Final Report
ARCP2014-13CMY-STHIANNOPKAO

"Developing Scientific and Management Tools to Address Impacts of Changing Climate and Land Use Patterns on Water Quality in East Asia's River Basins"

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"Developing Scientific and Management Tools to Address Impacts of Changing Climate and Land Use Patterns on Water Quality in East Asia's River Basins"

Final Report Submitted to the APN

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Part One: Overview of Project Work and Outcomes

Non-technical Summary

This project addresses the question: “What effects are climate change and land use pattern change having on the water cycle and water quality in East Asia’s river basins?”. Models showing interactions among climate, hydrology, land use and water quality are constructed for both the temperate climate of Korea and the tropical climate of Southeast Asia. Specifically, the expected impact of climate changes related to extreme events on loadings of nutrients and microorganisms are determined. This entails a hydrologic/water quality model combined with a climate change model. General Circulation Model (GCM) products are downscaled to be applicable to a hydrologic model. A Soil and Water Assessment Tool (SWAT) model simulates hydrologic processes and the water quality resulting. Validation of predicted with actual results is conducted using both our water quality monitoring data and data collected by local water quality agencies. This project furthermore generates knowledge about changing climate and land use pattern impacts on water quantity and quality at a river basin scale in East Asia. Finally, this project provides scientific baseline information that can be translated into practical knowledge, including tools for assessing and managing risks associated with changes in water quality under rapidly changing climate and land use patterns.

Keywords

SWAT, impacts, climate change, hydrologic cycle, East Asia´s river basins

Objectives

1. To develop scientific and management tools for analysing and predicting impacts from changing climate and land use patterns on hydrologic cycles and water quality in East Asia.
2. To advance the capacity of participants from Southeast Asia for water quality monitoring and management.

Amount Received and Number of Years Supported

The Grant awarded to this project was:

US$ 40,000 for Year 1

US$ 36,000 for Year 2

Activities Undertaken

- Organised a series of workshops with local universities in Bangkok, Thailand; Vientiane, Laos; and Gwangju, Republic of Korea
- Developed a basin-level model to predict impacts of changing climate and land use on surface water quality and hydrologic cycles with a focus on loadings of nutrients and microorganisms
- Conducted samplings of the Chao Phraya River
- Uploaded project outcomes onto our project website (www.apnseaclimate.com)

Results

- Series of meetings and workshops with local universities in Bangkok, Thailand; Vientiane, Laos; and Gwangju, Republic of Korea
  1. The 1st APN meeting entitled "Developing Scientific and Management Tools to Address Impacts of Changing Climate and Land Use Patterns on Water Quality in East Asia's River Basins" was organised at Chulalongkorn University in Bangkok, Thailand, August 5-6, 2014.
  2. The 2nd APN meeting entitled "Developing Scientific and Management Tools to Address Impacts of Changing Climate and Land Use Patterns on Water Quality in East Asia's River Basins" was held at the National University of Laos in Vientiane, Laos, August 11-12, 2015.
  3. The 2nd IEAEC workshop focusing on "Science and Technical Training for Water Quality Monitoring and Management of Sustainable Water Resources" was held at Gwangju Institute of Science and Technology (GIST) in Gwangju, Republic of Korea, October 7-17, 2014. Mr. Dalavone Xayasack from the National Center for Environmental Health and Water Supply of Laos was invited to participate with full financial support from IERC-GIST, Korea. Dr. Kenneth Widmer (our Co-PI of this project) works at IERC-GIST.
  4. The 3rd IEAEC workshop focusing on "Science and Technical Training for Water Quality Monitoring and Management of Sustainable Water Resources" was held at Gwangju Institute of Science and Technology (GIST) in Gwangju, Republic of Korea, July 21-31, 2015. The following 7 participants from Laos were invited to participate with full financial support from IERC-GIST, Korea.

Mr. Phetdala Oudone	Faculty of Environmental Sciences, National University of Laos
Mr. Sopha Keoinpaeng	Department of Chemistry, Faculty of Natural Science, National University of Laos
Mr. Vanhsamay Thongkhammerng	Department of Water Resources, Vientiane Province
Ms. Chanlakhone Homkingkeo	Department of Water Resource, Ministry of Natural Resources and the Environment (MoNRE)
Ms. Sengbouapha Palamy	Natural Resources and Environmental Institute, MoNRE
Mr. Saykham Nouanthasing	Department of Water Resources, Xiang Khouang Province
Ms. Kesone Sengchandala	Department of Water Resources, MoNRE

- Developing a basin-level model to predict impacts of changing climate and land use on surface water quality and hydrologic cycles with a focus on loadings of nutrients and microorganisms
    1. Hydrologic response to climate change impacts on water quality and quantity in the Chao Phraya River basin, Thailand
    2. Hydrologic response assessment in the Nam Khan watershed, Laos, using SWAT: Application of RCP scenarios from climate models and land use scenarios

- Samplings from the Chao Phraya River
    1. Ms. Thunchanok Thongsamer (our project member from KMUTT, Thailand) received financial support from IERC-GIST for a period of 6 months in 2014 for her training focusing on molecular analysis for verifying E. coli DNA in the Chao Phraya River.
    2. This project significantly expanded the capabilities of the following Masters students from KMUTT, Thailand for water quality sampling and analysis:

        Ms. Thunchanok Thongsamer

        Thesis title: Effect of Land Use on Microbial Quality along the Chao Phraya River

        Ms. Thippawan Tungsawat

        Thesis title: Water Quality of Irrigated Paddy Fields and Its Effect on the Vicinity

        Ms. Kwanjira Chantaraprabha

        Thesis title: Relation of Chemical and Physical Quality and Land Use Patterns along the Chao Phraya River

        Ms. Nanthachat Pookang

        Thesis title: Pollution Load along the Chao Phraya River Bank around Chong Nonsi Water Environment Control Plant

        Ms. Nathacha Wiriyaphong

        Thesis title: River Water Quality and Pollution Load during the Wet Season in Nakhon Sawan Municipality

    3. The technical report entitled "Effects of seasonal and land use changes on the Chao Phraya River´s water quality, Thailand''

- Uploading project outcomes onto our project website (www.apnseaclimate.com)
    1. Model results from various scenario analyses were uploaded on the website.

Relevance to the APN Goals, Science Agenda and to Policy Processes

This project is a regional study aimed at developing scientific and management tools for analysing and predicting impacts resulting from changing climate and land use patterns on water quality and hydrologic cycles in East Asia. Knowledge has been generated relevant to the prediction and management of loadings of nutrients and microorganisms according to changing climate and land use patterns. Policy makers in each participating country have been invited as team members to participate in developing a prediction model. In addition, both participating and invited scientists and policy makers from Southeast Asia have taken part in a series of workshops held in Bangkok, Thailand; Vientiane, Laos; and Gwangju, Republic of Korea to update their knowledge of water quality monitoring and management.

Self-evaluation

All planned research activities are carried out. Some difficulties occurred accessing monitoring data for the lower Mekong River, but our local participants in Laos have given their very best to provide the available data. However, the project goal of implementing the model we've developed has not yet been fully reached.

Potential for Further Work

1. More sampling activities are needed to verify our modelling results. In particular, we could not obtain sufficient data from the Laos watershed.
2. Implementation is needed for the model we've developed for the Chao Phraya River in Thailand.

Publications

1. SCI Journal

Ligaray, M., Kim, H., Sthiannopkao, S., Lee, S., Cho, K., & Kim, J. (2015). Assessment on Hydrologic Response by Climate Change in the Chao Phraya River Basin, Thailand. Water, 7(12), 6892–6909. http://doi.org/10.3390/w7126665

2. Conference Papers

Tungsawat, T., Vinitnantharat, S., & Phoolphund, S. (2015). Water quality in irrigated field and surface water. In PACCON 2015: Innovative Chemistry for Sustainability of the AEC and Beyond. Amari Watergate Hotel, Bangkok, Thailand. Retrieved from http://paccon2015.kmutt.ac.th/

Wiriyaphong, N., & Vinitnantharat, S. (2015). Water quality and organic loads along the Chao Phraya River in Nakhon Sawan municipality. In PACCON 2015: Innovative Chemistry for Sustainability of the AEC and Beyond. Amari Watergate Hotel, Bangkok, Thailand. Retrieved from http://paccon2015.kmutt.ac.th/

Thongsamer, T., Vinitnantharat, S., & Phoolphundh, S. (2015). Effect of water depth, season and land use on the microbial numbers along the Chao Phraya River. In The 5th National and International Graduate Study Conference 'Creative Education: Intellectual Capital toward ASEAN'. Princess Mahachakri Sirindhon Anthropology Centre, Thailand. Retrieved from http://www.graduate.su.ac.th/images/proceedings/2015/proceedings.pdf

Chantaraprabha, K., & Vinitnantharat, S. (2014). Effect of drought on water resource: a case study of Chao Phraya River. Presented at the The 5th International Conference on Sustainable Energy and Environment (SEE 2014): Science, Technology and Innovation for ASEAN Green Growth, Anantara Bangkok Riverside Resort and Spa, Bangkok, Thailand.

Pookang, N., Vinitnantharat, S., & Buddhawong, S. (2014). Investigation of nutrient and coliform bacteria from non-point source on the Chao Phraya river bank in dry season. Presented at the The 5th International Conference on Sustainable Energy and Environment

(SEE 2014): Science, Technology and Innovation for ASEAN Green Growth, Anantara Bangkok Riverside Resort and Spa, Bangkok, Thailand.

References

Ligaray, M., Kim, H., Sthiannopkao, S., Lee, S., Cho, K., & Kim, J. (2015). Assessment on Hydrologic Response by Climate Change in the Chao Phraya River Basin, Thailand. Water, 7(12), 6892–6909. http://doi.org/10.3390/w7126665

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We would like very much to thank firstly the APN (Asia-Pacific Network for Global Change Research) for funding this research project and the IERC-GIST, Republic of Korea, for funding our capacity building programs in the Republic of Korea. We likewise sincerely thank all of our team members from the Republic of Korea, Thailand and Laos for their hard work and for all the time they have dedicated to this project.

Part Two: Technical Report

Preface

In the 20th century, the challenge for water management was the rise and concentration of populations. In this century, the paramount challenge for water policy and technology is a changing climate. Changes in temperature and amounts and distribution of rainfall will affect how land is used, and that in turn affect the water running off it. Populations will rely on rivers whose water characteristics have altered. This research and its funding were organized with the aim of discovering what reasonable predictions can be made about how land use, water and rivers may change as this century progresses.

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1. Hydrologic response to climate change impacts on water quality and quantity in the Chao Phraya River basin, Thailand

1.1 Introduction

The Chao Phraya River basin has experienced many extreme floods in the past. The most recent occurred in 2011 and caused $45.7 billion in direct losses and secondary economic damage (Ziegler et al., 2012). It is necessary now to understand the characteristics of the Chao Phraya River basin's hydrological response to climate change in order to prepare the water resources management facilities needed to handle future events.

The objectives of this study are therefore 1) to simulate water quantity and water quality throughout the Chao Phraya River basin employing assessment tools, and 2) to assess water quantity and quality in response to climate change scenarios, using climate sensitivity scenarios and the special report on emission scenarios (SRES). The results of this research should help create the foundation for proper water resource planning based on climate change scenarios, and beyond this provide a means for evaluating and coping with highly variable climate conditions.

1.2 Methodology

1.2.1 SWAT model simulation

The SWAT model simulation period was the 9 years from 2003 to 2011. This was divided into 3 parts: a spin-up time (2003), a calibration period of 5 years (2004-2008) and a 3-year validation period (2009-2011).

1.2.2 Modelling setup

To build up the Chao Phraya River basin model, a model database was constructed of topographical data, consisting of digital elevation maps, land use, soil type and river basin extent; the meteorological data of precipitation and maximum and minimum temperature; and the observed monitoring data of flow discharge and water quality.

1.2.3 Model evaluation criteria

The evaluation criteria assess performance of the model through comparisons of simulated and observed data. To do this, we made use of a coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE).

1.2.4 Climate sensitivity scenarios

Hydrological response was assessed using hypothetical climate sensitivity scenarios. Table 1 displays the temperature, precipitation and CO_2 concentration components of climate sensitivity scenarios. The reference condition is no change in precipitation or temperature, under a 330ppm CO_2 concentration. For scenarios 1 through 3, CO_2 concentration is doubled to 660ppm, with high variations in precipitation and air temperature. For scenarios 4 through 7, precipitation is varied while CO_2 concentration and air temperature are held constant. For scenarios 8 through 10, air temperature increases while CO_2 concentration and precipitation are constant.

Table 1. Climate sensitivity scenarios for annual average conditions relative to the reference

Scenario	CO_2 concentration (ppm)	Precipitation change (%)	Temperature (° C)
Reference	330	0	0
1	CO_2×2 = 660	0	0
2	CO_2×2 = 660	+20	0
3	CO_2×2 = 660	0	+6
4	330	+10	0
5	330	+20	0
6	330	-10	0
7	330	-20	0
8	330	0	+1
9	330	0	+3
10	330	0	+6

1.3 Results & Discussion

1.3.1 Sensitivity analysis of the SWAT model

A sensitivity analysis was performed using Latin hypercube one factor at a time (LH-OAT). The process of calibrating the model was first for flow discharge, secondly for sediment, then for total phosphorus and total inorganic nitrogen (Van Griensven et al., 2006).

1.3.1.1 Flow discharge sensitivity analysis

Thirty-six hydrological model parameters were tested to identify those most sensitive for simulation of flow discharge (Table 2). Auto-calibration and uncertainty analysis (e.g., Parameter Solution (Para-Sol) and Sequential Uncertainty Fitting (SUFI-2) in the SWAT) were applied to determine the optimal model parameters (Schuol et al., 2008). Table 2 displays sensitivity analysis parameter rankings for flow discharge, according to the sensitivity value for each parameter. The results of the sensitivity analysis shows that initial SCS runoff curve numbers for moisture condition 2 (CN2) and baseflow alpha factor-baseflow recession (Alpha_Bf) were the most sensitive factors. Following these were deep aquifer percolation fraction (Rchrg_Dp), soil evaporation compensation factor (Esco), threshold depth of water in the shallow aquifer for percolation to the deep aquifer (Revapmn), effective hydraulic conductivity in main channel alluvium (Ch_K2), available water capacity of the soil layer (Sol_AWC), threshold depth of water in the shallow aquifer required for return flow to occur (Gwqmn), depth from soil surface to bottom of layer (Zol_Z) and groundwater “revap” coefficient (Gw_Revap); these parameters were mostly related to groundwater and soil processes. The ten most sensitive flow discharge parameters were selected for model calibration.

