



รายงานวิจัยฉบับสมบูรณ์

โครงการการปรับปรุงการพยากรณ์น้ำท่าในลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่าในประเทศไทย โดยใช้ข้อมูลดาวเทียมและข้อมูลคุณสมบัติของดิน

(Towards improving flow predictions for ungauged catchments in Thailand using satellite-based products and soil property data)

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สิงหาคม 2563

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ดาวเทียมและข้อมูลคุณสมบัติของดิน

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ชื่อโครงการ: โครงการการปรับปรุงการพยากรณ์น้ำท่าในลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่าในประเทศไทย โดยใช้ข้อมูลดาวเทียมและข้อมูลคุณสมบัติของดิน

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บทคัดย่อ: ข้อมูลน้ำท่าเป็นข้อมูลที่มีความสำคัญอย่างมากต่อการวางแผนและจัดการทรัพยากรน้ำ การพยากรณ์น้ำท่าในลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่ายังคงเป็นความท้าทายสำหรับการจัดการทรัพยากรน้ำสำหรับประเทศกำลังพัฒนาเนื่องจากสถานีอุทกวิทยาที่มีการติดตั้งเครื่องมือตรวจวัดน้ำท่านั้นมีอยู่ค่อนข้างน้อย การศึกษานี้จึงถูกพัฒนาขึ้นเพื่อประเมินศักยภาพของการใช้ข้อมูลฝนและข้อมูลคุณสมบัติทางกายภาพและเคมีของดินที่ได้จากข้อมูลดาวเทียมมาใช้พัฒนาแบบจำลองการถดถอยสำหรับพยากรณ์น้ำท่าในลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่าในประเทศไทย การศึกษานี้มีวัตถุประสงค์โดยรวมคือการพยากรณ์ข้อมูลน้ำท่าและประมาณช่วงค่าความไม่แน่นอนของการพยากรณ์เพื่อนำข้อมูลที่ได้ไปใช้สนับสนุนการวางแผนและจัดการทรัพยากรน้ำในลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่า วัตถุประสงค์ย่อยของการศึกษานี้คือ การพัฒนาฐานข้อมูลดินเพื่อใช้สนับสนุนการพยากรณ์น้ำท่า การใช้ประโยชน์จากข้อมูลจากดาวเทียมเพื่อการประมาณปริมาณฝนและการระบุแนวทางที่เหมาะสมสำหรับการพยากรณ์น้ำท่าในลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่าในประเทศไทย จากฐานข้อมูลน้ำฝนและคุณสมบัติดินที่ประมาณได้จากข้อมูลดาวเทียม พื้นที่สำหรับการศึกษานี้คือพื้นที่ลุ่มน้ำปิงตอนบน ซึ่งอยู่ในภาคเหนือของประเทศไทย การวิเคราะห์และประมาณค่าดัชนีน้ำท่าใช้ข้อมูลจากสถานีวัดน้ำท่า 34 สถานี ในช่วงปี พ.ศ. 2549-2557 ดัชนีน้ำท่าที่ใช้เพื่อมาหาความสัมพันธ์กับข้อมูลคุณสมบัติของลุ่มน้ำมีทั้งหมด 6 ดัชนี ได้แก่ สัมประสิทธิ์น้ำท่า ดัชนีการไหลพื้นฐาน ความยืดหยุ่นของน้ำท่า เปอร์เซนไทล์ที่ 95 50 และ 5 ของน้ำท่า คุณสมบัติของลุ่มน้ำที่ใช้เป็นข้อมูลนำเข้าในการพัฒนาตัวแบบสมการถดถอยมีทั้งหมด 18 คุณสมบัติ ประกอบด้วยคุณสมบัติด้านกายภาพ ภูมิอากาศ การใช้ที่ดิน และคุณสมบัติดิน ข้อมูลคุณสมบัติด้านกายภาพและการใช้ที่ดินได้จากการวิเคราะห์ด้วยซอฟต์แวร์ ArcGIS ข้อมูลด้านภูมิอากาศใช้การประมาณปริมาณฝนจากข้อมูลดาวเทียม TRMM ที่มีความละเอียดเชิงพื้นที่ 0.25×0.25 องศา ซึ่งมีความถูกต้องมากกว่าการใช้ข้อมูลจากสถานีตรวจวัดฝนเพียงอย่างเดียวเนื่องจากจำนวนสถานีในลุ่มน้ำมีจำนวนน้อย ข้อมูลคุณสมบัติของดินได้จากการนำข้อมูลในรายงานของกรมพัฒนาที่ดินมาวิเคราะห์ร่วมกับฐานข้อมูลดินของ ISRIC

ซึ่งมีความละเอียดเชิงพื้นที่ 1×1 กิโลเมตร ผลการศึกษาพบว่า เปอร์เซนไทล์ที่ 95 ของน้ำท่าเป็นดัชนีที่ใช้พยากรณ์ดัชนีน้ำท่าได้ดีที่สุด ตามด้วยสัมประสิทธิ์น้ำท่า และเปอร์เซนไทล์ที่ 50 ของน้ำท่า ตัวแบบสมการถดถอยไม่สามารถพยากรณ์เปอร์เซนไทล์ที่ 5 ของน้ำท่า และความยืดหยุ่นของน้ำท่าได้ดีนัก และไม่สามารถพยากรณ์ค่าดัชนีการไหลพื้นฐานได้ตามสมมติฐานที่ตั้งไว้ในตอนแรก เนื่องจากตัวแบบไม่สามารถระบุคุณสมบัติของกลุ่มน้ำที่มีความสัมพันธ์ต่อดัชนีการไหลพื้นฐานอย่างมีนัยสำคัญได้ ค่าสัมประสิทธิ์การตัดสินใจของสมการถดถอยสำหรับการพยากรณ์ดัชนีน้ำท่ามีค่าตั้งแต่ 0.48 ถึง 0.77 ความไม่แน่นอนของการพยากรณ์ดัชนีน้ำท่าและอนุกรมน้ำท่าคาดว่าจะมีผลมาจากหลายสาเหตุ ได้แก่ การประมาณค่าคุณสมบัติของกลุ่มน้ำที่ใช้เป็นข้อมูลน้ำเข้าในการพัฒนาตัวแบบสมการถดถอย พารามิเตอร์ และโครงสร้างของแบบจำลอง IHACRES แม้จะมีการจำกัดช่วงค่าพารามิเตอร์ตั้งต้นของแบบจำลอง IHACRES โดยใช้ช่วงความเชื่อมั่นและช่วงค่าพยากรณ์ของดัชนีที่น้ำท่าแล้วนั้น ความไม่แน่นอนของการพยากรณ์น้ำท่ายังคงมีค่าค่อนข้างสูง เพราะช่วงความไม่แน่นอนที่ได้จากแบบจำลองถดถอยไม่สามารถสะท้อนความไม่แน่นอนของโครงสร้างแบบจำลอง IHACRES ได้อย่างเพียงพอ โดยรวมแล้ววิธีการพยากรณ์น้ำท่าที่ใช้ในการศึกษานี้ให้ผลอยู่ในเกณฑ์ที่ยอมรับได้สำหรับกลุ่มน้ำที่มีขนาดเล็กถึงปานกลาง มีค่าระดับความสูงเฉลี่ยของกลุ่มน้ำต่ำถึงปานกลาง และมีความแตกต่างของฝนที่ตกในพื้นที่น้อย สำหรับการศึกษาในอนาคตควรพัฒนาวิธีการลดความไม่แน่นอนของการพยากรณ์น้ำท่าและการเพิ่มประสิทธิภาพของตัวแบบการพยากรณ์ ซึ่งอาจจะทำได้โดยการใช้ข้อมูลดินชุดใหม่ของ ISRIC ที่มีความละเอียดเชิงพื้นที่สูงขึ้นและมีตัวแปรคุณสมบัติที่ครอบคลุมมากขึ้นกว่าข้อมูลชุดที่ใช้ในการศึกษานี้

คำหลัก : การพยากรณ์น้ำท่า กลุ่มน้ำที่ไม่มีสถานีวัดน้ำท่า กลุ่มน้ำปิง ข้อมูลดิน

Abstract

Project Code : MRG5980149

Project Title : Towards improving flow predictions for ungauged catchments in Thailand using satellite-based products and soil property data

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Abstract: Flow data are critical for water resources planning and management. Predicting flow time series remains a challenge for water resources management in developing countries where hydrological gauge network is generally sparse. The intended contribution of this study is to identify the potential value of using satellite rainfall and soil products and a soils database containing physical and chemical properties for improving the regression model for flow estimates in Thai ungauged catchments. The overall objective of this study is to support water resources planning and management in ungauged catchments by providing improved flow data and uncertainty estimates. Specific objectives are to develop soils databases that are more suitable for supporting the Thai ungauged catchment problem., to fully take advantage of new remote-sensing products for estimating rainfall in ungauged Thai catchments, and to identify the optimal approach to regionalisation in Thai catchments using the rainfall and soils databases. Using data from 34 gauged sub-catchments of the upper Ping catchment in northern Thailand from the period 2006-2014, six rainfall-flow indices (runoff coefficient: RC, base flow index: BFI, seasonal flow elasticity: EL, 95th percentile flow: Q95, 50th percentile flow: Q50 and 5th percentile flow: Q5) were regionalised by regression against 18 catchment properties including topography, climate, land use and soil properties. The topography and land use properties were extracted using ArcGIS software. Regarding climate, the rainfall estimate from calibrated TRMM product at 0.25 x 0.25 degree was generally more accurate than interpolation of the gauged rainfall from sparse network. The TRMM products were therefore used for estimating areal rainfall over the catchment. The soil

properties were extracted from descriptive reports from LDD and from the ISRIC's WISE pedon-database at spatial resolution of 1 x 1 km. The 95th percentile flow was the most successfully regionalised, followed by runoff coefficient index and 50th percentile flow. The 5th percentile flow and seasonal elasticity of flow could not be well regionalised. The r^2 values of the regression equations range from 0.48 to 0.77. The base flow index which was expected to be an informative index for flow prediction could not be used for regionalisation using the regression method. This is because none of the 18 catchment properties was identified as significant predictor. Uncertainty in regionalised flow indices and flow time series was believed to be caused by multiple sources including the estimation of catchment properties used for developing the regression equations, IHACRES model parameter and model structure. The regionalised flow indices were used individually to constrain the IHACRES rainfall-runoff model using the regression confidence and prediction intervals. Using the variance of the regression coefficients and of the regression residuals had limited success in estimating the flow uncertainty intervals because uncertainty from the IHACRES model structure is not sufficiently represented by the variance of the regression. The regionalised model was considered to provide acceptable predictions generally for small to medium sized catchments with low to medium elevations and mild rainfall gradient. Further attempt to reduce prediction uncertainty and improve the performance of the regionalised model is needed for future research. Recommendation includes developing more precise soils databases using recent ISRIC's dataset of the soil grids data that are provided with higher resolutions and with more soil properties.

Keywords : flow predictions, predictions in ungauged basins, Ping basin, Soil data

Executive Summary

Background of the study

Predicting flow time series is one of the fundamental challenges for water resources study especially in least developed and developing countries. For this study, the regression method is selected because it is able to represent spatial variability of catchment properties and show explicit connections between spatial catchment properties and flow responses. Furthermore, uncertainty of flow predictions can be estimated using the variance of the regression coefficients and of the regression residuals. Further improvement of the regression performance for ungauged predictions might be to include soil properties that have been found as significant predictors for flow responses and used for regionalisation in many studies. This study therefore attempts to develop a soil database for the study catchment, the upper Ping catchment, using soil data from the Land Development Department, WISE pedon-database developed by the International Soil Reference and Information Centre (ISRIC) and the FAO-UNESCO Digital Soil Map of the World (FAO, 1995). The intended contribution of this study is to identify the potential value of using satellite rainfall and soil products and a soils database containing physical and chemical properties for improving the regression model for flow estimates in Thai ungauged catchments.

Objectives

The overall objective of the project is to support water resources planning and management in ungauged catchments by providing improved flow data and uncertainty estimates. Specific objectives are:

1. To develop soils databases that are more suitable for supporting the Thai ungauged catchment problem
2. To fully take advantage of new remote-sensing products for estimating rainfall in ungauged Thai catchments
3. To identify the optimal approach to regionalisation in Thai catchments using the rainfall and soils databases

Methodology

1. Catchment properties are determined for each ungauged sub-catchment based on the hypothesis that these properties are dominant controls on the hydrological responses. A soils database containing both physical and chemical properties will be developed using the WISE pedon-database and descriptive soil survey results provided by the Land Development Department. The TRMM rainfall estimates will be merged with ground-gauged rainfall data to improve the accuracy of areal rainfall estimates over the sub-catchment areas.
2. Flow indices including the runoff coefficient (RC), the Base Flow Index (BFI), the rainfall-flow seasonal elasticity (EL), the 95th, 50th and 5th percentiles flows (Q95, Q50, and Q5, accordingly) will be estimated based on daily data from 48 rain gauges and 34 flow gauges in the upper Ping catchment
3. The catchment properties and flow indices will be used to test the hypothesis, forward stepwise regression will be used to relate the flow indices with catchment properties.
4. Uncertainty arisen from all sources will be estimated using the variance of the regression coefficients and of the regression residuals.
5. The performance of regression model is tested using a cross-validation method. The confidence and prediction intervals of the regression equations will used to constrain the IHACRES rainfall-runoff model.
6. The modelled time-series for each ungauged sub-catchment is assessed using the Nash Sutcliffe Efficiency (NSE) and the *Reliability* as well as visual assessment.

Scope of research

The upper Ping catchment covering an approximate area of 25370 km² is selected for this study. The period of study from water year 2006 to 2014 is chosen as they provide sufficient records for hydrological data to test and validate model performance. This study uses daily ground-gauged data located in the upper Ping catchment and its surrounding catchments from 112 rain gauges across 84 sub-catchments, each of which has a flow gauge at its outlet. The Tropical Rainfall Measurement Mission (TRMM) satellite rainfall product is also used to merge with ground-gauged rainfall. The soil hydrological property data is not directly obtainable from available sources. This study attempts to

explore and develop relevant soil database and feature significant soil property data in regression equations.

Expected benefits

1. Developing understanding of the linkage between catchment properties and hydrological response
2. Improving the performance of a regression method for predicting flow in ungauged catchment given available data
3. Developing a database of hydrological soil properties which would be useful for a number of future studies
4. Providing data for flow time series and associated uncertainty which allow better management and decision making

TRMM satellite product

The performances of TRMM estimates and interpolation were compared using the daily data from 1 April 2006 to 31 March 2015. After an adjustment through the regression, the correlation coefficients between the calibrated TRMM and benchmark grid-averaged rainfall for the entire time-series including zero rainfall range from 0.47 to 0.67 across 10 test grids. The values of POD (0.86-0.93) are generally high and the values of FAR (0.04-0.10) are generally low. This suggests that TRMM is highly capable of capturing rainfall occurrence. TRMM at 0.25 x 0.25 degree is generally more accurate than the use of interpolated rainfall in catchments with sparse ground-gauged data and it can be used to improve the estimation of rainfall in ungauged catchments.

Soil property database

The soil database for the Ping catchment was developed using the guideline and initial soil database of the Mae Chaem sub-catchment performed by Thanapakpawin et al. (2007). The data from LDD soil survey report and the WISE30sec, v1.0 from the WISE pedon-database were used for used together to identity the values of soil properties. The soil profiles used to develop the WISE pedon-database and SoilGrids1km for Thailand are from a relatively small number of the soil profiles and even more limited for the Ping catchment. The data from the WIES pedon-database are available only for some soil

great groups and for few soil properties. The soil properties developed based on the coarse resolution of the SoilGrid1km over Thailand is almost homogeneous. This does not agree well with the distributions of variable soil types over the catchment. The contribution from using the soil properties to improve regionalization is therefore of limited.

Predicting flows in ungauged catchments

The 18 catchment properties and six rainfall-flow indices were used to develop the regression equation for predicting flow in the upper Ping catchment. Only three out of 18 catchment properties were found significant for predicting flow indices. This is because many catchment properties were highly correlated and removed when performing stepwise regression analysis. The attempt to estimate the soil properties and used them as the predictors of the flow indices was not successful. No soil properties were identified as significant variable for predicting flow indices. Area of the catchment was found to be significant for all, except BFI, indices. The r^2 values of the obtained regression are considered moderate ranging from 0.48-0.77. Constraining the parameter sets based on confidence intervals of RC and Q95 generally improves the performance of the model. The method of constraining parameter sets was demonstrated to be potentially useful for estimating the expected time-series of flow. Important errors are caused by input data for the regression and IHACRES parameter and model structure that is not sufficiently represented by the variance of the regression.

Recommendations

The soil property data used in this study were developed from the early version of the WISE pedon-database which are too little and too coarse to represent the heterogeneity of the soil over the catchment. The updated version of the soil grid provided in the Data Hub of ISRIC (<https://data.isric.org/geonetwork/srv/eng/catalog.search#/>) could contribute to the improvement of soil data mapping and allow the soil properties to be included in the regression equation. The assessment of the newer version of the soil grid data is recommended for future study.

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Chapter 1 Introduction

1.1. Background

The availability of flow data is critical for water resources planning and management. Most catchments in least developed and developing countries do not have flow data because of limited coverage and distribution of hydrological gauge networks (Schreider et al. 2002, Singhrattna et al. 2005, Lee 2006, Buytaert and Beven 2009, Piman and Babel 2013). Predicting flow time series is therefore one of the fundamental challenges for water resources study. Despite a number of regionalisation studies in many parts of the world, relatively few have been performed for Thai ungauged catchments.

Several regionalisation methods have been used for predictions in ungauged catchments. The simplest method is the scaling relationship. Other commonly used methods include spatial proximity, physical similarity, and regression methods. The choice of regionalisation methods depends on a number of factors such as data availability, the purpose of modelling, resource constraints, and knowledge of the modeller regarding catchment's hydrology. For this study, the regression method is selected because it is able to represent spatial variability of catchment properties and show explicit connections between spatial catchment properties and flow responses. Furthermore, uncertainty of flow predictions can be estimated using the variance of the regression coefficients and of the regression residuals. The estimation of uncertainty is a valuable source of information for constraining a model, providing ensemble predictions, and allowing better decision making based on uncertain information but, to the best of my knowledge, none of uncertainty analysis has been performed for Thai ungauged catchments.

The estimation of rainfall in Thailand is particular challenging because Thailand is located in a tropical climate zone (Köppen 1936) where rainfall is mainly characterised by monsoons and is highly variable. Spatial estimation of rainfall is not well represented in models due to insufficient distribution of hydrological

gauge networks and limited data quality. Investing in denser gauge networks contributes to improved rainfall estimation. However, this solution may not be optimal because of economic and environmental constraints, especially for mountainous or remote catchments (Campling 2001). Available satellite-based rainfall products offer an alternative for improving the estimation of areal rainfall. The accuracy of recent satellite-based rainfall products has considerably been improved due to increased temporal and spatial resolution together with new methods to merge various data sources (Stisen and Sandholt 2010). Although satellite rainfall products may be preferable to sole reliance of sparse ground-gauge networks, the problem of inability to capture extreme rainfall commonly been found by several studies remains a challenge (Chokngamwong and Chiu 2007, Ward et al. 2011, Visessri and McIntyre 2012).

Further improvement of the regression performance for ungauged predictions might be to include more catchment properties into the regression analysis with the aim of identifying additional significant predictors that lead to increased r^2 values. Soil hydrological properties have been found as significant predictors for flow responses and used for regionalisation in many studies such as Croke and Norton (2004), Mazvimavi et al. (2004), Maréchal and Holman (2005) and Bulygina et al. (2009). However, the lack of a database of soil hydrological properties has prevented their important roles to feature in regionalisation. A soil database for an approximate area of 3853 km² of Mae Chaem sub-catchment located in the upper Ping catchment was developed by Thanapakpawin et al. (2007) using soil data sampled from the WISE pedon-database (Batjes, 1995) developed by the International Soil Reference and Information Centre (ISRIC) and the FAO-UNESCO Digital Soil Map of the World (FAO, 1995). An attempt to transform descriptive soil survey data and merge them with the WISE pedon-database probably contributes to a better representation of spatial soil data. This is because the moderate quality of the remotely-sensed data covering relatively coarse area i.e. 1 x 1 km (downloadable from the WISE pedon-database at <http://soilgrids1km.isric.org/>) can be adjusted by using more precise soil core sampling data.

The intended contribution of this study is to identify the potential value of using satellite rainfall and soil products and a soils database containing physical and chemical properties for improving the regression model for flow estimates in Thai ungauged catchments. The value obtained from this study is expected to be extendable to other catchments with similar hydrological characteristics. In addition to the direct contribution to Thailand, this study will contribute to two areas of international literature including predictions in ‘totally ungauged catchment’ and the soils database.

1.2. Objectives

The overall objective of the project is to support water resources planning and management in ungauged catchments by providing improved flow data and uncertainty estimates. Specific objectives are:

4. To develop soils databases that are more suitable for supporting the Thai ungauged catchment problem
5. To fully take advantage of new remote-sensing products for estimating rainfall in ungauged Thai catchments
6. To identify the optimal approach to regionalisation in Thai catchments using the rainfall and soils databases

1.3. Methodology

Catchment properties representing topography, land use, soil types, and rainfall are determined for each ungauged sub-catchment based on the hypothesis that these properties are dominant controls on the hydrological responses. Information of topography and land use can be obtained directly from the Digital Elevation Model (DEM) and land use maps while prior processing for soil property data and rainfall is needed to improve their applicability. A soils database containing both physical and chemical properties will be developed using the WISE pedon-database and descriptive soil survey results provided by the Land Development Department. Potentials of using soil moisture data for modelling will be investigated. The TRMM rainfall estimates will be merged with ground-gauged rainfall data to improve the accuracy of areal rainfall estimates over the sub-

catchment areas. Flow indices including the runoff coefficient (RC), the Base Flow Index (BFI), the rainfall-flow seasonal elasticity (EL), the 95th, 50th and 5th percentiles flows (Q95, Q50, and Q5, accordingly) will be estimated based on daily data from 48 rain gauges and 34 flow gauges in the upper Ping catchment. The data from 64 rain gauges and 50 flow gauges in five surrounding catchments which are the lower Ping, Salawin, Kok, Wang, and Yom catchments will also be considered. To test the hypothesis, forward stepwise regression will be used to relate the three indices with catchment properties. Uncertainty arising from all sources will be estimated using the variance of the regression coefficients and of the regression residuals. A recent method for improving confidence interval estimation by error modelling proposed by Bourgin *et al.* (2015) will be attempted. The performance of regression model is tested using a cross-validation method. The confidence and prediction intervals of the regression equations will be used to constrain the IHACRES rainfall-runoff model. The modelled time-series for each ungauged sub-catchment is assessed using the Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) and the *Reliability* as well as visual assessment.

The practical value of this study will be demonstrated by performing a supply-demand balance for the Bhumibol dam positioned in the low end of the upper Ping catchment.

1.4. Scope of research

The upper Ping catchment covering an approximate area of 25370 km² is selected for this study. The period of study from water year 2006 to 2014 is chosen as they provide sufficient records for hydrological data to test and validate model performance. This study uses daily ground-gauged data located in the upper Ping catchment and its surrounding catchments from 112 rain gauges across 84 sub-catchments, each of which has a flow gauge at its outlet. The Tropical Rainfall Measurement Mission (TRMM) satellite rainfall product is also used to merge with ground-gauged rainfall. The soil hydrological property data is not directly obtainable from available sources. This study attempts to explore and develop relevant soil database and feature significant soil property data in regression equations.

1.5. Schedule for the entire project and outputs

Schedule of activities and outputs from the proposed study are shown in the Table 1.1.

1.6. Structure of the report

This report is structured into six chapters. Chapter 1 is the introduction to the study. Chapter 2 provides information about the Ping catchment which was selected as the study area. Chapter 3 to Chapter 5 present the evaluation of the TRMM satellite products, soil data, and regression method for predicting flows in ungauged catchments. Conclusion and recommendations for future study are provided in Chapter 6.

Table 1.1 Activities and outputs

Activities	Expected outputs
1. Data collection 1.1 Request rainfall, temperature, and flow data from the Royal Irrigation Department, the Department of Water Resources, and the Thai Meteorological Department 1.2 Request land use and soil data from the Land Development Department 1.3 Request soil moisture and demand data from the Water Resource System Research Unit, Chulalongkorn University 1.4 Download 0.25 x 0.25 degree TRMM rainfall estimates from http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=TRMM 1.5 Download 1 x 1 km soil data from http://soilgrids1km.isric.org/ 2. Data processing 2.1 Estimate catchment properties and flow indices 2.2 Merge the TRMM rainfall estimates to ground-gauged rainfall data 3. Soil database development 3.1 Assess the applicability of soil data downloaded from the WISE pedon-database 3.2 Merge descriptive soil survey data with soil data downloaded from the WISE pedon-database 3.3 Investigate the value of soil data	1. Hydrological data 2. Land use data 3. Soil data 4. Demand data 5. Improved areal rainfall estimates 6. Soil property database

Activities	Expected outputs
4. Model development 4.1 Perform regression analysis 4.2 Simulate flow time-series using the IHACRES rainfall-runoff model 4.3 Condition the IHACRES model using a Bayesian method 4.4 Improve confidence interval estimation by error modelling 5. Model evaluation 5.1 Evaluate at different time scales e.g. daily, monthly, and seasonally 5.2 Search for possible improvement for the model 6. Analysis of the results 6.1 Analyse the performance of the similarity-based and regression methods, IHACRES model, and Bayesian method 6.2 Interpret the results 7. Final report 7.1 Produce final report	7. Regression equations 8. Ensemble predictions of flow time series 9. Model performance 10. Understanding of catchment's hydrology 11. Applicability of the proposed methods to predictions in ungauged catchments 12. Final report

1.7. Expected benefits

This study aims to deliver the following benefits:

5. Developing understanding of the linkage between catchment properties and hydrological response
6. Improving the performance of a regression method for predicting flow in ungauged catchment given available data
7. Developing a database of hydrological soil properties which would be useful for a number of future studies
8. Providing data for flow time series and associated uncertainty which allow better management and decision making

Chapter 2 Hydrological data for the study catchment

2.1. Description of catchment characteristics

2.1.1 Location and topography

There are five catchments (Ping, Salawin, Kok Wang, and Yom) lying in northwest of Thailand. This study focuses on predicting flows for the upper Ping catchment. However, the characteristics of other catchments surrounding the upper Ping catchment are also presented here as they probably contribute to improved regression model and flow prediction.

The upper Ping catchment is located in northwest of Thailand comprising an approximate area of 25425 km². The upper Ping catchment lies vertically between latitudes 17°00'-19°48' N and the longitudes 98°05'-99°23' E as shown in Figure 2.1. North of the catchment is Myanmar, west of the catchment is the Salawin catchment (18950 km²), and the Kok (7275 km²) and Wang (10793 km²) catchments are to the northeast and southeast respectively. South of the catchment is the Bhumibol dam separating the upper and lower Ping catchments (9101 km²). On the east of the lower Ping catchment is the Yom catchment (24047 km²). The elevations of the upper Ping catchment range from mean sea level to 2633 meters above mean sea level (m.a.s.l.), with the central alluvial plains being surrounded by mountains (Figure 2.1).

2.1.2 Stream network and water resources

The Ping River headwater originates from the Pee Pan Nam mountain range in the upper part of Chiang Mai province. The Ping River drains water from the north to the south of the catchment and merges with the Wang, Yom and Nan Rivers forming the Chao Phraya River in the central plain (Department of Environmental Quality Promotion 1994).

2.1.3 Climate and hydrology

The climate of the upper Ping catchment is tropical with three seasons - rainy, winter and summer - which are mainly characterised by the Southwest

and Northeast monsoons. The upper Ping catchment is also subject to rainfall associated with south winds and tropical cyclones. The Southwest monsoon is formed in a high pressure zone in the Indian Ocean causing the rainy season between mid-May and mid-October, while the Northeast monsoon originates from a high pressure zone near Mongolia and China, bringing dry and cold air to the catchment between mid-October and mid-February. Summer, the transition period between the Southwest and Northeast monsoons, from mid-February to mid-May, is usually dry and hot.

