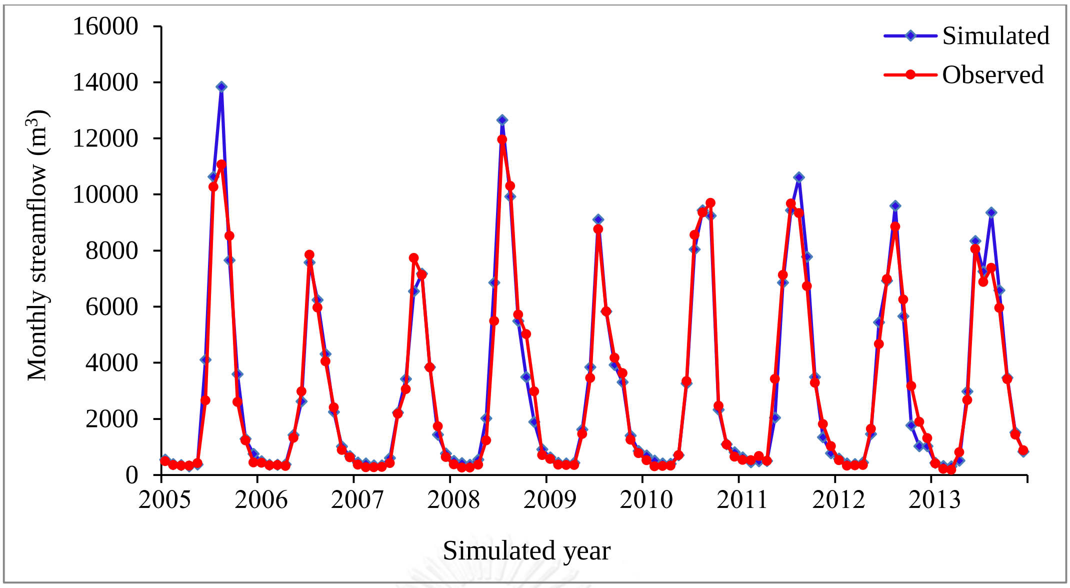


Figure 5.19 Comparison of measured with HEC_HMS simulated monthly streamflow time series for the validation period

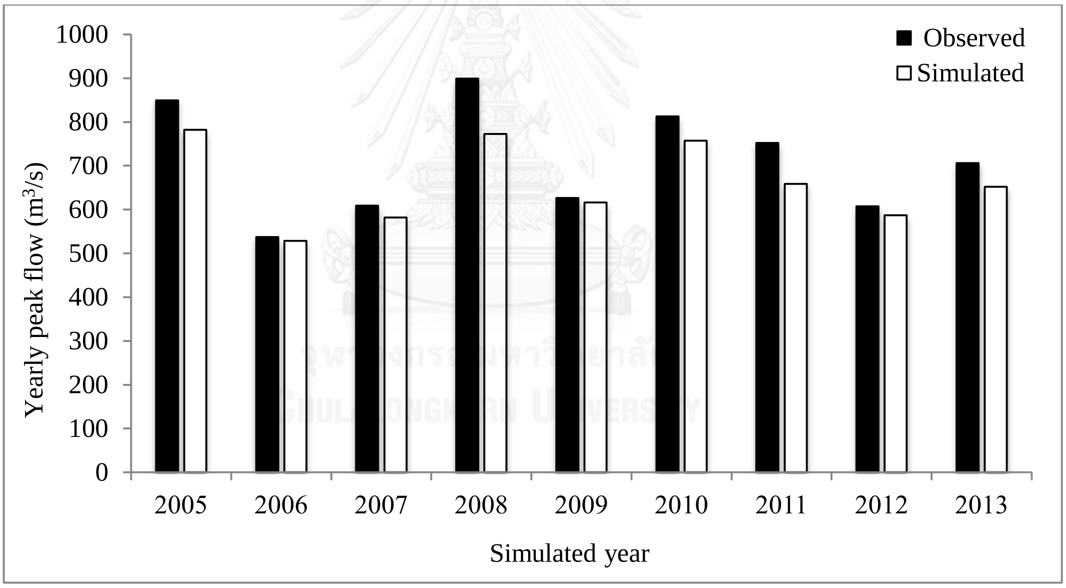


Figure 5.20 Comparison of measured with HEC-HMS simulated yearly peak flow for the validation period

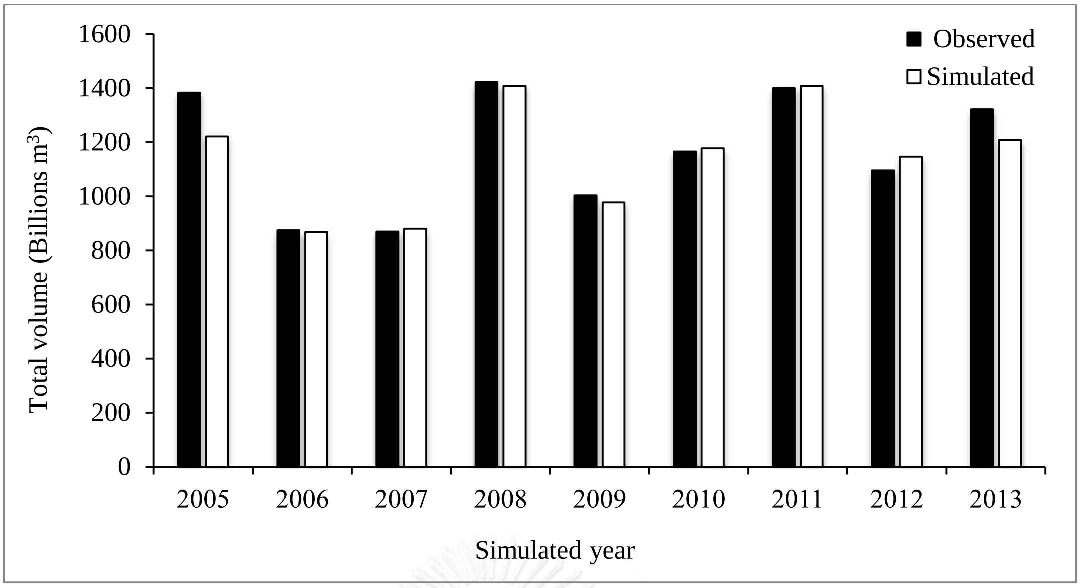


Figure 5.21 Comparison of measured with HEC-HMS simulated yearly total volume for the validation period

5.3 Result from IFAS model

5.3.1 Parameter sensitivity analysis

The IFAS model has been calibrated by manual method to optimize the best possible parameter based on the Tank model. The surface tank, groundwater tank and river channel tank model were used in this study. The parameters values used for the flow simulation were selected based on the literatures and IFAS documentation. The results of sensitivity analyses of parameters influences the streamflow (Table 5.6 and Table 5.7) found that the highest sensitive parameter of the surface tank model were Final infiltration capacity (SKF) and Surface roughness coefficient (SNF). For the groundwater tank model Runoff coefficient of groundwater (AGD) while the river channel tank model was Manning’s coefficient of roughness (RNS). The parameters affected to target points as shown in Table 5.7.