Table 2. Flow discharge parameters for the sensitivity analysis with bounds, sensitivity rank, sensitivity value and calibration

RANK	NAME	Min	Max	Sensitivity value	Calibration value	Definition	Process
1	Cn2	35	98	1.49E+00	2.56E+00	SCS runoff curve number for moisture condition 2	Runoff
2	Alpha_Bf	0.00	1.00	1.42E+00	9.47E-01	Baseflow alpha factor (days)	Groundwater
3	Rchrg_Dp	0.00	1.00	6.57E-01	1.30E-01	Deep aquifer percolation fraction	Groundwater
4	Esco	0.00	1.00	4.76E-01	2.63E-02	Soil evaporation compensation factor	Evaporation
5	Revapmn	-100.0	100.0	2.21E-01	-9.94E+01	Threshold depth of water in the shallow aquifer for percolation to the deep aquifer (mmH_2O)	Groundwater
6	Ch_K2	0.00	150.0	1.95E-01	2.30E-01	Effective hydraulic conductivity in main channel alluvium (mm/hr)	Channel
7	Sol_Awc	-25.0	25.0	1.81E-01	-1.74E+01	Available water capacity of the soil layer (mm/mm soil)	Soil
8	Gwqmn	-1000.0	1000.0	1.39E-01	1.08E+02	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	Soil
9	Sol_Z	-25.0	25.0	6.93E-02	-5.14E+00	Soil depth	Soil
10	Gw_Revap	-0.036	0.036	5.74E-02	6.05E-03	Groundwater “revap” coefficient	Groundwater
11	Surlag	0.00	10.00	4.87E-02	4.00E-07	Surface runoff lag coefficient	Runoff
12	Blai	0.00	1.00	2.23E-02		Leaf area index for crops	Crop
13	Slope	0.0001	0.6	1.50E-02		Average slope steepness (m/m)	Geomorphology
14	Canmx	0.00	10.00	1.32E-02		Maximum canopy index	Runoff
15	Epco	0.00	1.00	1.20E-02		Threshold depth of water in the shallow aquifer to percolation to the deep aquifer (mmH_2O)	Evaporation
16	Ch_N2	0.00	1.00	9.62E-03		Manning coefficient for channel	Channel
17	Sol_K	0	100	8.55E-03		Soil conductivity	Soil
18	Gw_Delay	1	50	5.80E-03		Groundwater delay time (days)	Groundwater
19	Timp	0.00	1.00	2.31E-04		Snow pack temperature lag factor	Snow
20	Slsubbsn	10	150	1.97E-04		Average slope length (m)	Geomorphology

RANK	NAME	Min	Max	Sensitivity value	Calibration value	Definition	Process
21	Biomix	0.00	1.00	1.83E-04		Biological mixing efficiency	Soil
22	Smtmp	-25.0	25.0	8.15E-05		Snow melt temperature	Snow
23	Nperco	0.00	1.00	7.78E-05		Nitrogen percolation coefficient	Soil
24	Phoskd	100.0	200.0	0.00E+00		Phosphorus soil partitioning coefficient	Soil
25	Pperco	10.0	18.0	0.00E+00		Phosphorus percolation coefficient	Soil
26	Sftmp	0.00	5.00	0.00E+00		Snowfall temperature	Snow
27	Shallst_N	0.00	10.00	0.00E+00		Initial concentration of nitrate in shallow aquifer (mgN/L orppm)	Groundwater
28	Smfmn	0.00	10.00	0.00E+00		Melt factor for snow on December 21	Snow
29	Smfmx	0.00	10.00	0.00E+00		Melt factor for snow on June 21	Snow
30	Sol_Alb	-25.0	25.0	0.00E+00		Soil albedo	Evaporation
31	Sol_Labp	-25.0	25.0	0.00E+00		Moist soil albedo	Soil
32	Sol_No3	-25.0	25.0	0.00E+00		Initial NO3 concentration (mg/kg) in the soil layer	Soil
33	Sol_Orgn	-25.0	25.0	0.00E+00		Initial organic N concentration in surface soil layer (kg/ha)	Soil
34	Sol_Orgp	-25.0	25.0	0.00E+00		Initial organic P concentration in surface soil layer (kg/ha)	Soil
35	Tlaps	0.00	50.00	0.00E+00		Temperature lapse rate (°C /km)	Geomorphology

1.3.1.2 Sediment sensitivity analysis

Seven sediment model parameters were tested to identify the most sensitive parameters for simulation. Table 3 indicates the sensitivity analysis rankings for sediment according to the sensitivity value for each parameter, and shows the parameter range minimum and maximum, and the calibration value. The sensitivity analysis results show the channel cover factor (CH_COV) was the most sensitive factor, followed by channel erodibility factor (CH_EROD), peak rate adjustment factor for sediment routing in the main channel (PRF), linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing (SPCON) and exponent parameter for calculating sediment reentrained in channel sediment routing (SPEXP). These five sensitive sediment parameters were selected to calibrate the model.

Table 3. Sediment parameters for sensitivity analysis with bounds, sensitivity rank, sensitivity value and calibration

RANK	NAME	Min	Max	Sensitivity value	Calibration value	Definition	Process
1	CH_COV	-0.001	1.00	2.74E+02	0.031	Channel cover factor	Sediment
2	CH_EROD	-0.05	0.60	1.42E+02	0.403	Channel erodibility factor	Sediment
3	PRF	0.00	2.00	1.32E+02	0.001	Peak rate adjustment factor for sediment routing in the main channel	Sediment
4	SPCON	0.0001	0.001	1.10E+02	1	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	Sediment
5	SPEXP	1.0	1.5	2.35E+01	0.953	Exponent parameter for calculating sediment reentrained in channel sediment routing	Sediment
6	USLE_P	0.1	1.0	0.00E+00		USLE support practice factor	Sediment
7	ADJ_PKR	0.5	1.5	0.00E+00		Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)	Sediment

1.3.1.3 Total phosphorus sensitivity analysis

Thirteen total phosphorus model parameters were tested to identify the most sensitive parameters for simulation. Table 4 shows the sensitivity analysis rank for the total phosphorus parameters, displaying the parameter range minimum and maximum, along with the calibration value. The sensitivity analysis results show that concentration of soluble P in ground water contribution to streamflow from the subbasin (GWSOLP) was the most sensitive factor, followed by phosphorus uptake distribution parameter (P_UPDIS), phosphorus sorption coefficient (PSP), phosphorus soil partitioning coefficient (PHOSKD) and phosphorus percolation coefficient (PPERCO). These five total phosphorus parameters were selected as the most sensitive for model calibration.

Table 4. Total phosphorus parameters for the sensitivity analysis with bounds, sensitivity rank, sensitivity value and calibration

RANK	NAME	Min	Max	Sensitivity value	Calibration value	Definition	Process
1	GWSOLP	0.001	1.000	1.34E+02	0.076	Concentration of soluble P in ground water contribution to streamflow from the subbasin (mg P/ L or ppm)	Groundwater

RANK	NAME	Min	Max	Sensitivity value	Calibration value	Definition	Process
2	P_UPDIS	1.00	100.0	3.55E-01	1.031	Phosphorus uptake distribution parameter	Phosphorus
3	PSP	0.01	0.7	2.24E-01	0.698	Phosphorus sorption coefficient	Phosphorus
4	PHOSKD	50	400	3.11E-02	225	Phosphorus soil partitioning coefficient (m^3 mg^{-1})	Phosphorus
5	PPERCO	10.00	17.50	3.02E-02	13.75	Phosphorus percolation coefficient (m^3 mg^{-1})	Phosphorus
6	RHOQ	0.05	0.50	1.01E-06		Algal respiration rate	Algae
7	MUMAX	1.0	3.0	1.13E-08		Maximum specific algal growth rate	Algae
8	RSDCO	0.02	0.20	0.00E+00		Residue decomposition coefficient	Nutrient
9	BC4	0.01	0.70	0.00E+00		Rate constant for mineralization of organic P to dissolved P (1/day)	Phosphorus
10	RS5	0.001	0.100	0.00E+00		Organic phosphorus settling rate in the reach to 20°C (1/day)	Phosphorus
11	RS2	0.001	0.100	0.00E+00		Benthic (sediment) source rate for dissolved P in reach at 20°C	Phosphorus
12	AI2	0.01	0.20	0.00E+00		Fraction of algal biomass that is phosphorus (mg P/ mg alg)	Algae
13	ERORGP	0.00	5.00	0.00E+00		Organic P enrichment ratio	Phosphorus

1.3.1.4 Total inorganic nitrogen sensitivity analysis

Total inorganic nitrogen consists of ammonium nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N) and nitrate nitrogen (NO_3^--N). Sixteen total inorganic nitrogen model parameters were tested to identify the parameters sufficiently sensitive for use in simulation. Table 5 indicates the sensitivity analysis ranks for total inorganic nitrogen according to the sensitivity values of each parameter; it also shows the parameter range minimum and maximum, and calibration values. The sensitivity analysis results show that denitrification threshold water content (SDNCO) was the most sensitive factor, and with half-life of nitrate in the shallow aquifer (HLIFE_NGW), denitrification exponential rate coefficient (CDN), nitrogen percolation coefficient (NPERCO), concentration of nitrate in precipitation (RCN) and benthic source rate for NH_4^+-N in the reach at 20°C (RS3) constituted the six sensitive total inorganic nitrogen parameters selected for model calibration.

Table 5. Total inorganic nitrogen parameters for the sensitivity analysis with bounds, sensitivity rank, sensitivity value and calibration

RANK	NAME	Min	Max	Sensitivity value	Calibration value	Definition	Process
1	SDNCO	0.00	1.40	6.17E+02	0.948	Denitrification threshold water content	Nitrogen Cycle
2	HLIFE_NGW	0.0	200.0	3.10E+02	0.031	Half-life of nitrate in the shallow aquifer	Nitrogen
3	CDN	0.0	3.0	4.51E+01	0.075	Denitrification exponential rate coefficient	Nitrogen
4	NPERCO	0.00	1.00	2.05E+01	0.068	Nitrogen percolation coefficient	Nutrient
5	RCN	0.25	1.50	5.46E+00	1.48	Concentration of nitrate in precipitation (mg N/L)	Nitrogen
6	RS3	0.001	0.100	1.21E+00	0.004	Benthic source rate for NH4-N in the reach at 20°C (mg NH_4-N/(m^2·day)	Channel Nutrient Routing
7	N_UPDIS	1.00	100.0	1.66E-01		Nitrogen uptake distribution parameter	Nitrogen Cycle
8	BC2	0.20	2.00	9.04E-03		Rate constant for biological oxidation of NO2 to NO3 in the reach at 20°C (day^{-1})	Channel Nutrient Routing
9	BC1	0.10	1.00	8.06E-03		Rate constant for biological oxidation of NH4 to NO2 in the reach at 20°C (day^{-1})	Channel Nutrient Routing
10	BC3	0.2	0.4	1.00E-04		Benthic source rate for NH4-N in the reach at 20°C	Channel Nutrient Routing
11	RS4	0.001	0.100	6.74E-05		Rate coefficient for organic N settling in the reach at 20°C (day^{-1})	Channel Nutrient Routing
12	CMN	0.0001	0.003	0.00E+00		Rate factor for humus mineralization of active organic nitrogen	Nitrogen
13	RSDCO	0.02	0.20	0.00E+00		Residue decomposition coefficient	Nutrient
14	SHALLST_N	0	1000	0.00E+00		Initial concentration of nitrate in shallow aquifer [mg N/L]	Nitrogen
15	AI1	0.20	0.09	0.00E+00		Fraction of algal biomass that is nitrogen [mg N/mg alg]	Nitrogen
16	ERORGN	0.00	5.00	0.00E+00		Organic N enrichment ratio	Nutrient

1.3.2 Calibration and validation of the SWAT model

Following on the sensitivity analysis, the calibration and validation of SWAT were performed. The time period of the SWAT model was 9 years, including spin-up time (2003), calibration (2004-2008) and validation (2009-2011).

1.3.2.1 Flow discharge calibration and validation

The calibration process for flow discharge was determined from the sensitivity analysis results. The topmost 10 parameters were selected, and the result was observed and simulated calibration and validation. Results from statistical evaluations using R^2, NSE and RMSE are listed in Table 6. R^2 for daily streamflow simulation were 0.81 and 0.89 for the five-year calibration and three-year validation periods, respectively. NSEs for daily streamflow simulation were 0.56 and 0.66 for the five-year calibration and three-year validation periods, respectively. The model for validation worked better than calibration of simulation. The model for flow discharge showed acceptable performance, with NSE values for calibration and validation greater than 0.5. Figure 1 shows model performance relatively underestimated observed data.

Table 6. Prediction accuracy for flow discharge in terms of R^2, NSE and RMSE

	Calibration	Validation
R^2	0.81	0.89
NSE	0.56	0.66
RMSE	2.5466e+003	3.0224e+003

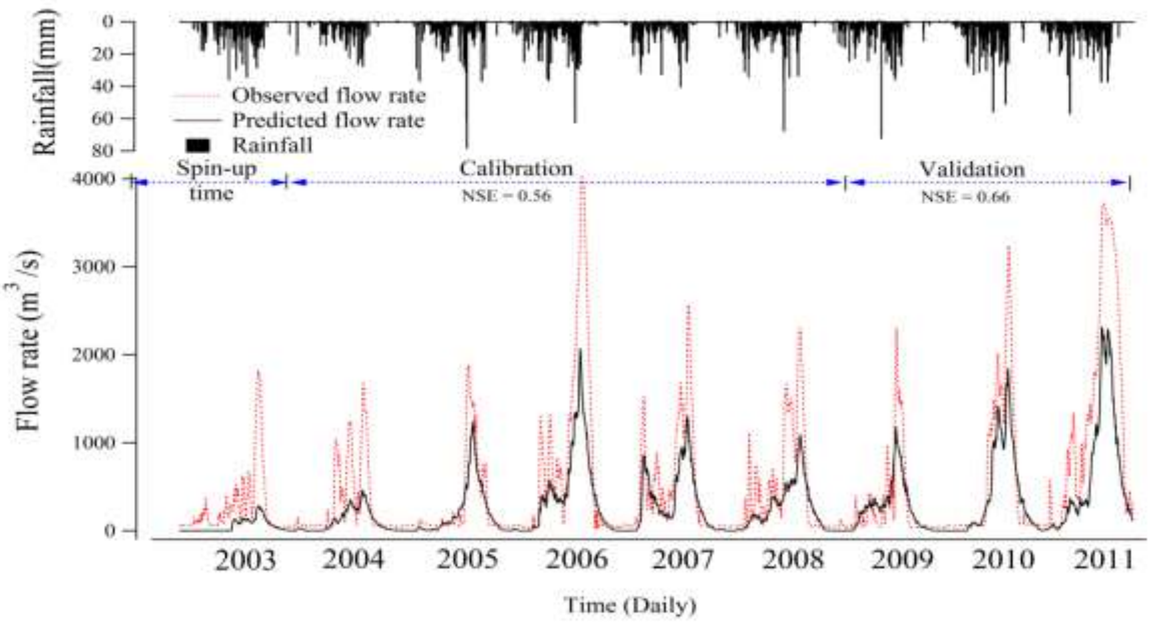

Figure 1. Comparison of observed and simulated daily flow rate during the 9-year simulation period

1.3.2.2 Sediment calibration and validation

The calibration process for sediment was determined by the results of sensitivity analysis. The top 5 parameters were selected with regard to the result of simulated calibration and validation. Results from statistical evaluations using R^2, NSE and RMSE are listed in Table7. R^2 for monthly sediment simulation were 0.75 and 0.86 for the five-year calibration and three-year validation periods, respectively. NSEs for monthly sediment simulation were 0.54 and 0.84 for the five-year calibration and three-year validation. The model for validation performed better than for calibration of simulation. The model for sediment had acceptable performance, as NSE values for calibration and validation were greater than 0.5. Figure 4 shows that simulation model performance relatively underestimated the observed data.