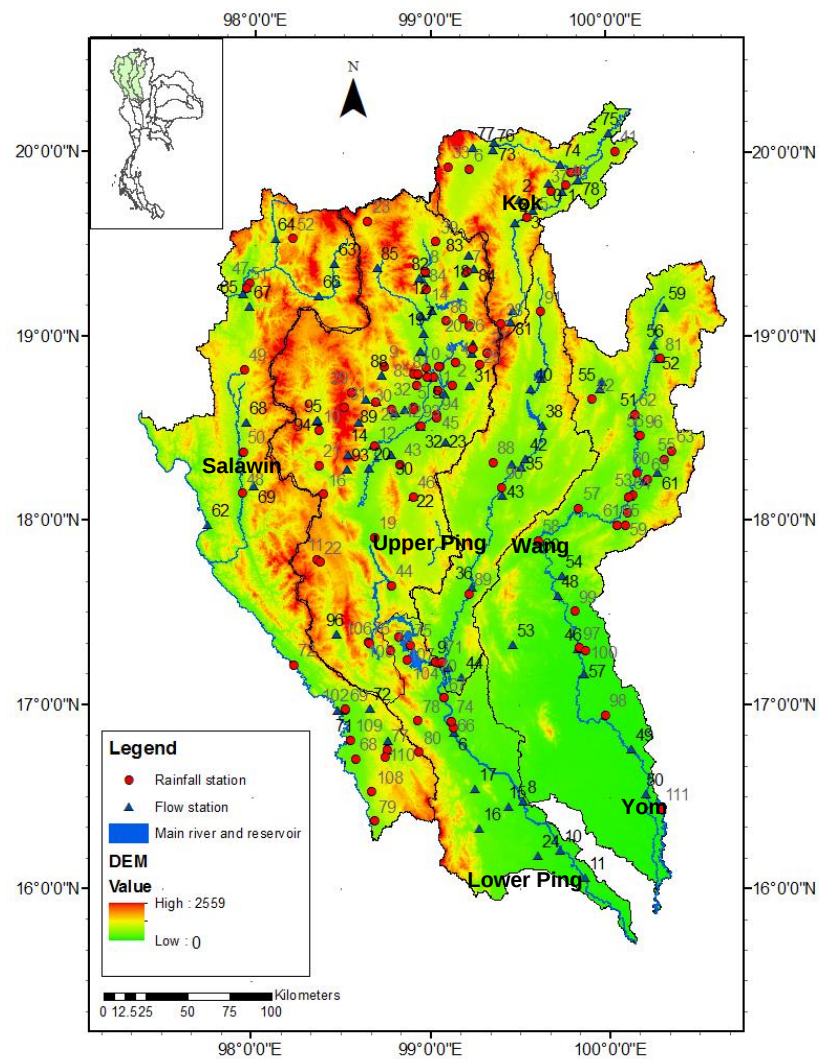


Figure 2.1 Location plan of the upper Ping and its surrounding catchments with elevations and locations of hydrological gauges. Grey and black numbers shown within the catchment area are rain and flow gauge orders which can be linked to gauge code using Table A. 1 and Table A. 2, accordingly.

2.1.4 Geology and soils

Based on the information from the Department of Mineral Resources, the stratigraphies of rocks in the upper Ping catchment are complex and spatially variable. The rocks range in age from the oldest Precambrian to Lower Paleozoic, Upper Paleozoic, Mesozoic and the latest Igneous. In terms of soil types, the analysis described in this study is based on the ‘great group level’ referring to the third class of the US Soil Taxonomy (United States Department of Agriculture (USDA) 1999) with six hierarchical categories ranging from the coarsest to finest classes, which are order, suborder, great group, subgroup, family and series. The upper Ping catchment soil types comprise of 42 out of 62 soil great groups found in Thailand. ‘Mountainous soil’ (soil great group 62) is the most prevalent soil type for the upper Ping and also its surrounding catchments (Land Development Department 2006). Mountainous soil is less common when moving from the upper to lower parts of the catchments. The description and distribution of the major soil great groups (occupying more than 5% of any catchment areas) are shown in Table 2.1 and Figure 2.2.

2.1.5 Land use

The major land use is forest including dry dipterocarp, mixed deciduous, dry evergreen, hill evergreen and coniferous forests. The dry dipterocarp and mixed deciduous forest, consisting of teak, afzelia xylocarpa, pterocarpus macrocarpus, rosewood and xylia xylocarpa taub (leguminosae), are found in the valleys and hills at elevations less than 1000 m.a.s.l., while the evergreen and coniferous are common at higher elevations. The principal commercial crops grown are rice, corn, longan and other tropical fruit trees. Agriculture is common to the alluvial plains along both sides of the upper Ping River. Intensive agriculture is found in the lower part of the Ping and Yom catchments. The degree of urban cover is low. The description and distribution of the major land use in the upper Ping and its surrounding catchments are shown in Table 2.2 and Figure 2.3.

Apart from land use data obtained from the LDD, 1 x 1 km soil data was also downloaded from <http://soilgrids1km.isric.org/>. The analysis of soilgrids data is provided in Chapter 4.

Table 2.1 Description of major soil great groups found in the upper Ping and its surrounding catchments

Soil great group	Description	Catchment											
		Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
		Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
5	Formed from residuum and colluvium from basalt, andesite and occasionally rhyolite. Moderately deep soils found on gently undulating to rolling terrains where the slope is between 3-16%.	591	2.32	112	1.23	7	0.04	624	8.59	105	0.97	415	1.73
7	Formed from colluvial and residual materials of basic to intermediate igneous rocks having very fine texture. Strongly weathered, very deep soils found on undulating to hilly terrains	166	0.65	272	2.99	68	0.36	139	1.92	146	1.36	2566	10.67

Soil great group	Description	Catchment											
		Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
		Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
	with the slopes between 3-35%.												
15	Formed from alluvial deposits (mainly from granite) over residuum of granitic rocks on the coalescing fans or fans. Very deep soils found on gently undulating to rolling terrains where the slope is between 2-16%	28	0.11	135	1.49	0	0.00	99	1.36	112	1.04	1460	6.07
29	Formed from alluvium on the terrace, channel sediment or erosion of various soil types having	844	3.32	86	0.95	972	5.13	894	12.29	635	5.89	557	2.32

Soil great group	Description	Catchment											
		Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
		Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
	very fine texture. Very deep soils found on undulating to gently rolling terrains where the slope is between 2-8%.												
33	Formed from residuum and local colluvium from micaceous gneiss and mica schist. Moderately deep, gravelly to stony soils found on hills and footslopes where the slope is between 6-35%.	16	0.06	455	5.00	4	0.02	41	0.58	177	1.65	1905	7.92
35	Formed from alluvium on the terrace. Moderately deep soils found on	346	1.36	657	7.22	51	0.27	97	1.35	177	1.65	158	0.66

Soil great group	Description	Catchment											
		Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
		Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
	undulating to gently rolling terrains where the slope is between 2-8%.												
46	Formed from transported material over marly beds. Shallow and calcareous soils found on gently undulating to undulating terrains where the slope is between 2-12%.	151	0.60	723	7.95	81	0.43	97	1.35	125	1.16	154	0.64
47	Formed from residuum and colluvium from andesite and equivalent igneous rocks and occur on (dissected) erosion surface	64	0.25	182	2.01	2	0.01	6	0.08	1304	12.09	2097	8.72

Soil great group	Description	Catchment											
		Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
		Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
	and footslope. Gravelly and moderately deep soils found on undulating to hilly terrains where the slope is between 3 -20%.												
48	Formed from recent alluvium and occur on the alluvial fan mostly from andesite and basalt. Very deep, slightly acid to mildly alkaline soils found on level to nearly level where the slope is not greater than 2%.	2496	9.82	943	10.37	638	3.37	105	1.45	1872	17.35	1515	6.30

Soil great group	Description	Catchment											
		Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
		Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
62	Mountainous soil where the slope is greater than 35%.	17555	69.05	2930	32.19	16304	86.04	4431	60.91	4621	42.82	9131	37.97
Other	-	3168	12.46	2606	28.60	823	4.33	742	10.12	1519	14.02	4088	17.00

Table 2.2 Description of land use in the upper Ping and its surrounding catchments

Land use type	Catchment											
	Upper Ping		Lower Ping		Salawin		Kok		Wang		Yom	
	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
Agriculture including all crops and pastoral agriculture	4391	17.27	3384	37.19	2357	12.44	3440	47.28	2101	19.47	9453	39.31
Forest i.e. dense deciduous/evergreen forest, disturbed deciduous/evergreen forest, and dense forest plantation	20001	78.67	5086	55.88	16396	86.52	3413	46.91	7859	72.81	13623	56.65
Mixed land use i.e. laterite pit, mine, landfill, garbage dump, beach, scrub, marsh and swamp	208	0.82	140	1.54	50	0.26	80	1.10	506	4.69	360	1.50
Urban including villages, recreation areas and highways	651	2.56	232	2.55	97	0.51	294	4.04	264	2.45	514	2.14
Open water i.e. river, lake, reservoir and canal	173	0.68	258	2.84	50	0.27	48	0.66	63	0.58	97	0.40

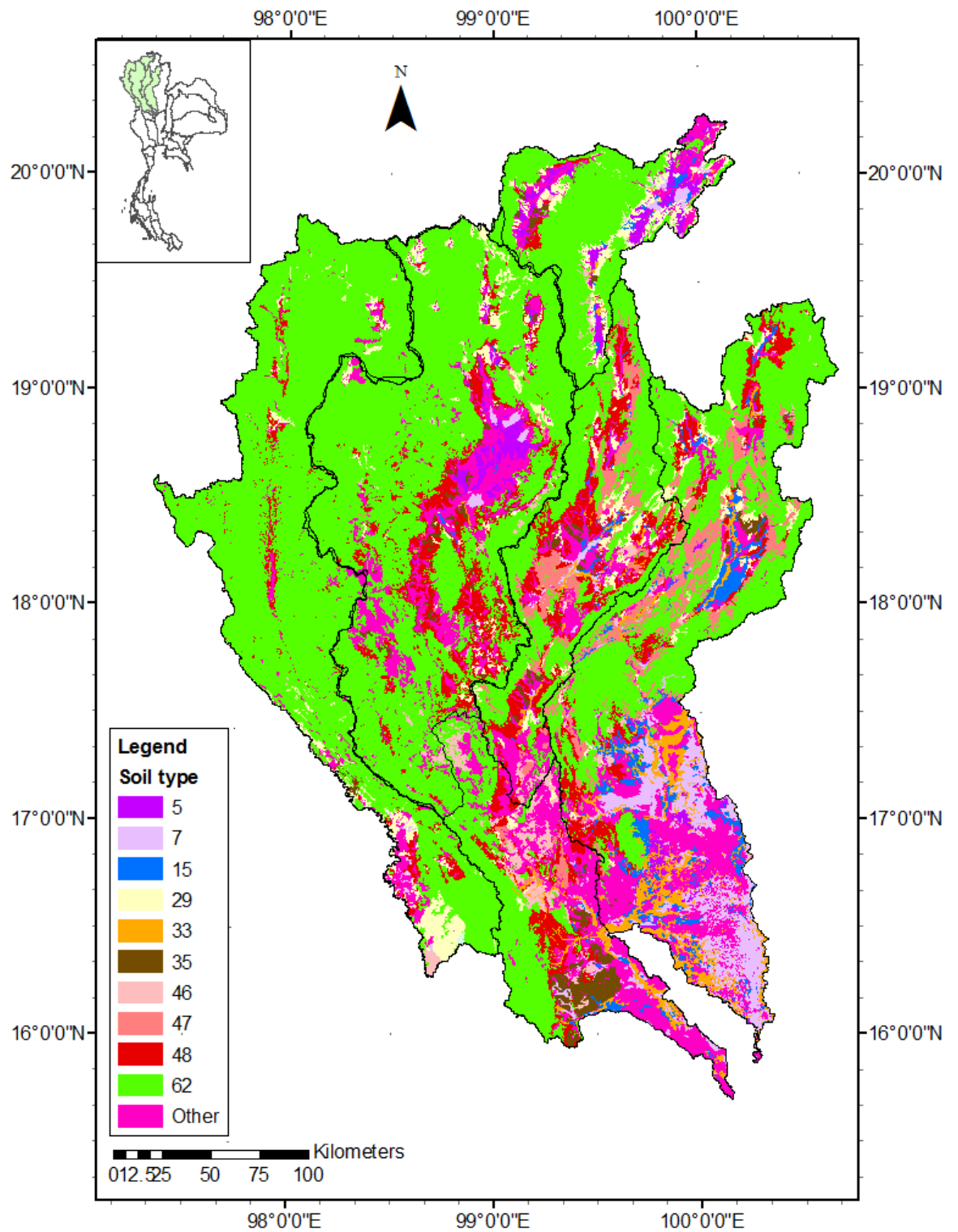


Figure 2.2 Soil types distribution of the upper Ping and its surrounding catchments.

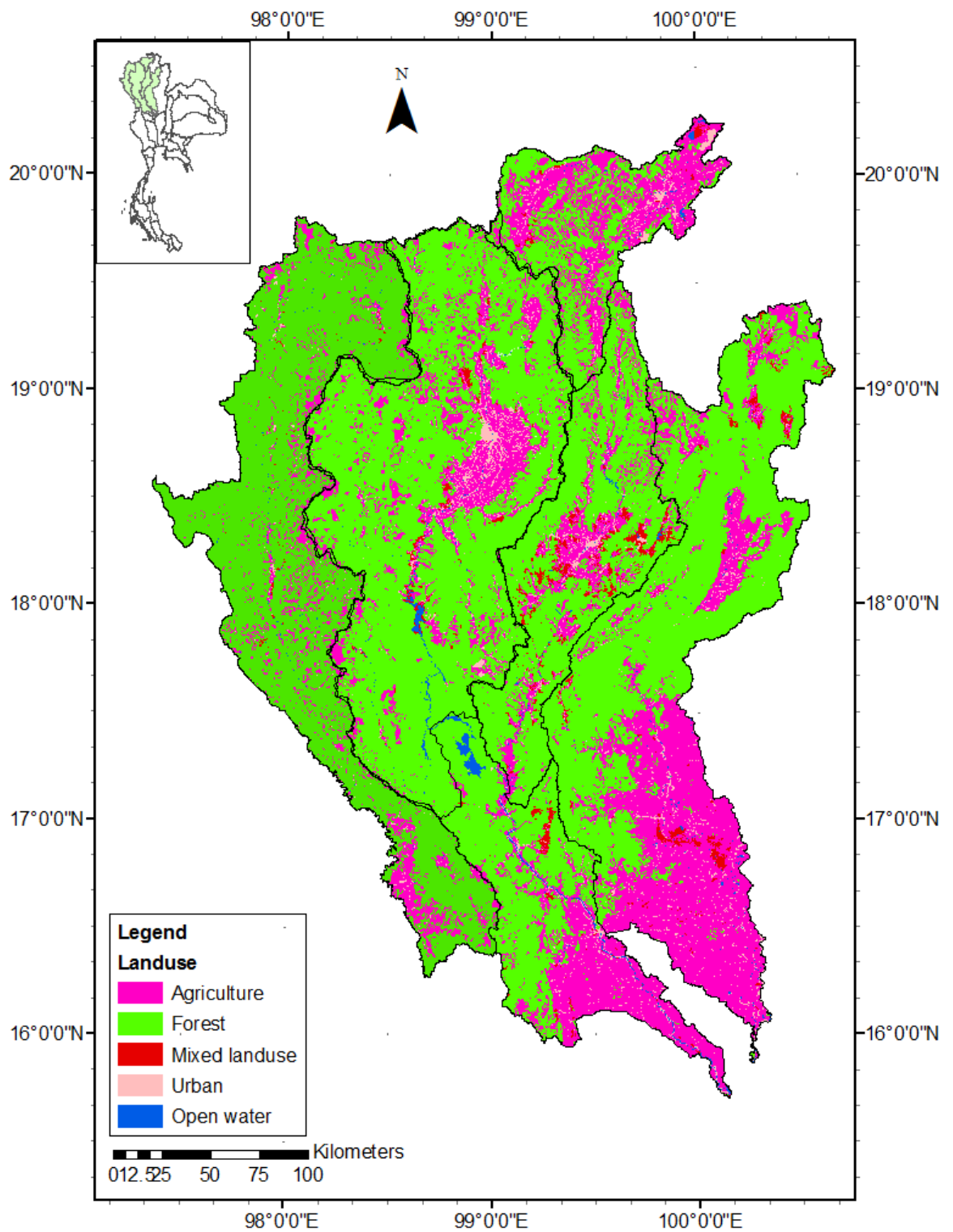


Figure 2.3 Land use distribution of the upper Ping and its surrounding catchments.

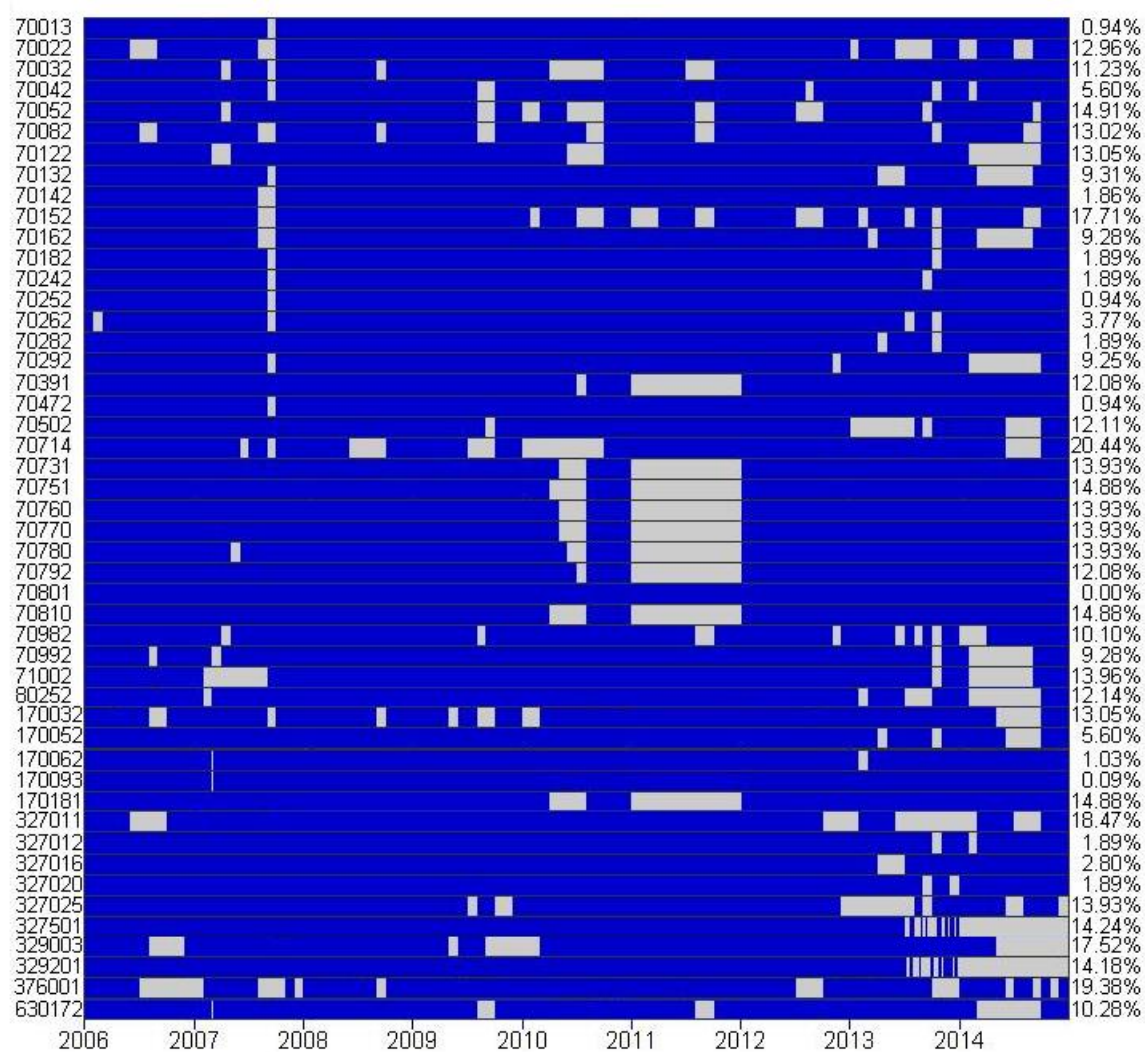
2.2. Hydrological gauges and data availability

Rainfall and temperature data used in this study were obtained from three sources: the Thai Meteorological Department (TMD), the Royal Irrigation Department (RID) and the Department of Water Resources (DWR). Flow data were provided by the RID and the DWR.

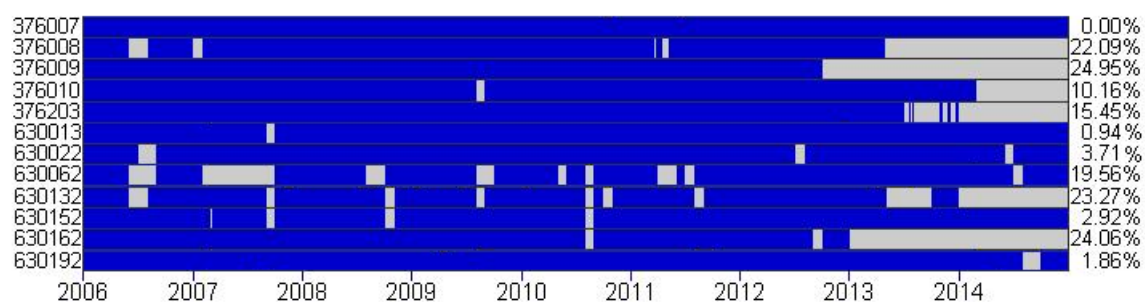
2.2.1 Rain gauges data availability

This study uses daily data from 48 rain gauges in the upper Ping catchment. Apart from 48 rain gauges located within the upper Ping catchment, rain gauges located in adjacent catchments were also analysed as they could probably contribute to the improvement of the regression model used for flow predictions in the upper Ping catchment.

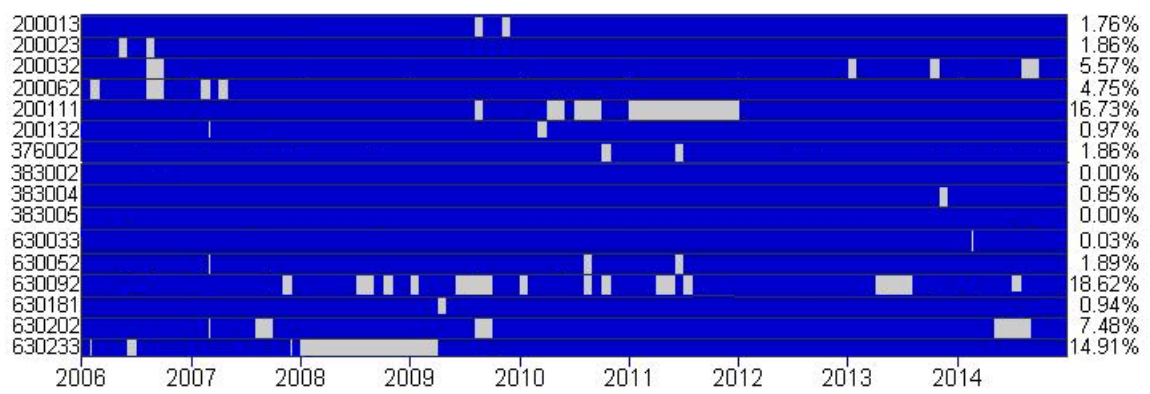
Figure 2.4 shows availability of rainfall data in the upper Ping and its surrounding catchments. Additional to the local rain gauges data, TRMM rainfall estimates were also downloaded from <http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=TRMM>. The analysis of satellite rainfall estimate is shown in Chapter 3.



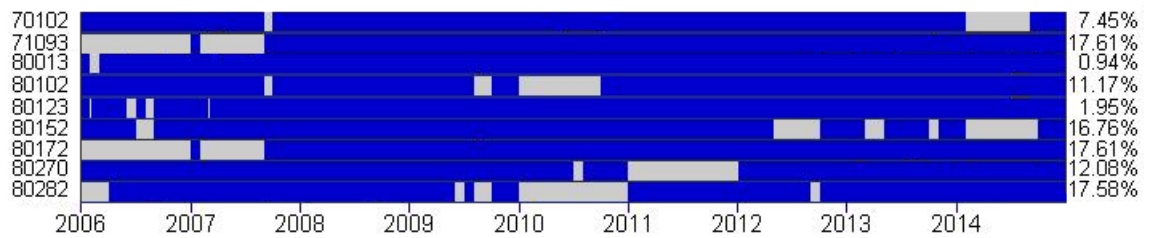
(a) Upper Ping catchment



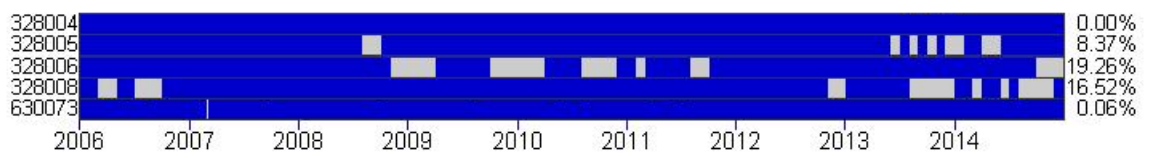
(b) Lower Ping catchment



(c) Salawin catchment



(d) Kok catchment



(e) Wang catchment

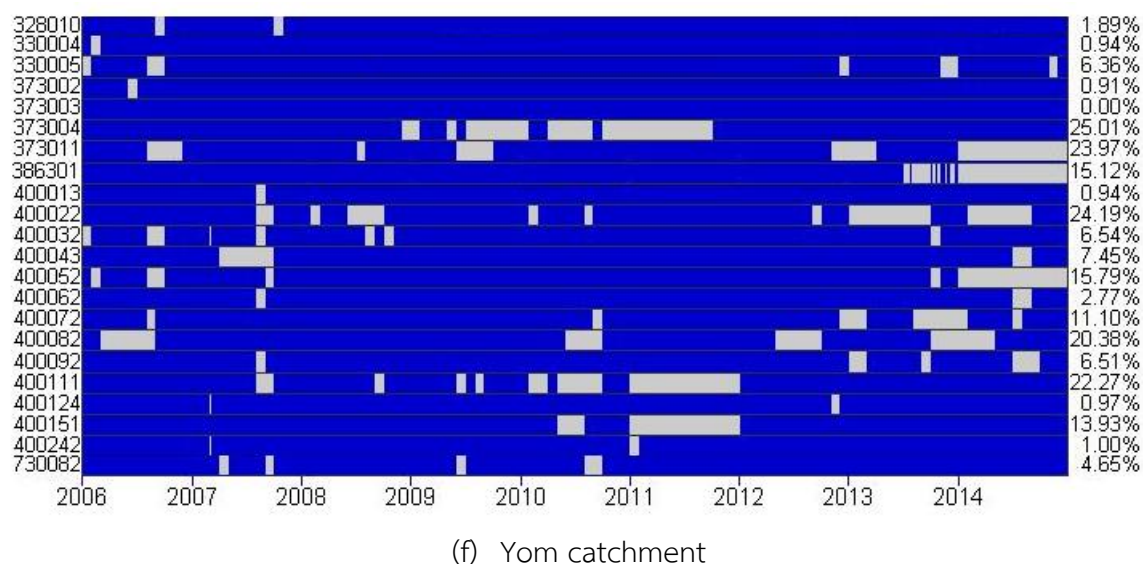
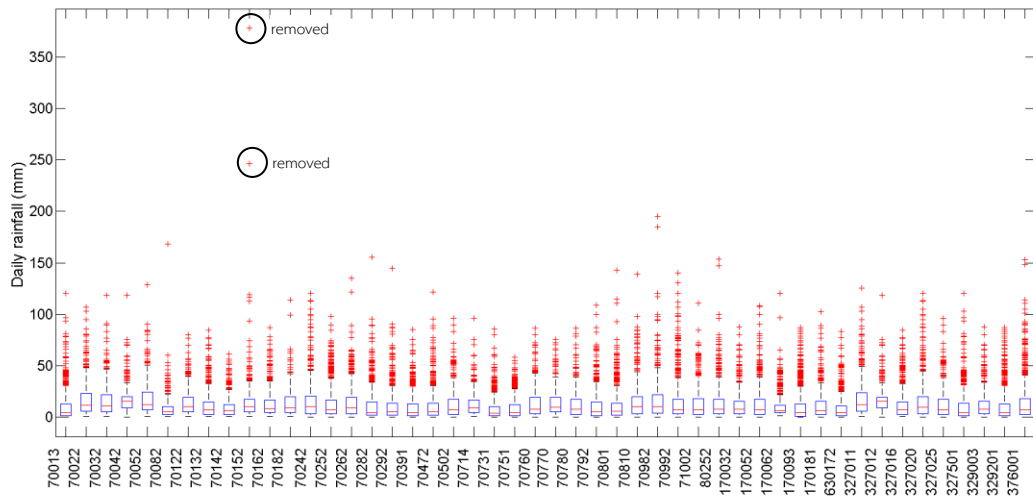


Figure 2.4 Length and missing data of the rainfall time-series plotted on daily time scale. Gauge codes and percentage of missing data are shown on the left and right hand side accordingly. Days with missing data are indicated by gray and days with complete data are indicated by blue. Availability of rainfall data for the upper Ping, lower Ping, Salawin, Kok, Wang, and Yom catchments is presented in panel (a), (b), (c), (d), (e), and (f) accordingly.