Table 5.6 Parameters sensitive to streamflow in IFAS model

Parameter	Test of parameter value									Fitted parameter value
	-20%			Default			+20%			
	Parameter value	r	NSE	Parameter value	r	NSE	Parameter value	r	NSE	
SKF (cm/s)	0.0472	0.392	0.332	0.059	0.484	0.412	0.0708	0.384	0.318	0.0041
RNS	0.028	0.573	0.546	0.035	0.645	0.623	0.042	0.563	0.547	0.035
AGD	0.00024	0.721	0.635	0.0003	0.762	0.684	0.00036	0.721	0.647	0.003
SNF	0.5464	0.776	0.687	0.683	0.811	0.723	0.8196	0.776	0.695	1.942
HCGD (m)	2.32	0.848	0.724	2.9	0.872	0.751	3.48	0.844	0.735	2.291
FALFX	0.00008	0.883	0.774	0.0001	0.89	0.78	0.00012	0.883	0.776	0.0001

Table 5.7 Summarize of the parameters sensitive level to streamflow of IFAS

Parameters model	**Definition**	**Level of sensitivity**
Loss	Curve Number	high
Routing	Muskingum X	high
	Muskingum K (hr)	middle
Baseflow	Initial Discharge (m3/s)	middle
	Recession Constance	low
Transform	Lag Time (min)	low

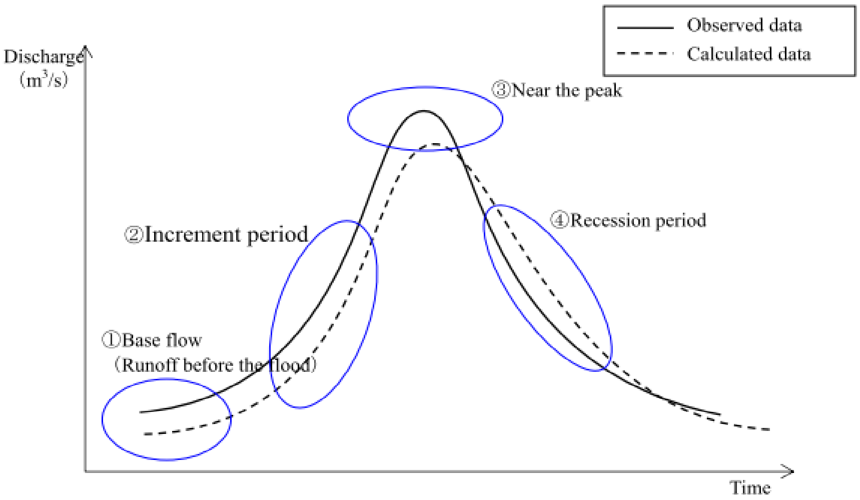


Figure 5.22 Tuning point on flood hydrograph (ICHARM, 2011)

Base flow (runoff before flood) is depended on the Groundwater runoff coefficient (AGD); it is possible to increase base flow by increasing AGD value. However, the condition of “Initial water height higher than Height water where the unconfined aquifer runs off” the slow subsurface flow is generated from the calculation start time and calculation is unstable. Increment period or rising phase is depended on rapid subsurface flow and storage height of surface layer tank. It is possible to increase discharge during increment period by decreasing Final infiltration capacity (SKF) and increasing rapid intermediate flow (FALFX). Near the peak flow is depended on SKF and SNF, it is possible to generate overland flow faster by decreasing the infiltration capacity (SKF) and decreases Manning’s coefficient of roughness (RNS) to generate overland flow faster and increase the peak flow. For the recession phase is depended on slow flow in aquifer layer tank such Final infiltration capacity (SKF) and Runoff coefficient of groundwater (AGD).

5.3.2 Model calibration results

Six parameters are chosen for IFAS model calibration according to initial parameter sensitivity. Parameters were calibrated through the adjustment values until a good agreement between the observed and simulated hydrographs were achieved. The results of model calibration indicated that the simulated and measured daily streamflow values are well fitting as demonstrated in Figure 5.23. The good fitting of the streamflow simulated by the IFAS model compared to those observed was found for the high streamflow simulation. The results of model calibration can be checked by statistical indexes such Correlation coefficient (r) and Nash-Sutcliffe coefficient (NSE). The results (Figure 5.23) were shown that Correlation coefficient (r) = 0.89 and Nash-

Sutcliffe coefficient (NSE) = 0.78. Correlation coefficient indicated that relationship of simulated daily flow was likely to be in line with the measured daily streamflow while Nash-Sutcliffe coefficient indicated that the most of daily peak flow was good estimation, except the several low flow years as presented in Figure 5.25 and scatter plots results with $R^2 = 0.80$ as in Figure 5.24.

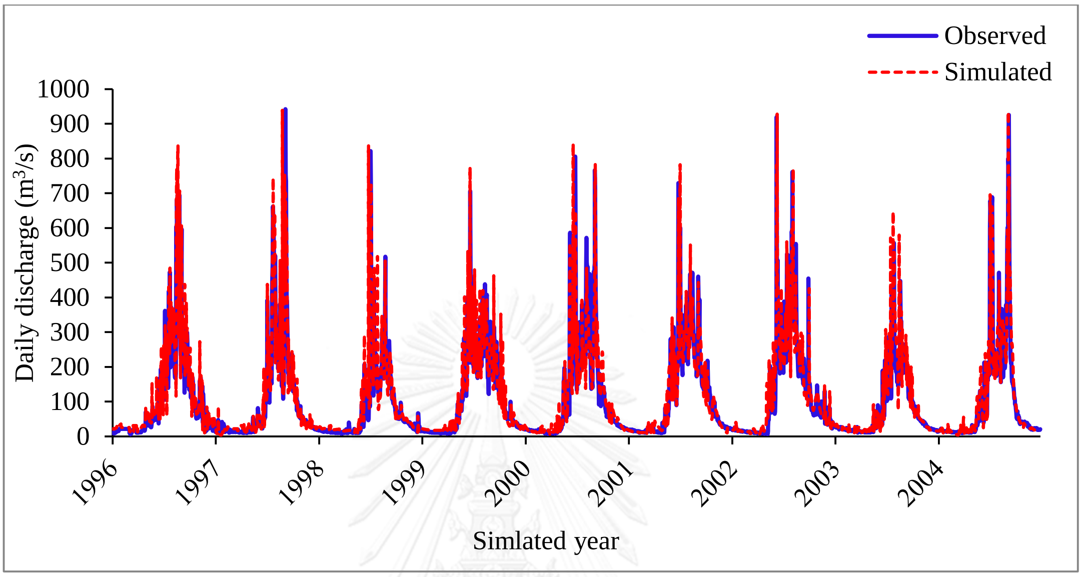


Figure 5.23 Comparison of measured hydrograph with IFAS simulated time series for the calibration period

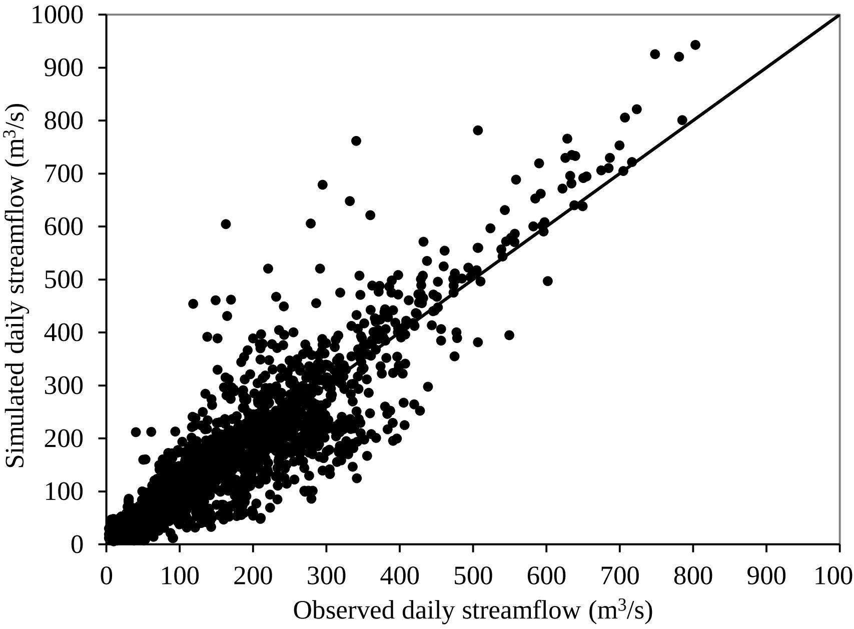


Figure 5.24 Scatter plots of observed and IFAS simulated daily streamflow time series for the calibration period