Table 7. Prediction accuracy for sediment in terms of R^2, NSE and RMSE

	Calibration	Validation
R^2	0.75	0.86
NSE	0.54	0.84
RMSE	8.2719e+004	4.6736e+004

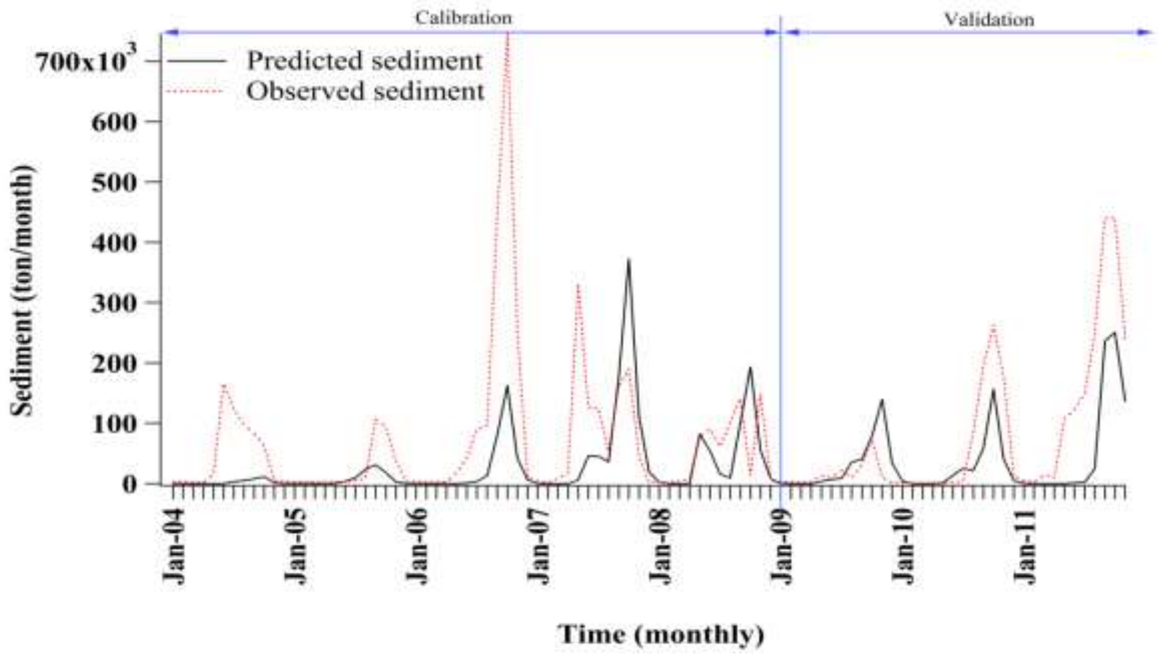

Figure 2. Comparison of observed and simulated monthly sediment during the 9-year simulation period

1.3.2.3 Total phosphorus calibration and validation

The calibration process for TP was determined by sensitivity analysis results. The top 5 parameters were selected with regard for the results of simulated calibration validation. Results from statistical evaluations using R^2, NSE and RMSE are presented in Table 8. R^2

for monthly TP simulations were 0.30 and 0.84 for, respectively, the five-year calibration and three-year validation periods. NSEs for monthly TP simulation were 0.20 and 0.66 for the five-year calibration and three-year validation. The model for validation was better than for calibration of simulation. The model for TP was not considered to perform satisfactorily, as NSE values of calibration were less than 0.5. The accuracy of TP simulation indicated uncertainty from the limited number of observed data. Consistent monitoring of water quality is required to select appropriate parameters involving land use and soil type to improve modelling accuracy. How the model underestimated the observed data can be seen in Figure 3.

Table 8. Prediction accuracy for total phosphorus in terms of R^2, NSE and RMSE

	Calibration	Validation
R^2	0.30	0.84
NSE	0.20	0.66
RMSE	1.3331e+005	4.5655e+004

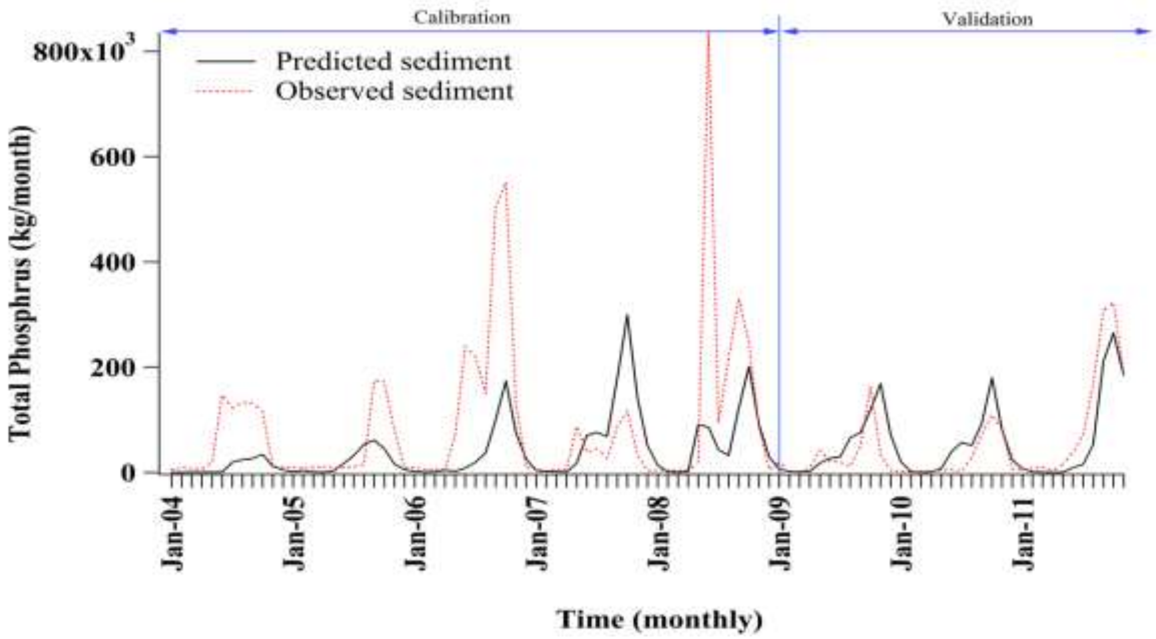

Figure 3. Comparison of observed and simulated monthly TP during the 9-year simulation period

1.3.2.4 Total inorganic nitrogen calibration and validation

The calibration process for total inorganic nitrogen was determined by the results of sensitivity analysis. The topmost 6 parameters were selected with regard to the result of simulated calibration and validation. Results from statistical evaluations using R^2, NSE and RMSE are listed in Table 9. R^2 for monthly total inorganic nitrogen simulation were 0.72 and 0.38 for the five-year calibration and three-year validation periods, respectively. NSEs for monthly total inorganic nitrogen simulation were 0.70 and 0.31 for the calibration and validation periods. The model for validation was better than for calibration of simulation. The model uncertainty seemed due to the limited number of observed data, for a model with high data input requirements. Consistent monitoring of water quality is required to select the appropriate land use and soil type parameters to improve modelling accuracy. Figure 4 shows how model performance tended to underestimate the observed data.

Table 9. Prediction accuracy for total inorganic nitrogen in terms of R^2, NSE and RMSE (NH_4-N, NO_2-N, NO_3-N)

	Calibration	Validation
R^2	0.72	0.38
NSE	0.71	0.31
RMSE	5.2785e+005	2.2792e+006

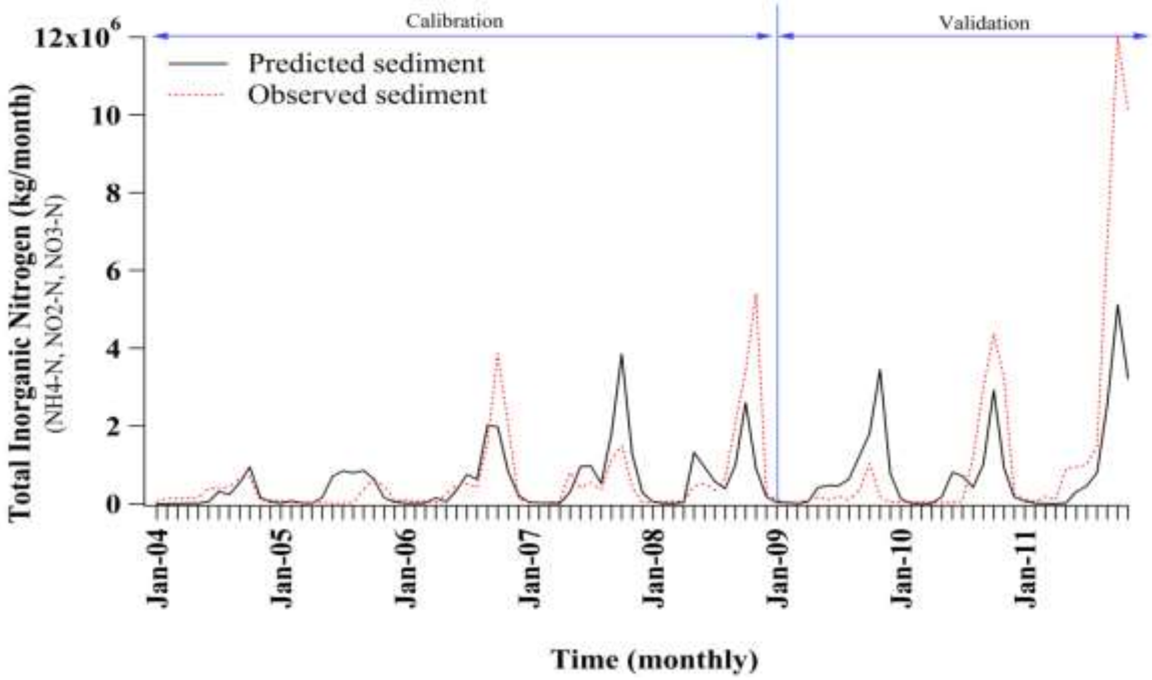

Figure 4. Comparison of observed and simulated monthly total inorganic nitrogen during the 9-year simulation period

1.3.3 Climate sensitivity scenarios

1.3.3.1 CO_2 concentration

Scenarios 1 through 3 shown in Table 1 prescribe doubling atmospheric CO_2 concentration, first with no change in precipitation or temperature, then with maximum variation in precipitation and then in temperature. These three scenarios are associated with the variable stomatal conductance reaction dependent on CO_2 concentration. When CO_2 concentration is increasing, transpiration decreases because of fewer stoma opening on leaves to absorb the necessary amount of CO_2 for photosynthesis. Plant growth, depending on vegetation type, can be affected by CO_2 concentration (Wu et al., 2012). Figures 5a-5e show simulated monthly water yield, soil water content, groundwater recharge, soluble P load and NO_3-N load under baseline conditions and with changes in precipitation and temperature under increasing CO_2 concentration.

Figures 5a, 5b & 5c show the water yield, soil water contents and groundwater recharge in representative HRUs (hydrologic response units). The water yield was the sum of surface runoff, lateral flow and groundwater baseflow. Water yield was reduced from the baseline in response to increased CO_2, as well as to increased CO_2 plus a 6°C temperature increase. In contrast, the soil water content, groundwater recharge and soluble P load were reduced from the baseline by 21%, 20% and 20% respectively under the condition of doubled CO_2 plus a 20% increase in precipitation. The NO_3-N load was not significantly different from the baseline.

1.3.3.2 Precipitation

Scenarios 4 through 7 represented precipitation changes of +10%, +20%, -10% and -20% while CO_2 concentration was kept at the baseline (330ppm) and the temperature condition was not changed. Figures 5f-5j depict the variation in measurements under the different precipitation conditions. Water yield was similar to baseline, while soil water content and groundwater recharge rose or fell with precipitation. For example, with the four precipitation changes, water yield varied by, respectively, 0.26%, 0.44%, -0.28% and -0.59%. Figure 5g shows soil water content changes of 9.7%, 19.4%, -10.3% and -21.1%, respectively. In addition, soluble P load changed by 10.2%, 20.8%, -11% and -22.8% under this precipitation scenario. The response of soil water content, groundwater recharge and soluble P load to the variations in precipitation indicates a significant effect on them during the June through September wet season. NO_3-N load, in contrast, was not significantly affected by the precipitation change condition.

1.3.3.3 Temperature

Scenarios 8 through 10 represented temperature changes of 1°C, 3°C and 6°C while holding the CO_2 concentration at the 330ppm baseline, and with no change in precipitation. Figures 5k-5o show the variations in measurements under the different temperature conditions. Water yield was similar to the baseline, as well as soil water content, groundwater recharge, soluble P load and NO_3-N load; none were significantly affected by the change in temperature. Water yield, for example, changed by -0.12%, -0.35% and -0.98%, respectively, with the three temperature changes. Precipitation changed by 0.08%, 0.19% and 0.04%, respectively (Figure 5l). In addition, soluble P load varied by -0.23%, -2.21% and -2.5% under the three temperatures, and NO_3-N load changes were measured at -1.36%, -1.75% and -2.74%.

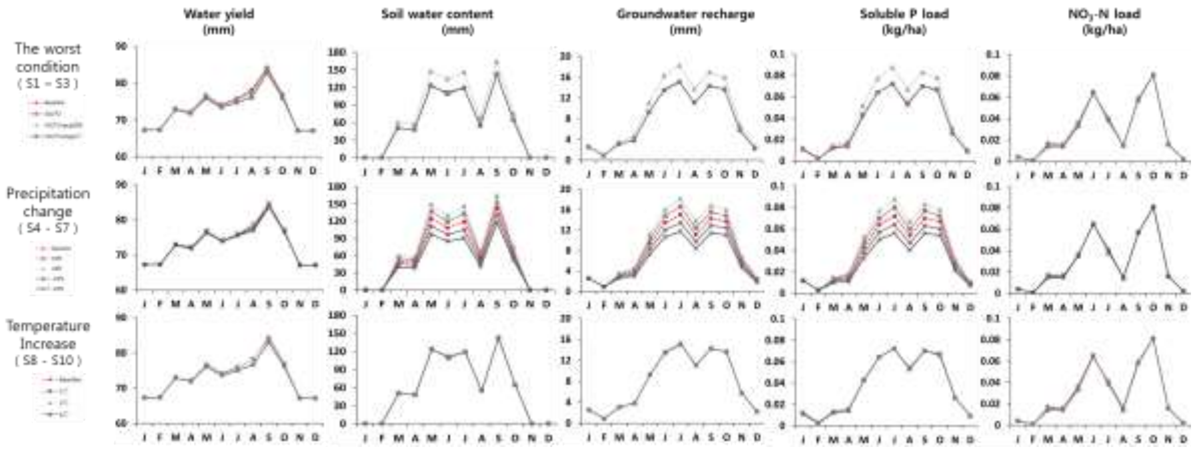

Figure 5. Comparison of simulated monthly water yield, soil water content, groundwater recharge, soluble P load and NO_3-N load under climate sensitivity scenarios

1.4 Conclusions

The SWAT model was used to create a hydrological model of the Chao Phraya Watershed to investigate the effect of climate sensitivity and greenhouse gas emission scenarios on its streamflow. The model yielded percentage increases in the streamflow that revealed a need to create safety measures during flood events: in the daily average streamflow (72.3% increase), during the wet season in early May (22.7%) and after May (70.1%). This study also achieved its objectives.

1. The SWAT model showed a satisfactory performance in terms of calibration and validation for the flow discharge and sediment, with R^2 and NSE values greater than 0.5.