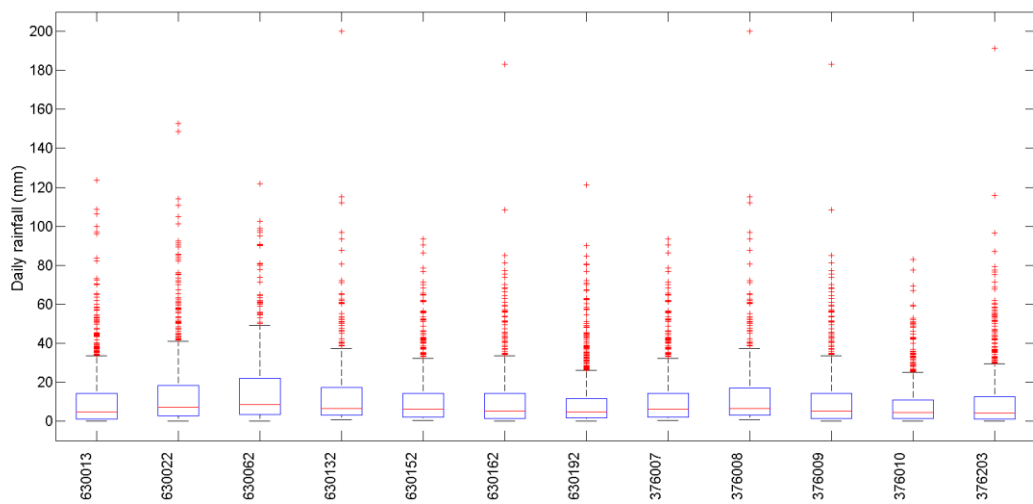
2.2.2 Daily rainfall

Box plot was used to assess daily rainfall data as it could indicate the distribution of the data and key statistics such as mean and standard deviation. It is also useful for identifying suspicious values. Only were daily rainfall values above zero used to develop box plot otherwise all quartiles could be close to zero and the analysis of box plot could be difficult. Any gauges with extreme values, having more than 50 mm higher than the next highest value at that gauge, were identified to as potentially suspicious. To decide if these potentially suspicious values should be removed from the record, they were compared with rainfall values from nearby rain gauges and with flow values at a corresponding flow gauge. The historical record of floods and droughts were used as supplementary information to support the decision on removal of suspicious values. From the initial box plot together

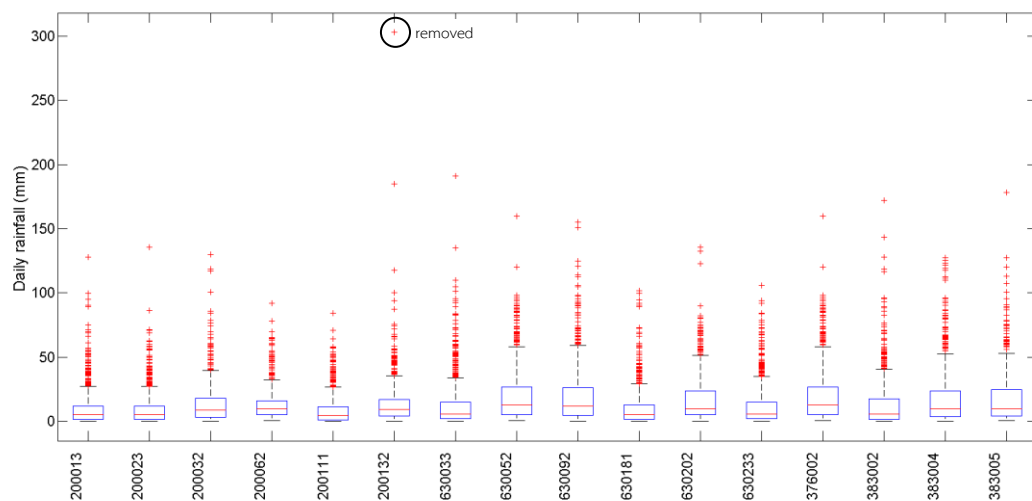
with historical comparison, five suspicious daily rainfall values shown in Figure 2.5, were removed.



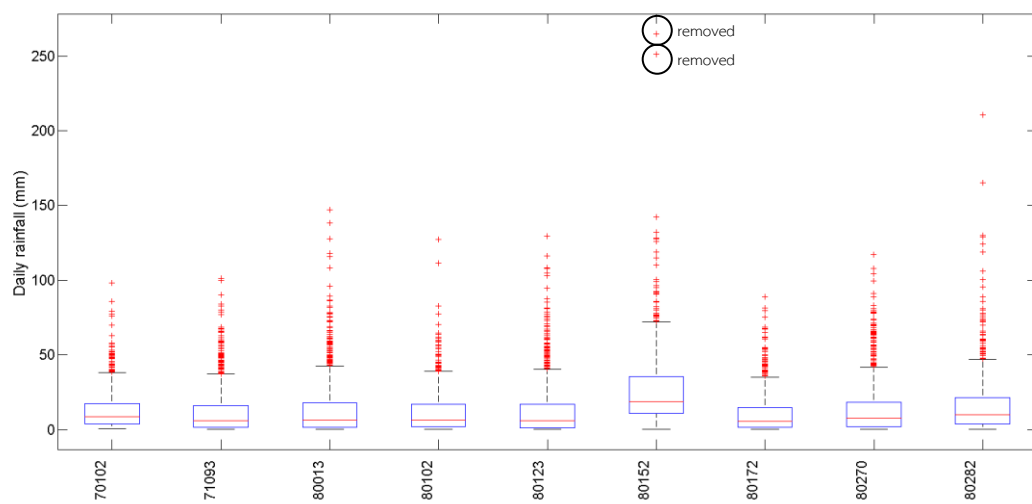
(a) Upper Ping catchment



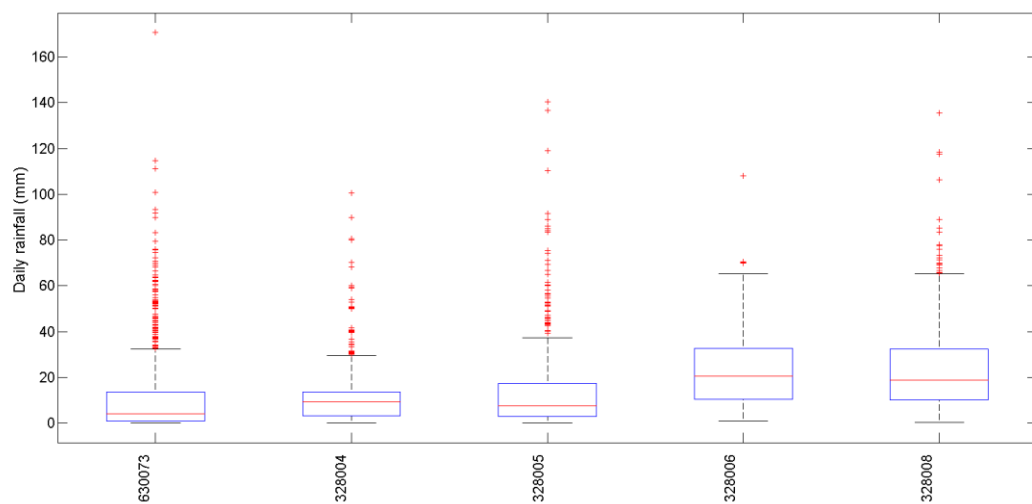
(b) Lower Ping catchment



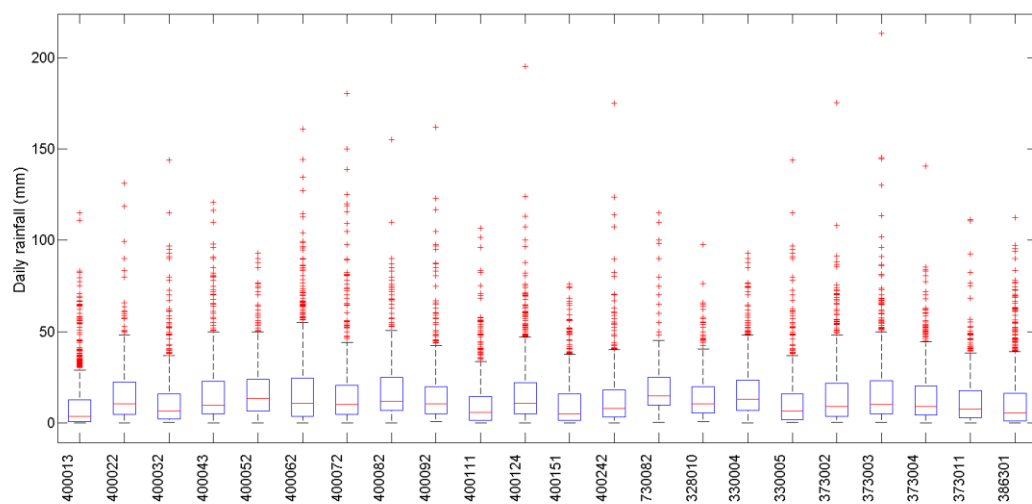
(c) Salawin catchment



(d) Kok catchment



(e) Wang catchment



(f) Yom catchment

Figure 2.5 Box plot for daily rainfall for the (a) upper Ping, (b) lower Ping, (c) Salawin, (d) Kok, (e) Wang, and (f) Yom catchments.

2.2.3 Monthly rainfall

To observe the seasonality of rainfall in the catchments, the amount of average rainfall in each month is plotted as shown in Figure 2.6. The figure shows the consistency in rainfall pattern for all gauges and also indicates similar seasonality. There are three seasons, commonly called the rainy, winter and summer seasons. The rainy season is between mid-May and mid-October (the Southwest monsoon) while winter is between mid-October and mid-February (the Northeast monsoon). Summer, from mid-February to mid-May, is usually dry and hot.

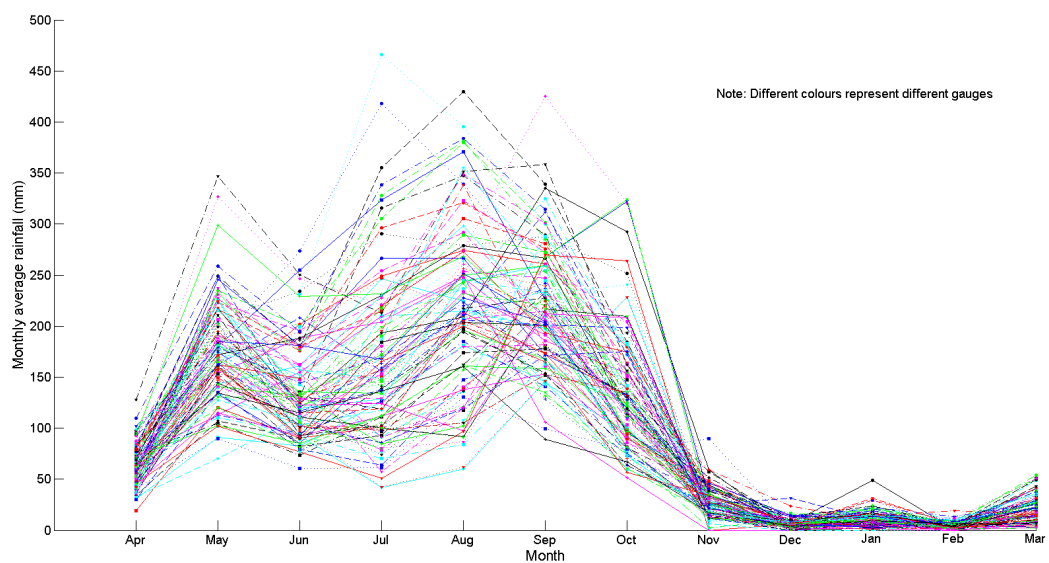


Figure 2.6 Monthly average rainfall for the upper Ping and its surrounding catchments

2.2.4 Annual rainfall

To observe the inter-annual variability of rainfall in the catchments, the amount of average rainfall in each year is plotted as shown in Figure 2.7. Strong inter-annual variability can be seen. Considering the amount of annual rainfall, the years 2010 and 2011 were wet years. While the years 2007 and 2008 were wet years for the majority of gauges, these years were dry years for some gauges.

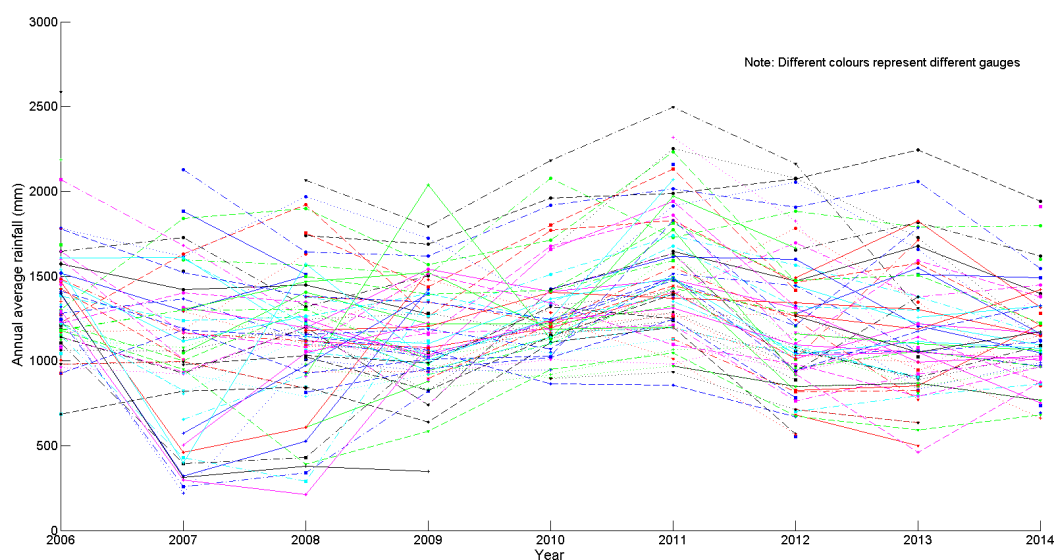
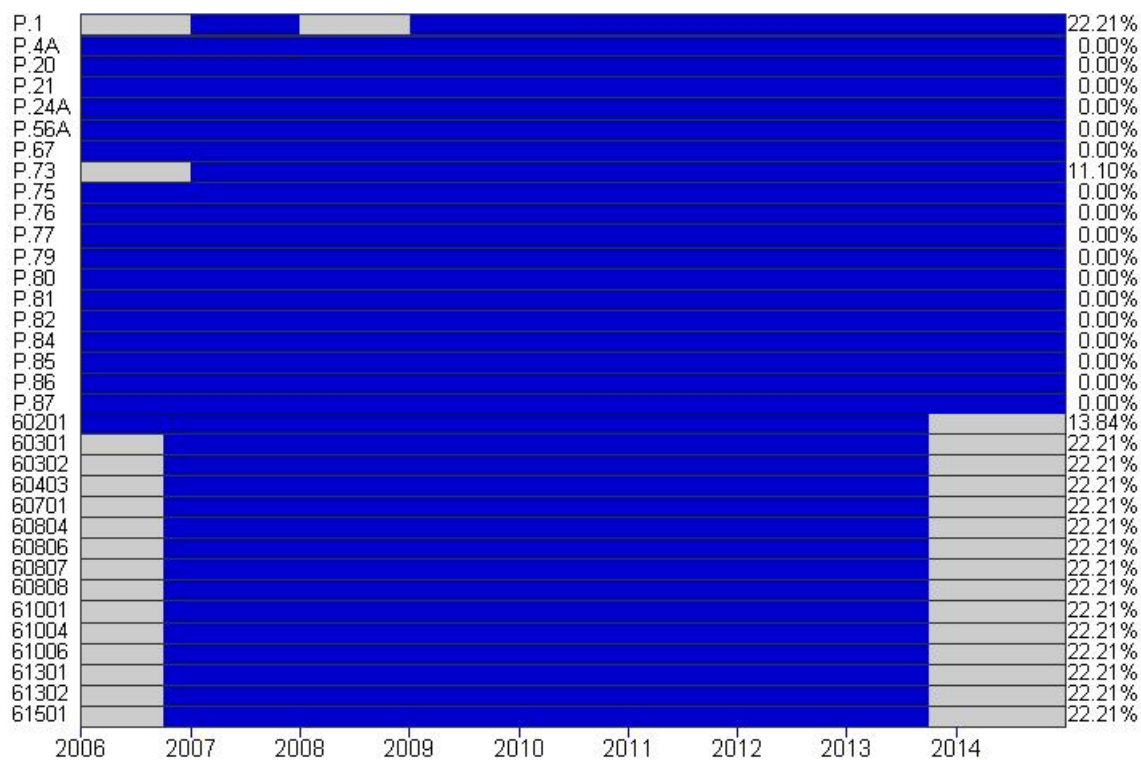


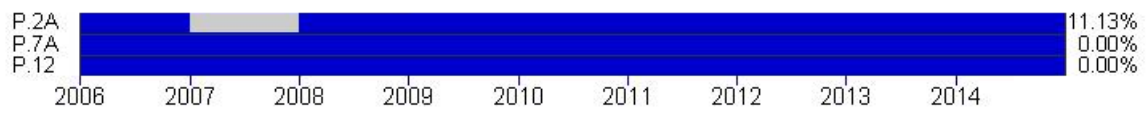
Figure 2.7 Annual average rainfall for the upper Ping and its surrounding catchments

2.2.5 Flow gauges data availability

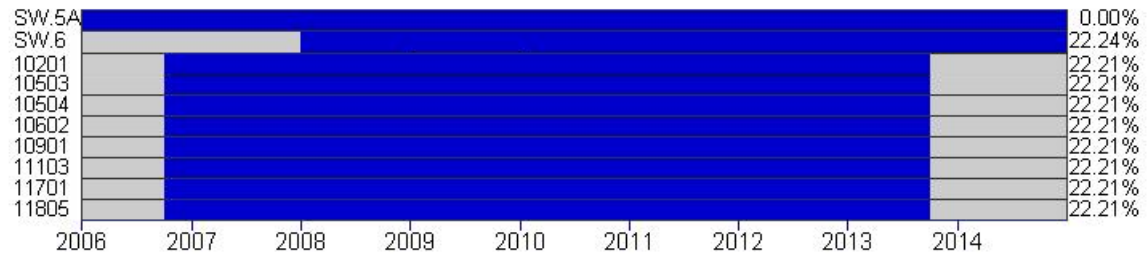
This study uses daily data from 34 flow gauges in the upper Ping catchment. 50 flow gauges in adjacent catchments are also analysed. Figure 2.8 shows availability of flow data in the upper Ping and its surrounding catchments.



(a) Upper Ping catchment



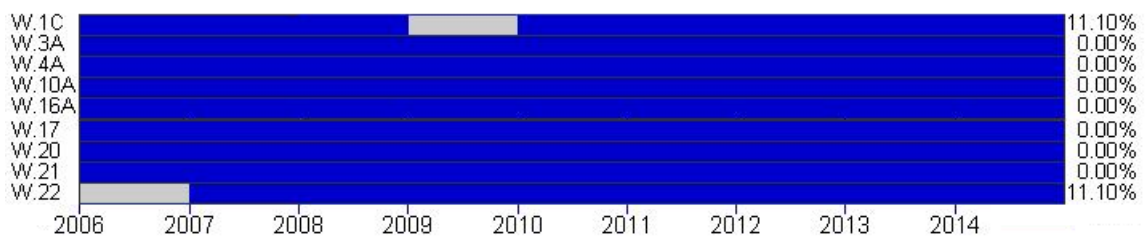
(b) Lower Ping catchment



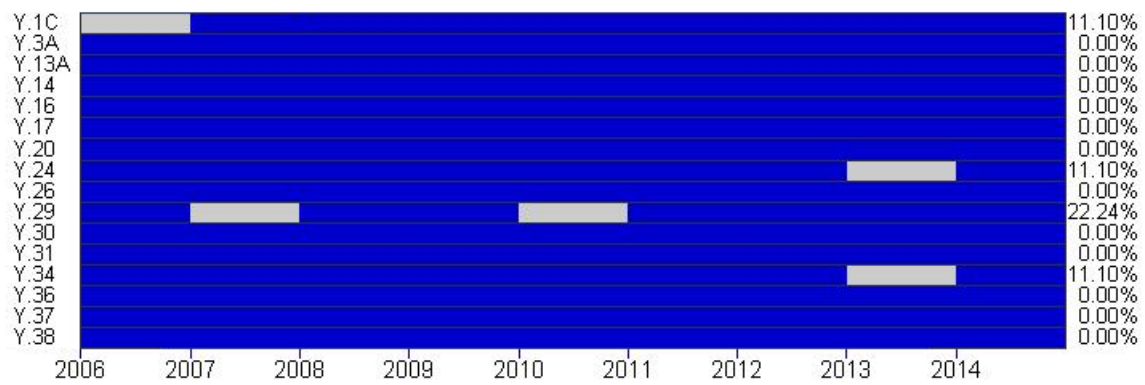
(c) Salawin catchment



(d) Kok catchment



(e) Wang catchment



(f) Yom catchment

Figure 2.8 Length and missing data of the flow time-series plotted on daily time scale. Gauge codes and percentage of missing data are shown on the left and right hand side accordingly. Days with missing data are indicated by gray and days with complete data are indicated by blue. Availability of flow data for the upper Ping, lower Ping, Salawin, Kok, Wang, and Yom catchments is presented in panel (a), (b), (c), (d), (e), and (f) accordingly.

2.2.6 Daily flow

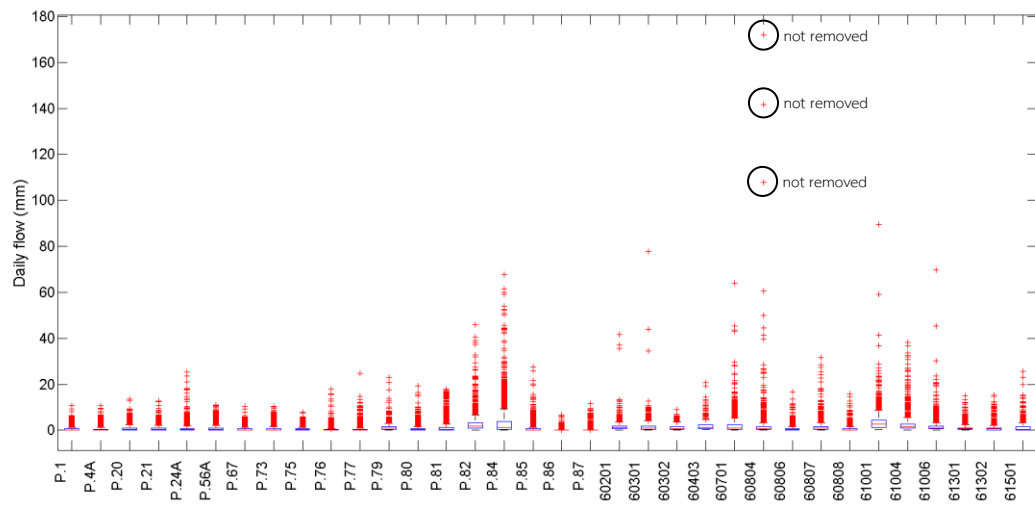
All the flow values excluding zero were used to develop a box plot as shown in Yom catchment

(a)

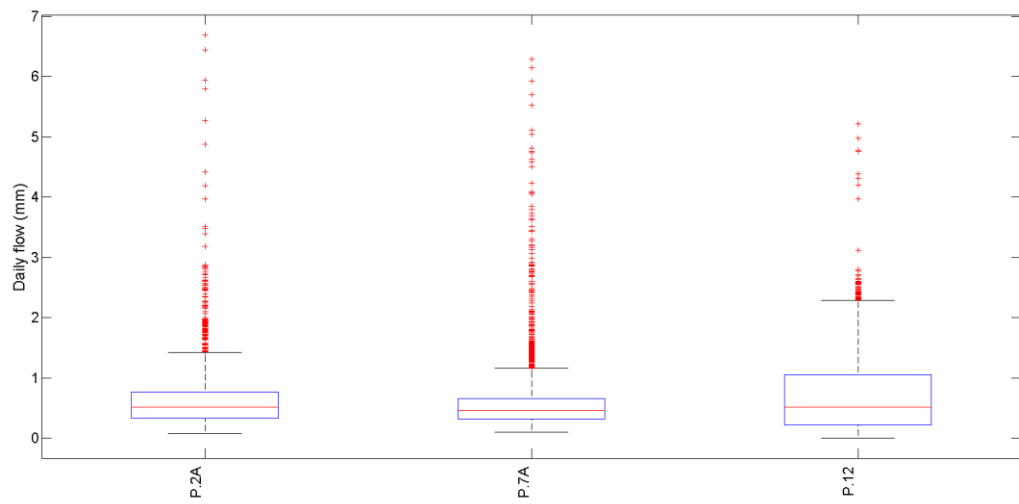
Figure 2.9. A similar procedure used for rainfall as described in Section 2.2.2 was also used for identifying suspicious daily flow values (more than 30 mm higher than the next highest value at the same gauge). After the analysis, no suspicious daily flow values shown in Yom catchment

(b)

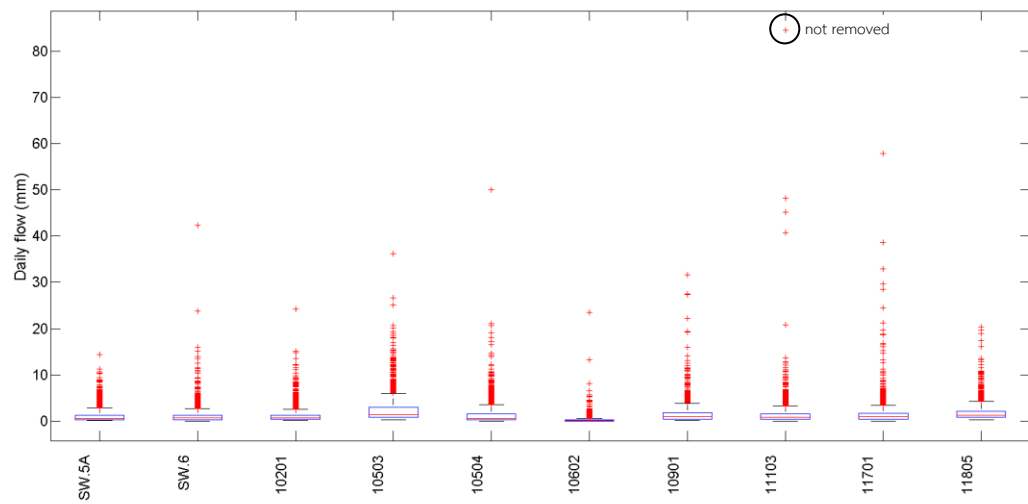
Figure 2.9 were removed. The suspicious flow values were likely to be caused by flash flood during rainy season.



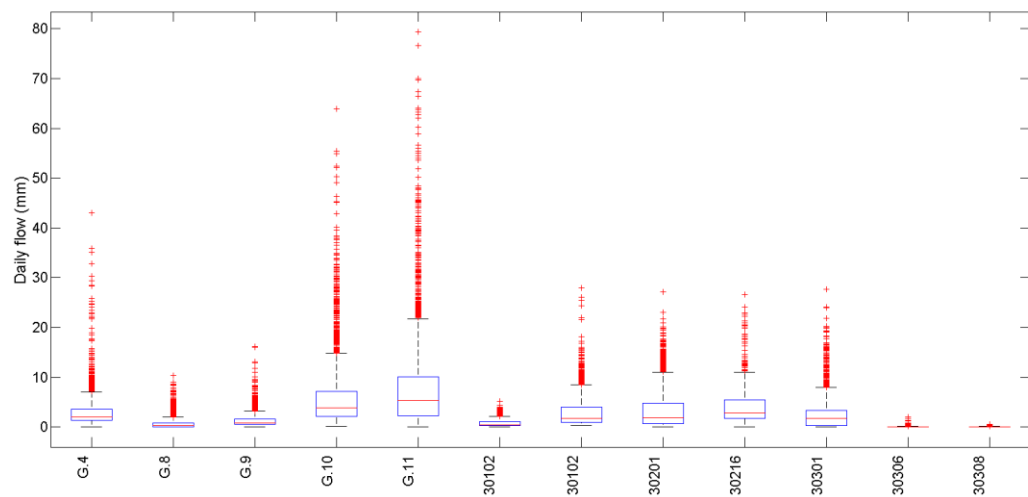
(c) Upper Ping catchment



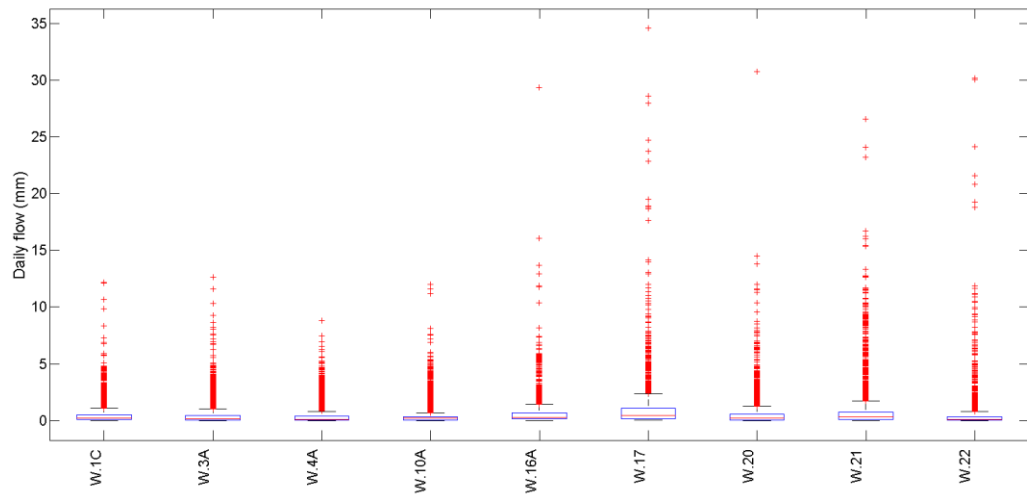
(d) Lower Ping catchment



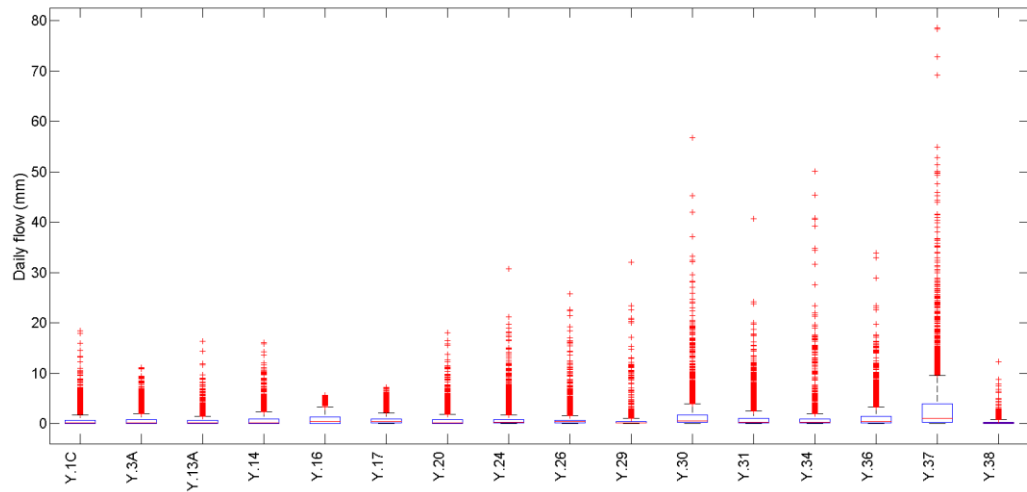
(e) Salawin catchment



(f) Kok catchment



(g) Wang catchment



(h) Yom catchment

(i)

Figure 2.9 Box plot for daily flow for the (a) upper Ping, (b) lower Ping, (c) Salawin, (d) Kok, (e) Wang, and (f) Yom catchments.