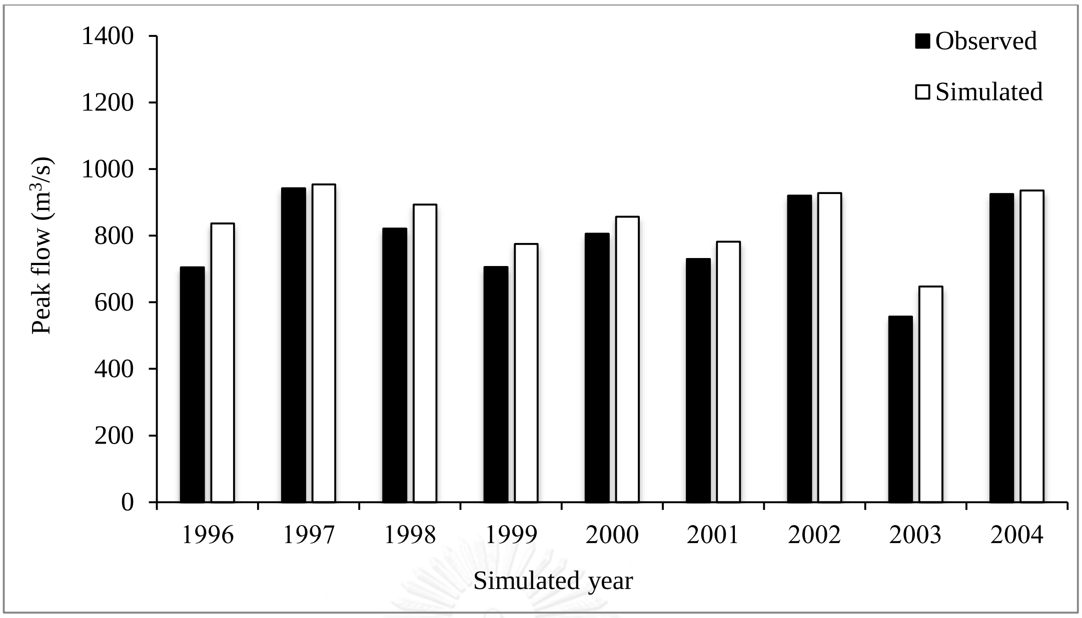


Figure 5.25 Comparison of measured with IFAS simulated yearly peak flow for the calibration period

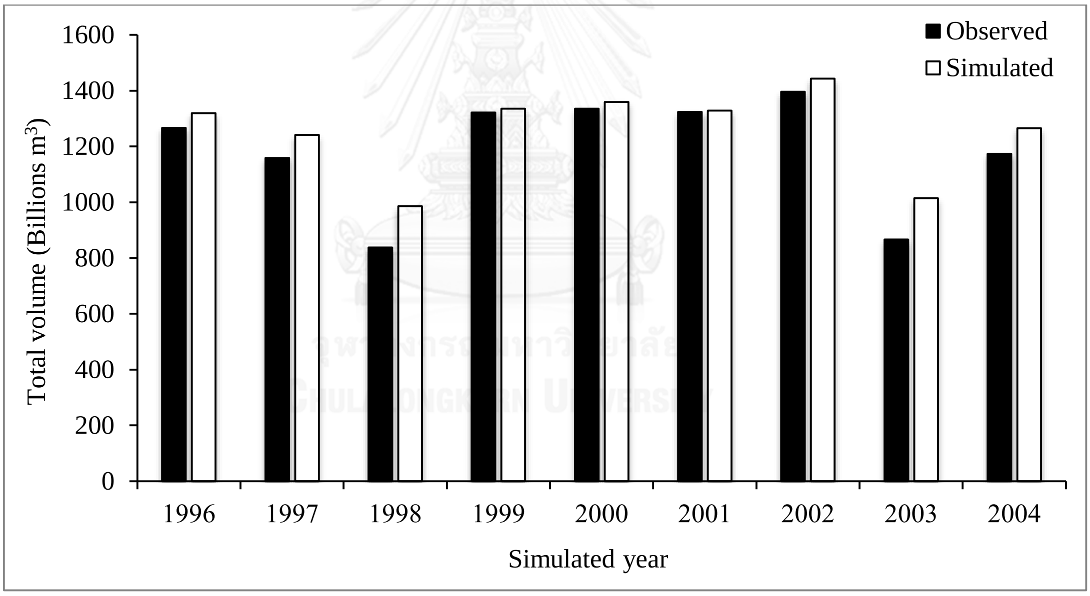


Figure 5.26 Comparison of measured with IFAS simulated yearly peak flow for the calibration period

5.3.3 Model validation results

According to statistic index value, the validation results show that the comparison between the simulated and the observed daily stream flow is very good for the high streamflow simulation as presented in Figure 5.27. The simulated daily flow matches the observed values for the validation period with Correlation coefficient (r) = 0.83 and Nash-Sutcliffe coefficient (NSE) = 0.75. Correlation coefficient indicated that relationship of simulated daily flow was likely to be fitted in line with the measured daily streamflow. The Nash-Sutcliffe coefficient indicated that the most of daily peak flow was good estimation as presented in Figure 5.27. However, the daily simulation in some years was slightly underestimated in the low flow years and overestimates in the recession period of the hydrograph as appeared in calibration period. The comparing of the monthly observed and simulated flow hydrograph at the Outlet station during the validation period as presented Figure 5.29 was better when compares with the results of daily streamflow simulation. The performance of the observed and simulated monthly streamflow time series for the validation period was very good with r = 0.97, and NSE = 0.95. For the results of total volume and peak flow as show in Figure 5.30 and Figure 5.31 show that the average percentage difference in the simulated and observed volume of runoff and peak flow were – 4.32 % and + 7.15 % respectively.

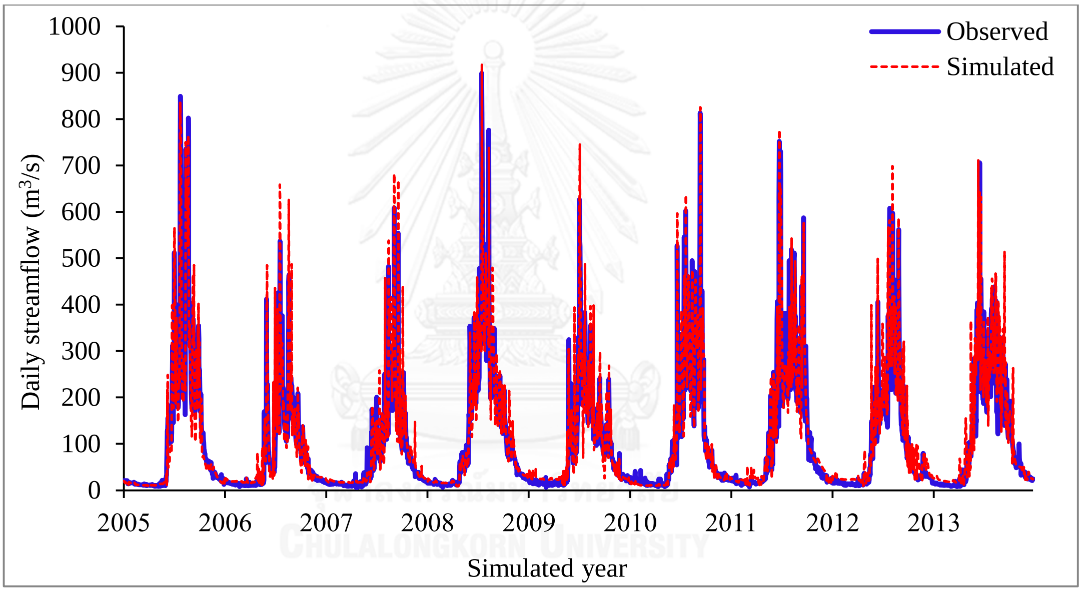


Figure 5.27 Comparison of measured hydrograph with IFAS simulated time series for the validation period