2. Precipitation scenarios yielded streamflow variations that corresponded to the change of rainfall intensity and amount of rainfall, while scenarios with increased air temperature yielded a decrease in water level leading to a water shortage. However, the three greenhouse gas emission scenarios from 2051–2059 had streamflow variations that increased from the baseline (2003–2011).

3. Scenarios 1 to 3 were related to an increase in CO_2 concentration scenarios, which reduced stomatal conductance and increased the leaf area index. The results showed an increase in streamflow levels; however, a negative change in streamflow was also observed when the air temperature increased.

Further increasing the uncertainty of climate change brings a corresponding uncertainty into the predictions of severe flood and drought. In addition, change in the land use of the Chao Phraya River subbasins may result in a different distribution, which also depends on the changes of climate conditions such as climate sensitivity scenarios and the three emission scenarios.

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2. Hydrologic response assessment of the Nam Khan watershed, Laos using SWAT: Application of RCP scenarios from climate models and land use scenarios

2.1 Introduction

Earth has been experiencing climate change throughout history. One of its indicators is the varying global concentration of carbon dioxide (CO_2). The trend of CO_2 levels has changed seven times over the past 650,000 years without ever in that span surpassing 300 parts per million (ppm)—until, that is, 1950, when its rise continued beyond 300ppm, attributed to increases in certain human activities, many associated with rapid developments in technology. Scientists have also predicted that CO_2 emissions will continue to rise for the foreseeable future. While CO_2 emissions continue to rise, future climate change models, such as the Coupled Model Intercomparison Project (CMIP) models, have predicted that the global surface temperatures will correspondingly increase to alarming levels. This will create a huge impact on the hydrologic cycle of watersheds, since surface waters are sensitive to changes in the climate and environment. Surface waters have also been affected by the rapid rate of urbanization in recent years. As land is developed, its imperviousness comes to play a key role in disturbing the natural hydrologic processes associated with soil, thus affecting water quantity and water quality.

To address these issues, this study investigated scenarios for climate change and land use in temperate and tropical watersheds using the Soil and Water Assessment Tool (SWAT model). The objectives include: 1) the calibration and validation of water quantity of the Nam

Khan watershed using the SWAT model; 2) the assessment of hydrologic responses in the Nam Khan watershed after applying the Representative Concentration Pathways (RCPs) scenarios of five climate models; and 3) the evaluation of water quality in the Nam Khan and Yeongsan rivers after applying the land use scenarios. The results of this study will help stakeholders prepare for any changes that might occur in the future. This will lessen economic losses due to extreme events caused by climate change and rapid urbanization.

2.2 Methodology

The methodology of this study has three parts as shown in Figure 6: The SWAT model, Bias Correction and Land Use Scenarios. The results of the study are listed under Assessment.

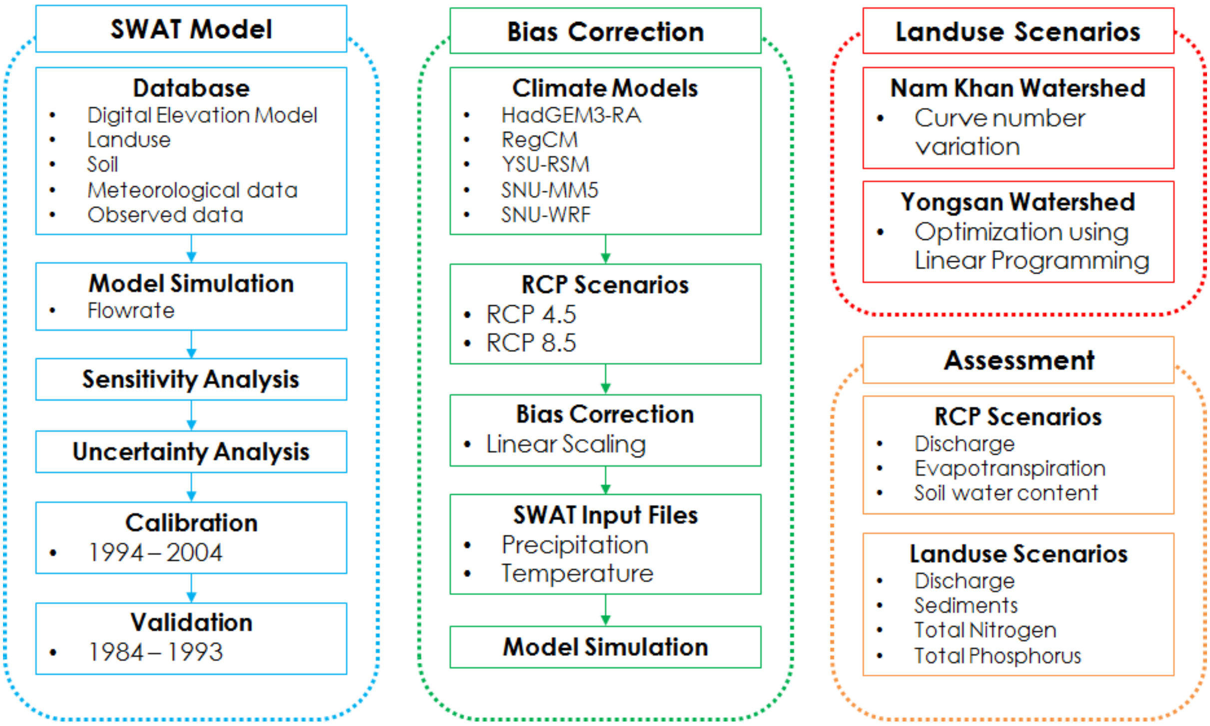


Figure 6. Flow chart of the methods. The chart summarizes the methodology of the study, which includes the list of evaluated results under Assessment.

2.2.1 Areas studied

2.2.1.1 Nam Khan watershed

The Nam Khan River flows through Luang Prabang Province in Laos. It drains a catchment area of 7,490 sq. km. More than 90% of the catchment basin is nearly covered in deciduous, evergreen and mixed forests. Figure 7 shows that there are mountainous regions in the basin which form a valley around the river.

2.2.1.2 Yeongsan watershed

The Yeongsan River is situated in the south-western part of South Korea. One of the four main rivers of this country, its catchment area comprises 724 sq. km. Figure 3 shows the land use map of the Yeongsan watershed.

2.2.2 SWAT Model

The SWAT model was built to simulate the water cycle in the Nam Khan watershed. Several types of input data were gathered before building the model, including a 90m digital elevation model (DEM) provided by the United States Geological Survey (USGS), a 1-km resolution land use map from Global Land Cover Classification, a soil map with a spatial resolution of 10 km (5x5 arc-minute raster) and the weather data from Global Weather Data for SWAT.

Setting up the SWAT model for the Nam Khan watershed was carried out up to the validation stage. The model has a calibration period of 11 years (1994 to 2004) and a validation period of 10 years (1984 to 1993). The performance of the model was then evaluated using Nash-Sutcliffe efficiency (NSE) and the coefficient of determination (R^2). After getting a good performance from the SWAT model (NSE > 0.5 and R^2 > 0.5), bias-corrected climate models were used as weather input data. Sensitivity and uncertainty analyses were also applied using the SWAT-Calibration and Uncertainty Program (SWAT-CUP). The Latin Hypercube (LH) sampling and One-factor-At-a-Time (OAT) methods were implemented to determine the sensitive parameters of the discharge. Table 10 lists the values for water quality and discharge parameters. Parameters 1 to 6 are water quality parameters calibrated for a tropical watershed. The rest of the parameters are for discharge and were calibrated specifically for the Nam Khan watershed. Sequential Uncertainty Fitting v2 (SUFI2) method was then applied to the SWAT model to yield the 95% prediction uncertainty band of the simulated results.

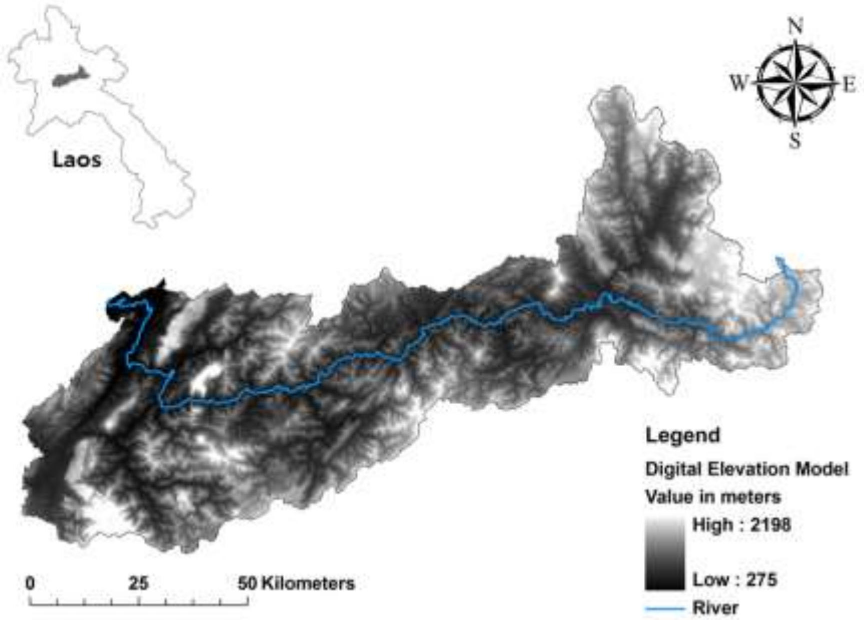


Figure 7. Digital elevation model of the Nam Khan watershed

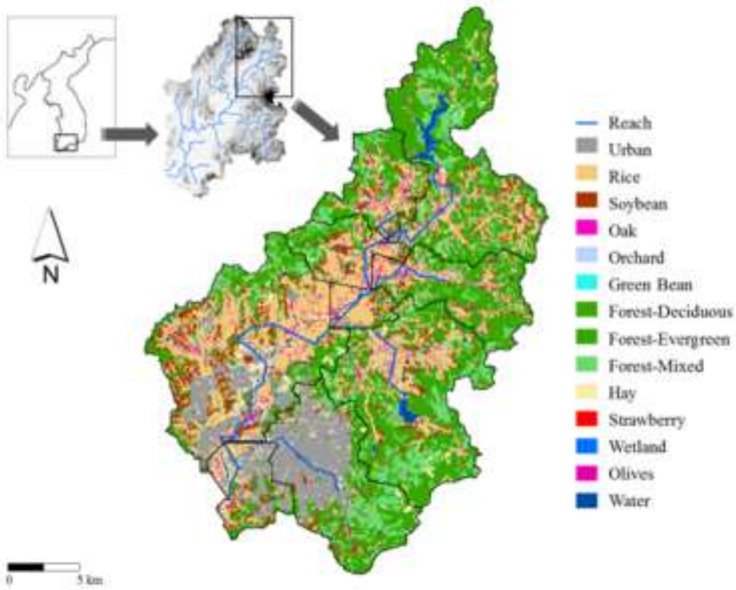


Figure 8. Land use map of the Yeongsan watershed

2.2.3 Bias Correction

Bias correction was applied to the climate models to amend certain biases included in the models. Typical biases among the many encountered were: a) too many wet days with low-intensity rain, b) incorrect estimation of extreme temperatures, and c) over- or underestimation of precipitation. The climate models that were considered in this study were HadGEM3-RA, RegCM, YSU-RSM, SNU-MM5 and SNU-WRF, with RCP scenarios 4.5 and 8.5 as the available climate change scenarios of each model. Linear scaling was the bias correction method applied to the precipitation and temperature data from the climate models. The historical period spans from 1981 to 2004, and the scenario period from 2016 to 2045.

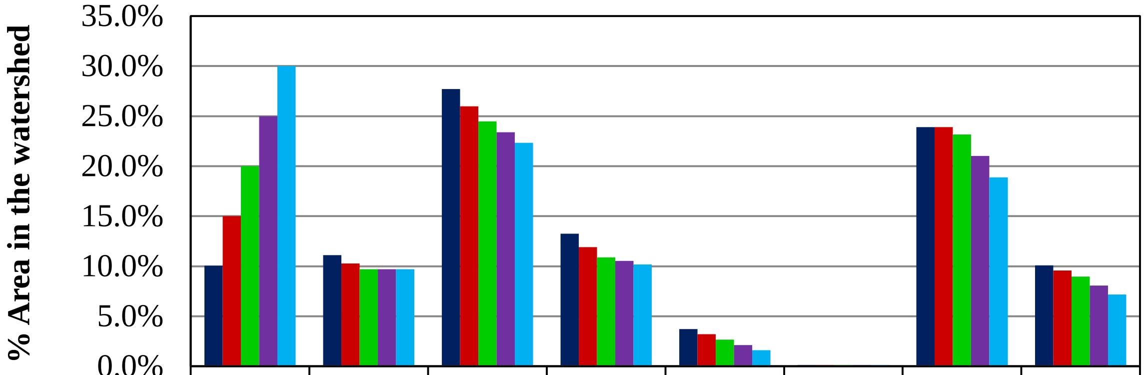
The resulting weather data (precipitation and temperature) replaced the original input data in the SWAT model to simulate the impact of RCP scenarios on discharge, evapotranspiration and soil water content.

2.2.4 Land use scenarios

Land use scenarios were applied to the two areas studied, the Nam Khan and Yeongsan watersheds. The level of imperviousness of the Nam Khan watershed was varied by changing the values of the curve number (CN2), while the fractions of hydrologic response units (HRU) for the Yeongsan watershed were altered using linear programming, an optimization function in MATLAB. Table 10 shows varied CN2 values that were applied to the Nam Khan SWAT model. From the calibrated CN2 value of -0.48 (a -48% change from the default SWAT value), the imperviousness level of the watershed was varied from -0.20, 0 (the default SWAT value), 0.20 and 0.40. Figure 4 shows the optimized percentage for land use areas in the Yeongsan watershed. The urban (BERM) area was fixed at 10%, 15%, 20%, 25% and 30%. The other land use areas were optimized using the linear programming of MATLAB. The discharge and water quality parameters (sediments, total nitrogen and total phosphorus) of both watersheds were then assessed.

Table 10. Water quality and discharge parameters in the Nam Khan SWAT model

No.	Parameter Name	Description	Method	Value
1	SDNCO	Denitrification threshold water content	Replace	0.948
2	HLIFE_NGW	Half-life of nitrate in the shallow aquifer (days)	Replace	0.031
3	CDN	Denitrification exponential rate coefficient	Replace	0.075
4	NPERCO	Nitrate percolation coefficient	Replace	0.068
5	RCN	Concentration of nitrogen in rainfall (mg N/L)	Replace	1.48
6	RS3	Benthic source rate for the NH_4.N in the reach at 20°C (mg NH_4.N/(m^2.day)	Relative	0.004
7	CN2	Initial Soil Conversion Service (SCS) runoff curve number for moisture condition 2	**Relative**	-0.48 (best); **-**0.20; 0; 0.20; 0.40
8	ALPHA_BF	Baseflow alpha factor (days)	Replace	0.837
9	GW_DELAY	Groundwater delay time (days)	Replace	77.2
10	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	Replace	1881.1
11	RCHRG_DP	Deep aquifer percolation fraction	Replace	0.586
12	SOL_K	Saturated hydraulic conductivity (mm/hr)	Relative	0.127
13	ESCO	Soil evaporation compensation factor in the HRU	Replace	0.0871
14	EPCO	Plant uptake compensation factor in the HRU	Replace	0.701
15	SURLAG	Surface runoff lag coefficient	Replace	8.15



	BERM	FRSD	FRSE	FRST	HAY	OAK	RICE	SOYB
Original	10.06%	11.12%	27.72%	13.27%	3.74%	0.13%	23.90%	10.08%
15% urban	15.00%	10.27%	25.99%	11.92%	3.20%	0.13%	23.90%	9.59%
20% urban	20.00%	9.71%	24.46%	10.90%	2.66%	0.13%	23.17%	8.96%
25% urban	25.00%	9.71%	23.39%	10.54%	2.14%	0.13%	21.02%	8.07%
30% urban	30.00%	9.71%	22.32%	10.17%	1.61%	0.13%	18.87%	7.18%

Figure 9. Land use areas in the Yeongsan watershed, by percent. Five levels of urbanisation were considered.