2.2.7 Monthly flow

Figure 2.10 presents similar patterns of flow seasonality over 84 flow gauges. From the start of the water year in April, flow is increasing and reaching the first peak in May. It is decreasing between June and July due to less rainfall but it is increasing again between August and September when the ITCZ produces more rainfall. Rainfall is clearly the most influential factor causing temporal differences in flow.

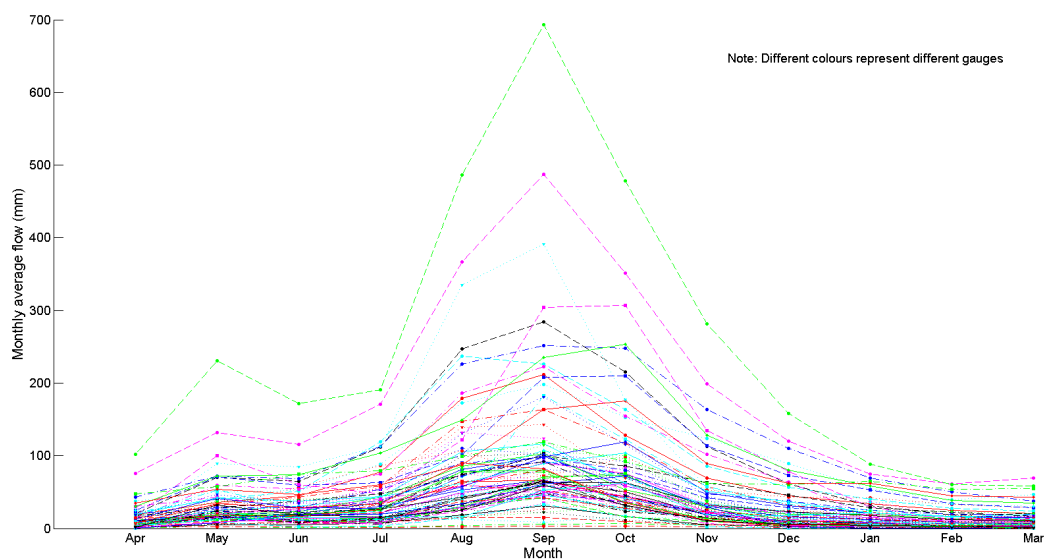


Figure 2.10 Monthly average flow for the upper Ping and it surrounding catchments.

2.2.8 Annual flow

Figure 2.11 shows inter-annual variability for the flow data. High flow occurred in 2010. In 2007 and 2008, strong spatial variability of flow was found. Some flow gauges show high flows while the others show low flow.

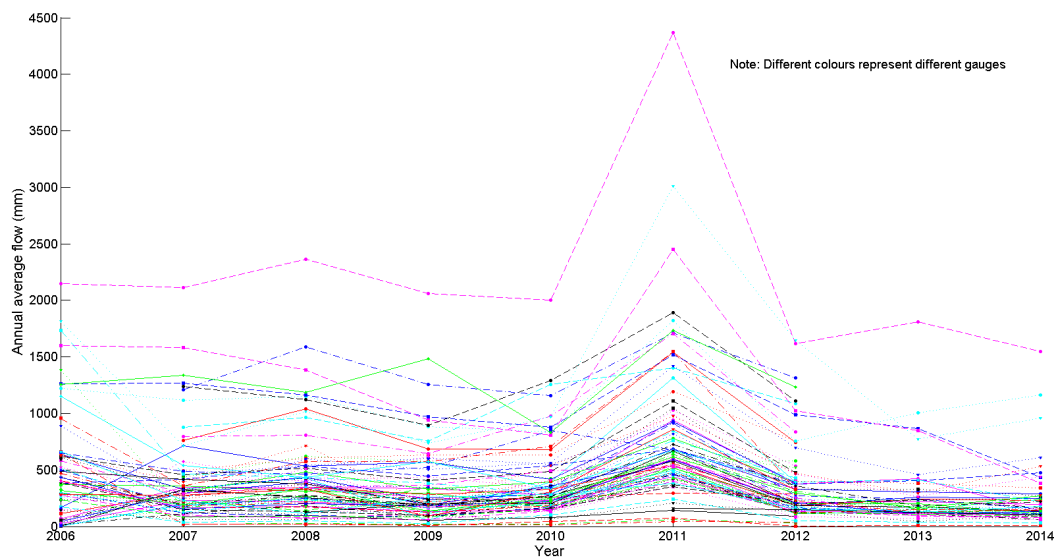


Figure 2.11 Annual average flow for the upper Ping and it surrounding catchments.

2.2.9 Temperature gauges data availability

All the 10 temperature gauges used in this study were considered to have good data quality with a small percentage of missing data as shown in Figure 2.12. Only temperature gauges located in the Ping catchment were considered here as temperature data does not vary much over northern Thailand.

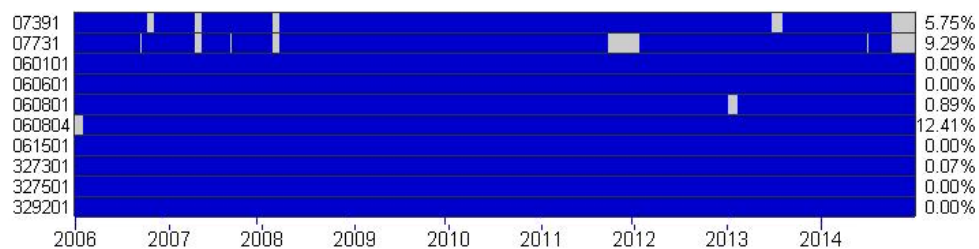


Figure 2.12 Length and missing data of the temperature time-series plotted on daily time scale. Gauge codes and percentage of missing data are shown on the left and right hand side accordingly. Days with missing data are indicated by gray and days with complete data are indicated by blue.

2.2.10 Daily temperature

According to the box plot shown in Figure 2.13, no suspicious values were found for temperature data.

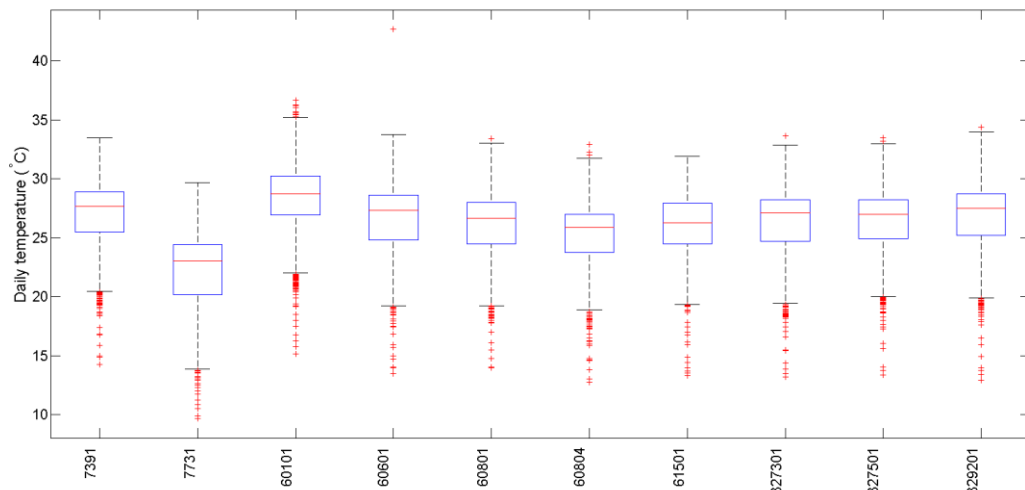


Figure 2.13 Box plot for daily temperature.

2.2.11 Monthly temperature

Similar patterns of monthly average temperature were found across the ten temperature gauges as shown in Figure 2.14. Highest temperature happens between March and April. After April, the temperature is decreasing as it is the start of the rainy season caused by the Southwest monsoon. The lowest temperature is in December or January when the catchment is governed by the cold air brought to land by the Northwest monsoon.

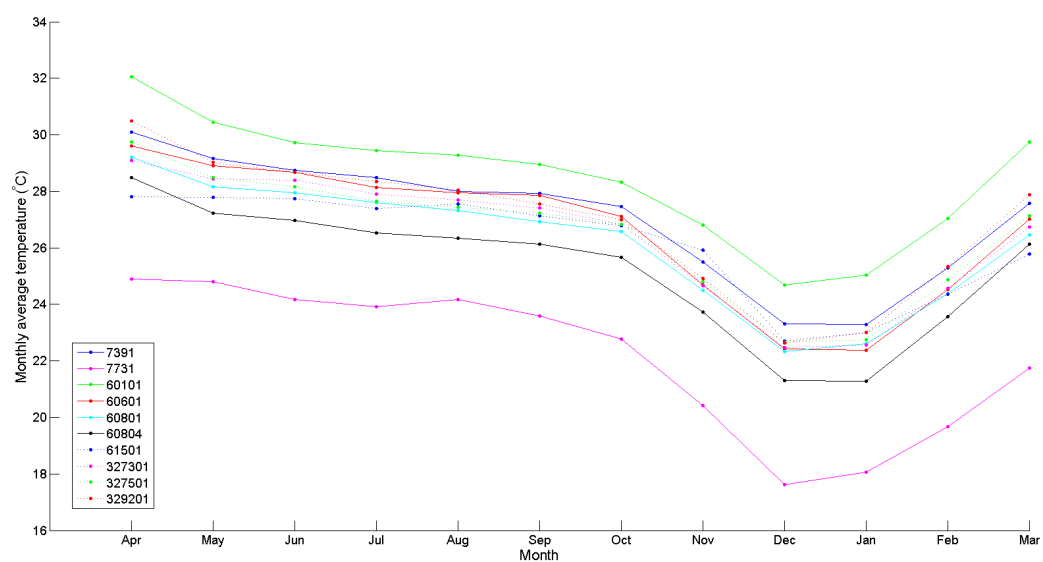


Figure 2.14 Monthly average temperature.

2.2.12 Annual temperature

Figure 2.15 shows annual average temperature for each ten gauges, most of which vary between 1-2 °C except for 061501.

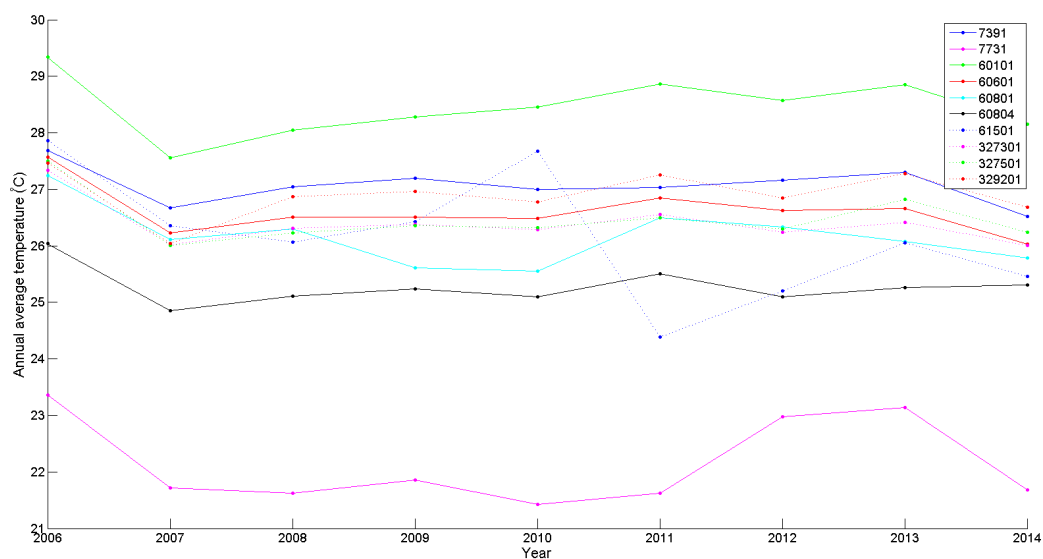


Figure 2.15 Annual average temperature.

2.3. Catchment properties and flow indices

14 sub-catchment properties used for this study were: 1) sub-catchment area (A), 2) mean elevation of the sub-catchment (Ele), 3) mean slope of the sub-catchment (Slp), 4) main channel length (ChL), 5) drainage density (DD), 6) % mountainous soil (%MS), 7) % agriculture (%Agr), 8) % forest (%For), 9) % mixed land use (%Mix) (i.e. mine, landfill, garbage dump, marsh and swamp), 10) % urban (%Urb), 11) % open water (%Wat) (river, natural water resource, farm pond, canal and reservoir), 12) mean annual rainfall (MAR) (referring to the areal rainfall estimated by the rainfall gradient and inverse distance weighting method), 13) mean wet month rainfall (MWR) (similar to the estimation of mean annual rainfall but using the monthly averaged between May and October) and 14) mean dry month rainfall (MDR) (similar to the estimation of mean annual rainfall but using the monthly averaged between January-April and November-December). Based on hydrological data obtained in section 2.1 and 2.2, catchment properties and flow indices can be estimated and summarised in Table 2.3.

Table 2.3 Catchment properties and flow indices

No.	Code	Catchment properties and flow indices																
		A	Ele	Slp	ChL	DD	%MS	%Agr	%For	%Mix	%Urb	%Wat	MAR	MWR	MDR	RC	BFI	EL
Upper Ping catchment																		
1	P.1	6350.00	779.07	28.59	2787.77	1.49	75.18	17.83	78.50	0.25	3.11	0.30	2761.92	1592.37	1169.55	0.27	0.24	0.27
2	P.4A	1930.00	1010.55	34.35	703.81	1.60	89.85	17.21	81.38	0.04	1.21	0.10	3202.46	2671.17	531.29	0.16	0.14	0.17
3	P.20	1345.00	784.28	31.75	536.99	1.07	77.29	13.65	85.67	0.00	0.67	0.00	3081.89	2456.80	625.10	0.36	0.33	0.36
4	P.21	452.00	722.94	22.62	278.02	1.61	79.56	11.12	86.73	0.00	2.15	0.00	1425.61	1133.84	291.77	0.19	0.28	0.31
5	P.24	616.00	952.43	26.57	355.96	1.55	82.09	13.16	83.76	2.25	0.81	0.02	1909.26	1506.95	402.31	0.15	0.70	0.82
6	P.56A	546.00	713.97	25.61	145.47	1.61	71.89	29.40	66.70	0.30	3.41	0.19	1799.53	1491.05	308.48	0.16	0.15	0.16
7	P.67	5323.00	810.87	30.46	2137.53	1.48	78.67	16.92	80.89	0.27	1.61	0.29	2306.69	1290.34	1016.35	0.54	0.49	0.54
8	P.73	14814.00	689.39	23.57	5994.39	1.56	63.94	21.22	71.67	2.05	4.65	0.40	2025.32	775.33	1249.99	0.14	0.79	0.87
9	P.75	3080.00	719.95	29.10	1263.82	1.39	74.38	15.83	81.79	0.00	1.56	0.41	3501.89	2448.57	1053.32	0.89	0.80	0.88
10	P.76	2030.00	1033.53	33.46	717.23	1.47	91.82	11.26	87.79	0.11	0.76	0.05	2828.88	2410.78	418.10	0.63	0.56	0.77
11	P.77	550.00	628.62	24.08	130.99	1.99	71.72	13.22	82.91	1.77	2.04	0.07	1207.21	1032.52	174.69	0.16	0.16	0.18
12	P.79	136.00	973.75	38.90	42.36	1.56	99.06	0.00	99.38	0.00	0.62	0.00	635.40	440.28	195.12	0.64	0.38	0.41
13	P.80	222.20	1029.85	32.48	156.16	1.75	93.48	6.13	93.10	0.00	0.77	0.00	634.08	469.03	165.05	0.39	0.75	0.82
14	P.81	787.00	952.43	26.57	355.96	1.55	82.09	13.16	83.76	2.25	0.81	0.02	3673.79	3019.39	654.40	0.12	0.51	0.63
15	P.82	203.00	1029.85	32.48	99.26	1.53	93.48	6.13	93.10	0.00	0.77	0.00	2431.02	1670.94	760.08	0.43	0.39	0.43
16	P.84	113.00	1193.76	33.98	42.36	1.34	94.88	16.03	83.51	0.00	0.46	0.00	1602.95	1236.88	366.07	0.77	0.64	0.68
17	P.85	1280.00	753.61	25.31	409.32	1.43	75.79	14.99	79.99	1.27	3.54	0.21	2915.14	2529.94	385.20	0.68	0.61	0.83
18	P.86	708.30	952.43	26.57	382.64	1.64	82.09	13.16	83.76	2.25	0.81	0.02	755.62	506.61	249.01	0.12	0.66	0.73
19	P.87	1078.00	817.83	27.04	409.32	1.49	87.64	8.75	88.32	0.49	2.42	0.01	970.76	926.31	44.45	0.53	0.47	0.54
20	60201	47.40	1012.81	33.82	39.10	1.51	94.21	5.15	92.18	0.00	2.67	0.00	312.32	206.41	105.91	0.31	0.28	0.30
21	60301	80.70	830.88	34.56	43.44	1.61	97.42	10.28	89.40	0.00	0.33	0.00	513.89	356.91	156.98	0.60	0.54	0.59
22	60302	43.90	920.33	34.00	12.11	1.99	98.01	12.63	83.54	3.83	0.00	0.00	213.86	145.69	68.17	0.11	0.10	0.11

No.	Code	Catchment properties and flow indices																
		A	Ele	Slp	ChL	DD	%MS	%Agr	%For	%Mix	%Urb	%Wat	MAR	MWR	MDR	RC	BFI	EL
23	60403	19.50	1221.78	37.40	25.72	1.29	99.65	15.01	84.73	0.00	0.25	0.00	195.15	117.94	77.21	0.85	0.77	0.84
24	60701	53.10	1102.03	41.04	27.63	1.96	100.00	0.00	98.18	0.00	1.82	0.00	440.38	347.41	92.97	0.21	0.19	0.20
25	60804	34.60	1066.44	22.97	14.57	1.41	75.22	14.10	85.69	0.00	0.21	0.00	243.25	179.05	64.20	0.69	0.62	0.66
26	60806	548.00	976.61	27.29	131.75	1.59	96.14	3.93	94.87	0.00	1.20	0.00	1493.61	1205.62	287.99	0.16	0.42	0.44
27	60807	343.00	1085.95	26.07	156.16	1.57	87.89	12.26	86.82	0.00	0.92	0.00	2021.87	1450.33	571.54	0.26	0.14	0.15
28	60808	1170.00	817.83	27.04	409.32	1.50	87.64	8.75	88.32	0.49	2.42	0.01	2683.65	2177.02	506.63	0.51	0.46	0.51
29	61001	92.40	1528.97	28.73	81.85	1.55	85.86	24.13	75.10	0.00	0.77	0.00	1347.39	956.25	391.15	0.67	0.60	0.65
30	61004	25.50	1300.04	26.79	18.36	1.45	96.66	12.86	87.14	0.00	0.00	0.00	273.35	174.90	98.45	0.36	0.32	0.34
31	61006	39.50	1167.03	27.79	21.26	1.92	75.09	27.67	72.33	0.00	0.00	0.00	248.79	174.23	74.56	0.28	0.25	0.28
32	61301	86.50	1078.57	34.33	35.66	1.34	99.73	23.96	76.04	0.00	0.00	0.00	338.64	233.66	104.98	0.80	0.72	0.78
33	61302	1950.00	1056.51	32.57	730.65	1.54	93.80	5.30	94.19	0.19	0.31	0.01	4353.15	2995.20	1357.95	0.58	0.52	0.91
34	61501	1470.00	974.66	26.11	601.28	1.77	74.82	8.42	91.29	0.00	0.28	0.01	3436.57	2767.14	669.42	0.12	0.21	0.23
Lower Ping catchment																		
35	P.2A	38862.00	559.83	26.33	44.06	1.12	88.10	20.94	74.95	0.10	3.60	0.41	338.64	233.66	104.98	0.52	0.47	0.52
36	P.7A	42700.00	689.39	23.57	102.77	1.13	63.94	21.22	71.67	2.05	4.65	0.40	2709.45	1998.67	710.78	0.94	0.84	0.94
37	P.12	26396.00	689.39	23.57	21.91	1.12	63.94	21.22	71.67	2.05	4.65	0.40	3436.57	2767.14	669.42	0.31	0.28	0.31
Salawin catchment																		
38	Sw.5A	4466.00	464.46	21.41	3.66	1.12	78.67	8.18	90.95	0.11	0.63	0.14	1415.59	591.38	824.22	0.17	0.15	0.17
39	Sw.6	1038.00	797.63	31.51	6.77	1.11	87.64	15.09	83.13	0.91	0.75	0.13	824.74	591.38	233.36	0.47	0.22	0.35
40	10201	368.00	1034.57	30.65	18.01	1.12	87.89	8.04	91.89	0.00	0.06	0.01	360.77	270.68	90.09	0.75	0.67	0.78
41	10503	2274.00	485.09	34.09	5.33	1.12	91.82	11.80	87.36	0.03	0.72	0.10	1787.79	696.61	1091.18	0.64	0.58	0.64
42	10504	1368.00	946.66	29.01	68.27	1.16	77.29	7.37	91.66	0.27	0.59	0.12	983.62	696.61	287.00	0.43	0.17	0.44
43	10602	669.00	602.11	33.03	25.73	1.14	79.56	2.54	97.24	0.07	0.14	0.01	743.62	634.14	109.48	0.13	0.40	0.47
44	10901	442.00	929.07	34.61	15.46	1.12	79.56	23.41	76.12	0.07	0.32	0.09	525.24	400.19	125.06	0.16	0.14	0.18

No.	Code	Catchment properties and flow indices																
		A	Ele	Slp	ChL	DD	%MS	%Agr	%For	%Mix	%Urb	%Wat	MAR	MWR	MDR	RC	BFI	EL
45	11103	316.00	789.44	35.04	98.95	1.38	87.89	7.46	89.37	0.83	0.84	1.50	329.84	233.86	95.97	0.91	0.82	0.91
46	11701	1022.00	494.29	43.88	4.44	1.11	87.64	11.55	87.93	0.02	0.49	0.02	1099.37	820.98	278.39	0.47	0.09	0.11
47	11805	131.00	403.32	23.80	4.67	1.03	99.06	10.61	88.85	0.00	0.51	0.03	1023.71	681.07	342.64	0.65	0.55	0.64
Kok catchment																		
48	G.4	50.00	625.63	22.32	93.95	1.51	97.11	45.29	54.52	0.00	0.19	0.00	639.47	413.40	226.07	0.86	0.78	0.86
49	G.8	2934.00	729.92	23.50	1.70	1.12	93.80	42.83	46.56	0.16	9.45	1.00	638.67	281.63	357.04	0.32	0.29	0.32
50	G.9	366.00	828.93	25.82	3.25	1.08	87.89	55.92	43.63	0.00	0.45	0.00	400.11	281.63	118.48	0.46	0.42	0.46
51	G.10	439.20	1134.71	38.18	4.85	1.09	79.56	46.52	50.76	0.00	2.47	0.24	1447.04	844.95	602.09	0.83	0.75	0.83
52	G.11	189.00	1091.61	34.38	5.83	1.06	99.06	33.24	64.61	0.35	1.71	0.10	1172.82	844.95	327.87	0.17	0.15	0.21
53	030101	671.00	471.18	11.39	1.27	1.10	82.09	33.99	62.19	0.71	2.96	0.16	2693.19	1388.33	1304.86	0.70	0.63	0.70
54	030102	968.10	749.87	22.44	2.46	1.11	76.29	45.83	53.10	0.00	0.68	0.39	3210.43	1388.33	1822.09	0.43	0.39	0.43
55	030201	671.00	848.95	24.15	87.99	1.23	82.09	20.65	76.79	0.00	2.57	0.00	1792.33	1388.33	404.00	0.68	0.15	0.18
56	030216	79.00	694.52	31.36	49.27	1.53	94.34	13.61	86.36	0.00	0.03	0.00	265.97	179.11	86.86	0.63	0.56	0.63
57	030301	968.10	437.96	9.37	14.32	1.12	82.47	64.94	32.56	0.00	1.69	0.80	887.04	397.42	489.62	0.32	0.28	0.32
58	030306	1512.40	598.65	20.71	18.14	1.12	83.39	17.28	82.25	0.11	0.36	0.00	610.26	397.42	212.84	0.92	0.82	0.92
59	030308	1592.00	911.72	32.77	7.91	1.12	84.31	5.39	94.37	0.00	0.24	0.00	90.07	52.38	37.69	0.27	0.37	0.44
Wang catchment																		
60	W.1C	3478.00	597.19	22.45	7.29	1.12	86.23	55.08	23.57	12.50	0.00	8.85	2477.98	1637.69	840.30	0.67	0.60	0.67
61	W.3A	8985.00	636.68	36.23	100.29	1.13	81.41	16.11	68.16	4.21	0.79	10.73	3673.93	1998.67	1675.26	0.73	0.66	0.73
62	W.4A	10507.00	689.39	23.57	101.29	1.13	63.94	14.56	80.45	2.00	0.76	2.24	4157.66	2767.14	1390.51	0.81	0.73	0.81
63	W.10A	2798.00	607.51	28.79	26.86	1.13	92.81	12.72	82.95	1.71	1.44	1.19	3977.63	2776.28	1201.35	0.31	0.28	0.52
64	W.16A	1379.00	790.64	29.92	70.97	1.16	82.52	20.05	75.85	1.33	0.06	2.71	3438.74	2254.83	1183.91	0.15	0.13	0.15
65	W.17	619.00	718.67	23.79	19.27	1.13	81.45	15.61	82.94	1.15	0.05	0.25	2547.72	2026.78	520.94	0.15	0.13	0.16
66	W.20	1065.00	746.20	34.80	49.89	1.15	84.19	22.32	70.31	2.46	0.12	4.79	2420.87	2014.03	406.84	0.16	0.15	0.18

No.	Code	Catchment properties and flow indices																
		A	Ele	Slp	ChL	DD	%MS	%Agr	%For	%Mix	%Urb	%Wat	MAR	MWR	MDR	RC	BFI	EL
67	W.21	1659.90	885.39	28.04	37.29	1.14	84.08	24.15	66.48	3.62	0.13	5.62	3219.42	2688.06	531.37	0.10	0.21	0.24
68	W.22	1278.00	880.86	28.48	10.98	1.12	79.26	9.55	89.24	0.19	0.99	0.04	2133.30	1869.33	263.97	0.54	0.49	0.69
Yom catchment																		
69	Y.1C	7624.00	692.33	27.28	419.09	1.18	78.67	31.15	59.16	3.93	4.37	1.39	633.25	270.49	362.76	0.53	0.48	0.53
70	Y.3A	13583.00	521.56	19.89	479.25	1.16	63.94	77.41	6.42	4.57	7.86	3.74	640.88	161.50	479.37	0.35	0.31	0.35
71	Y.13A	380.00	585.27	25.05	287.05	1.83	82.33	14.57	82.47	0.56	2.23	0.17	202.35	161.50	40.85	0.47	0.42	0.47
72	Y.14	12131.00	655.05	26.59	272.48	1.14	63.94	18.60	76.47	1.92	2.47	0.54	1048.45	345.97	702.49	0.45	0.41	0.45
73	Y.16	20841.00	535.29	24.69	149.61	1.13	63.94	64.60	0.84	11.29	8.87	14.39	681.34	345.97	335.37	0.27	0.24	0.27
74	Y.17	21415.00	456.21	19.67	1863.57	1.21	63.94	88.11	1.10	3.28	5.96	1.55	681.34	345.97	335.37	0.88	0.80	0.88
75	Y.20	5410.00	465.32	23.32	270.88	1.17	77.51	13.39	83.95	1.33	1.04	0.29	681.34	345.97	335.37	0.27	0.24	0.27
76	Y.24	597.00	461.16	22.31	286.11	1.57	81.37	22.71	75.84	0.19	1.09	0.17	400.24	345.97	54.27	0.80	0.68	0.94
77	Y.26	785.00	340.38	17.26	660.89	1.94	79.19	5.30	90.95	0.38	1.17	2.21	348.86	195.02	153.84	0.74	0.10	0.39
78	Y.29	57.00	233.20	20.17	58.39	1.84	96.85	5.32	94.41	0.23	0.04	0.00	137.88	121.02	16.85	0.62	0.56	0.62
79	Y.30	96.00	310.17	21.07	82.29	1.80	95.52	17.84	80.22	0.31	1.59	0.03	739.02	603.16	135.86	0.90	0.81	0.90
80	Y.31	1976.00	399.48	23.11	397.01	1.32	91.82	21.68	75.62	0.66	1.53	0.51	403.15	191.65	211.50	0.24	0.22	0.24
81	Y.34	331.00	57.69	1.30	110.91	1.41	87.89	27.81	64.90	3.84	2.46	0.99	244.68	191.65	53.03	0.32	0.29	0.53
82	Y.36	822.00	45.51	1.16	29.30	1.14	76.29	16.71	82.11	0.52	0.55	0.11	697.27	564.52	132.75	0.67	0.77	0.86
83	Y.37	2332.00	893.22	28.03	69.00	1.15	93.80	24.06	70.38	0.18	4.88	0.50	786.13	285.66	500.47	0.48	0.43	0.48
84	Y.38	1677.00	46.93	1.32	6.23	1.12	83.91	24.77	66.17	6.12	2.75	0.19	335.01	285.66	49.35	0.28	0.17	0.24

2.4. Water demand

Estimation of water demand is divided based on the user sectors into domestic, industrial, and agriculture sectors. The data used for the estimation of water demand are obtained from the Water Resource System Research Unit, Chulalongkorn University and RID. The procedure for demand estimation is explained below. The result of water demand estimation is shown in Figure 2.16.