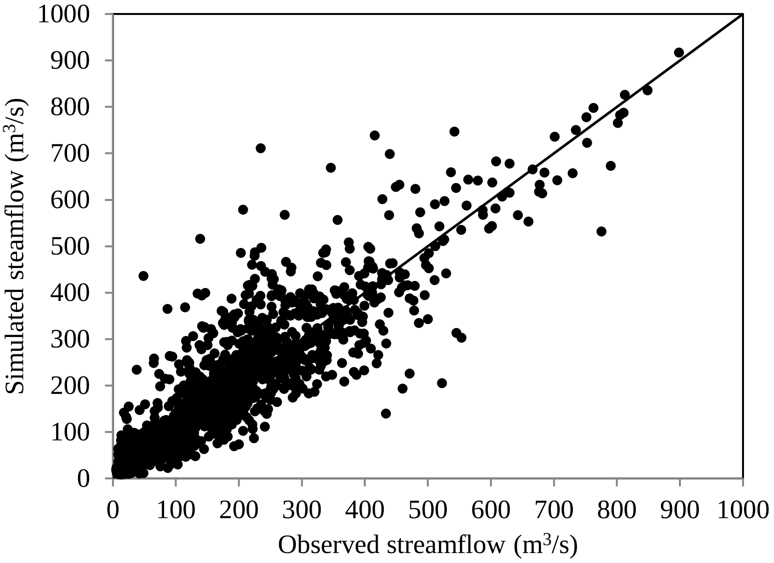


Figure 5.28 Scatter plots of observed and IFAS simulated daily streamflow time series for the validation period

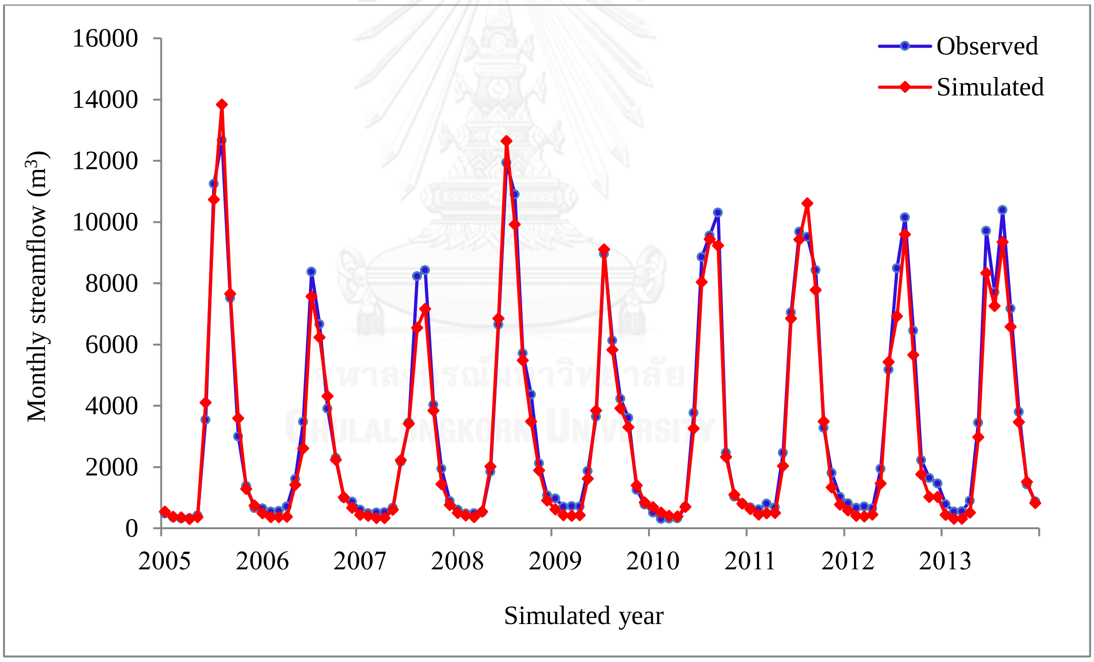


Figure 5.29 Comparison of measured with IFAS simulated monthly streamflow time series for the validation period

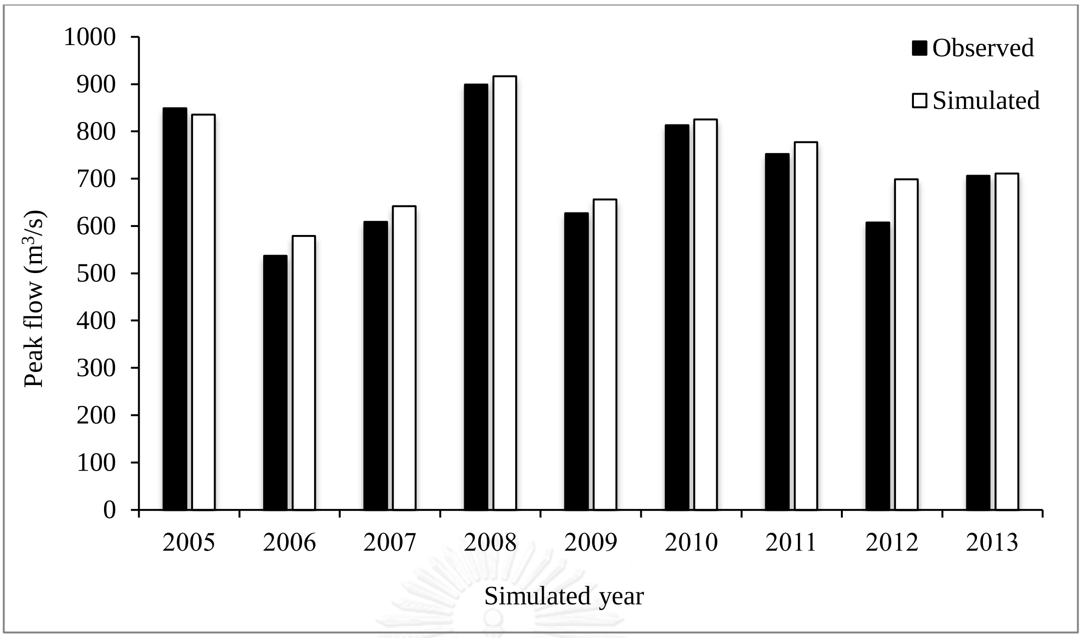


Figure 5.30 Comparison of measured with IFAS simulated yearly peak flow for the validation period