2.3 Results & Discussion

2.3.1 SWAT model of the Nam Khan watershed

Figures 5 and 6 are the calibration and validation periods of the discharge, respectively. The calibrated discharge has an R^2 value of 0.74, indicating a good fit. Its NSE value of 0.72 also meant that the model performed well during simulations. The validated discharge, however, showed a poor fit and an unsatisfactory performance of the model, with R^2 and NSE values of 0.47 and 0.03, respectively. From Table 10, the discharge parameters start from no. 7 and are ordered by their decreasing sensitivity. These parameters were chosen during the initial calibration from eighteen other parameters related to discharge. CN2 was determined to be the most sensitive parameter among the nine parameters which indicate that the imperviousness of the basin's soil has a great influence on the discharge. Groundwater processes also seem to be the most dominant processes that affect discharge, with four parameters coming under this group (GW_DELAY, RCHRG_DP, ALPHA_BF and GWQMN).

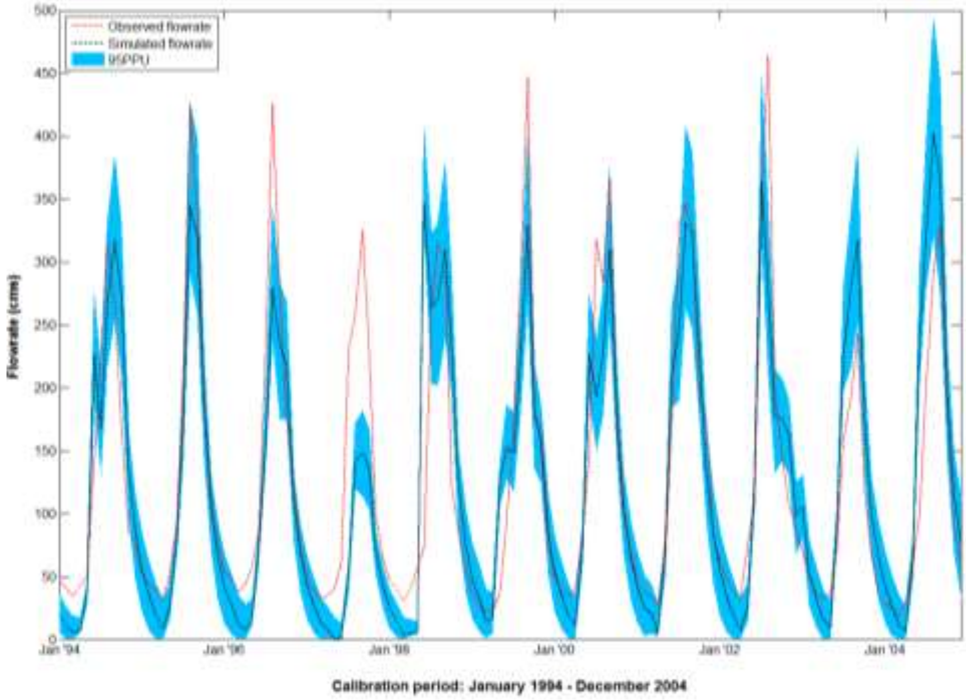


Figure 10. Calibrated discharge for the Nam Khan watershed (R^2 = 0.74; NSE = 0.72). The calibration period spanned 1994 to 2004.

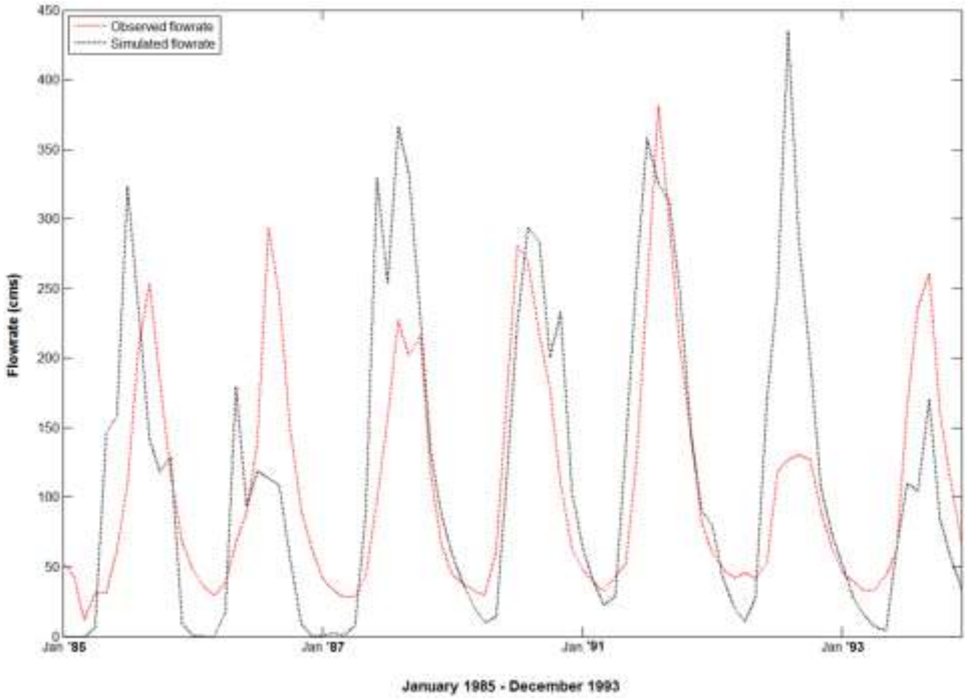


Figure 11. Validated discharge for the Nam Khan watershed (R^2 = 0.47; NSE = 0.03). The validation period spanned 1994 to 2004.

2.3.2 RCP scenarios

2.3.2.1 Precipitation

Figure 12 shows the precipitation levels of the bias-corrected historical (2004) and projected RCP scenarios (2045) for the climate models. The historical data show two peaks occurring in the rainy season of the tropics, between May and September. RCP 4.5 and 8.5 of RegCM show the most similar trend, despite a significant difference for the second peak in August. HadGEM3-RA, RegCM, YSU-RSM and SNU-WRF underestimated the second peak. Only SNU-MM5 was able to yield a value relatively close to the observed data. The model that greatly deviated from the trend of the observed data was YSU-RSM. Its RCP 4.5 scenario showed three peaks that underestimated the precipitation levels while its RCP 8.5 underestimated April to August.

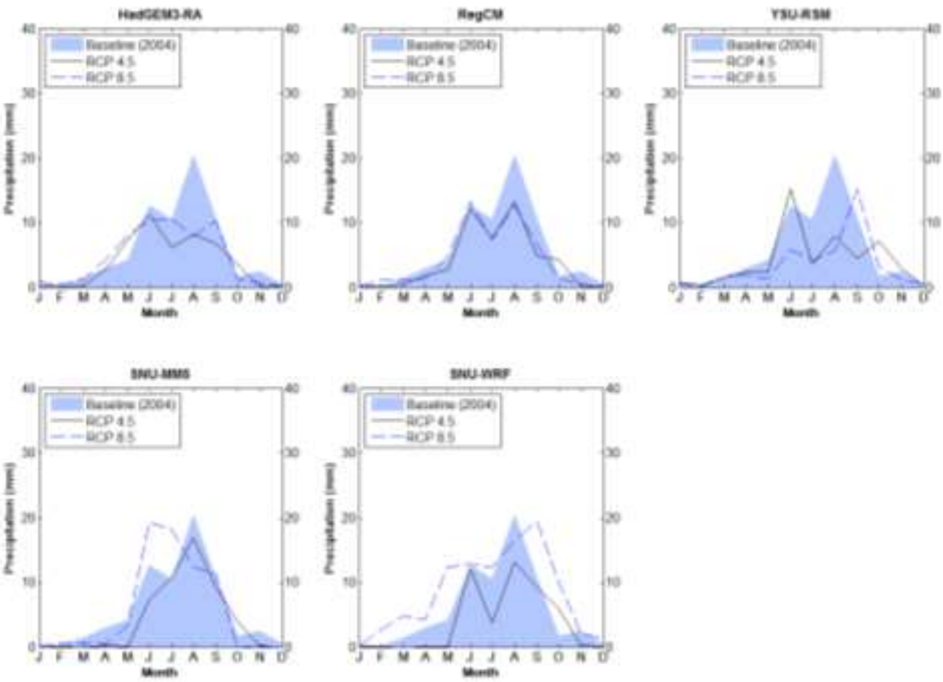


Figure 12. Precipitation levels of the bias-corrected historical and projected RCP scenarios

2.3.2.2 Discharge

Figure 13 shows the observed discharge had an increasing trend from June to September, then gradually deceased until December. Among the ten combinations of climate models and RCP scenarios, RCP 4.5 for SNU-WRF best matched the trends of the observations. Its RCP 8.5 counterpart though greatly overestimated the discharge. Both RCP scenarios for SNU-MM5 also overestimated the discharge. Both RCP scenarios for HadGEN3-RA and RegCM had values comparable with the observations; however, the placements and numbers of the peaks were different. The peaks of both models occurred in June with the secondary peaks in August. The RCP 8.5 for YSU-RSM also showed a similar peak in September, after a sharp increase from August instead of a gradual increase over earlier months.

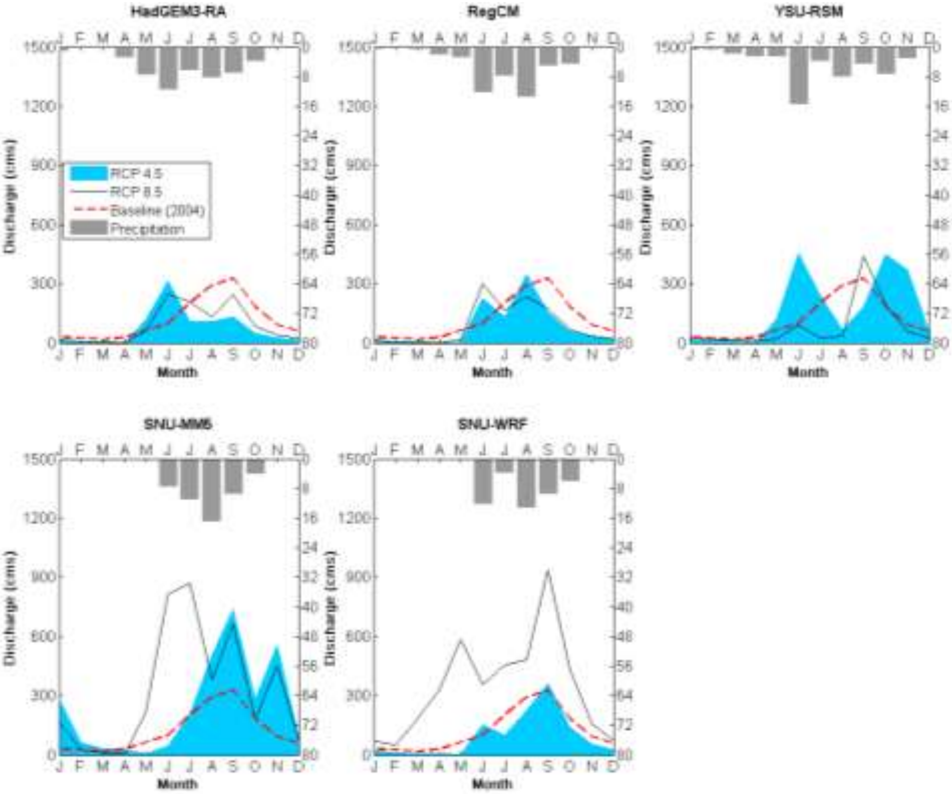


Figure 13. Discharge from the observed data and by the projected RCP scenarios

2.3.2.3 Evapotranspiration

The evapotranspiration of the RCP 4.5 for each model showed similar trends and peaks, as seen in Figure 9. However, the evapotranspiration levels for the first six months for YSU-RSM were greater than for the other models. The RCP 8.5 for the models, excluding SNU-WRF, also followed their respective RCP 4.5 trends. Levels for the first five months of RCP 8.5 for SNU-WRF were almost 2 mm greater than for its RCP 4.5 counterpart.

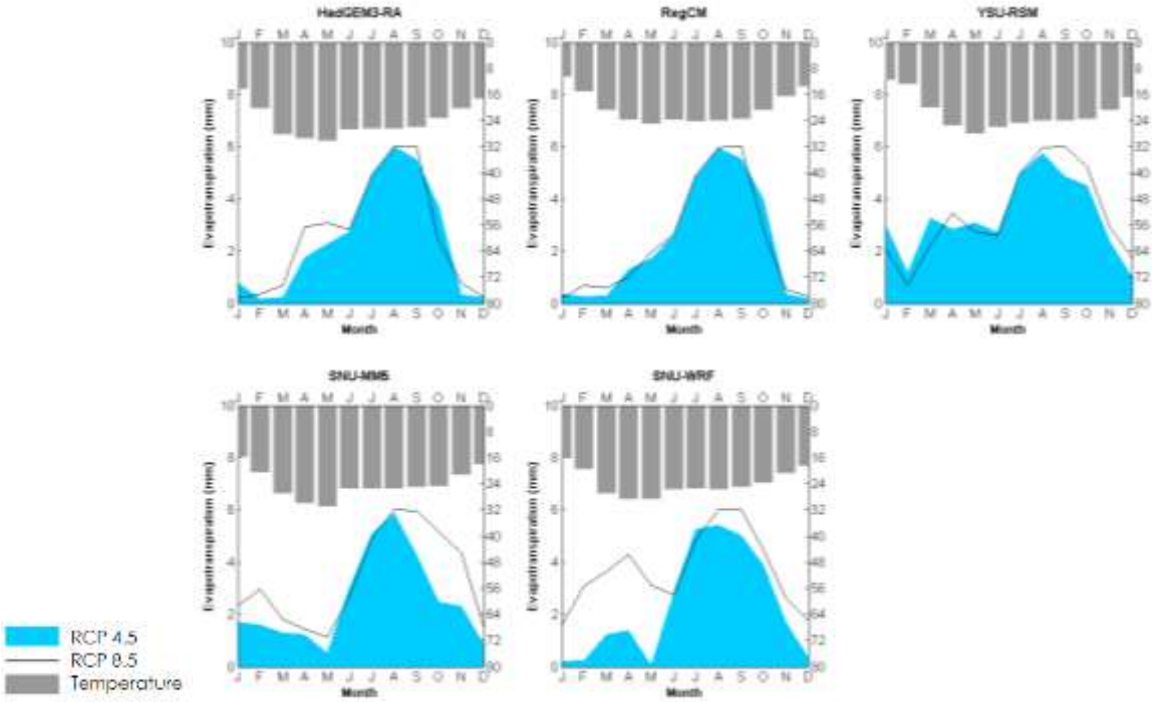


Figure 14. Evapotranspiration for the projected RCP scenarios

2.3.2.4 Soil water content

Figure 15 shows the soil water content of the RCP scenarios. The RCP 4.5 and 8.5 scenarios for HadGEM3-RA, RegCM and SNU-MM5 showed similar trends, with a sharp increase from either April or May to June. The soil water content levels of the three models were thereafter consistent from June to September. The trend then gradually decreased until December, except for SNU-MM5, which held its level until November. RCP 8.5 for SNU-WRF, compared to the other scenarios, had the most soil water content during the first five months. This result is inconsistent with the factor of RCP 8.5 having a higher temperature than RCP 4.5.