Domestic sector

Domestic demand is estimated using the number of population and per capita daily water use as shown in (2.1).

$$DP = POP \times PCD \times DAY \quad (2.1)$$

Where DP: Domestic demand in a day (m^3)

POP: Total number of population in the basin (person)

PCD: Per capita daily water use (m^3 /person/day)

DAY: Number of days in a time step being considered (day)

Industrial sector

Industrial demand is estimated by (2-2) using the data of horsepower and water consumption per horsepower.

$$DI = HP \times PHP \times DAY \quad (2-2)$$

Where DI: Industrial demand (m^3)

HP: Total horsepower (HP)

PHP: Water consumption per horsepower (m^3 /HP/day)

DAY: Number of days in a time step being considered (day)

Agricultural sector

Agricultural demand is estimated by (2-3) which requires the data of crop coefficient, potential evapotranspiration, and crop area.

$$DA = Kc \times ETp \times A \times DAY \times 1000 \quad (2-3)$$

Where DA: Agricultural demand (m³)

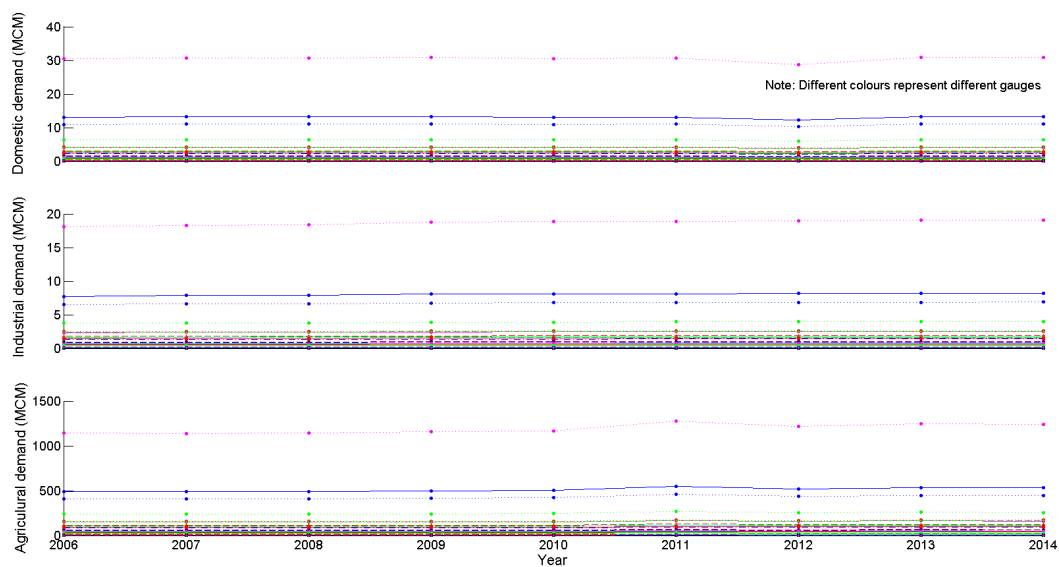
Kc: Crop coefficient (-)

ETp: Potential evapotranspiration (mm/day)

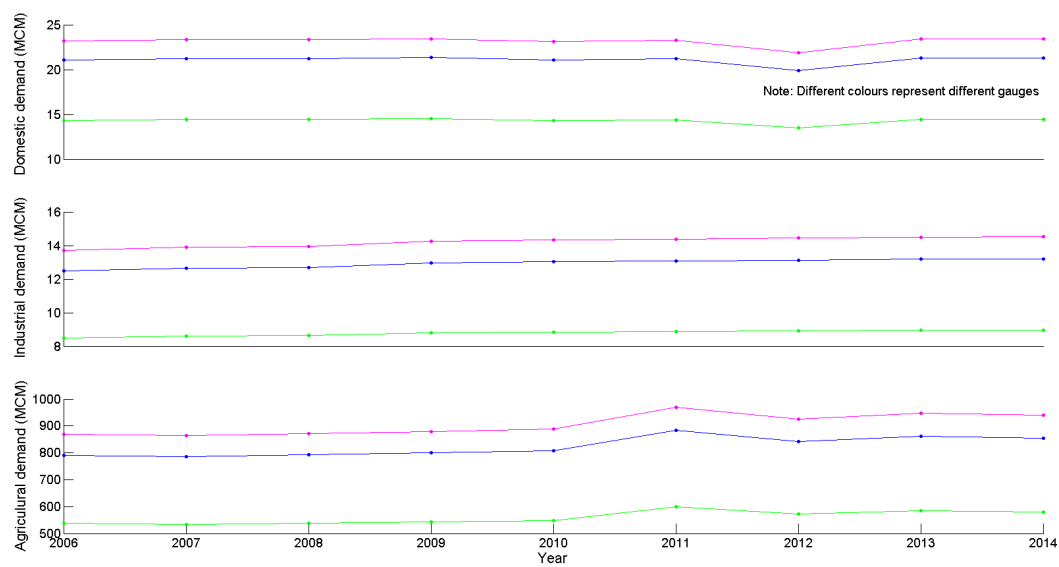
A: Crop area (km²)

DAY: Number of days in a time step being considered (day)

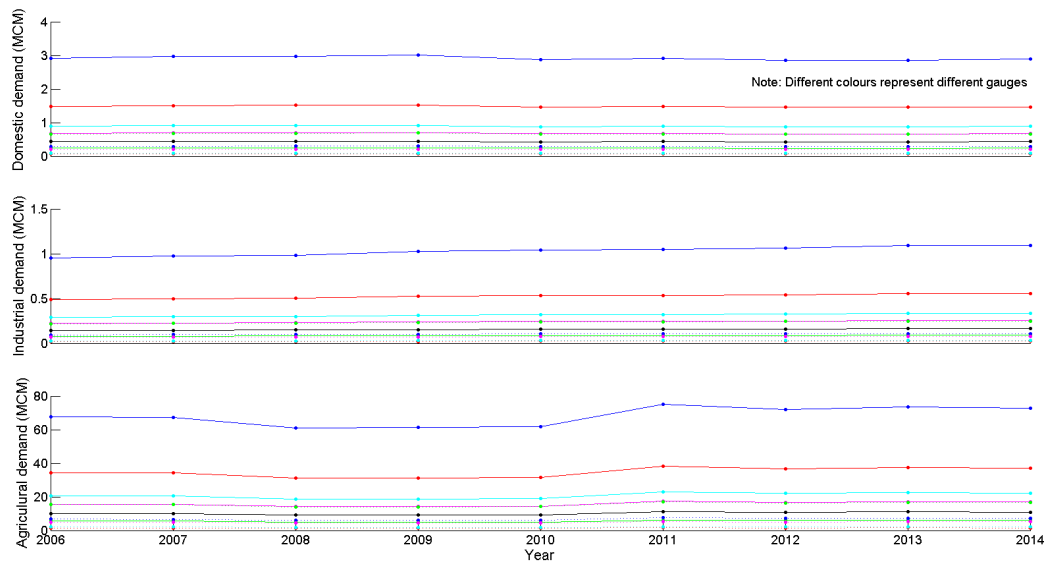
It can be seen from Figure 2.16 (a)-(f) that agriculture is the largest sector for water demand. Average agricultural demand accounts for approximately 91.37-98.13% while domestic and industrial demands take about 1.31-4.05% and 0.56-4.86% of the total water demand accordingly. High total demand is found for the Yom catchment followed by the upper Ping, lower Ping, Kok, Wang, and Salawin catchments. This is due to extensive agricultural area in the Yom catchment as shown in Figure 2.3. In overall, no strong trends for water demand are detected except in the Wang and Yom catchments where increasing trends for industrial demand are found. An increase in agricultural demand is noticeable between 2010-2011. This is believed to be the impacts of high water years which encourage farmers to grow multiple times of off-season rice. A decrease in agricultural demand is detected in later year in 2012 after the 2011 catastrophic flood that affected most parts of Thailand and caused heavy economic damage including in agricultural sector.



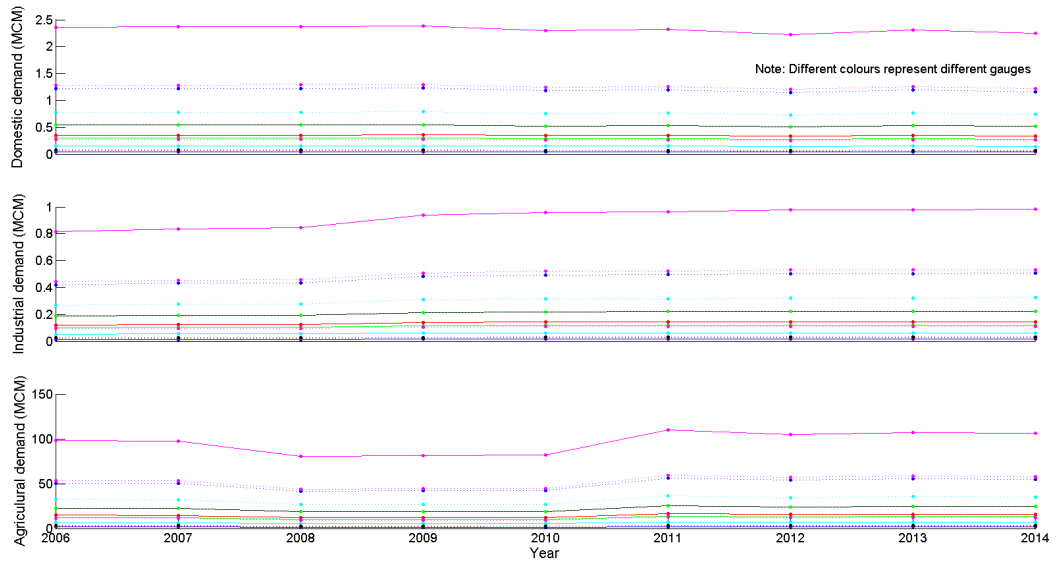
(a) Upper Ping catchment



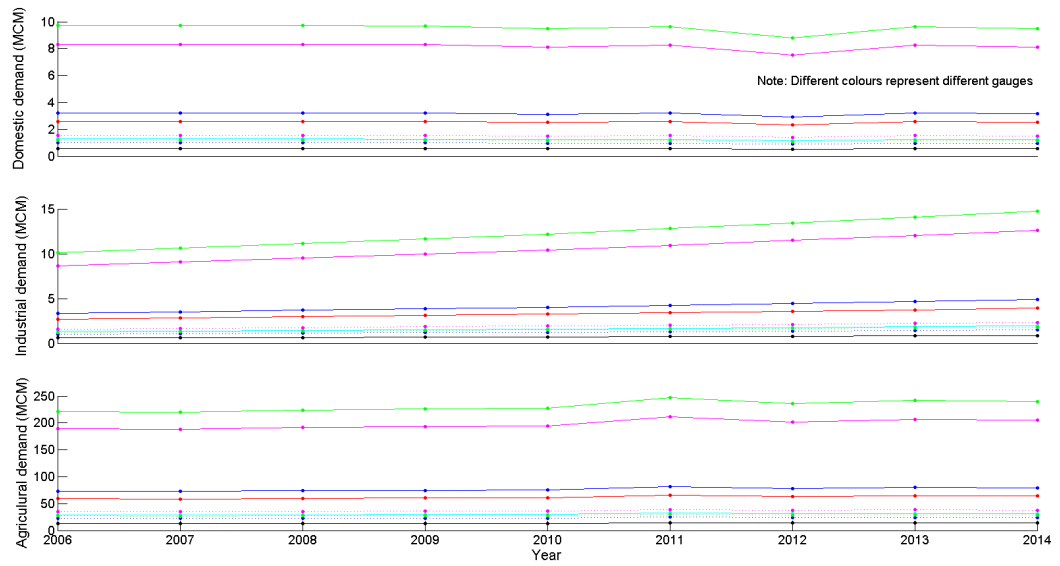
(b) Lower Ping catchment



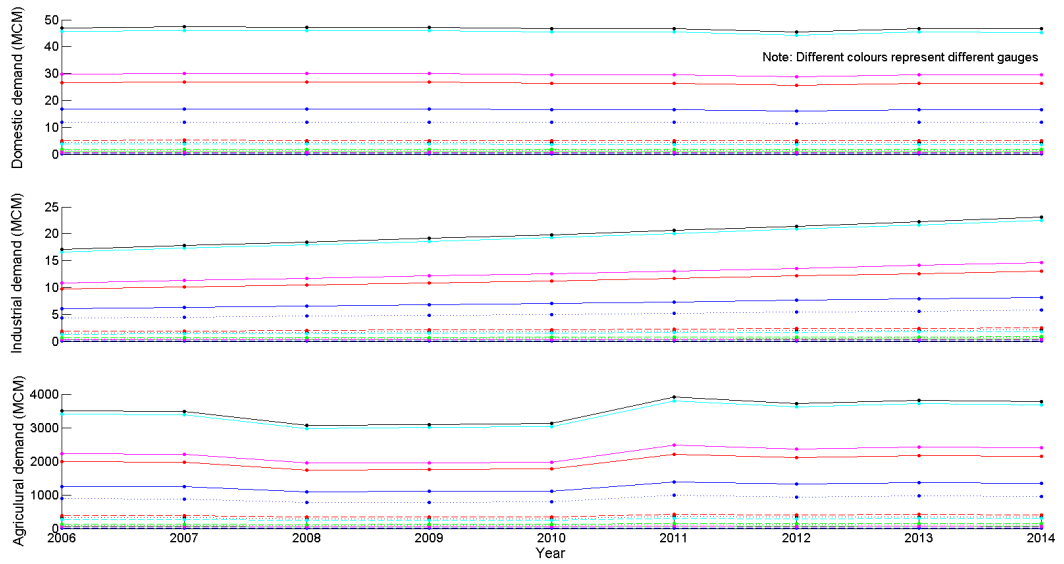
(c) Salawin catchment



(d) Kok catchment



(e) Wang catchment



(f) Yom catchment

Figure 2.16 Water demand for the upper Ping, lower Ping, Salawin, Kok, Wang, and Yom catchments is presented in panel (a), (b), (c), (d), (e), and (f) accordingly.

Chapter 3 TRMM satellite product

3.1. Overview of the TRMM satellite product

The TRMM is a polar-orbiting satellite owned by National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). It was launched in November 1997 at 350 km above the Earth to measure rainfall in the tropical region between 35°N and 35°S. The present sampling frequency is 16 times a day for each grid square (approximately 90 minute/earth rotation) and orbital height is 403 km above the Earth (Ward et al. 2011).

The TRMM 3B42 algorithm is selected for this study. It merges the TRMM data with multiple satellite data sources including microwave from polar orbiting and infrared from geostationary satellites to produce daily rainfall at 0.25 x 0.25 degree spatial resolution.

3.2. Assessment of the TRMM satellite product for rainfall estimation

The performances of TRMM estimates and interpolation were compared using the daily data from 1 April 2006 to 31 March 2015. Table 3.1 and Figure 3.1 summarise the data used for comparison between the TRMM estimates and interpolation and the area of comparison accordingly.

Table 3.1 Data used in this study

Product	Spatial resolution	Duration
Rain gauges	point	Apr 2006- Mar 2015
Benchmark grid-averaged rain gauges	Averaged over 0.25° x 0.25°	Apr 2006- Mar 2015
Interpolated rain gauge data	0.05° x 0.05°, then scaled up to 0.25° x 0.25°	Apr 2006- Mar 2015
TRMM 3B42	0.25° x 0.25°	Apr 2006- Mar 2015

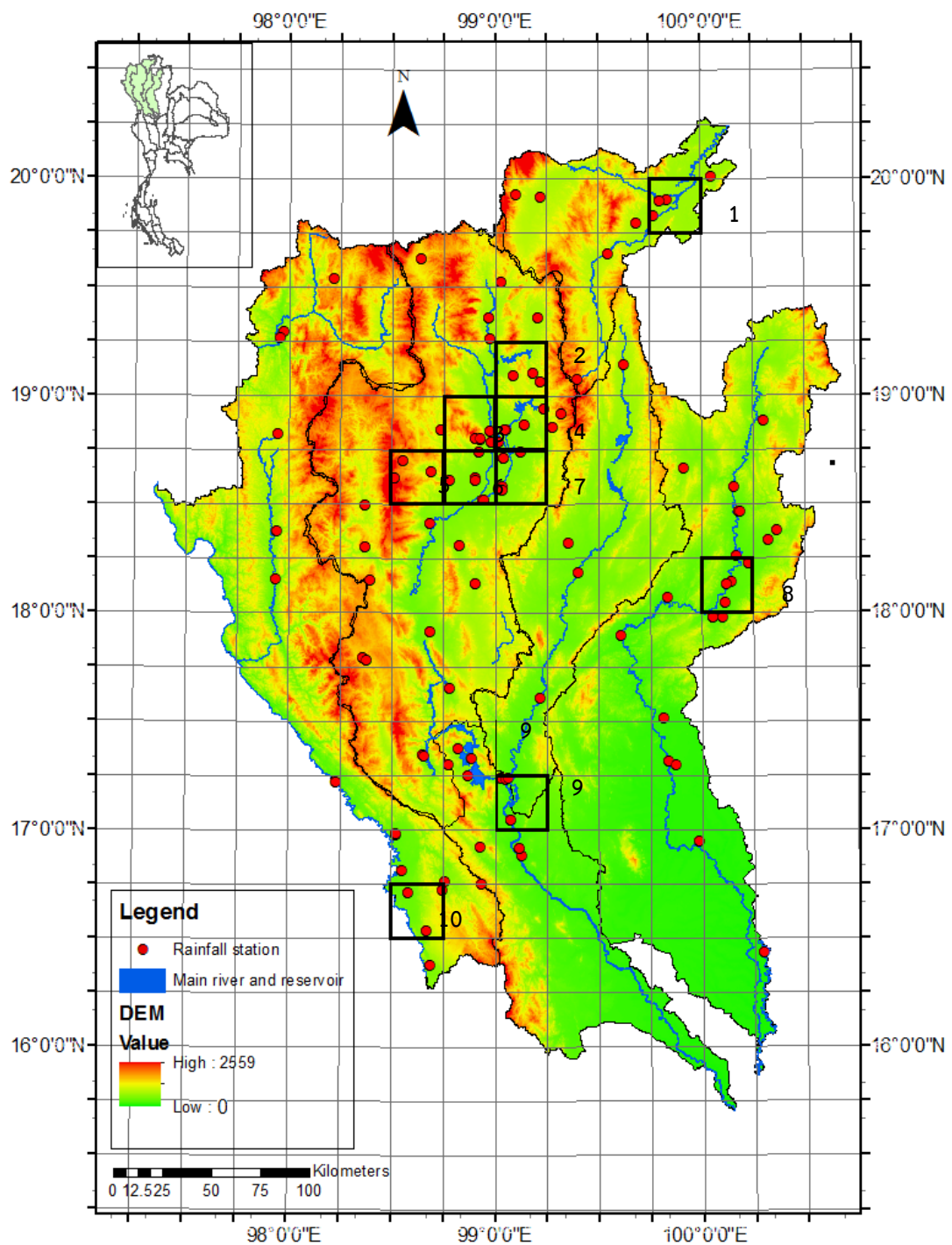


Figure 3.1 The terrain of the upper Ping and its surrounding catchments with the distribution of rain gauges over 0.25 x 0.25 degree grid squares. Ten grid squares with black bold border are used for comparing TRMM and interpolation for areal rainfall estimates

The TRMM rainfall estimates were merged to ground-gauged rainfall data through linear regression against gauged rainfall (excluding the benchmark gauges). Only non-zero rainfall values measured by both data sources were used for developing the regression equations as shown in Figure 3.2 and only non-zero TRMM estimates were adjusted.

After an adjustment through the regression, the correlation coefficients between the calibrated TRMM and benchmark grid-averaged rainfall for the entire time-series including zero rainfall range from 0.47 to 0.67 across 10 test grids. The daily assessment of the calibrated TRMM estimates and interpolation relative to the 10 benchmark grids was performed based on Equations (3.1) to (3.3). Additional measures of how well TRMM detects number of rain days including the probability of detection (POD) and false alarm rate (FAR) are assessed using Equations (3.4) and (3.5).

$$\text{Bias (\%)} = [\Sigma(x-y)/n] / \text{mean}(y) \times 100 \quad (3.1)$$

$$\text{MAE (\%)} = [\Sigma[\text{abs}(x-y)]/n] / \text{mean}(y) \times 100 \quad (3.2)$$

$$r = (n\Sigma xy - \Sigma x \Sigma y) / \sqrt{[(n\Sigma x^2 - (\Sigma x)^2)(n\Sigma y^2 - (\Sigma y)^2)]} \quad (3.3)$$

where x is interpolated rainfall depth (mm)

y is gauged rainfall depth (mm)

n is number of time steps (days or months)

$$\text{POD} = H/(H+M) \quad (3.4)$$

$$\text{FAR} = FA/(H+FA) \quad (3.5)$$

where H = Number of days when both gauges and TRMM record rainfall

M = Number of days when gauges record rainfall but TRMM does not

FA = Number days when TRMM records rainfall but gauges do not

Performance statistics of the calibrated TRMM are summarised in Table 3.2 and Figure 3.3. Over the test grids, the values of POD (0.86-0.93) are generally high and the values of FAR (0.04-0.10) are generally low. This suggests that TRMM is highly capable of capturing rainfall occurrence.

Table 3.2 Performance statistics of the calibrated TRMM

Performance statistics	Grid									
	1	2	3	4	5	6	7	8	9	10
Bias (mm/day)	-0.88	-0.59	-1.28	-0.52	-1.27	-0.57	-0.78	-0.48	-0.92	-1.49
MAE (mm/day)	3.44	2.42	3.21	2.08	3.43	2.19	2.58	2.26	2.74	3.55
POD	0.91	0.93	0.89	0.91	0.86	0.92	0.91	0.92	0.88	0.88
FAR	0.04	0.10	0.05	0.09	0.04	0.08	0.08	0.08	0.05	0.05

The daily rainfall from a randomly selected rain gauge in each benchmark grid square is also included in this analysis to investigate how much of the error is associated with lack of rain gauges to provide the benchmark estimate (on the assumption that using a random single gauge will in general give a poorer grid-averaged estimate than using all available gauges, and this error gives a general indication of the potential spatial sampling error). The results for daily assessment in Figure 3.4 indicate a similar pattern of errors produced by TRMM and interpolation but the former outperforms interpolation in estimating areal rainfall for most of the test grids when assessed through bias and MAE.

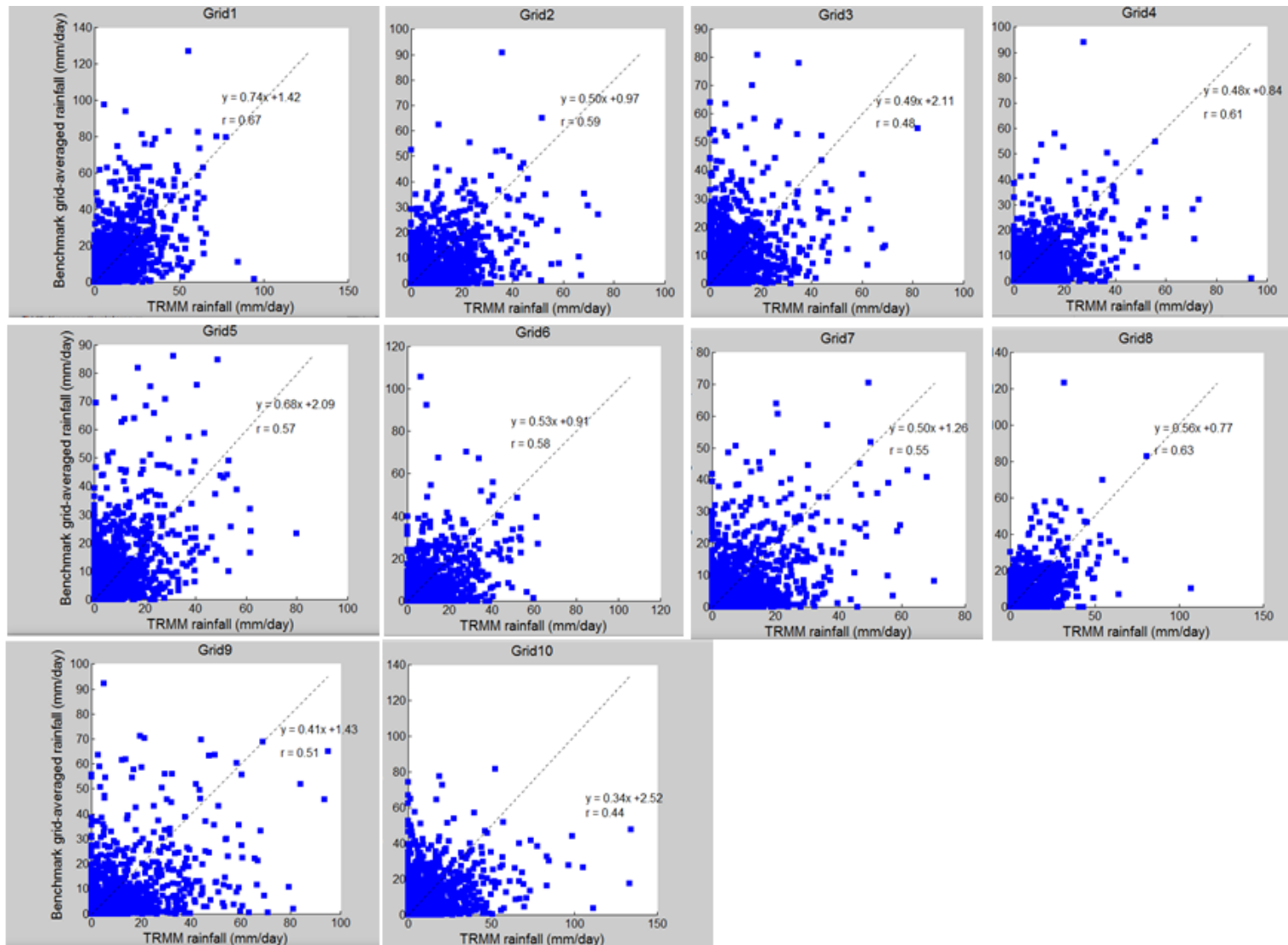


Figure 3.2 Relationships between daily uncalibrated TRMM and gauged rainfall with the regression equations used for adjusting TRMM estimates for 10 test grids. Zero rainfall not included.