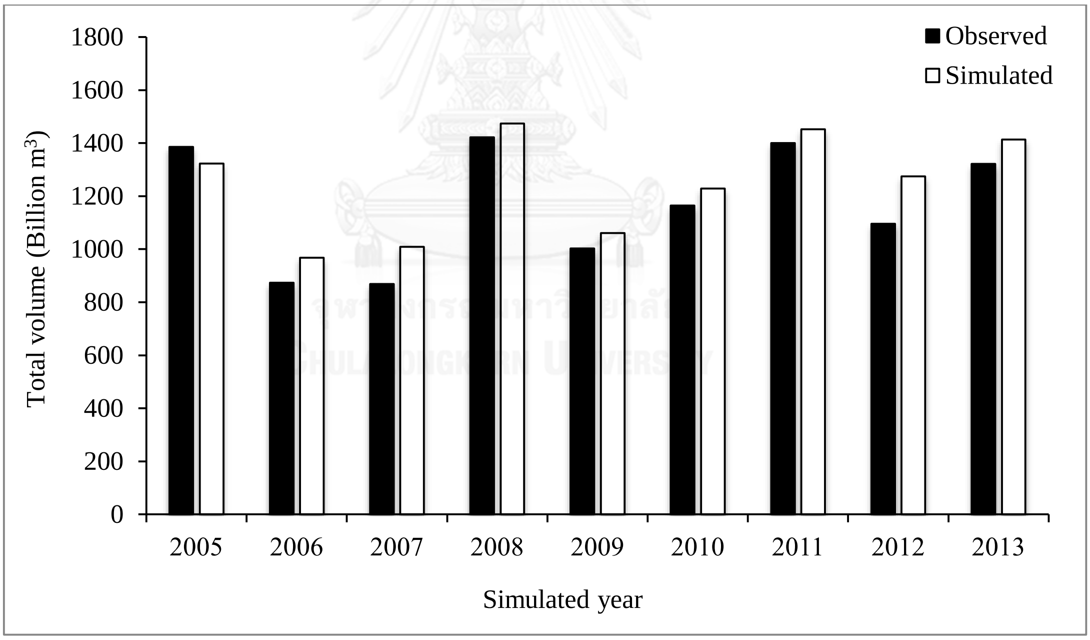


Figure 5.31 Comparison of measured with IFAS simulated yearly total volume for the validation period

5.4 Model results comparison

Three model calibration and validation results from each model will be compared together such daily, monthly simulated streamflow, peak flow, total volume by using statistical index criteria. The daily streamflow, three models can simulate good results in both of calibration and validation periods. The model performance based on statistical analysis demonstrated that the calibration results are quite higher than validation results as presented in Table 5.8. For the statistical analysis of monthly streamflow of three models compare with observed streamflow in validation period was improved as presented in Table 5.9. According to the statistical analysis, the highest model performance is IFAS model while the lowest is SWAT model.

Table 5.8 Statistical analysis of daily streamflow

Calibration					
Model	Performance indices				
	r	r^2	NSE	Total volume error (%)	Peak flow error (%)
HEC-HMS	0.85	0.72	0.75	7.17	5.71
IFAS	0.89	0.8	0.78	-7.81	-4.54
SWAT	0.81	0.67	0.70	6.55	5.27

Validation					
Model	Performance indices				
	r	r^2	NSE	Total volume error (%)	Peak flow error (%)
HEC-HMS	0.81	0.682	0.72	1.88	6.66
IFAS	0.83	0.736	0.75	-7.15	-4.32
SWAT	0.77	0.61	0.68	9.06	7.35

Table 5.9 Statistical analysis of monthly streamflow from three models

Model	Validation		
	r^2	r	NSE
SWAT	0.76	0.87	0.82
HEC-HMS	0.83	0.91	0.87
IFAS	0.94	0.97	0.95

Figure 5.32 and table 5.10 indicated that the peak flow from three models was closed with the observed data. However, there are several years have error simulation of peak flow. The daily simulation of SWAT model was slightly underestimated in the low flow years and overestimates in the high flow years of the hydrograph. HEC-HMS model simulation was slightly underestimated in the high flow years and overestimates in the recession period. The daily simulation of IFAS model was slightly underestimated in the low flow years and overestimates in the recession period of the

hydrograph as appeared in calibration period. The average percentage differences in the simulated and observed peak flow of streamflow of SWAT, HEC-HMS, and IFAS model were 7.35 %, 6.66 %, and -4.32 % respectively. The average percentage differences in the simulated and observed volume of streamflow were 9.06 %, 1.88 %, and -7.15 % respectively.

Figure 5.33 demonstrated that HEC-HMS and SWAT models outperformed IFAS model when predicting total volume, because loss model in HEC-HMS and SWAT models used SCS Curve Number method. Bansode A., 2014 and Ahmad I. et al, 2015 presented that SCS Curve Number method could predict well total volume and base flow

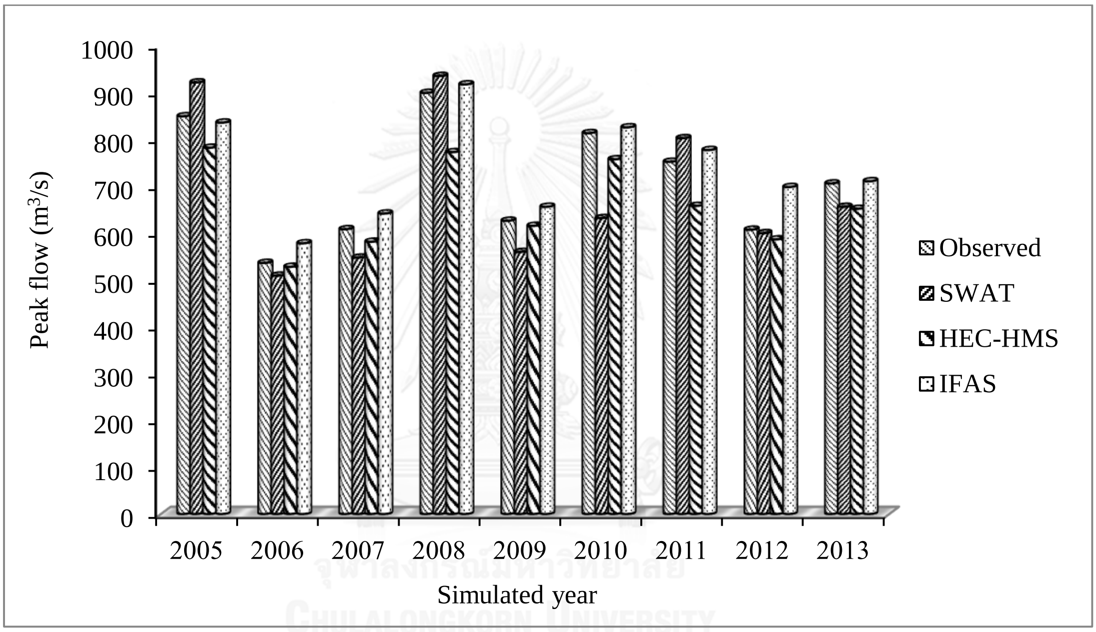


Figure 5.32 Comparison of simulated yearly peak flow from SWAT, HEC-HMS, and IFAS model with observed

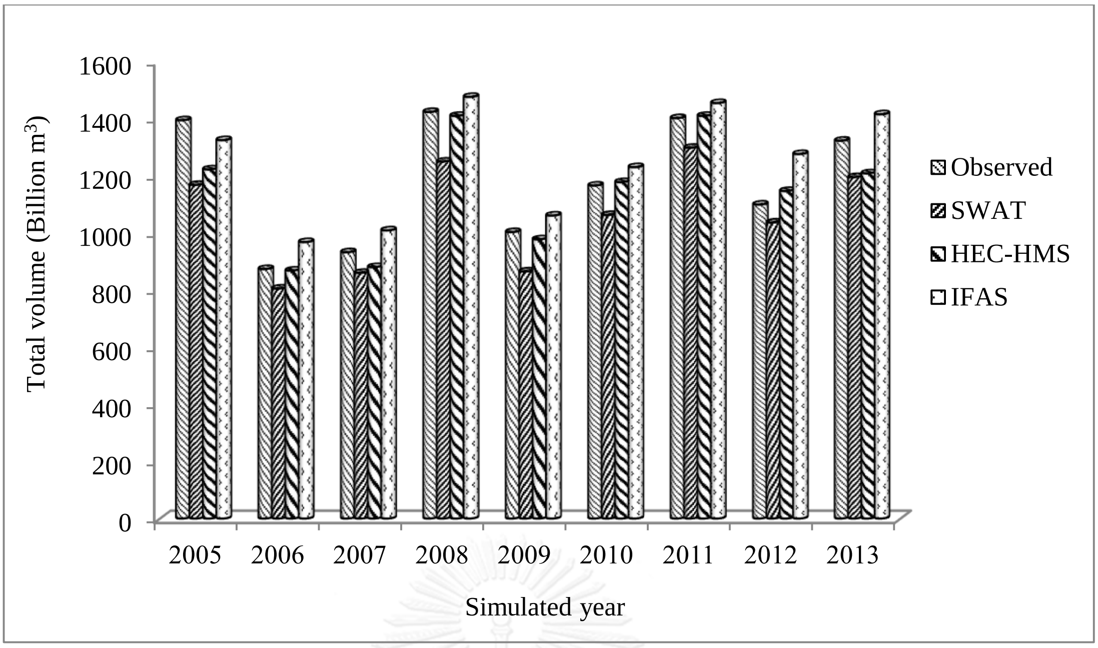


Figure 5.33 Comparison of simulated total volume from SWAT, HEC-HMS, and IFAS model with observed