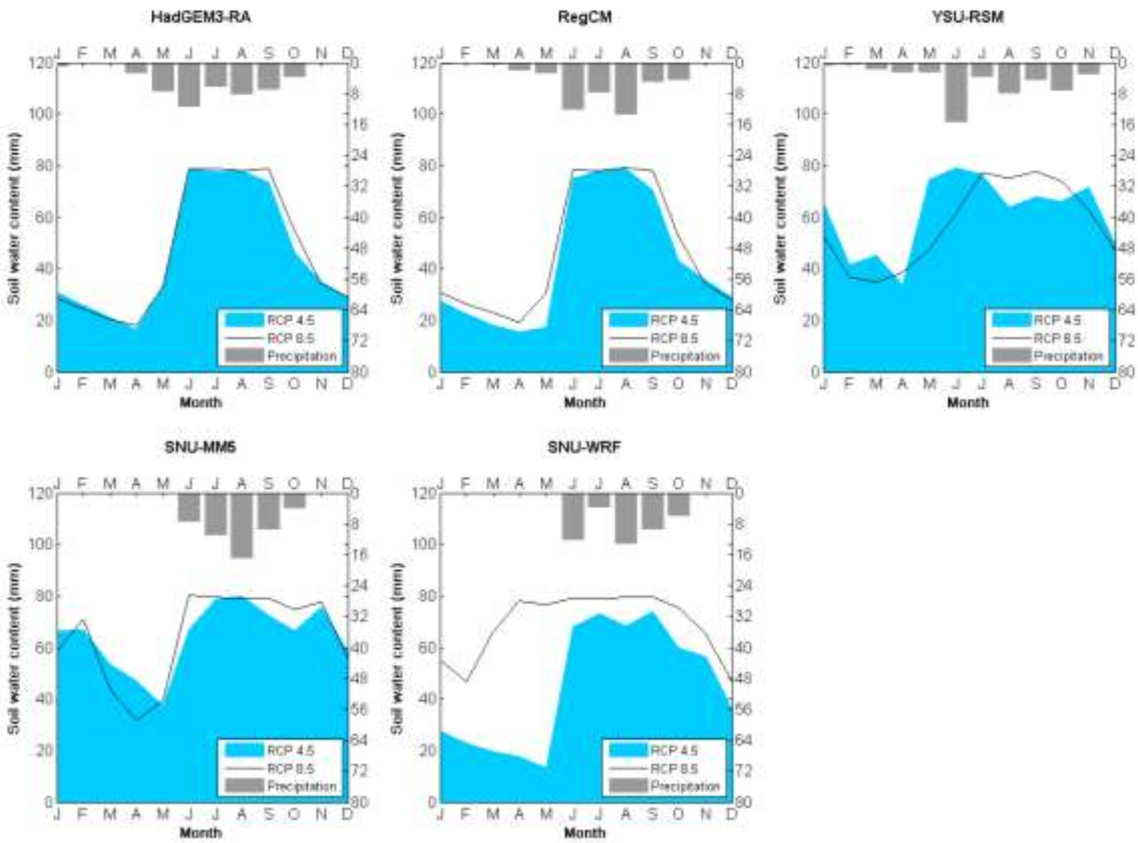


Figure 15. Soil water content of the projected RCP scenarios.

2.3.3 Land use scenarios

2.3.3.1 Nam Khan watershed

The discharge and water quality of the Nam Khan watershed were evaluated after varying its CN2. All the plots in Figure 16 show an increasing trend, caused solely by the increasing imperviousness of the basin. Surface runoff tends to increase as the basin becomes less pervious. Impervious covers of the basin nullify the effect of infiltration; runoff thus goes directly to the channel instead of percolating into the soil. This occurrence will increase the discharge thereby increasing the sediment loading. Since the land use classifications of the HRUs remain the same, the total nitrogen and total phosphorus loadings for the basin will also end up in the channel. Both these nutrients are expected to increase.

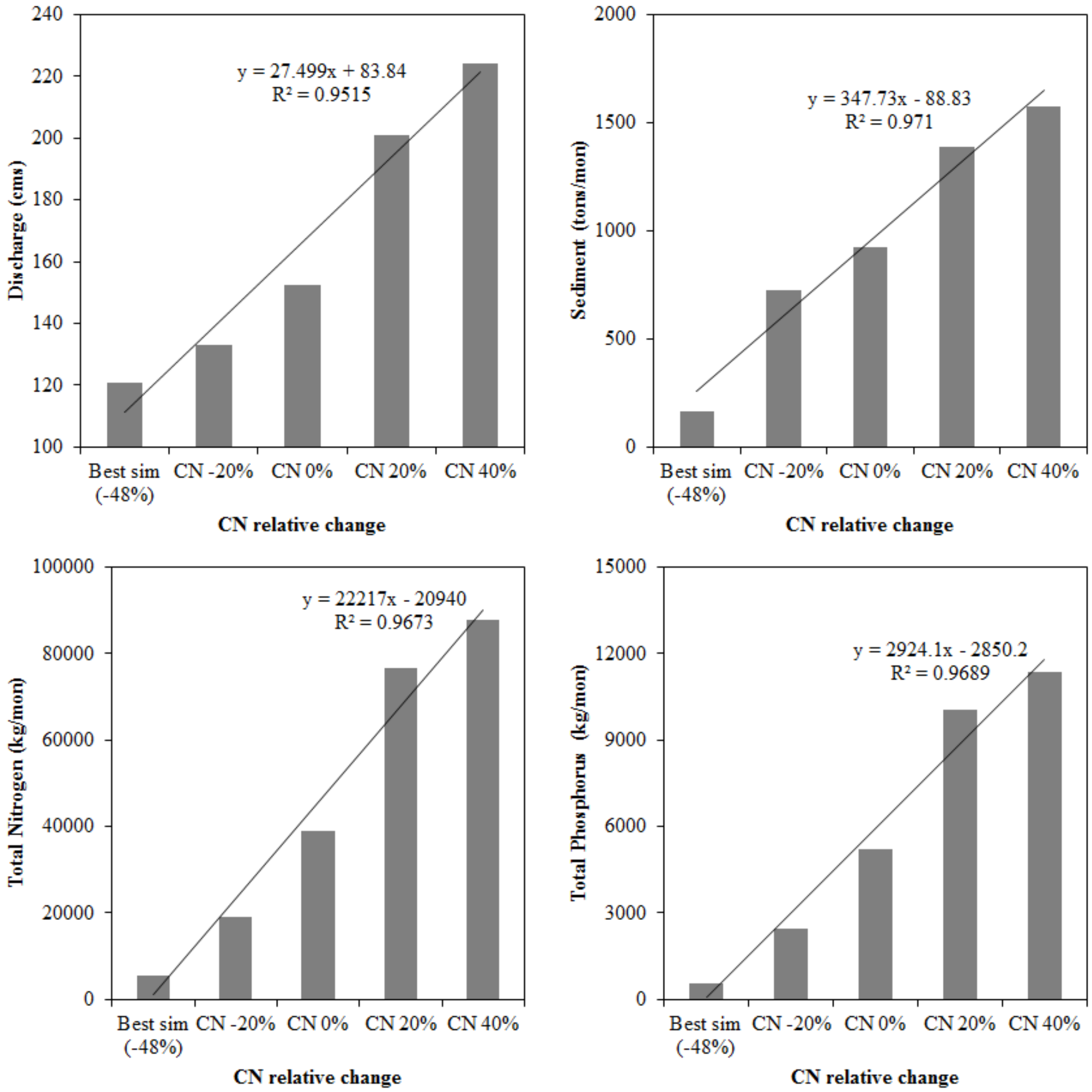


Figure 16. Discharge and water quality versus the increasing imperviousness of the Nam Khan watershed.

2.3.3.2 Yeongsan watershed

As opposed to the increasing trend of nutrients in the Nam Khan watershed, the Yeongsan watershed showed a decreasing loading for both total nitrogen and total phosphorus. This is attributed to a difference in the methods. The optimisation method applied to the Yeongsan watershed changed the percentages of its land use areas. Increases in the urban area decreased the percentages of other land use classifications. Figure 17 displays how the percentage of agricultural areas decreased when urban areas increased. This decreasing trend brought on a decline in the nutrients, since this also meant less fertilizer being spread for crops. However, increasing the urbanization of the basin also made it more impervious, thereby increasing the discharge due to surface runoff. Since surface runoff introduces new sediments into the channel, this will also increase the sediment loading.

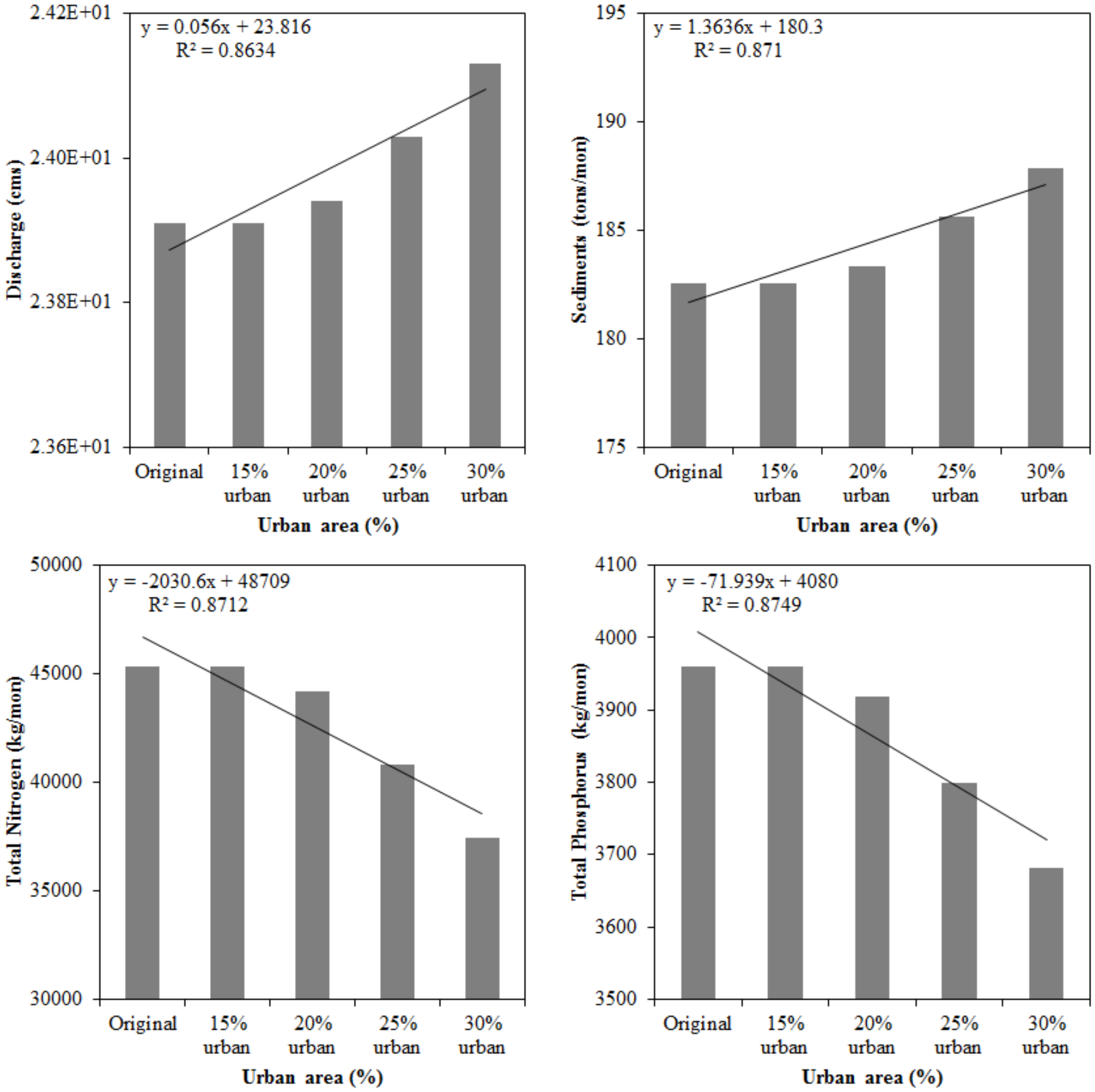


Figure 17. Discharge and water quality versus the increasing urbanization of the Yeongsan watershed

2.4 Conclusions

This study investigated the impacts of climate change and land use scenarios on the Nam Khan and Yeongsan watersheds using the SWAT model. The Nam Khan SWAT model was able to perform well during calibration of discharge, yielding an R^2 of 0.74 and an NSE value of 0.72. CN2 was determined to be the most sensitive parameter. Its performance during validation was not as good (R^2 = 0.47, NSE = 0.03). RCP scenarios for five climate models were bias-corrected using linear scaling. The resulting discharge, evapotranspiration and soil water content were then assessed.

The land use scenarios, on the other hand, increased the imperviousness of the Nam Khan watershed and varied the percentages of the land use areas in the Yeongsan watershed. The different methods applied to each watershed produced greatly differing trends for the nutrients total nitrogen and total phosphorus. Both methods increased the imperviousness of the basin by lessening the permeability of the soil, thereby raising the discharge and the sediments for both watersheds.

2.5 Future Directions

1. More sampling activities are needed to verify our modelling results. In particular, we were unable to obtain sufficient data from the Laos watershed.
2. Implementation is needed for the model we've developed for the Chao Phraya River, Thailand.

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3. Effects of seasonal and land use changes on the Chao Phraya River water quality, Thailand

3.1 Introduction

The Chao Phraya is Thailand's principle river, formed from the confluence of the Ping, Wang, Yom and Nan rivers. It flows for 380 km, passing through 15 provinces then into the Gulf of Thailand (Figure 18). The river is subdivided into three sections: the lower (RKM 7 to 62), middle (RKM 62 to 142) and upper (RKM 142 to 379). These sections are according to surface water classification, the uses and specific characteristics of which are shown in Table 11.