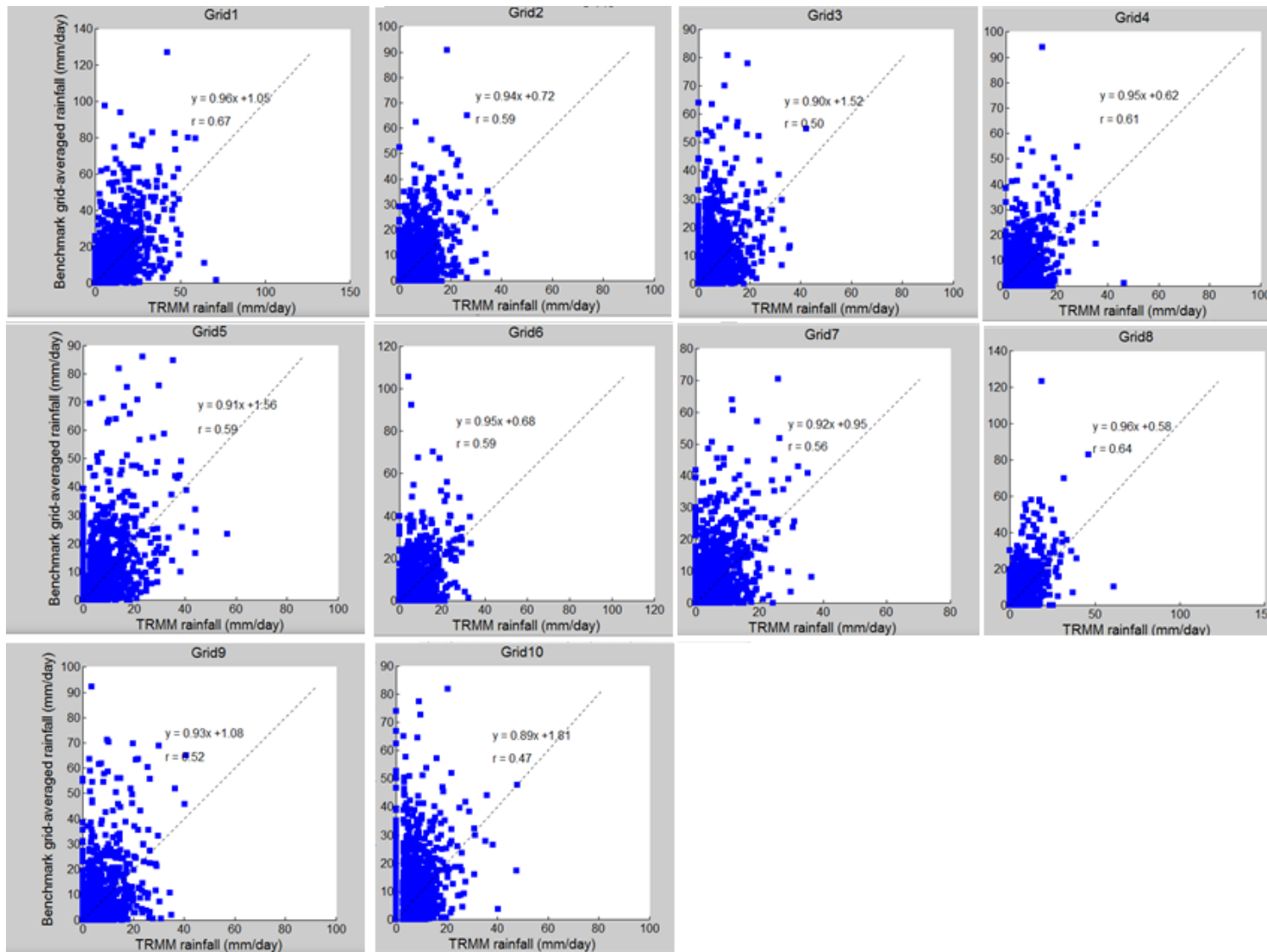
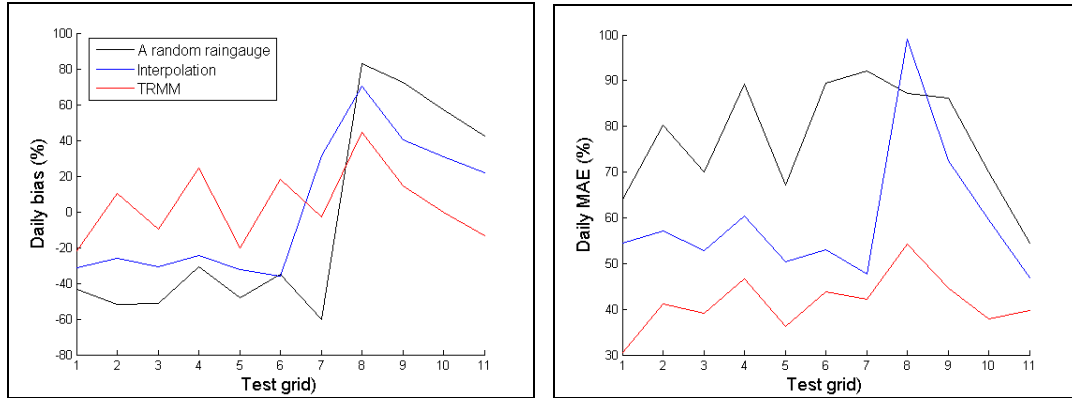


Figure 3.3 Relationships between daily calibrated TRMM and gauged rainfall with the regression equations used for adjusting TRMM estimates for 10 test grids. Zero rainfall not included.



(a) Bias

(b) MAE

Figure 3.4 (a) Bias and (b) MAE values for a randomly selected point rain gauge, the calibrated TRMM estimates, and the interpolation.

The analysis in this chapter suggests that using TRMM at 0.25×0.25 degree is generally more accurate than the use of interpolated rainfall in catchments with sparse ground-gauged data. The TRMM will then be used for developing regionalisation model in following Chapter.

Chapter 4 Soil property database

4.1 WISE databases

There are two types of WISE databases. The first comprises a set of harmonised soil profile data considered to be representative for the soil units of the FAO Soil Map of the World, and later the Harmonised World Soil Database (HWSD) as shown in Fig. 4.1. These profiles were used to develop consistent taxotransfer rules to estimate soil property estimates, by FAO soil unit and depth zone, including: organic carbon, total nitrogen, pHwater, cation exchange capacity, base saturation, aluminium saturation, calcium-carbonate and gypsum content, exchangeable sodium, electric conductivity, bulk density and the sand, silt and clay fractions. In the second type of WISE databases, the above soil property estimates were linked to the spatial data of the 1:M FAO Soil Map of the World respectively used to fill gaps in SOTER databases (so-called SOTWIS databases), using the FAO soil classification as main ‘carrier-of-soil information’. In this study, the WISE30sec, v1.0 (Batjes 2016) is used. Main elements of taxotransfer procedure are listed below.

- Soil profiles: ~21,000
- Layer model: 7, i.e. 5 x 20 cm up to 100 cm depth, and 2 x 50 cm up to 200 cm depth
- Textural classes: 5 (SOTER conventions: Coarse, Medium, Medium Fine, Fine, and Very Fine)
- Co-variates: climate (Peel et al. 2007)
- Soil variables: 19 (as listed in Table 4.1)
- Measure of uncertainty: mean $\pm$ std by map unit; descriptive statistics per soil ‘cluster’ including 10% and 25% percentiles

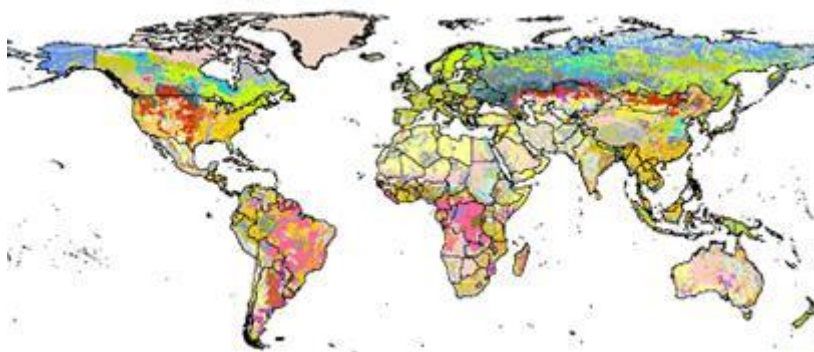


Figure 4.1 Overview of HWSD

4.2 Soil database development

The physical properties of the soil performed in Chapter 2 were obtained from ArcGIS. This section presents the methods and results for extracting additional soil properties from the WISE pedon-database. The soil database for the Ping catchment was developed using the guideline and initial soil database of the Mae Chaem sub-catchment performed by Thanapakpawin et al. (2007). The data from LDD soil survey report and WISE pedon-database were used for used together to identity the values of soil properties. Reliability of the information contained in the database is variable over the world. Most of the areas covered by SOTER databases are considered to have the highest reliability (Central and Southern Africa, Latin America and the Caribbean, Central and Eastern Europe) (FAO/IIASA/ISRIC/ISSCAS/JRC. 2012). It can be seen from Fig. 4.2 showing the distribution of the soil profile used to develop the WISE pedon-database.that the SoilGrids1km for Thailand was developed from a relatively small number of the soil profiles and even more limited for the Ping catchment. The soil properties such as soil carbon stocks shown in Fig. 4.3 obtained from the SoilGrids1km for Thailand is almost homogeneous ranging from 60-90 Kg C/m². This does not agree well with the distributions of variable soil types over the catchment as shown in Fig. 2.2.

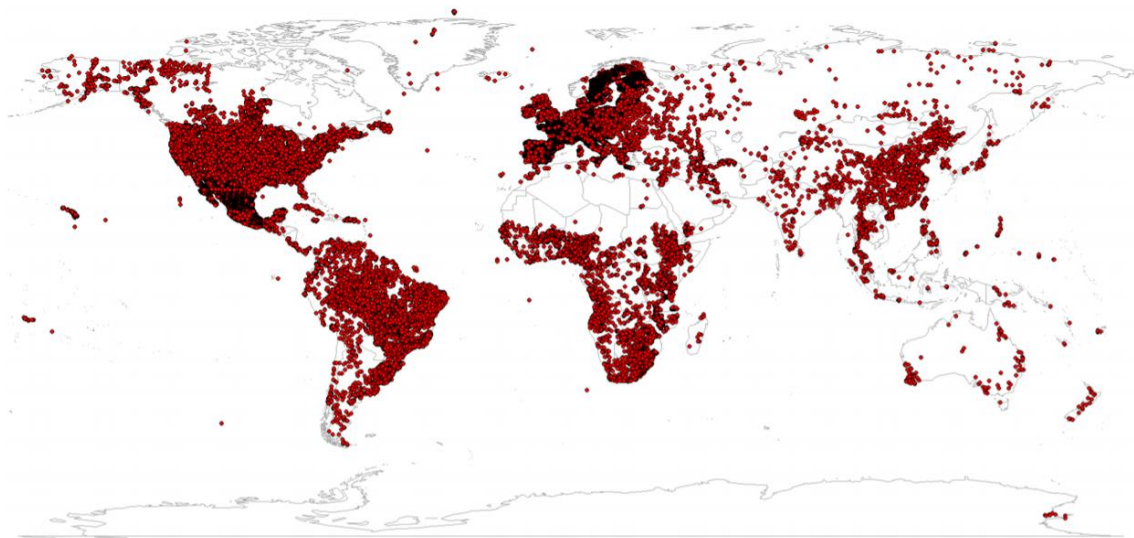


Figure 4.2 World distribution of soil profiles used to generate the SoilGrids1km product (Hengl et.al. 2014)

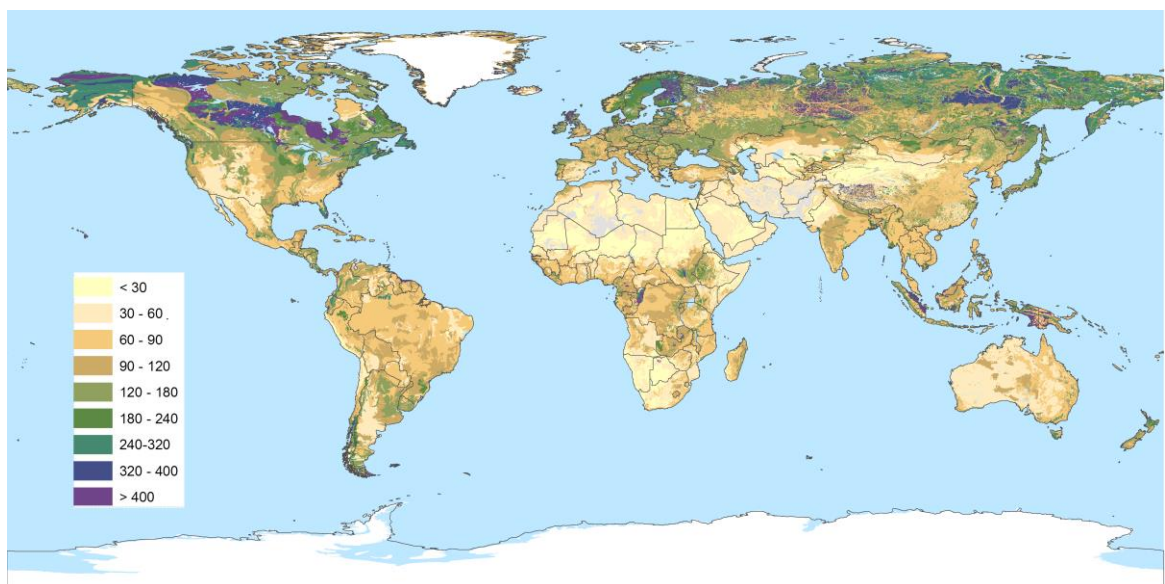


Figure 4.3 Soil carbon stocks (Kg C/m²) to 1 m depth

Table 4.1 Example of the WISE30sec, v1.0 metadata

OBJECTID	SoilGroup	ma	LayerID	LabNumber	GeneticHorizons	DiagnosticHorizons	Sand	Silt	Clay	VCSand	CSand	MSand	FSand	VFSand	AllSand	LabTexture	FieldTexture	Air_Dry	Min/Max	AllSand	Silt	Clay	Air_Dry
3867	1 Bm	1	Pa -494	Apg1	Ochric epipedon		3	29	68						3	c	c	6.599999905	Min	1.50	2.50	49.90	0.10
3868	1 Bm	2	Pa -495	Apg2	Ochric epipedon		2	29	69						2	c	c	6.800000191	Max	57.30	45.70	95.50	9.80
3869	1 Bm	3	Pa -496	Bssg1	Cambic horizon		1.5	26	72.5						1.5	c	c	8					
3870	1 Bm	4	Pa -497	Bssg2	Cambic horizon		6	21.5	72.5						6	c	c	8.100000381					
3871	1 Bm	5	Pa -498	Ck	-		9.5	25.5	65						9.5	c	c	7.900000095					
3905	1 Ck	1	AO5931	Apg	Ochric epipedon		8.199999809	24.5	67.30000305	0.200000003	0	0.200000003	2.200000048		7	17.79999986	c	c					
3906	1 Ck	2	AO5932	Bg	Cambic horizon		5.699999809	19.20000076	75.09999847		1	6.800000191	5.400000095	3.700000048	5.900000095	28.50000024	c	c					
3907	1 Ck	3	AO5933	Bssg	Cambic horizon		6.199999809	22	71.80000305	2	3.700000048	3.200000048	2.599999905	6.599999905	24.29999971	c	c						
4115	1 Bpo	1	6-16345	Ap	Ochric epipedon		3.700000048	30.60000038	65.69999695	0.400000006	0.5	0.899999976	2.400000095		23.5	31.40000013	c	sic	6.800000191				
4116	1 Bpo	2	6-16346	BA	-		6.800000191	27.29999924	65.90000153	0.100000001	0.600000024	9.5	29.20000076	11.10000038	57.30000136	c	c	8.100000381					
4117	1 Bpo	3	6-16347	Bss1	Cambic horizon		5.300000191	34	60.70000076						5.300000191	c	c	6.5					
4118	1 Bpo	4	6-16348	Bss2	Cambic horizon		5.599999905	34.40000153	60						5.599999905	c	c	6.800000191					
4119	1 Bpo	5	6-16349	Bw	Cambic horizon		4.400000095	45.70000076	49.90000153						4.400000095	sic	c	5.300000191					
3948	1 Kk	1	P-784	Apg1-2	Ochric epipedon		3.700000048	12.30000019	84						3.700000048	c	c	9.800000191					
3949	1 Kk	2	P-785	Bssg1	Ochric epipedon		2.299999952	11.69999981	86						2.299999952	c	c	9					
3950	1 Kk	3	P-786	Bssg2	Cambic horizon		2	2.5	95.5						2	c	c	9.600000381					
3951	1 Kk	4	P-787	Bssg3	Cambic horizon		3.200000048	5.300000191	91.5						3.200000048	c	c	9.5					
3952	1 Kk	5	P-788	Bssg4	Cambic horizon		4.5	8	87.5						4.5	c	c	9.699999809					
3953	1 Kk	6	P-789	BCg	-		11.30000019	23.20000076	65.5						11.30000019	c	c	9.800000191					
4350	1 Wa	1	P-309	Apg	Mollic epipedon		7.300000191	41.79999924	50.90000153						7.300000191	c	c	1.200000048					
4351	1 Wa	2	P-310	Bssg1	Cambic horizon		6.300000191	36.29999924	57.40000153						6.300000191	c	c	1.100000024					
4352	1 Wa	3	P-311	Bssg2	Cambic horizon		6.599999905	32.09999847	61.29999924						6.599999905	c	c	0.100000001					
4353	1 Wa	4	P-312	Bssg3	Cambic horizon		8	37.79999924	54.20000076						8	c	c	0.800000012					
3845	2 Ay	1	Pa 514	Apg	Ochric epipedon		3	30	67						3	c	c	5	Min	0.50	17.00	24.30	1.60
3846	2 Ay	2	Pa 515	Bssg1	Cambic horizon		4.5	26	69.5						4.5	c	c	4.800000191	Max	90.80	49.20	69.50	8.90
3847	2 Ay	3	Pa 516	Bssg2	Cambic horizon		4	33.5	62.5	3.299999952	0.699999988	0.699999988	2.5	10.30000019	21.50000012	c	c	5.400000095					
3848	2 Ay	4	Pa 517	Bg1	Cambic horizon		17.5	17	65.5	3.599999905	0.699999988	0.899999976	3.299999952	8.699999809	34.69999963	c	c	8					
3849	2 Ay	5	Pa 518	Bjg	Cambic horizon		4	31	65	0.300000012	0.400000006	0.5	2.400000095	6.400000095	14.00000021	c	c	6.099999905					
3850	2 Ay	6	Pa 519	Bg2	Cambic horizon		1.5	31	67.5	0.5	0.400000006	0.699999988	2.599999905	6.699999809	12.39999971	c	c	5.699999809					
3851	2 Ay	7	Pa 520	Cg1	-		1.5	35	63.5	0	0.5	0.899999976	2.900000095	9.5	15.30000007	c	c	6.099999905					
3852	2 Ay	8	Pa 521	Cg2	-		1.5	33.5	65	0.200000003	0.200000003	0.5	2	7.5	11.90000001	c	c	6					
3872	2 Bn	1	416418	Apg	Ochric epipedon		0.800000012	33.79999924	65.40000153						0.800000012	c	c	3.900000095					
3873	2 Bn	2	416419	BAg	Cambic horizon		0.5	32.20000076	67.30000305						0.5	c	c	3.700000048					
3874	2 Bn	3	416420	Bssg1	Cambic horizon		0.699999988	34.90000153	64.40000153						0.699999988	c	c	3.200000048					
3875	2 Bn	4	416421	Bssg2	Cambic horizon		1.299999952	40.59999847	58.09999847	2.599999905	8.399999619	20.10000038	14.89999962	22.79999924	70.09999871	sic	c	3.700000048					
3876	2 Bn	5	416422	Bwg1	Cambic horizon		5.599999905	49.20000076	45.20000076	1.799999952	6	13	21.60000038	15.80000019	63.80000043	sic	c	3.599999905					
3877	2 Bn	6	416423	Bwg2	Cambic horizon		1.399999976	33.90000153	64.69999695	1.700000048	6.099999905	14.60000038	12.30000019	22.70000076	58.80000126	c	c	4.400000095					
3878	2 Bn	7	416424	Bwg3	Cambic horizon		2.299999952	41.59999847	56.09999847	1.700000048	6.099999905	11.39999962	17.60000038	12	51.0999999	sic	c	3.599999905					
3879	2 Bp	1	P-1112	Apg	Ochric epipedon		2.400000095	43.59999847	54	4.099999905	7.199999809	10.69999981	7.900000095	16.20000076	48.50000048	sic	c	6					
3880	2 Bp	2	P-1113	ABg	-		2.700000048	35.79999924	61.5	6	14.5	18.29999924	24.10000038	13.89999962	79.49999928	c	c	5.300000191					
3881	2 Bp	3	P-1114	Bssg1	Cambic horizon		13.69999981	26.79999924	59.5	5.900000095	12.60000038	17.20000076	24.70000076	14.80000019	88.900002	c	c	6					
3882	2 Bp	4	P-1115	Bssg2	Cambic horizon		2.299999952	39.20000076	58.5	10.60000038	16.10000038	17.60000038	19.5	11.30000019	77.40000129	c	c	5.599999905					
3883	2 Bp	5	P-1116	BCg	Cambic horizon		1.100000024	33.90000153	65	14	17.39999962	16.5	17.39999962	10.19999981	76.59999907	c	c	6.300000191					
3884	2 Bp	6	P-1117	Cg1	-		7.199999809	43.29999924	49.5	13.5	18.5	17.60000038	16.60000038	10.89999962	84.30000019	sic	c	8.800000191					
3885	2 Bp	7	P-1118	Cg2	-		8.300000191	37.20000076	54.5	20.29999924	21.60000038	17.79999924	15.10000038	7.699999809	90.79999924	c	c	8.899999619					
3975	2 Ma	1	406886	Apg	Umbric epipedon		1	33.5	65.5	0.5	0.899999976	2	5.099999905	3.900000095	13.39999998	c	sic	3.599999905					
3976	2 Ma	2	406887	Bssg1	Cambic horizon		3	31.5	65	0.300000012	0.699999988	1.100000024	3.099999905	4	12.69999993	c	sic	3.900000095					
3977	2 Ma	3	406888	Bssg2	Cambic horizon		2.900000095	33.70000076	63.40000153	0.200000003	1	1.5	3.200000048	5.800000191	14.60000034	c	sic	3.599999905					
3978	2 Ma	4	406889	Bssjg	Cambic horizon		1.399999976	33	65.59999847	0.5	0.899999976	1.399999976	2.700000048	4.699999809	11.59999979	c	sic	3.5					

Table 4.2 Summary of soil database for the major soil great group found in the upper Ping and its surrounding catchments.

Soil Great group	Sand (%)			Silt (%)			Clay (%)			Air dry (Day)		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
5	2.30	40.00	21.15	26.50	56.50	41.50	25.20	68.40	46.80	0.30	3.50	1.90
7	0.80	1.83	1.32	0.60	60.30	30.45	5.30	68.50	36.90	0.10	6.80	3.45
15	4.90	85.20	45.05	28.50	63.50	46.00	8.50	55.00	31.75	0.40	7.20	3.80
29	2.30	99.00	50.65	8.30	57.00	32.65	11.80	84.60	48.20	0.70	9.20	4.95
33	6.19	90.40	48.30	13.50	70.00	41.75	6.00	65.00	35.50	0.90	4.70	2.80
35	41.60	1.47	21.54	14.00	33.00	23.50	0.50	38.90	19.70	0.10	1.60	0.85
46	17.00	53.50	35.25	8.50	40.40	24.45	17.50	73.00	45.25	2.00	4.90	3.45
47	9.20	97.00	53.10	15.70	50.00	32.85	5.50	71.50	38.50	0.21	19.60	9.91
48	27.00	1.25	14.13	4.10	42.30	23.20	5.00	52.40	28.70	0.40	6.80	3.60
62	0.70	1.90	1.30	3.50	65.00	34.25	1.00	78.50	39.75	0.00	7.10	3.55

The analysis of the soil great group performed in Chapter 2 shows that there are 38 soil great groups found in the upper Ping and its surrounding catchments. However, based on the availability of the soil properties in the WISE30sec, v1.0 metadata, only the soil particle sizes and air dry property can be obtained and matched with the LDD soil great group data. The summary of soil database for the major soil great group found in the upper Ping and its surrounding catchments is shown in Table 4.2. This soil properties will be added as the input for catchment characteristics into the regression model. The value of the obtained soil database to the regression equation for predicting flows is presented in Chapter 5.

Chapter 5 Predicting flows in ungauged catchments

5.1. Regression equations for predicting rainfall-flow indices

The regression method was selected for this study because: it estimates an explicit link between the flow response and the catchment properties and so can add to understanding of dominant mechanisms; an estimate of the variance is implicit to the regression allowing uncertainty analysis; and numerous studies have shown the regression method to be useful when using a comparable number of gauged catchments (Sefton and Boorman 1997, Fernandez et al. 2000, Mazvimavi et al. 2005, Heuvelmans et al. 2006, Pallard et al. 2009, Visessri 2014). The indices of the rainfall-runoff relationship were regressed against sub-catchment properties using a least-squares method (Yadav et al. 2007, Zhang et al. 2008b).

When using the data of the Ping and its surrounding catchments shown in Table 2.3 and Table 4.2 to develop the regression equations for predicting flow indices, the increasing number of the data pairs do not contribute to power of prediction as the data points are widely scattered. This is probably due to different characteristics of the catchments caused by topography, land use and soil type. Figure 2.1 shows that the Ping catchment is a mountainous catchment with steeper slopes and higher elevations compared to the surrounding catchments. Figure 2.2 shows the difference in the distribution of the soil types. The Ping catchment is dominated mostly by the soil great group 62 followed by the soil great group 48 clustered in the middle of the catchment. The soil great group 48 is present in wider area across the Wang and Yom catchments compared to that of the Ping. The Salawin and Kok catchments have much lower soil great group 62 and 48 compared to the Ping. The land use of the Ping is mostly forest with agriculture in the middle of the catchment. Agriculture area occupies larger proportion of the Kok, Wang i Yom catchments compared to that of the Ping. The land use of the Salawin catchment is mostly forest.