CHAPTER 6

CONCLUSION AND FURTHER STUDY

6.1 Conclusion

The whole aim of this study is to access the effectiveness of rainfall-runoff models for streamflow simulation under limitation of data scarcity. Three models, HEC-HMS, IFAS and SWAT models were used for hydrological daily rainfall-runoff simulation of the Nam Song River Basin. The hydrological observed data used in this study were obtained from four rainfall gauges and two streamflow gauges. The period of the study was from 1996 to 2013. The training data set for parameter estimation and sensitivity analysis was from 1996 to 2004 and a testing data set was from 2005 to 2013 for validation of the models. The effectiveness of models were evaluated at two temporal resolutions including daily and monthly scales. The determination coefficient (r^2), Nash-Sutcliffe efficiency (NSE), and correlation coefficient (r) were used as performance indices.

The results indicated that three models have the same high sensitive parameter such land cover parameters, because one of factors affecting on river discharge is land use/land cover, these were also present by Gholami V. et al, 2015 and Kundu M.P. et al, 2011. Three of the rainfall-runoff models were tested in this study performance equally well for simulating daily and monthly streamflow time series. The daily flow simulation of SWAT model matches the observed values for the validation period with correlation coefficient (r) = 0.77, Nash-Sutcliffe coefficient (NSE) = 0.68, and determination coefficient (r^2) = 0.61. The performance of the monthly simulation for validation period was tested obtaining r = 0.87, NSE = 0.82, and r^2 = 0.76. The average percentage difference in the simulated volume of runoff and peak flow was 8.35 % and 9.26% respectively.

The daily flow simulation of HEC-HMS model matches the observed values for the validation period with Correlation coefficient (r) = 0.81, Nash-Sutcliffe coefficient (NSE) = 0.72, and determination coefficient (r^2) = 0.68. The performance of the observed and simulated monthly streamflow time series for the validation period was performed with r = 0.91, NSE = 0.87, and r^2 = 0.682. The average percentage difference in the simulated volume of runoff and peak flow was + 1.88 % and + 6.66 % respectively.

The daily flow simulation of IFAS model matches the observed values for the validation period with Correlation coefficient (r) = 0.83, Nash-Sutcliffe coefficient

(NSE) = 0.75, and determination coefficient (r^2) = 0.74. The performance of the observed and simulated monthly streamflow time series for the validation period was performed with r = 0.97, and NSE = 0.95. The average percentage difference in the simulated volume of runoff and peak flow was – 4.32 % and – 7.15 % respectively.

From the result and comparison between daily observed and simulated time series could be also found that the average values of Time to peak and Lag time are 3.24 days and 1.07 day respectively.

According to the results presented in previous paragraphs, the performance of SWAT model is likely to be less efficient in simulating flow for the Nam Song basin. This is expected to be caused by limited ability of the model to reproduce the hydrograph of the basin and capture high variation of rainfall between wet and dry years. The daily simulation of SWAT model was slightly underestimated in the low flow years and overestimates in the high flow years of the hydrograph. According to Figure 5.10, the performance of the observed and simulated monthly streamflow time series for the validation period was underestimated. The daily simulation of HEC-HMS model in some year was slightly underestimated in the high flow years and overestimates in the recession period of the hydrograph as appeared in calibration period. Figure 5.19 comparing the monthly observed and simulated flow hydrograph at the outlet station during the validation period indicated that HEC-HMS model under-estimated the high peak flow values. The daily simulation of IFAS in some years was slightly underestimated in the low flow years and overestimates in the recession period of the hydrograph as appeared in calibration period.

The comparing of the monthly observed and simulated flow hydrograph at the outlet station during the validation period as presented Figure 5.30 was better when compares with the results of daily streamflow simulation. Thus it was concluded that in over all, three rainfall-runoff models (HEC, IFAS and SWAT) tested in this study performed equally well for predicting daily and monthly streamflow time series. They had different capabilities in prediction high flows that might lead to flooding. IFAS outperformed HEC-HMS and SWAT when predicting high flows. Due to its best performance in predicting high flows and overall streamflow time series, IFAS was considered to be the most suitable rainfall-runoff model for the Nam Song River basin.

This study may be helpful to potential rainfall-runoff model users (especially beginner one) to select their model based on the given problem.

6.2 Further study

1) Further studies should be predicted including high, normal and low flow to make more accurate of suitable rainfall-runoff model selection.

2) The Nam Song basin could be good area for study about water resources because this area has been conserved to be water sources area so that, the land use/land cover in this area is rather sustainable.

3) Runoff measurement in small basins by measuring discharge through the weir and rating curve methods should be recorded at least eight times per day (Suwanlertcharoen, 2011). Because the river characteristic in basin is small, the variation of water level in the river is changing fast when it rains. It will be good and accurate if the budget for automatic record station is available.

4) This research was conducted using Thiessen polygon method to estimate the average rainfall over the Nam Song River basin. Future research in this basin should explore others methods in order to accurately account for runoff from ungauged areas of this basin.

5) Data scarcity and incompleteness made the calibration difficult to fit the simulated and observed values. Future modeling should always be supplemented with available relevant data sources from field based measurements.

From the results of flow in calibration period at Vangvieng station, the parameters cannot fit. This problem may causes of the error of the data recording because this station used rating curve for recording flow data and also the elevation between left and right river bank are different.

REFERENCES

APPENDIX

Appendix A:

SCS Curve Number

Table A1: Runoff curve numbers for urban areas[1]

Cover description	Curve numbers for Hydrologic soil group			
Cover type and hydrologic	A	B	C	D
Fully developed urban areas (vegetation established)				
Open space (lawns, parks, golf courses, cemeteries)3				
Poor condition (grass cover < 50%)	68	79	86	89
Fair condition (grass cover 50% to 75%)	49	69	79	84
Good condition (grass cover > 75%)	39	61	74	80
Impervious areas:				
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)	98	98	98	98
Streets and roads:				
Paved; curbs and storm sewers (excluding right-of-way)	98	98	98	98
Paved; open ditches (including right-of-way)	83	89	92	93
Gravel (including right-of-way)	76	85	89	91
Dirt (including right-of-way)	72	82	87	89
Western desert urban areas:				
Natural desert landscaping (pervious areas only)4	63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)	96	96	96	96
Urban districts:				
Commercial and business	89	92	94	95
Industrial	81	88	91	93
Residential districts by average lot size:				
1/8 acre or less (town houses)	77	85	90	92
1/4 acre	61	75	83	87
1/3 acre	57	72	81	86
1/2 acre	54	70	80	85
1 acre	51	68	79	84
2 acres	46	65	77	82
Developing urban areas				
Newly graded areas (pervious areas only, no vegetation)5	77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).				