Figure 18. Map of Thailand's rivers

Source: www.mapsofworld.com

Table 11. Thailand's surface water classifications

Classification	Condition and Beneficial Usage	Characteristics
Class 1	Extra clean fresh surface water resources, used for: (1) consumption without water treatment processing, except basic treatment for pathogen destruction (2) ecosystem conservation where basic organisms can breed naturally	Natural
Class 2 **(Upper Chao Phraya river)**	Very clean fresh surface water resources, used for: (1) consumption, following ordinary water treatment processing (2) aquatic organism conservation (3) fisheries (4) recreation	DO > 6 mg/L, BOD < 1.5 mg/L, TCB < 5,000 MPN /100 mL, FCB < 1,000 MPN /100 mL
Class 3 **(Middle Chao Phraya river)**	Medium clean fresh surface water resources, used for: (1) consumption, following ordinary water treatment processing (2) agriculture	DO > 4 mg/L, BOD < 2 mg/L, TCB < 20,000 MPN/100 mL, FCB < 4,000 MPN /100 mL
Class 4 **(Lower Chao Phraya river)**	Fairly clean fresh surface water resources, used for: (1) consumption, only after special water treatment processing (2) industry	DO > 2 mg/L, BOD < 4 mg/L
Class 5	Resources not under classes 1-4, and for navigation	

The Chao Phraya River has been monitored since 1981 by the Pollution Control Department (PCD) of Thailand. The results indicate a trend toward deterioration in water quality, particularly in biochemical oxygen demand (BOD), dissolved oxygen (DO) and total coliform bacteria (TCB)**.** Li et al. (2012) reported how changing climate and land use patterns significantly affected the chemical, physical and biological quality of water. The amounts of nitrogen and phosphorus were highest in forested areas, followed by agricultural land and urbanized areas. When rain fell, soluble organic carbon was at a maximum during the onset of the rain, and decreased continuously thereafter. Microorganisms also take part in the nutrient cycle in the catchment area, influencing the fate and effects of other non-nutrient contaminants, including pathogens (Johnson et al., 2009). It was known that nonpoint source pollution contributed the largest source of pollution to the river. Nonpoint source can be classified as agricultural, residential, from forestry and from mining. Water pollutants from agriculture are organic substances, nutrients and sediments. Li et al. (2012) found that a great proportion of carbon was transported under colloidal form. As a fertilizer, pig slurry increases total organic carbon by five times and cattle manure by seven (Delpla et al., 2011). This is reflected in increased biological and chemical oxygen demand, particularly during a flood event (Hrdinka et al., 2012). Intensive livestock production in an agricultural watershed greatly increased discharged particulate materials and nutrients; these two were mainly influenced, respectively, by direct runoff and by base flow (Kato et al., 2009). Nitrogen runoff from paddy field watersheds, however, depends on fertilization rates (Kim et al., 2006). According to some reports, the impact of climate on water quality can also be expressed in pollution loads. It has been indicated that the annual pollution load in urban runoff is lower than the pollution load in sanitary wastewater in areas with low precipitation, but is higher in areas with high precipitation. Advanced wastewater treatment is thus suitable for areas with low precipitation, and surface runoff control for areas with high (Taebi and Droste, 2004). Liu et al. (2011) reported the pollutant loads from industrial sewage have stronger impacts on the water environment than general sewage. Chemical oxygen demand mainly results from land-based point pollutant sources, while phosphorus is a nonpoint source pollutant along the seacoast. Tsuzuki (2006) proposed the index of pollution load per capita for water flowing into the body draining the inner city area of Chiba city, Japan. The BOD load/capita flowing into this water body was calculated as 0.83 gBOD/capita-day for the population served by the wastewater treatment plant. From the result of such indices, high-efficiency treatment methods, including wastewater treatment plants, agricultural village wastewater treatment facilities and combined treatment, are seen as effective in reducing pollutant loads flowing into a body of water. Due to the rapid population rise and urbanization along the Chao Phraya, this river is expected to face more problems of water quality. This led us to investigate the effect of land use on the Chao Phraya, in both wet and dry seasons.

3.2 Methodology

The water quality of the Chao Phraya river basin was investigated by collecting water samples from upstream to downstream of at a depth of 0.5 m in the wet and dry seasons of 2014-2015. Water was also collected to study the effects of extreme events. Samples were collected by vertical water sampling. Collected samples were separated into two groups. The first group was collected by aseptic techniques for microbial examination, and the rest collected for physical and chemical determination after measuring pH, water temperature and dissolved oxygen (DO).

3.2.1 Sampling sites and sampling points

The Chao Phraya River was the study site. There were two water sampling tasks.
Task 1: Water sampling along the Chao Phraya during wet and dry seasons. This was to investigate the effects of land use and season on water quality.
Task 2: Water sampling during extreme events. This task investigated the fluctuation of water quality in some land use areas during daylight hours in wet and dry seasons.
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3.2.1.1 Water sampling along the Chao Phraya

The 15 sampling sites for this study were selected for their different land uses: residential (R), agricultural (A), urban (U) and industrial (I). The sites ranged from the upper part of the river, to Ayutthaya Province in the middle and to the lower part, including Bangkok. Descriptions of these sampling sites are shown in Table 12 and Figures 19-22. Samples were collected along the river twice a year (in wet and dry seasons) for 2 years (2014-2015).

Table 12. Sampling points for this study

Sampling name	Land use type	Location	Local name	Description	
				West /North	East/ South
R1	Commercial & residential areas	15.7011N 100.1410E	Nakhon sawan @ Pak Nam Pho	Ferry pier, Market, Hotels, Household	Temple
R2	Commercial & residential areas	15.6889N 100.1227E	Nakhon sawan @ Dechatiwong Bridge	Government Office, Household	Open space, Small factory
A1	Commercial & residential areas	15.1807N 100.1245E	Chainat @ Maung (before Dam)	Ferry pier,Household, Market	Household, Ferry pier, Fish net cages
A2	Agricultural area (Paddy	15.0814N 100.2891E	Chainat @ Sappaya (after Dam)Paddy field	Ferry pier, Temple	Ferry pier, Temple, Paddy field
A3	Agricultural area (Paddy	14.9829N 100.3521E	Singburi @ Inburi	Ferry pier,Household, Paddy field	Ferry pier, Temple
R3	Agricutural & commercial	14.3590N 100.5438E	Ayutthaya @Ferry of Wat Thagarong	Temple, Market raft	Household, Tree in the riverside
R4	Commercial & residential areas	14.3529N 100.5468E	Ayutthaya @ Chedi Sri Suriyothai	Open space, Restaurant	Historical Park
R5	Commercial & residential areas	14.3418N 100.5607E	Ayutthaya @ Hospital	Hospital (North)	Household (South)
R6	Commercial & residential areas	14.3472N 100.5699E	Ayutthaya @ Ferry of Wat Bangkhunprom	Temple (North)	Restaurant (South)
R7	Commercial & residential areas	14.3333N 100.5761E	Ayutthaya @Portuguese Settlement	Household	Historical Park
U1	Urban area	13.8144N 100.5133E	Bangkok/Nonthaburi @ Rama 7 Bridge	Commercial area (North)	Commercial area (South)
U2	Urban area	13.7389N 100.4990E	Bangkok @ Rama I Bridge (Memorial Bridge)	Ferry pier, Commercial area, Floated log	Ferry pier, Commercial area
U3	Urban area	13.6836N 100.5158E	Bangkok @ Rama 9 Bridge	Commercial area (North)	Public park, Floated log (South)
U4	Urban area	13.6996N 100.5500E	Bangkok @ Chongnonsi WWTP	Commercial area, Household, Wastewater	Natural ecosystem (Nypa palm)
I	Industrial areas	13.6578N 100.5360E	Samut Prakarn @ Prapradaeng	Ferry pier,Household, School	Ferry pier, House & Tree, Factories