Table 5.1 Catchment properties in the upper Ping catchment

No.	Code	Catchment properties																	
		A	Ele	Slp	ChL	DD	%MS	%Agr	%For	%Mix	%Urb	%Wat	MAR	MWR	MDR	%Sand	%Silt	%Clay	Air dry
1	P.1	6350.00	779.07	28.59	2787.77	1.49	75.18	17.83	78.50	0.25	3.11	0.30	2761.92	1592.37	1169.55	2.83	33.44	39.00	3.59
2	P.4A	1930.00	1010.55	34.35	703.81	1.60	89.85	17.21	81.38	0.04	1.21	0.10	3202.46	2671.17	531.29	3.64	34.02	39.88	3.59
3	P.20	1345.00	784.28	31.75	536.99	1.07	77.29	13.65	85.67	0.00	0.67	0.00	3081.89	2456.80	625.10	8.39	33.95	40.53	3.63
4	P.21	452.00	722.94	22.62	278.02	1.61	79.56	11.12	86.73	0.00	2.15	0.00	1425.61	1133.84	291.77	9.63	29.36	35.15	3.45
5	P.24	616.00	952.43	26.57	355.96	1.55	82.09	13.16	83.76	2.25	0.81	0.02	1909.26	1506.95	402.31	8.59	31.37	36.30	3.33
6	P.56A	546.00	713.97	25.61	145.47	1.61	71.89	29.40	66.70	0.30	3.41	0.19	1799.53	1491.05	308.48	6.45	33.41	38.89	3.44
7	P.67	5323.00	810.87	30.46	2137.53	1.48	78.67	16.92	80.89	0.27	1.61	0.29	2306.69	1290.34	1016.35	12.47	32.72	39.27	3.73
8	P.73	14814.00	689.39	23.57	5994.39	1.56	63.94	21.22	71.67	2.05	4.65	0.40	2025.32	775.33	1249.99	10.56	29.68	35.43	3.56
9	P.75	3080.00	719.95	29.10	1263.82	1.39	74.38	15.83	81.79	0.00	1.56	0.41	3501.89	2448.57	1053.32	5.83	33.35	39.32	3.65
10	P.76	2030.00	1033.53	33.46	717.23	1.47	91.82	11.26	87.79	0.11	0.76	0.05	2828.88	2410.78	418.10	6.16	34.09	40.58	3.69
11	P.77	550.00	628.62	24.08	130.99	1.99	71.72	13.22	82.91	1.77	2.04	0.07	1207.21	1032.52	174.69	7.28	32.08	39.03	3.58
12	P.79	136.00	973.75	38.90	42.36	1.56	99.06	0.00	99.38	0.00	0.62	0.00	635.40	440.28	195.12	7.30	30.50	36.17	3.54
13	P.80	222.20	1029.85	32.48	156.16	1.75	93.48	6.13	93.10	0.00	0.77	0.00	634.08	469.03	165.05	5.35	34.12	40.44	3.66
14	P.81	787.00	952.43	26.57	355.96	1.55	82.09	13.16	83.76	2.25	0.81	0.02	3673.79	3019.39	654.40	2.87	33.15	38.30	3.45
15	P.82	203.00	1029.85	32.48	99.26	1.53	93.48	6.13	93.10	0.00	0.77	0.00	2431.02	1670.94	760.08	6.90	33.29	39.44	3.60
16	P.84	113.00	1193.76	33.98	42.36	1.34	94.88	16.03	83.51	0.00	0.46	0.00	1602.95	1236.88	366.07	6.90	33.29	39.44	3.60
17	P.85	1280.00	753.61	25.31	409.32	1.43	75.79	14.99	79.99	1.27	3.54	0.21	2915.14	2529.94	385.20	6.90	33.29	39.44	3.60
18	P.86	708.30	952.43	26.57	382.64	1.64	82.09	13.16	83.76	2.25	0.81	0.02	755.62	506.61	249.01	6.90	33.29	39.44	3.60
19	P.87	1078.00	817.83	27.04	409.32	1.49	87.64	8.75	88.32	0.49	2.42	0.01	970.76	926.31	44.45	6.90	33.29	39.44	3.60
20	60201	47.40	1012.81	33.82	39.10	1.51	94.21	5.15	92.18	0.00	2.67	0.00	312.32	206.41	105.91	12.58	33.11	40.55	3.79
21	60301	80.70	830.88	34.56	43.44	1.61	97.42	10.28	89.40	0.00	0.33	0.00	513.89	356.91	156.98	7.75	33.82	40.55	3.72
22	60302	43.90	920.33	34.00	12.11	1.99	98.01	12.63	83.54	3.83	0.00	0.00	213.86	145.69	68.17	2.67	34.06	39.82	3.51
23	60403	19.50	1221.78	37.40	25.72	1.29	99.65	15.01	84.73	0.00	0.25	0.00	195.15	117.94	77.21	5.82	34.09	40.42	3.64

No.	Code	Catchment properties																	
		A	Ele	Slp	ChL	DD	%MS	%Agr	%For	%Mix	%Urb	%Wat	MAR	MWR	MDR	%Sand	%Silt	%Clay	Air dry
24	60701	53.10	1102.03	41.04	27.63	1.96	100.00	0.00	98.18	0.00	1.82	0.00	440.38	347.41	92.97	1.44	34.13	39.63	3.55
25	60804	34.60	1066.44	22.97	14.57	1.41	75.22	14.10	85.69	0.00	0.21	0.00	243.25	179.05	64.20	2.47	33.24	38.74	3.55
26	60806	548.00	976.61	27.29	131.75	1.59	96.14	3.93	94.87	0.00	1.20	0.00	1493.61	1205.62	287.99	1.61	34.10	39.61	3.55
27	60807	343.00	1085.95	26.07	156.16	1.57	87.89	12.26	86.82	0.00	0.92	0.00	2021.87	1450.33	571.54	1.49	34.08	39.58	3.55
28	60808	1170.00	817.83	27.04	409.32	1.50	87.64	8.75	88.32	0.49	2.42	0.01	2683.65	2177.02	506.63	14.80	28.78	35.79	3.79
29	61001	92.40	1528.97	28.73	81.85	1.55	85.86	24.13	75.10	0.00	0.77	0.00	1347.39	956.25	391.15	3.56	32.32	37.82	3.56
30	61004	25.50	1300.04	26.79	18.36	1.45	96.66	12.86	87.14	0.00	0.00	0.00	273.35	174.90	98.45	8.60	33.70	39.25	3.25
31	61006	39.50	1167.03	27.79	21.26	1.92	75.09	27.67	72.33	0.00	0.00	0.00	248.79	174.23	74.56	2.99	34.20	40.04	3.60
32	61301	86.50	1078.57	34.33	35.66	1.34	99.73	23.96	76.04	0.00	0.00	0.00	338.64	233.66	104.98	2.89	34.13	39.94	3.59
33	61302	1950.00	1056.51	32.57	730.65	1.54	93.80	5.30	94.19	0.19	0.31	0.01	4353.15	2995.20	1357.95	2.40	33.93	39.63	3.57
34	61501	1470.00	974.66	26.11	601.28	1.77	74.82	8.42	91.29	0.00	0.28	0.01	3436.57	2767.14	669.42	2.64	33.19	38.55	3.51

Table 5.2 Flow indices in the upper Ping catchment

No.	Code	Flow indices					
		RC	BFI	EL	Q95	Q50	Q5
1	P.1	0.27	0.24	0.27	1.73	0.29	0.01
2	P.4A	0.16	0.14	0.17	1.89	0.05	0.00
3	P.20	0.36	0.33	0.36	2.78	0.40	0.02
4	P.21	0.19	0.28	0.31	2.61	0.36	0.04
5	P.24	0.15	0.70	0.82	2.79	0.34	0.04
6	P.56A	0.16	0.15	0.16	3.01	0.34	0.05
7	P.67	0.54	0.49	0.54	1.85	0.24	0.01
8	P.73	0.14	0.79	0.87	2.90	0.26	0.00
9	P.75	0.89	0.80	0.88	1.76	0.35	0.01
10	P.76	0.63	0.56	0.77	1.65	0.10	0.01
11	P.77	0.16	0.16	0.18	2.37	0.13	0.00
12	P.79	0.64	0.38	0.41	2.84	0.86	0.10
13	P.80	0.39	0.75	0.82	2.19	0.35	0.07
14	P.81	0.12	0.51	0.63	4.80	0.49	0.07
15	P.82	0.43	0.39	0.43	8.22	1.84	0.51
16	P.84	0.77	0.64	0.68	13.07	1.32	0.10
17	P.85	0.68	0.61	0.83	3.10	0.08	0.00
18	P.86	0.12	0.66	0.73	1.69	0.02	0.00
19	P.87	0.53	0.47	0.54	1.29	0.01	0.00
20	60201	0.31	0.28	0.30	3.90	1.24	0.35
21	60301	0.60	0.54	0.59	3.95	1.03	0.26
22	60302	0.11	0.10	0.11	2.99	0.83	0.24
23	60403	0.85	0.77	0.84	8.44	1.46	0.53
24	60701	0.21	0.19	0.20	6.57	0.95	0.20
25	60804	0.69	0.62	0.66	4.97	0.80	0.15
26	60806	0.16	0.42	0.44	2.33	0.32	0.03
27	60807	0.26	0.14	0.15	4.13	0.86	0.20
28	60808	0.51	0.46	0.51	2.30	0.21	0.01
29	61001	0.67	0.60	0.65	8.88	2.49	0.76
30	61004	0.36	0.32	0.34	7.69	1.52	0.44
31	61006	0.28	0.25	0.28	3.92	0.96	0.24
32	61301	0.80	0.72	0.78	2.66	0.62	0.08
33	61302	0.58	0.52	0.91	2.81	0.54	0.03
34	61501	0.12	0.21	0.23	3.68	0.55	0.03

Due to the above-mentioned reasons, only the dataset of the upper Ping catchment with 34 flow stations were used for regression analysis in the next steps. The soil properties were calculated based on the weighted average properties of each soil great group found in the sub-catchments. Apart from the three commonly used rainfall-flow indices (RC, BFI, and EL), more rainfall-flow indices (Q95, Q50, and Q5) were developed to allow higher opportunity to identify informative indices for flow predictions. Q95, Q50, and Q5 are the 95th, 50th, and 5th percentiles of the flow values. These indices are expected to help capture the shape of the hydrograph with high medium and low flows values. The catchment properties and rainfall-flow indices that were used to develop the regression equation for predicting flow in the upper Ping catchment are shown in Table 5.1 and Table 5.2 accordingly. The obtained regression equations for are summarised in Table 5.3.

Table 5.3 Regression equations for predicting flows in the upper Ping catchment

Index	Regression equation	r^2
RC	$RC = 0.29 - 0.08Area$	0.48
EL	$EL = -4.72 + 8.36MAR - 0.33Area$	0.59
Q95	$Q95 = 0.57 + 0.10Area$	0.52
Q50	$Q50 = 0.73 - 0.16Area + 0.15Elev$	0.58
Q5	$Q5 = -2.96 - 1.08Area + 0.33Elev$	0.77

It is noted that the equation for BFI cannot be obtained because none of the catchment properties were found to be significant when testing with p-value = 0.05. In this study, only three out of 18 catchment properties were found significant. This is because many catchment properties were highly correlated and removed when performing stepwise regression analysis. The attempt to estimate the soil properties and used them as the predictors of the flow indices was not successful. No soil properties were identified as significant variable for predicting

flow indices. Area of the catchment was found to be significant for all indices. Elevation was significant for Q50 and Q5. Mean annual rainfall was significant only for EL. The r^2 values of the obtained regression are considered moderate ranging from 0.48-0.77. The highest r^2 was found for EL while the lowest r^2 was found for RC.

Confidence Intervals (CI) and Prediction Intervals (PI) representing the regression coefficient uncertainty were estimated and used to constrain the trial parameter sets for IHACRES rainfall-runoff model. 5000 trial parameter sets were drawn randomly from prior uniform distributions defined by the suggested parameter ranges (Visessri 2014). Generally, the large number of trial parameter sets were excluded as they fell out of the ranges of CI and PI. Example of conditioning parameter sets for P.1 is illustrated in Figure 5.1. When constrained using PI, the parameter sets were reduced to 1,201 set (24.02%) and when constrained using CI, the parameter sets were reduced to 445 sets (8.92%). Based on Figure. 5.1, the value of RC for P.1 may not be well predicted as the mean of the regression is not close to the observed value. The percentage of constrained parameter sets based on CI and PI is provided in Table 5.4. Figure 5.2 shows the range of the CI over the 34 test sub-catchment using RC, EL, Q95, Q50, and Q5. The performance of the constrained parameter (CI interval) sets for predicting the flow indices is measured using NSE* ($NSE^* = 1 - NSE$) and shown in Figure 5.3.

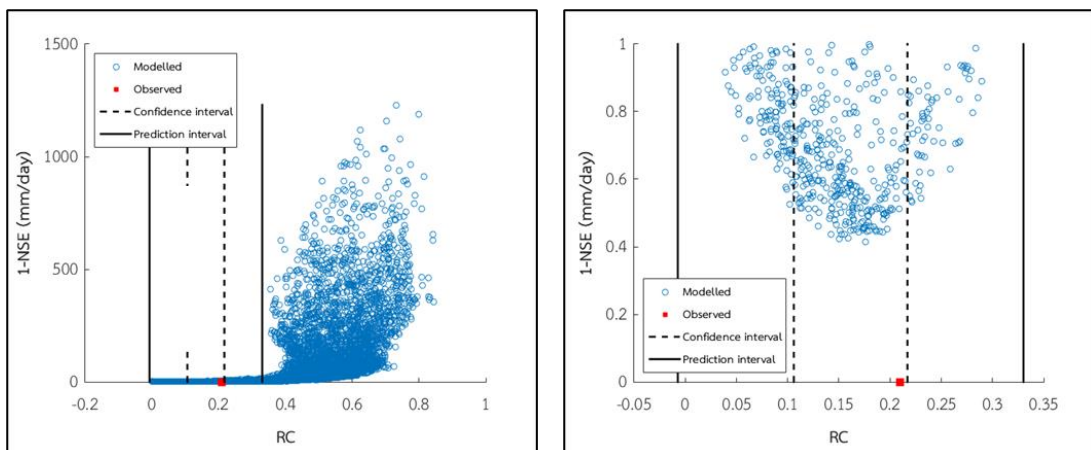
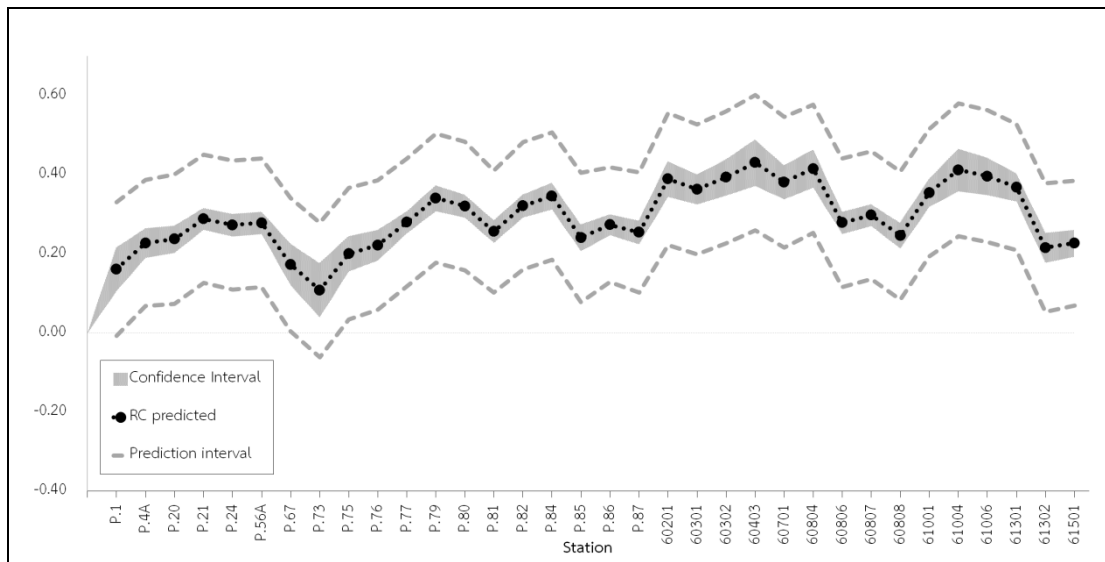


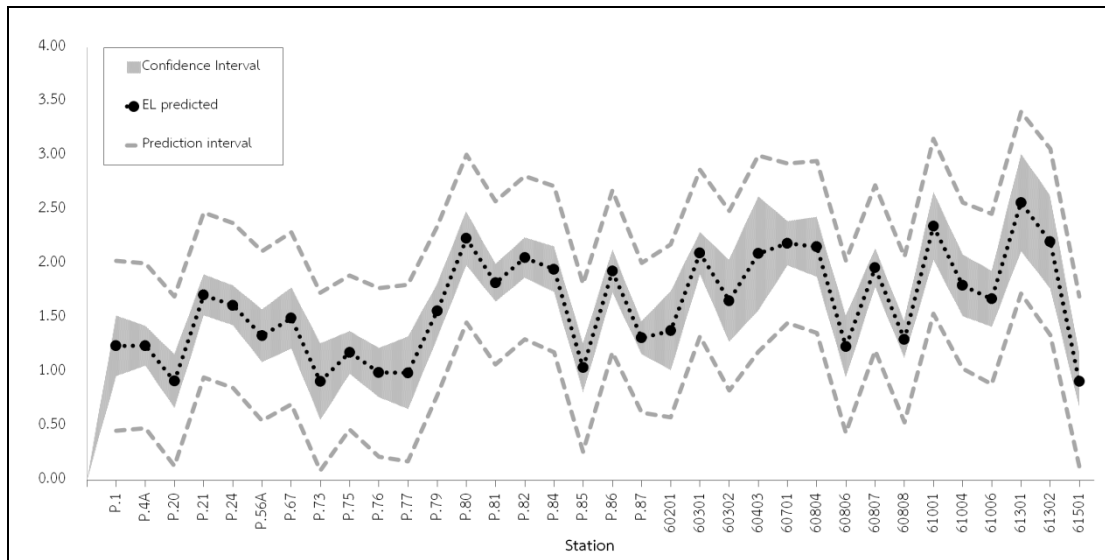
Figure 5.1 Conditioning parameter sets for P.1 using CI and PI of the regression for predicting RC

Table 5.4 The percentage of conditioned parameter sets

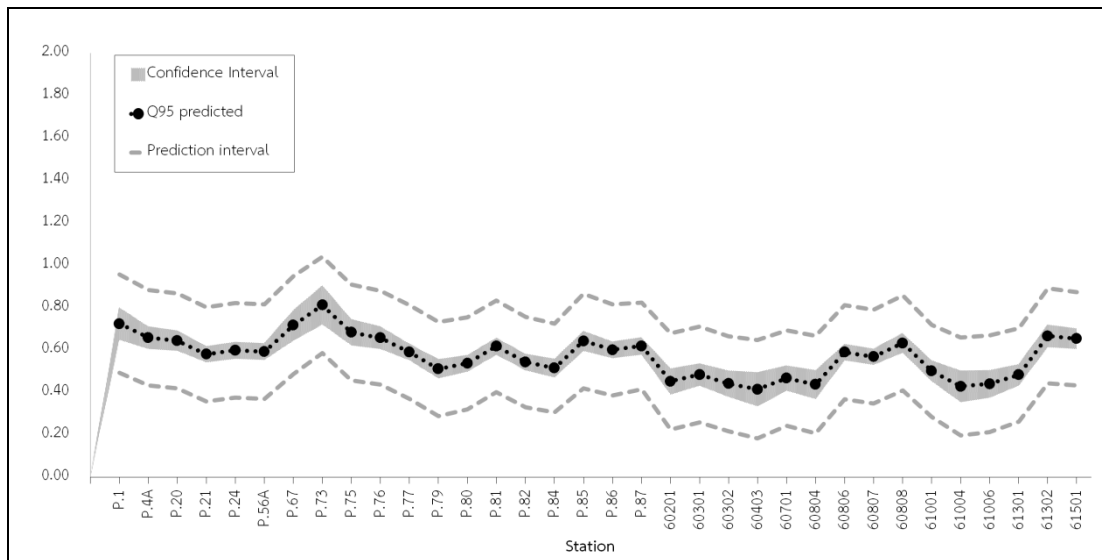
No.	Station	Flow Indices									
		RC		Q95		Q50		Q5		EL	
		PI	CI	PI	CI	PI	CI	PI	CI	PI	CI
1	P.1	24.02	8.92	13.74	3.56	26.50	8.86	24.12	7.10	100.00	99.92
2	P.4A	20.68	5.16	12.94	2.42	33.74	10.24	33.00	10.20	100.00	54.74
3	P.20	26.00	5.22	25.20	4.28	32.48	8.94	32.58	7.92	100.00	81.30
4	P.21	32.34	5.94	33.24	4.56	43.14	15.48	42.96	13.14	100.00	0.58
5	P.24	35.12	5.68	33.94	4.92	68.54	14.08	56.10	10.18	100.00	5.62
6	P.56A	29.02	4.38	31.92	4.50	49.78	17.42	42.86	13.80	100.00	28.28
7	P.67	22.54	7.28	14.34	3.58	30.44	10.18	27.82	7.80	100.00	10.92
8	P.73	22.60	10.24	13.82	4.66	32.84	10.32	22.02	8.36	99.10	83.98
9	P.75	27.52	7.44	19.68	4.50	26.22	7.86	27.60	7.58	100.00	96.42
10	P.76	25.96	6.36	23.36	4.36	47.22	16.58	37.30	11.64	100.00	86.74
11	P.77	45.22	6.58	39.58	6.16	70.84	35.30	52.34	21.48	100.00	98.16
12	P.79	42.58	7.00	39.20	5.62	62.16	14.60	52.08	13.66	100.00	2.46
13	P.80	48.10	7.28	48.16	7.90	67.34	13.22	40.60	9.28	0.00*	0.00*
14	P.81	33.92	5.70	28.94	4.64	59.16	12.44	49.10	9.50	0.00*	0.00*
15	P.82	30.78	4.70	15.24	2.30	40.56	7.40	47.50	9.24	0.00*	0.00*
16	P.84	45.10	6.96	32.96	5.26	50.56	14.34	54.42	16.34	21.20	0.14
17	P.85	27.88	6.10	26.04	4.22	37.78	10.90	35.52	9.18	100.00	90.58
18	P.86	28.94	5.36	31.76	4.44	62.12	12.46	45.88	8.68	18.34	0.02
19	P.87	33.12	6.68	28.16	5.16	52.14	12.74	42.90	9.00	100.00	22.24
20	60201	48.72	8.92	64.48	13.56	54.92	17.40	55.66	18.66	100.00	74.06
21	60301	52.96	9.02	50.94	8.68	52.68	21.56	53.32	20.78	0.00*	0.00*
22	60302	59.20	11.00	71.28	15.72	63.48	24.60	48.34	20.18	100.00	2.14
23	60403	60.74	21.66	78.76	28.02	53.24	19.06	22.86	5.38	0.00*	0.00*
24	60701	52.40	12.34	49.66	10.34	56.82	15.40	42.50	14.30	0.00*	0.00*
25	60804	46.40	11.18	34.06	6.38	28.06	9.12	57.26	19.04	0.00*	0.00*
26	60806	30.62	5.14	30.30	4.14	49.60	9.44	46.38	8.16	100.00	100.00
27	60807	28.10	3.70	22.82	2.90	49.64	12.28	49.38	11.14	0.00*	0.00*
28	60808	28.22	5.70	24.84	4.36	41.22	10.60	36.68	8.28	100.00	20.58
29	61001	33.60	5.90	18.06	2.70	33.02	19.16	61.86	38.54	0.00*	0.00*
30	61004	60.28	15.66	79.90	24.96	52.62	19.88	26.26	7.70	0.00*	0.00*
31	61006	56.68	12.66	78.58	20.10	57.76	17.12	36.92	12.54	0.00*	0.00*
32	61301	51.90	9.54	47.48	8.64	59.24	14.66	46.48	12.54	0.00*	0.00*
33	61302	28.70	7.10	17.96	3.34	61.32	24.22	39.06	13.42	0.00*	0.00*
34	61501	33.38	7.02	30.62	6.32	73.58	22.12	50.72	13.22	100.00	74.64



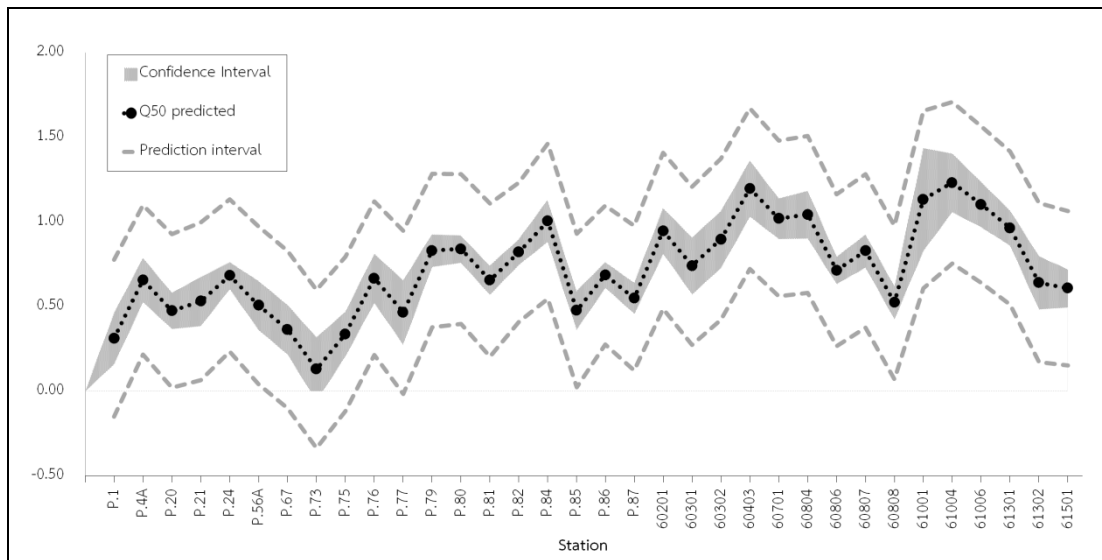
(a) RC



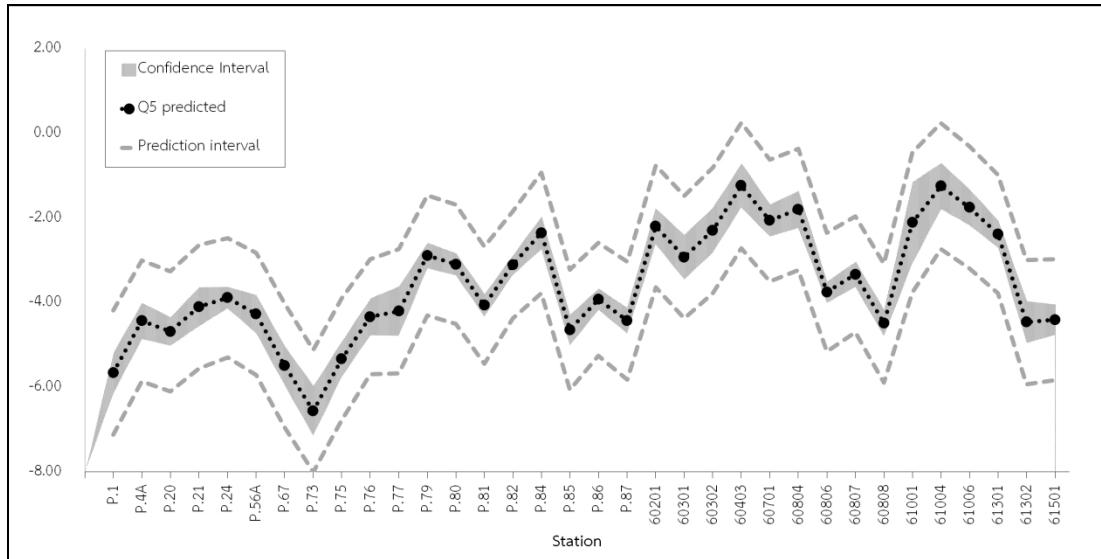
(b) EL



(c) Q95



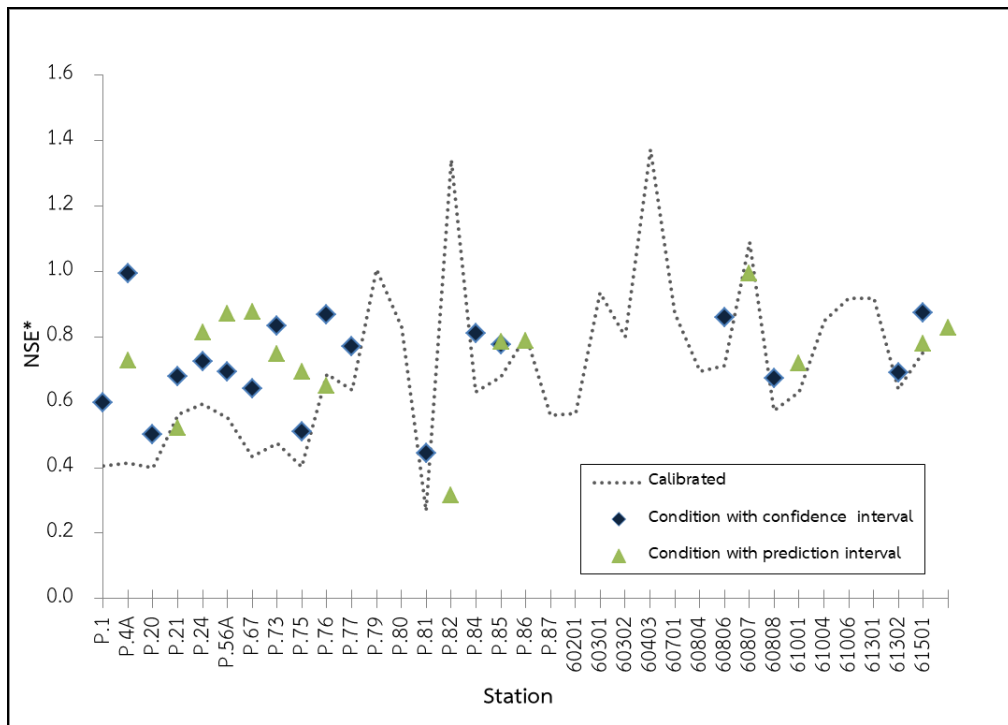
(d) Q50



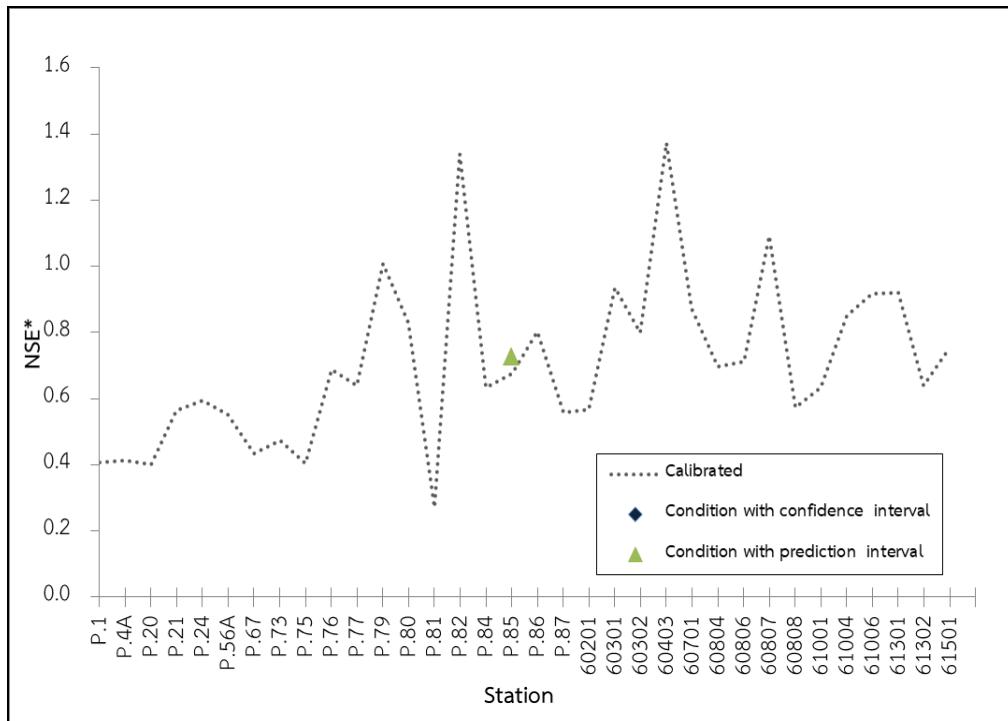
(e) Q5

Figure 5.2 CI of (a) RC, (b) EL, (c) Q95, (d) Q50, and (e) Q5.