Note:

[1] Average runoff condition, and $I_a = 0.2S$.

[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

[4] Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas (Service, 1986).

Table A2: Runoff curve numbers for cultivated agricultural lands[1]

Cover description			Curve numbers for Hydrologic soil group			
Cover type	Treatment[2]	Hydrologic condition[3]	A	B	C	D
Fallow	Bare soil	----	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C).	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C & T	Poor	61	72	79	82
		Good	59	70	78	81
	C & T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C & T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and $I_a = 0.2S$

[2] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

[3] Hydraulic conditions is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (Service, 1986).

Table A3: Runoff curve numbers for other agricultural lands[1]

Cover description		Curve numbers for Hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland or range-continuous forage for grazing.[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow-continuous grass, protected from grazing and generally mowed for hay	----	30	58	71	78
Brush-brush-weed-grass mixture with brush the major element.[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[4]	48	65	73
Woods-grass combination (orchard or tree farm).[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods.[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30[4]	55	70	77
Farmsteads buildings, lanes, driveways, and surrounding lots	----	59	74	82	86

---

[1] Average runoff condition, and $I_a = 0.2S$.

[2] Poor: <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

[3] Poor: <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

[4] Actual curve number is less than 30; use CN = 30 for runoff computations.

[5] CN’s shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN’s for woods and pasture.

[6] Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil (Service, 1986).

Table A4: Runoff curve numbers for arid and semiarid rangelands[1]

Cover description		Curve numbers for Hydrologic soil group			
Cover type	Hydrologic condition[2]	A[3]	B	C	D
Herbaceous-mixture of grass, weeds, and low-growing brush, with brush the minor element	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen-mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon, juniper-pinyon, juniper, or both; grass understory	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub-major plants include saltbush, greasewood, creosote bush, black brush, bursage, palo verde, mesquite, and cactus	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

[1] Average runoff condition, $I_a = 0.2S$. For range in humid regions, use table 2-2c.

[2] Poor: < 30% ground cover (litter, grass, and brush over story).
Fair: 30 to 70% ground cover.
Good: > 70% ground cover.

[3] Curve numbers for group A have been developed only for desert shrub (Service, 1986)

Table A5: Basic SCS rainfall-runoff relationship for different CN values (Service, 1986).

Rainfall (inch)	Direct runoff (inch) for Curve Number (CN)												
	40	45	50	55	60	65	70	75	80	85	90	95	98
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	0.56	0.79
1.2	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.15	0.27	0.46	0.74	0.99
1.4	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.13	0.24	0.39	0.61	0.92	1.18
1.6	0.00	0.00	0.00	0.00	0.01	0.06	0.11	0.20	0.34	0.52	0.76	1.11	1.38
1.8	0.00	0.00	0.00	0.00	0.03	0.09	0.17	0.29	0.44	0.65	0.93	1.29	1.58
2.0	0.00	0.00	0.00	0.02	0.06	0.14	0.24	0.38	0.56	0.80	1.09	1.48	1.77
2.5	0.00	0.00	0.02	0.08	0.17	0.30	0.46	0.65	0.89	1.18	1.53	1.96	2.27
3.0	0.00	0.02	0.09	0.19	0.33	0.51	0.71	0.96	1.25	1.59	1.98	2.45	2.77
3.5	0.02	0.08	0.20	0.35	0.53	0.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	0.06	0.18	0.33	0.53	0.76	1.03	1.33	1.67	2.04	2.46	2.92	3.46	3.77
4.5	0.14	0.30	0.50	0.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	3.92	4.26
5.0	0.24	0.44	0.69	0.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	4.42	4.76
6.0	0.50	0.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	5.41	5.76
7.0	0.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.33	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

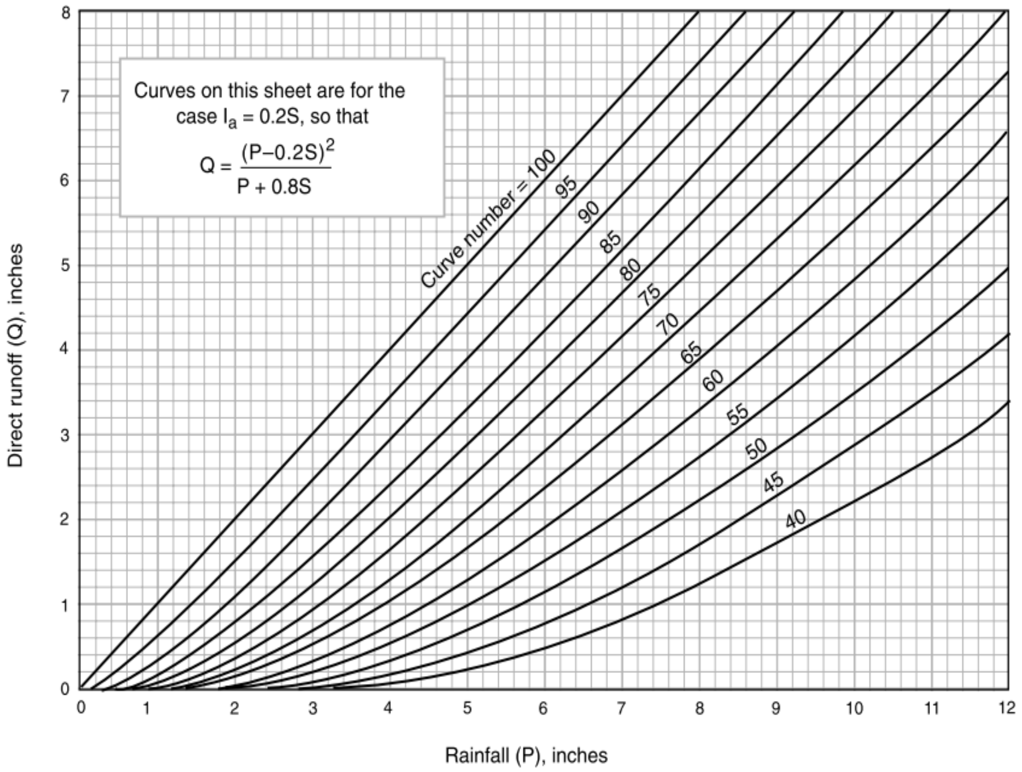


Figure A1: Solution of the SCS runoff equation (Service, 1986).

Table A6: Curve Number values for Nam Song Sub-basins

Sub-basins	Curve Number
Nam Noy	73.99
Nam Sanen	74.87
Nam Po	70.46
Nam Koang	74.93
Nam Ngat	74.68
Nam Song	55.42
Average	70.72

Appendix B:
Hydraulic conductivity

Table B1: Hydraulic conductivity for bed material characteristics (Xu, 2016)

Bed material group	Bed material characteristics	Hydraulic conductivity (mm/hr)
1. Very high loss rate	Very clean gravel and large sand	> 127
2. high loss rate	Clean sand and gravel, field conditions	51 - 127
3. Moderate high loss rate	Sand and gravel mixture with low silt-clay content	25 - 76
4. Moderate loss rate	Sand and gravel mixture with high silt-clay content	6 - 25
5. Insignificant to loss rate	Consolidated bed material; high silt-clay content	0.025 - 2.5

Table B2: Hydraulic conductivity value ranged by soil texture (Merli & Capatti, 2016)

Texture	Hydraulic conductivity(m/day)
Gravel coarse sand	10 - 50
Medium sand	1 - 5
Sandy loam, fine sand	1 - 3
Loam, clay loam, clay (well structured)	0.5 - 2
Very fine sandy loam	0.2 - 0.5
Clay loam, clay (poorly structured)	0.002 - 0.2
Dense clay (no cracks, pores)	< 0.002