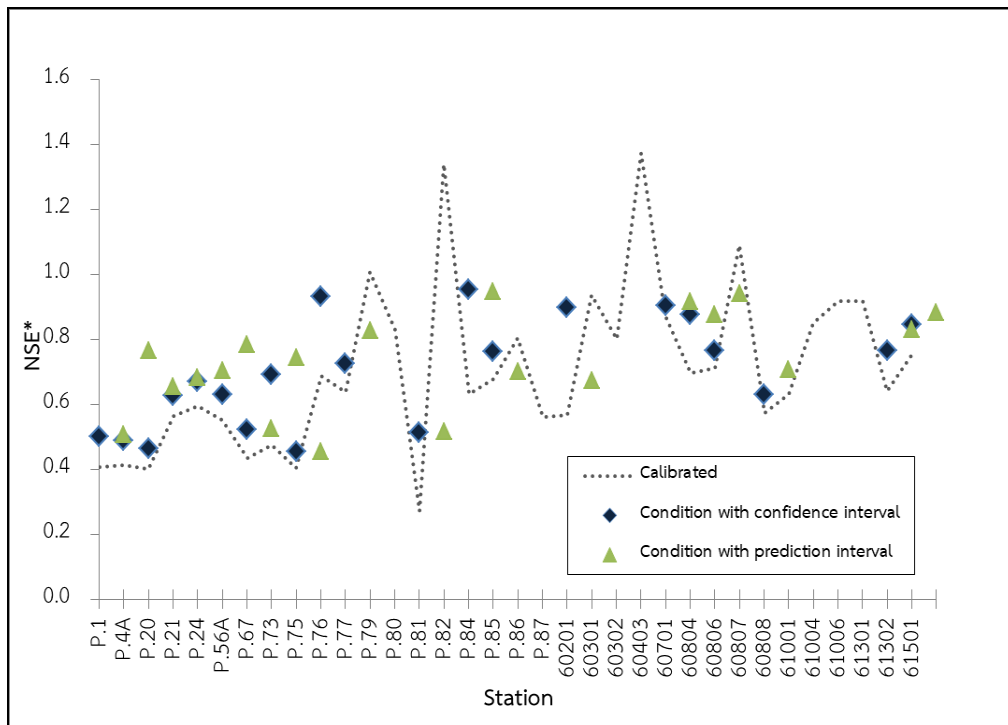
When compared to the performance of the calibrated parameter set, the constrained parameter sets performed generally better for predicting RC and Q95 compared to other indices. Constraining using CI gave better NSE* values than using the PI. Constraining method failed to capture the parameter sets for predicting EL and Q5 as almost or no parameter set was obtained as shown in Figure 5.3. Figure 5.4 compares the performance of using prior parameter space and constraining the parameter sets with different flow indices. Constraining the parameter sets based on CI of RC and Q95 yielded better performance than using the prior parameter sets for all 34 test sub-catchments. Constraining the parameter sets based on EL and Q5 did not contribute to the improvement of the model and could deteriorate the performance for some stations such as P.79 and P.86 as shown in Figure 5.4.



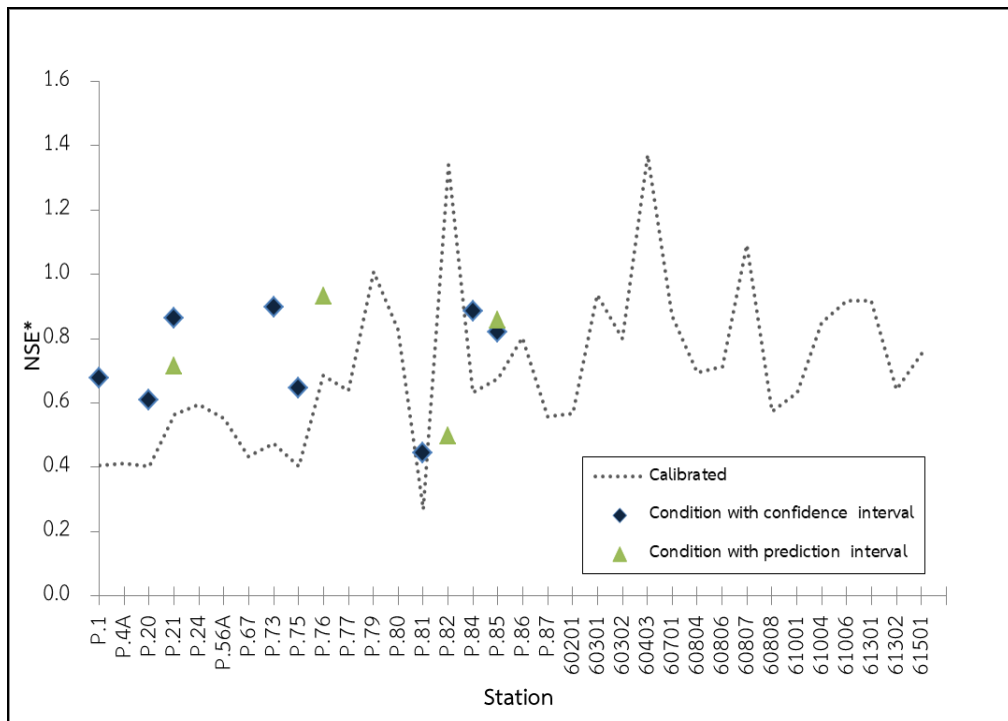
(a) RC



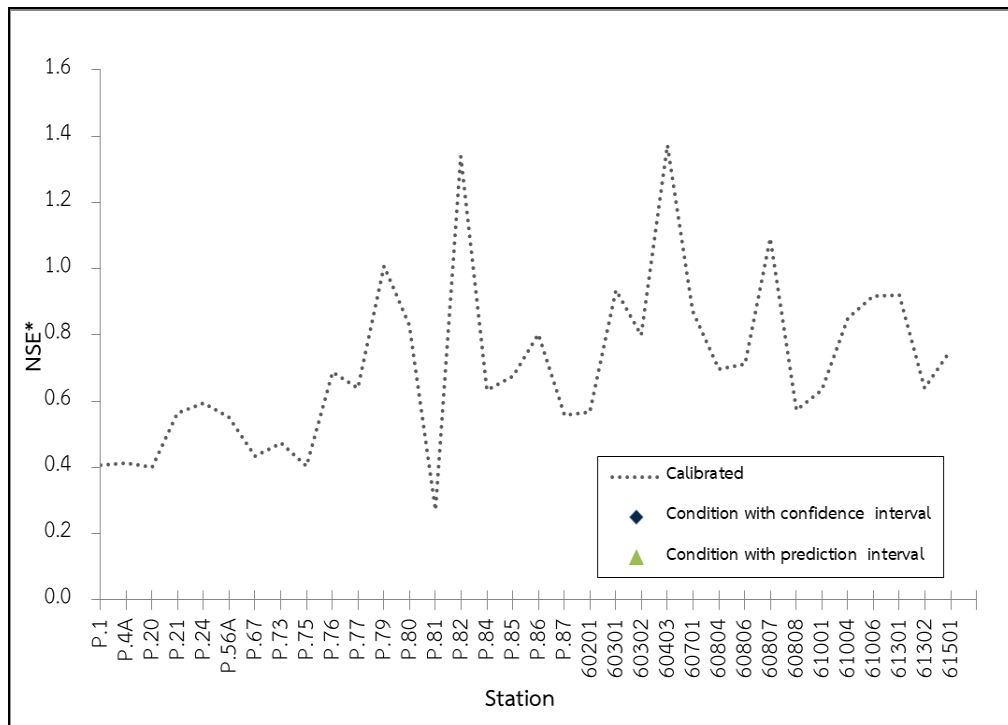
(b) EL



(c) Q95



(d) Q50



(e) Q5

Figure 5.3 NSE* based on the mean and mode of the flow ensemble for the test sub-catchments when the model parameter sets are constrained (conditioned) upon (a) RC, (b) EL, (c) Q95, (d) Q50, and (e) Q5. NSE values < 0 are omitted from the plots.

Variable improvement obtained from constraining the parameter sets is probably due to different characteristics of the catchment. The improved performance of the model when its parameters were constraining using RC was found for the sub-catchments with area less than 2,000 km², elevation less than 800 m. and mild rainfall gradient such as P.20, P.81 and P.75. The constraining method cannot provide good prediction for sub-catchments with steep slopes. The Reliability of the constrained parameter sets based on RC and Q95 is shown in Figure 5.5. When considering Figure 5.4 together with Figure 5.5, it can be seen that Reliability and NSE can be complementary performance measures, as low Reliability can be obtained either for the test sub-catchments with good or poor NSE.

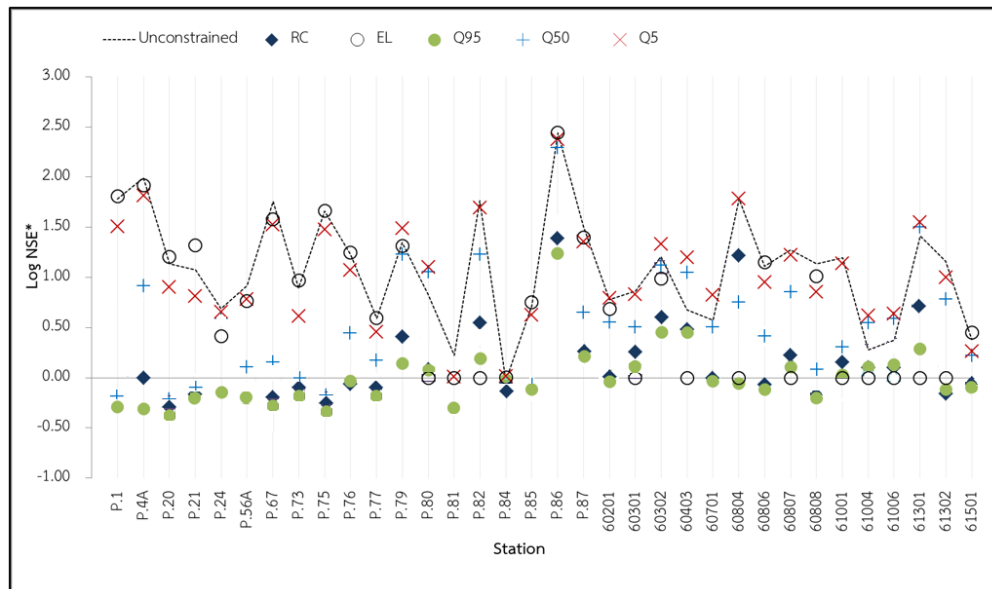


Figure 5.4 Log NSE* for the 34 test sub-catchments when using prior (unconstrained) parameter sets and CI constraining upon different flow indices.

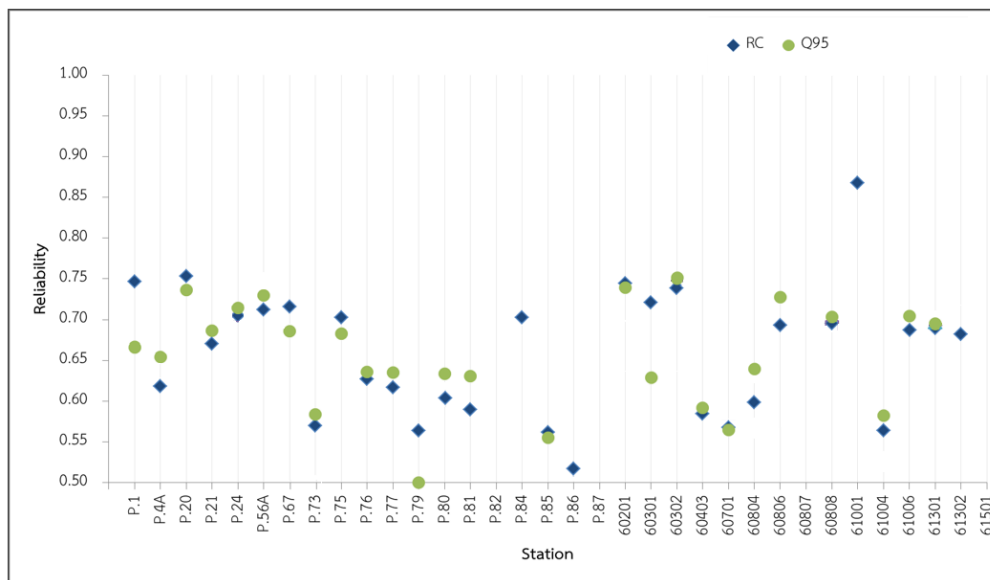
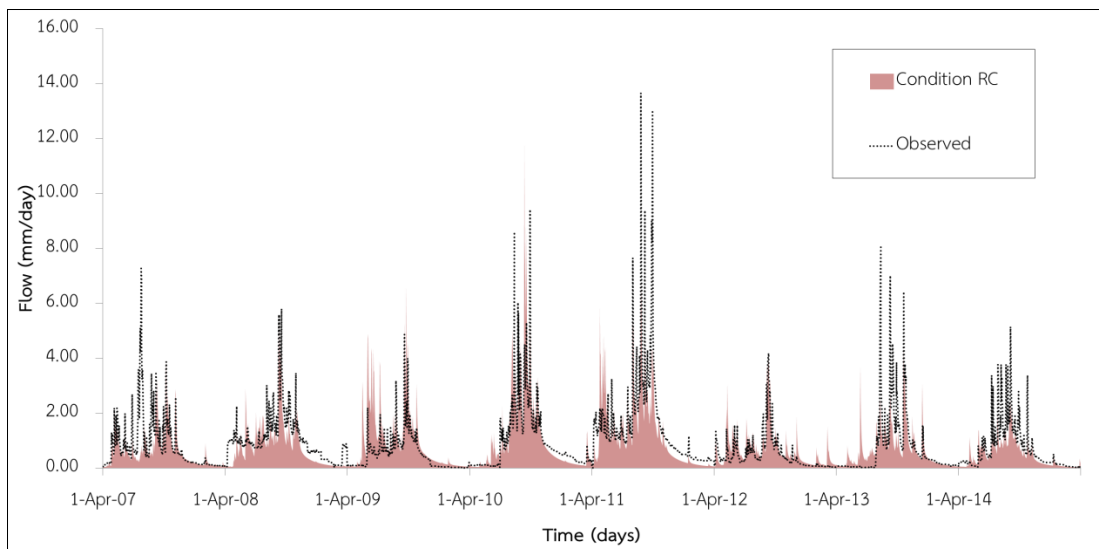


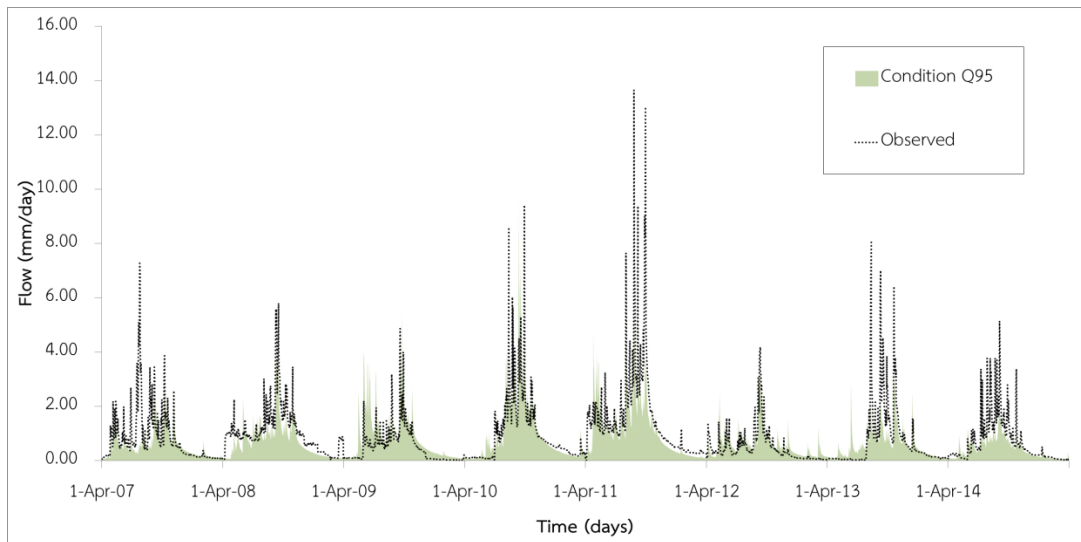
Figure 5.5 Reliability for the 34 test sub-catchments when constraining the parameter sets upon different RC and Q95. Reliability values < 0.5 are omitted from the plots.

5.2. Regionalisation using rainfall-flow indices

The results in section 5.1 suggested that constrained parameter sets based on CI of RC and Q95 could lead to acceptable prediction of the flow indices. Figure 5.6 shows the results of flow predictions for an example of a sub-catchment, P.81. The constrained parameter sets yielded satisfactory results for predicting the overall shape and volume of the hydrograph. However, peak flows and low flows are generally underestimated. The improvement in predicting peak flows and low flows could probably be achieved if the regression equations for rainfall-flow indices such as BFI that is closely linked to soil properties are able to be developed and if some soil properties are identified as significant predictor. It is because the soil data are believed to play an important role in characterising the rising and receding limbs of the hydrograph. The data of soil texture and air dry used in this study are not sufficient to allow them to be included in any regression equations.



(a) RC



(b) Q95

Figure 5.6 Flow prediction for P.81 obtained from constrained parameter sets based on RC and Q95.

The method of constraining parameter sets was demonstrated to be potentially useful for estimating the expected time-series of flow at test ‘ungauged’ sub-catchments; and for estimating the uncertainty intervals, although with less success compared to similar studies in different climate regimes and with better data quality. Important errors are caused by input data for the regression and IHACRES parameter and model structure that is not sufficiently represented by the variance of the regression.

Chapter 5 Conclusion and recommendations

6.1. Conclusion

This study aims to improve flow predictions for ungauged catchments in Thailand using satellite-based products and soil property data. The upper Ping catchment with 48 rain gauges and 34 flow gauges were used as a study catchment. The TRMM satellite rainfall products were used to improve the estimation of the areal rainfall over the catchment. The regression equations for predicting six rainfall-flow indices including RC, BFI, EL, Q95, Q50, and Q5 were developed. 18 catchment properties representing topography, climate, land use and soil characteristics were used as input variables to develop the regression equations. A forward stepwise regression model was adopted for this study. Only three (catchment area, elevation, and mean annual rainfall) out of 18 catchment properties were identified as significant predictors for the flow indices. The r^2 values of the obtained regression range from 0.48 to 0.77. While this study expected to improve the prediction in ungauged catchments by an attempt to collate soil property data from available sources and use them as input into stepwise regression, the regression equation for predicting BFI could not be developed because none of the catchment properties were identified as significant variable. To test the applicability of the obtained regression in predicting the flow indices and flow in the following step, the 5,000 prior parameter sets of the IHACRES rainfall-runoff model were constrained using the CI and PI of the regression equations. When the IHACRES model parameter sets were constrained using the CI and PI of RC and Q95, generally, they yielded satisfactory performance in terms of NSE* ($\text{NSE}^* = 1 - \text{NSE}$) for predicting the flow indices over all 34 test sub-catchments compared to that of the EL, Q50, and Q5. Constraining using CI gave better NSE* values than using the PI. While the ranges of CI and PI for EL and Q5 were not small, they were too narrow to constrain the parameter sets; only one or none parameter set could be obtained from constraining using the CI and PI of EL and Q5. The constraining method performs particularly well for sub-catchments with the area less than 2,000 km², elevation less than 800 m.

and mild rainfall gradient. The constrained parameter sets of RC and Q95 yielded satisfactory results for predicting the overall shape and volume of the hydrograph but they underestimated peak flows and low flows. While constraining method could reduce uncertainty generated by the prior parameter sets, uncertainty caused by the input and IHACRES model parameter and structure passed on to flow predictions is yet high. Further improvement is still needed for future research.

6.2. Recommendations

It is believed that soil property data are important to the prediction of the hydrograph and flow time series in ungauged catchments. However, the soil property data used in this study were probably too little and too coarse. When mapping the descriptive soil data from LDD with satellite-based soil data from the WISE pedon-database, only the property of soil particle sizes (%sand, %silt, and %clay) and air dry were obtained. Other properties, such as available and saturated water capacity, texture, bulk density, and chemical properties that could be closely linked to the flow were not available in the WISE pedon-database for Thailand. The 1 x1 km soil grid data originally provided in the WISE pedon-database at the initial stage of the development of the soil grid data were too coarse to represent heterogeneity of the soil over each sub-catchment in the Ping catchment. The updated version of the soil grid provided in the Data Hub of ISRIC (<https://data.isric.org/geonetwork/srv/eng/catalog.search#/>) could contribute to the improvement of soil data mapping and allow the soil properties to be included in the regression equation. The assessment of the newer version of the soil grid data is recommended for future study.

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Appendix

Table A. 1 Locations of 112 rain gauges

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)	Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
1	200013	19.2981	97.9681	21	80123	19.9000	99.8002
2	200023	18.1567	97.9347	22	80152	19.8000	99.6835
3	200032	18.8292	97.9394	23	80172	19.0772	99.3989
4	200062	18.3792	97.9369	24	80270	19.8319	99.7680
5	200111	19.2694	97.9486	25	80282	20.0128	100.0564
6	200132	19.5414	98.2108	26	70013	18.8397	98.9756
7	630033	16.7119	98.5789	27	70022	18.7133	99.0414
8	630052	16.9806	98.5206	28	70032	18.7442	99.1244
9	630092	17.2244	98.2281	29	70042	18.8475	99.0483
10	630181	16.7622	98.7539	30	70052	18.8689	99.1394
11	630202	16.3744	98.6853	31	70082	18.6269	98.8989
12	630233	16.7500	98.9333	32	70122	19.3644	99.2047
13	376002	16.9822	98.5203	33	70132	19.3647	98.9667
14	383002	16.5333	104.6667	34	70142	18.8478	98.7358
15	383004	16.8161	104.5472	35	70152	18.4983	98.3650
16	383005	16.7250	104.7433	36	70162	17.7958	98.3600
17	70102	19.9172	99.2167	37	70182	18.4158	98.6797
18	71093	19.9314	99.0983	38	70242	18.8028	98.9250
19	80013	19.9072	99.8360	39	70252	19.2686	98.9756
20	80102	19.6550	99.5468	40	70262	18.8067	98.9033

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
41	70282	18.1503	98.3931
42	70292	18.6111	98.9006
43	70391	18.7892	99.0169
44	70472	17.9167	98.6833
45	70502	19.0667	99.2167
46	70714	18.3069	98.3658
47	70731	17.7836	98.3753
48	70751	19.6367	98.6389
49	70760	18.9408	99.2378
50	70770	18.8594	99.2772
51	70780	19.1094	99.1808
52	70792	18.9219	99.3181
53	70801	18.6517	98.6897
54	70810	18.7053	98.5508
55	70982	18.6119	98.7747
56	70992	18.6231	98.5117
57	71002	18.7436	98.9222
58	80252	19.5269	99.0291
59	170032	18.5256	98.9397
60	170052	18.3144	98.8225

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
61	170062	17.6556	98.7750
62	170093	18.5833	99.0333
63	170181	18.1397	98.8994
64	630172	17.3453	98.6464
65	327011	18.7131	99.0411
66	327012	18.8475	99.0453
67	327016	19.3647	98.9675
68	327020	18.8058	98.9225
69	327025	19.0947	99.0869
70	327501	18.7900	98.9769
71	329003	18.5236	98.9436
72	329201	18.5667	99.0333
73	376001	17.0464	99.0758
74	630013	16.8806	99.1267
75	630022	17.0461	99.0761
76	630062	17.2422	99.0244
77	630132	17.3020	98.7738
78	630152	16.9167	99.1167
79	630162	17.3333	98.8833
80	630192	16.9198	98.9290

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
81	376007	16.9167	99.1167
82	376008	17.2497	98.8658
83	376009	17.3742	98.8225
84	376010	17.3442	98.6569
85	376203	17.2333	99.0531
86	630073	17.2417	99.0625
87	328004	18.3256	99.3514
88	328005	17.6097	99.2189
89	328006	18.1900	99.3986
90	328008	19.1444	99.6217
91	400013	18.1456	100.1450
92	400022	18.0494	100.1147
93	400032	18.3392	100.3200
94	400043	18.4700	100.1833
95	400052	18.0736	99.8361
96	400062	17.8989	99.6067
97	400072	17.9833	100.1000
98	400082	18.2667	100.1667
99	400092	17.9822	100.0544
100	400111	18.5842	100.1547

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
101	400124	18.3833	100.3667
102	400151	18.1331	100.1217
103	400242	18.2297	100.2239
104	730082	18.8864	100.3033
105	328010	18.6667	99.9167
106	330004	17.9822	100.0553
107	330005	18.4678	100.1883
108	373002	17.3153	99.8347
109	373003	16.9506	99.9803
110	373004	17.5158	99.8139
111	373011	17.2989	99.8742
112	386301	16.4361	100.2889

Table A. 2 Locations of 84 flow gauges

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)	Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
1	Sw.5A	19.2683	97.9486	26	P.21	18.9247	98.9428
2	Sw.6	16.7600	98.7544	27	P.24	18.4169	98.6747
3	10201	19.4000	98.4533	28	P.56A	19.2839	99.1903
4	10503	19.2333	97.9333	29	P.67	19.0197	98.9617
5	10504	19.2231	98.3658	30	P.73	18.2883	98.6531
6	10602	19.1667	97.9700	31	P.75	19.1478	99.0100
7	10901	18.5367	97.9533	32	P.76	18.1397	98.8994
8	11103	18.1911	97.9992	33	P.77	18.4325	99.0833
9	11701	16.8100	98.7600	34	P.79	18.9672	99.2444
10	11805	16.9817	98.6583	35	P.80	18.9119	99.2381
11	G.4	19.8397	99.6742	36	P.81	18.6936	99.0819
12	G.8	19.7897	99.7531	37	P.82	18.6522	98.6906
13	G.9	19.7475	99.5075	38	P.84	18.5889	98.7997
14	G.10	19.6558	99.5472	39	P.85	18.3639	98.7756
15	G.11	19.6206	99.4806	40	P.86	18.7383	99.2217
16	030101	20.0600	99.3633	41	P.87	18.5178	98.9450
17	030102	19.9400	99.7383	42	60201	19.3211	98.9344
18	030201	20.0200	99.3583	43	60301	19.4506	99.2178
19	030216	20.0331	99.2456	44	60302	19.3739	99.2489
20	030301	19.8533	99.8433	45	60403	19.3792	98.6956
21	030306	19.1458	99.4697	46	60701	18.9567	99.2386
22	030308	19.0833	99.4583	47	60804	18.6650	98.6317
23	P.1	18.7858	99.0081	48	60806	18.7950	98.7247
24	P.4A	19.1208	98.9475	49	60807	18.6517	98.6917
25	P.20	19.3525	98.9736	50	60808	18.6083	98.8567

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
51	61001	18.5400	98.5950
52	61004	18.3625	98.5350
53	61006	18.2828	98.5286
54	61301	18.5461	98.3553
55	61302	18.5483	98.3583
56	61501	17.3864	98.4711
57	P.2A	16.8539	99.1306
58	P.7A	16.4772	99.5183
59	P.12	17.2417	99.0125
60	W.1C	18.2975	99.5156
61	W.3A	17.6414	99.2344
62	W.4A	17.2061	99.1022
63	W.10A	18.5211	99.6311
64	W.16A	18.7792	99.6311
65	W.17	18.7211	99.5700
66	W.20	18.3097	99.4581
67	W.21	18.3406	99.5397

Gauge order	Gauge code	Latitude (°N)	Longitude (°E)
68	W.22	18.1442	99.4084
69	Y.1C	18.1331	100.1275
70	Y.3A	17.3081	99.8286
71	Y.13A	18.7589	99.9769
72	Y.14	17.5950	99.7189
73	Y.16	16.7597	100.1278
74	Y.17	16.5139	100.2111
75	Y.20	18.5842	100.1547
76	Y.24	18.8844	100.2900
77	Y.26	17.3292	99.4617
78	Y.29	17.7025	99.7403
79	Y.30	18.7164	99.9611
80	Y.31	18.9575	100.2689
81	Y.34	18.2197	100.2100
82	Y.36	19.1569	100.3269
83	Y.37	17.8947	99.6075
84	Y.38	18.2656	100.2886