Table B3: Ranges of Hydraulic Conductivity (Merli & Capatti, 2016)

Material	Hydraulic conductivity (cm/s)
Clay	10^{-9} - 10^{-6}
Silt, sand silts, clayey sand, till	10^{-6} - 10^{-4}
Silt sands, fine sands	10^{-5} - 10^{-3}
Well-sorted sands, glacial outwash	10^{-3} - 10^{-1}
Well-sorted gravel	10^{-2} - 1

Table B4: Representative values of Hydraulic Conductivity (S. Zhang, H., 2005)

Material	Hydraulic conductivity (cm/s)
Gravel, coarse	150
Gravel, medium	270
Gravel, fine	450
Sand, coarse	45
Sand, medium	12
Sand, fine	2.5
Silt	0.08
Clay	0.0002
Sandstone, fine-grained	0.2
Sandstone, medium-grained	3.1
Limestone	0.49
Dolomite	0.001
Dune sand	20
Loess	0.08
Peat	57
Schist	0.2
Slate	0.00008
Till, predominantly sand	0.49
Till, predominantly gravel	30
Tuff	0.2
Basalt	0.01
Gabbro, weathered	0.2
Granite, weathered	14

Table B5: Hydraulic Conductivity used for Nam Song Basin

Sub_basins	K (m/day)	K (mm/hr)
Nam Noy	0.79	32.81
Nam Sanen	0.79	32.81
Nam Po	0.99	41.24
Nam Koang	0.73	30.37
Nam Ngat	0.74	30.65
Nam Song	1.14	47.30
Average	0.86	35.86

Appendix C:
Manning values “n”

Table C1 : Manning values “n” for channel (Ayvaz, 2013)

Channel characteristics	Median	Range
Excavated or dredged		
Earth, straight and uniform	0.025	0.016 - 0.333
Earth, winding and sluggish	0.35	0.023 - 0.050
Not maintained, weeds and brush	0.075	0.040 - 0.140
Natural streams		
Few tree, stone or brush	0.05	0.025 - 0.065
Heavy timber and brush	0.1	0.050 - 0.150

Table C2: Manning values “n” for overland flow (Milad Jajarmizadeh, 2012)

Channel characteristics	Median	Range
Fall, no residue	0.010	0.008 - 0.012
Conventional tillage, no residue	0.090	0.06 - 0.12
Conventional tillage, residue	0.190	0.16 - 0.22
Chisel plow, no residue	0.090	0.06 - 0.12
Chisel plow, residue	0.130	0.1 - 0.16
Fall disking, residue	0.400	0.3 - 0.5
No till, no residue	0.070	0.04 - 0.1
No till, 0.5-1 t/ha residue	0.120	0.07 - 0.17
No till, 2-9 t/ha residue	0.300	0.17 - 0.47
Rangeland, 20% cover	0.600	0.45 - 0.73
Shot grass prairie	0.150	0.1 - 0.2
Dense grass	0.240	0.17 - 0.3
Bermuda grass	0.410	0.3 - 0.48

Table C3: Manning's n for Channels (Chow, 1959 cited by (Seree Chanyotha, 2013))

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at flood stage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
b. same as above, but more stones and weeds	0.03	0.035	0.04
c. clean, winding, some pools and shoals	0.033	0.04	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.05
e. same as above, lower stages, more ineffective slopes and sections	0.04	0.048	0.055
f. same as "d" with more stones	0.045	0.05	0.06
g. sluggish reaches, weedy, deep pools	0.05	0.07	0.08
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.1	0.15
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
b. bottom: cobbles with large boulders	0.04	0.05	0.07
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.03	0.035
2. high grass	0.03	0.035	0.05
b. Cultivated areas			
1. no crop	0.02	0.03	0.04
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.03	0.04	0.05
c. Brush			
1. scattered brush, heavy weeds	0.035	0.05	0.07
2. light brush and trees, in winter	0.035	0.05	0.06
3. light brush and trees, in summer	0.04	0.06	0.08
4. medium to dense brush, in winter	0.045	0.07	0.11
5. medium to dense brush, in summer	0.07	0.1	0.16
d. Trees			
1. dense willows, summer, straight	0.11	0.15	0.2
2. cleared land with tree stumps, no sprouts	0.03	0.04	0.05
3. same as above, but with heavy growth of sprouts	0.05	0.06	0.08
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.08	0.1	0.12
5. same as 4. with flood stage reaching branches	0.1	0.12	0.16

Table C4: Manning's n for Channels, Continued. (Chow, 1959 cited by (Seree Chanyotha, 2013))

4. Excavated or Dredged Channels			
a. Earth, straight, and uniform			
1. clean, recently completed	0.016	0.018	0.02
2. clean, after weathering	0.018	0.022	0.025
3. gravel, uniform section, clean	0.022	0.025	0.03
4. with short grass, few weeds	0.022	0.027	0.033
b. Earth winding and sluggish			
1. no vegetation	0.023	0.025	0.03
2. grass, some weeds	0.025	0.03	0.033
3. dense weeds or aquatic plants in deep channels	0.03	0.035	0.04
4. earth bottom and rubble sides	0.028	0.03	0.035
5. stony bottom and weedy banks	0.025	0.035	0.04
6. cobble bottom and clean sides	0.03	0.04	0.05
c. Dragline-excavated or dredged			
1. no vegetation	0.025	0.028	0.033
2. light brush on banks	0.035	0.05	0.06
d. Rock cuts			
1. smooth and uniform	0.025	0.035	0.04
2. jagged and irregular	0.035	0.04	0.05
e. Channels not maintained, weeds and brush uncut			
1. dense weeds, high as flow depth	0.05	0.08	0.12
2. clean bottom, brush on sides	0.04	0.05	0.08
3. same as above, highest stage of flow	0.045	0.07	0.11
4. dense brush, high stage	0.08	0.1	0.14
5. Lined or Constructed Channels			
a. Cement			
1. neat surface	0.01	0.011	0.013
2. mortar	0.011	0.013	0.015
b. Wood			
1. planed, untreated	0.01	0.012	0.014
2. planed, creosoted	0.011	0.012	0.015
3. unplaned	0.011	0.013	0.015
4. plank with battens	0.012	0.015	0.018
5. lined with roofing paper	0.01	0.014	0.017
c. Concrete			
1. trowel finish	0.011	0.013	0.015
2. float finish	0.013	0.015	0.016
3. finished, with gravel on bottom	0.015	0.017	0.02
4. unfinished	0.014	0.017	0.02
5. gunite, good section	0.016	0.019	0.023
6. gunite, wavy section	0.018	0.022	0.025
7. on good excavated rock	0.017	0.02	
8. on irregular excavated rock	0.022	0.027	

Table C5: Manning's n for Channels, Continued. (Chow, 1959 cited by (Seree Chanyotha, 2013))

d. Concrete bottom float finish with sides of:			
1. dressed stone in mortar	0.015	0.017	0.02
2. random stone in mortar	0.017	0.02	0.024
3. cement rubble masonry, plastered	0.016	0.02	0.024
4. cement rubble masonry	0.02	0.025	0.03
5. dry rubble or riprap	0.02	0.03	0.035
e. Gravel bottom with sides of:			
1. formed concrete	0.017	0.02	0.025
2. random stone mortar	0.02	0.023	0.026
3. dry rubble or riprap	0.023	0.033	0.036
f. Brick			
1. glazed	0.011	0.013	0.015
2. in cement mortar	0.012	0.015	0.018
g. Masonry			
1. cemented rubble	0.017	0.025	0.03
2. dry rubble	0.023	0.032	0.035
h. Dressed ashlar/stone paving	0.013	0.015	0.017
i. Asphalt			
1. smooth	0.013	0.013	
2. rough	0.016	0.016	
j. Vegetal lining	0.03		0.5

VITA

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