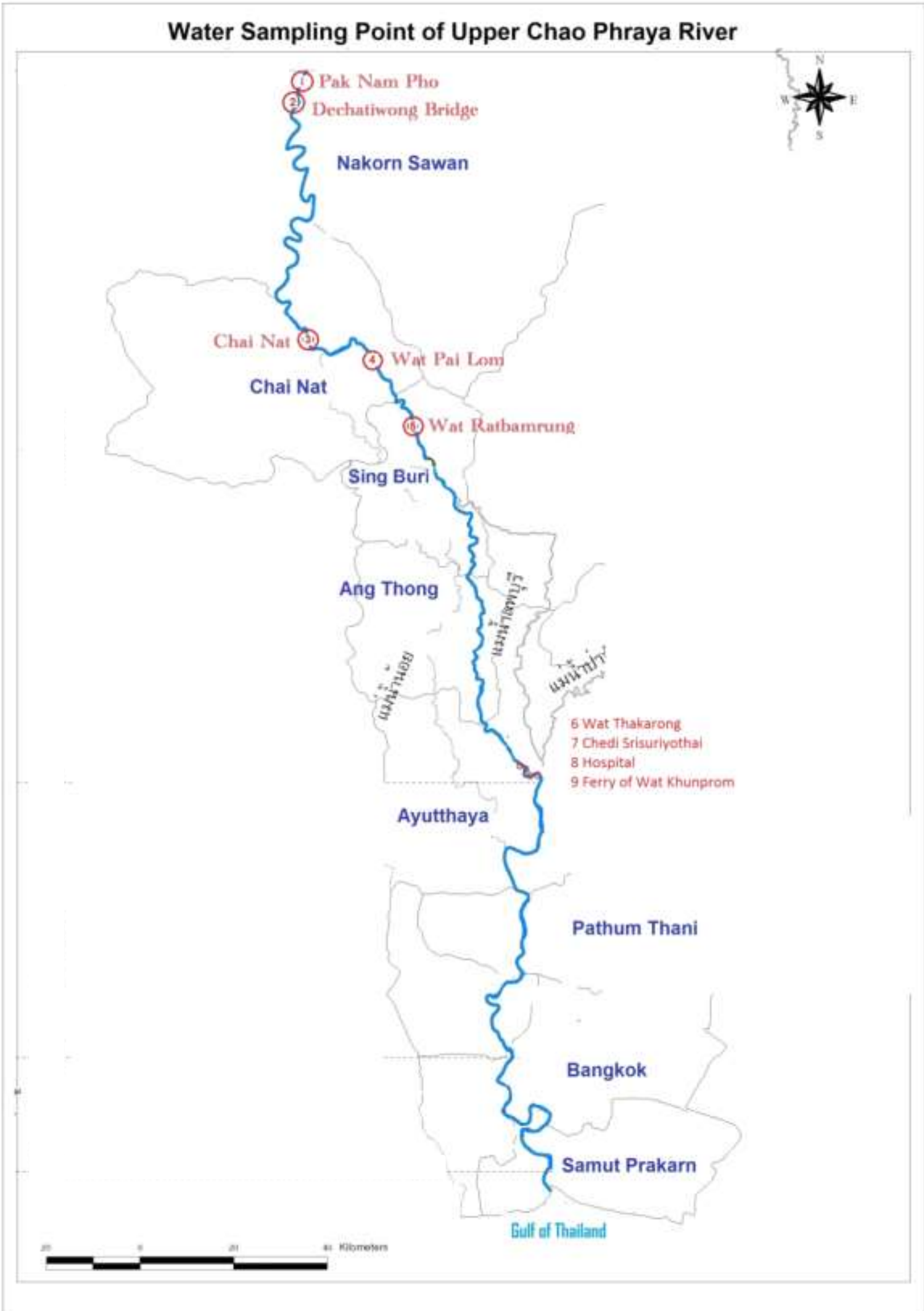


Figure 19. Sampling points on the upper Chao Phraya River

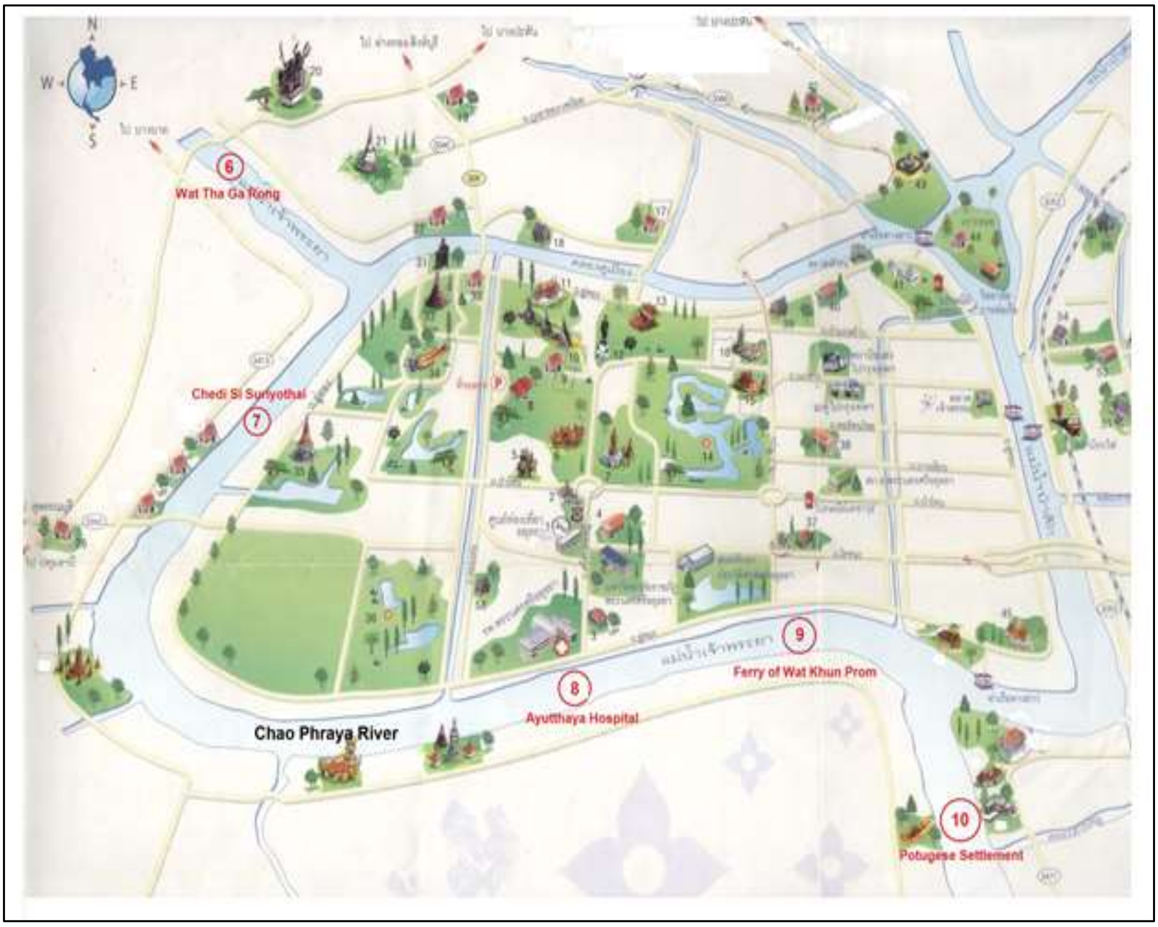


Figure 20. Sampling points in Ayutthaya Province

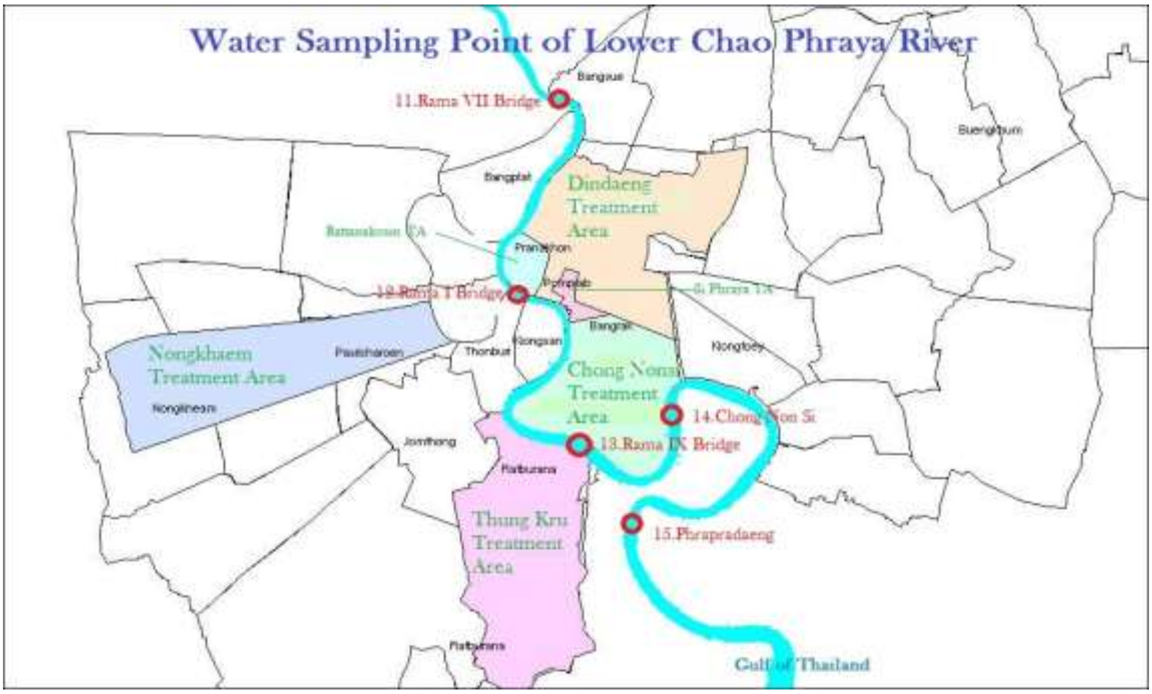


Figure 21. Sampling points on the lower Chao Phraya River

Figure 22. Photos of sampling sites and some of the researchers

Water samples from each location were integrated from the grab samples at the riversides, collected using a vertical water sampler. Both groups of mixed samples, the one for microbial examination and the other group for physical and chemical determination, were kept in 2L polypropylene containers and preserved in an ice box. Quality assurance/quality control (QA/QC) was implemented to assure the data quality for all steps of the measurement activities, from sampling collection to data reporting. In addition to grab samples at the depth of 0.5 m, the effect of depth on water quality was also done by grab samples at the depth of 2.0 m from the river surface.

3.2.1.2 Water sampling during an extreme event

Extreme event sampling was in the dry season (April-May), when Thailand faces water droughts. Water samples were taken on a one-day basis from 9.00 a.m. to 5.00 p.m. at three sampling sites. In addition, influent and effluent were collected from wastewater treatment plants near the sampling sites located in the upstream (the residential area of Nakhon Sawan) and downstream (the urban area of Bangkok) of the Chao Phraya. Details of water sampling for each sampling site and wastewater treatment plant are shown in Tables 13-14.

Table 13. Sampling sites for an extreme event

Sampling name	Land use type	Location	Sampling date	
			Dry season	Wet season
A	Agricultural area	A3: Singburi @ Inburi	March	September
R	Residential area	near water treatment plant effluent	-	September
U	Urban area	near water treatment plant effluent	May	September

Table 14. Wastewater treatment plants in the upstream and downstream of the river

Name	Treatment System	Location	Local name
WWTP-R	MSBR (Modified Sequencing Batch Reactor)	15.6973N 100.1366E	Nakhon Sawan Municipality Water Quality Development Plant
WWTP-U	CASS (Cyclic Activated Sludge System)	13.6947N 100.5484E	Chong Nonsi Water Quality Control Plant

3.2.2 Data collection methods

For each water sampling, the persons collecting samples and their supervisors met to check all materials and instruments used. The name of the person collecting each sample was recorded in the on-site log. The operation of sampling instruments, the cleanliness of sampling instruments and vessels, on-site sample handling and data documentation were inspected for each sampling. Care was taken to obtain the following information.

(1) Sampling site (location, site classification, measurement items, etc.)
(2) The surroundings of the site, at the immediate on-site scale (buildings, trees, parking lots, piers, roads, other circumstances and land use around the sampling sites)

(3) The larger-scale situation around the site (major roads, traffic, aviation, navigation, farming, major pollution sources, surrounding cities, the population, etc.)
(4) Sample collection instruments (pictures of instruments and design diagrams, thier model names, manufacturers, date of manufacture, etc.)
(5) Records for each sampling, relevant to the water collected (detailed information about the sampling site, sampling date, river velocity, water depth, sampling time, ambient and water temperature, pH, DO, etc.)

Transportation of samples from sampling sites to laboratories was done in cooler boxes filled with freezer packs. Water samples for microbial analysis were analyzed as soon as possible and within 24 h of drawing the sample.

3.2.3 Measurement and analysis

Water samples were analyzed following the standard method for water and wastewater examination (APHA et al., 2012) as shown in Table 15. Total coliform and E. coli were analyzed using the EPA Colilert method. This analysis produces a most probable number (MPN). A 100 mL water sample was combined with one packet of Colilert reagent. The mixture was poured into the incubation tray of a Quanti-tray sealer. Samples were incubated at 35±0.5 °C for 18-22 h. A positive result for total coliform was indicated by a yellow color, and for E. coli by fluorescence under ultraviolet light. An MPN table then allowed conversion to MPN/100 mL.

Table 15. Parameters and methods of analysis

Parameter	Method of analysis
pH	pH meter
Dissolved oxygen (DO)	DO meter
Electrical conductivity (EC)	Conductivity meter
Temperature	Thermometer
Suspended solids (SS)	Filtration + Dried at 103-105 ^{o}C
Total phosphate (TP)	Ascorbic acid
Nitrate (NO_3^-)	Sodium salicylate
Ammonia nitrogen (NH_3)	Phenate method
Total Kjdhal nitrogen (TKN)	Digestion + Distillation
Biochemical oxygen demand (BOD_5)	Azide modification
Chemical oxygen demand (COD)	Closed reflux
Chloride (Cl^-)	Tritration

3.3 Results and Discussion

Dry sampling was done on 6-7th April, 2014, and 28-29th March, 2015. Wet sampling was done on 8-9th August, 2014, and 8-9th August, 2015. The effects of water depth, season and land use change were investigated. The land uses of each province of this study are shown in Table 16. Although in Nakhon Sawan and Ayutthaya provinces the highest land use is for paddy fields, in this study the water samples were collected in the central areas of these provinces, areas classified as residential areas. Table 17 shows sizes and population numbers for the various areas studied in the Chao Phraya river basin. Note that the basin covers the main area from Singburi Province to Bangkok Province.

Table 16. Land use percentages in the areas studied

Provinces	Sampling sites	Paddy field (%)	Field crops (%)	Perennial & vegetable (%)	Other agricultural practices* (%)	Forest (%)	Others** (%)
Nakhon Sawan	R1-R2	44.48	24.57	0.93	2.80	9.24	17.97
Chainat	A1- 2	53.29	14.89	0.56	8.30	2.90	20.07
Singburi	A3	67.25	21.83	0.22	6.26	0.00	4.45
Ayutthaya	R3-R7	67.05	0.00	0.56	5.97	0.00	26.42
Nonthaburi	U1	41.14	0.00	6.33	6.14	0	46.39
Bangkok	U1-U4	13.11	0.00	2.13	7.09	0.06	77.62
Samut Prakan	I	6.64	0.00	0.60	26.11	1.21	65.44

Note * Fields for livestock, aquaculture, integrated field crops ** residential area, surface water and miscellaneous uses (Source: Office of Agricultural Economics)

Table 17. Total areas and populations in the areas studied

Provinces	Sampling sites	Province area (Km^2)	Water basin area (Km^2)	Population	Population/ Water basin area	Main land uses
Nakhon Sawan	R1-R2	9,567.04	6,292.77	1,073,142	170.54	Agricultural & residential areas
Chainat	A1- 2	2,500.40	853.67	332,769	389.81	Agricultural area
Singburi	A3	830.68	812.42	212,690	261.80	Agricultural area
Ayutthaya	R3-R7	2,557.82	2,359.16	797,970	338.24	Agricultural & residential areas
Nonthaburi	U1	637.06	633.81	1,156,271	1,824.32	Urban area
Bangkok	U1-U4	1,573.52	1,112.14	5,686,252	5,112.89	Urban area
Samut Prakan	I	953.86	424.54	1,241,610	2,924.60	Industrial & Miscellaneous areas

Source: Hydro and Agro Informatics Institute/ Department of Provincial Administration

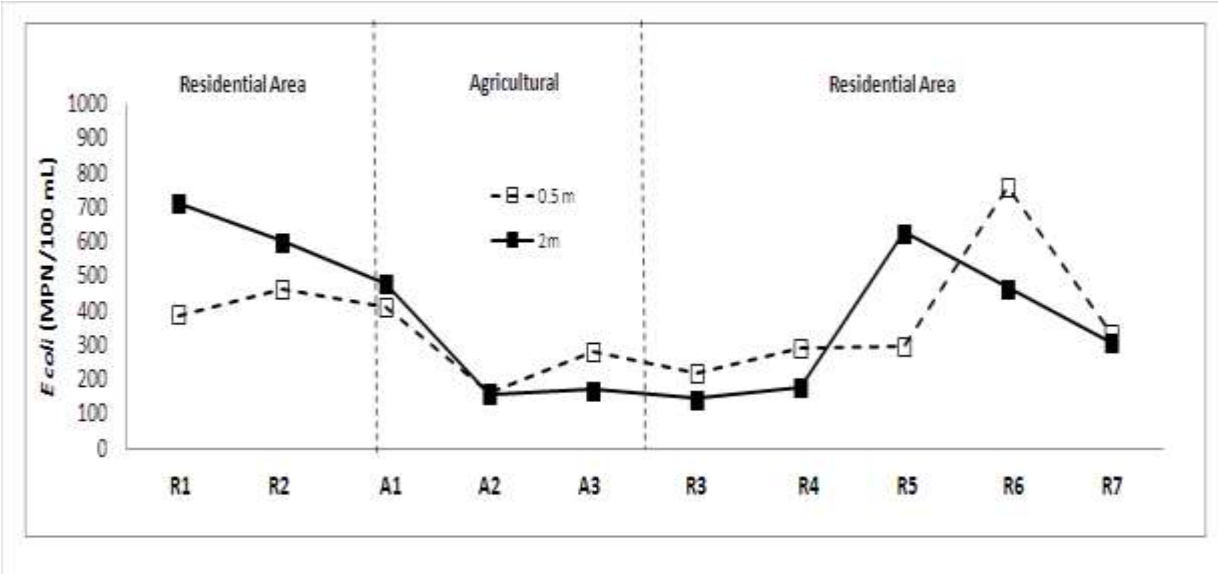
3.3.1 Effect of water depth on river water quality

The effect of water depth (0.5 m and 2.0 m depth) on water quality was investigated by using the mean data collected in the dry season of 2014 and 2015. The biological and chemical characteristics at different depths along the Chao Phraya are shown in Figures 23-25.

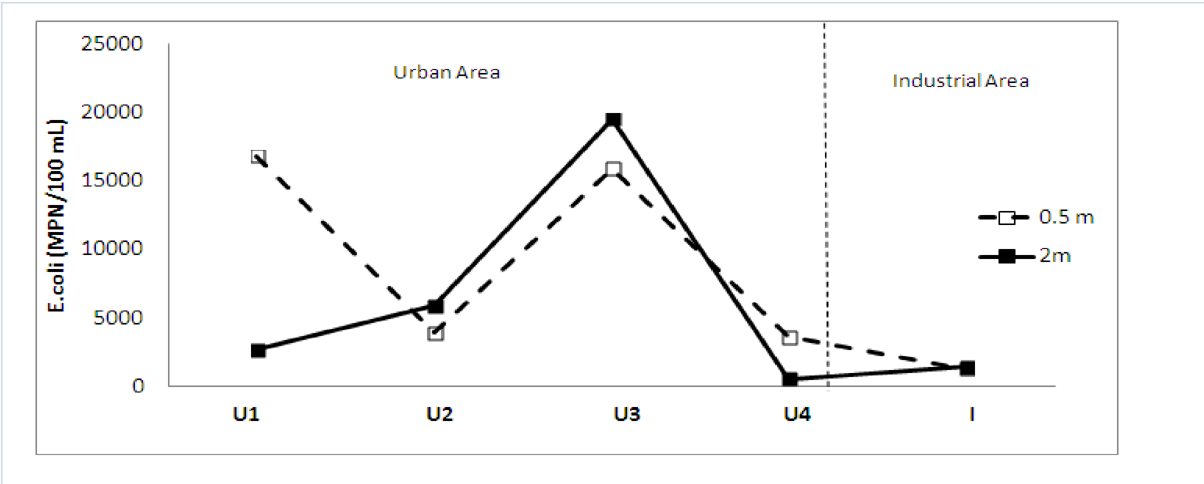
The highest E. coli count, 1.95×10^{4} MPN/100 mL, was found in urban areas, followed in diminishing order by industrial, residential and agricultural areas. The amount of E. coli at a 2 m depth was higher than at 0.5 m in the residential areas of Nakhon Sawan and Chainat provinces (sampling points R1-A1). However, E. coli at the 2 m depth is lower than at 0.5 m in samples collected from the agricultural areas of Sappaya (A2) and Singburi (A3) (Figure 6a). The high fecal contamination implies the risk of pathogenic organisms in the river.

During the dry season, the water level is very low and the water flow rate is not high. The flow was 173 m^3/s in the upstream in Nakhon Sawan and gradually decreased to 80 m^3/s in Chainat (A1). Although a centralized wastewater treatment plant operates in the city of Nakhon Sawan, the coliform bacteria count was still high. This may be because of high coliform bacteria levels in the Ping and Nan rivers. In addition, runoff from the land after heavy rains may have brought coliform to the river through underground sewers for drainage of storm water. Coliform bacteria tend to settle on the river bottom. Motorized tugboats and paddle boats operate during the daytime near these first three sampling points, and their activities can disturb the water and bring up coliform bacteria from the bottom to nearer the surface. The amount of coliform bacteria at the 2 m depth was thereby higher than at 0.5 m. Previous research (Crabill et al., 1999) also reported the association of E. coli with particles in the bottom sediments that have resuspended from boating activities. The number of E. coli at 0.5 m was higher than at 2 m in agricultural and in some residential areas in Ayutthaya Province because less fecal contaminants were discharged there in surface water. This indicates fecal contamination was coming from municipal wastewater discharges, septic tank leachate and nonpoint sources of human and warm-blooded animal wastes. In Ayutthaya Province, the river is more shallow and narrow than in the upper part. Ayutthaya is a flood plain area with a mean sea level of 0.81 m. E. coli in Ayutthaya is still high because houses and building line the river. Only the sampling point near the hospital shows higher E. coli at the 2m water depth than at 0.5 m (Figure 20). This figure points out the effect of water velocity and water depth on the microbial population. The river is shallow (2-3.4 m at the banks) and narrow; in addition the river velocity is low (0.1 m/s). Water collected at 2 m was close to the river bottom, leading to high amounts of E. coli. The amount of E. coli in the lower part of the Chao Phraya (Figure 23b) is very high, representing highly diffuse and nonpoint source pollution in Bangkok.

Figure 24 shows the biochemical oxygen demand (BOD) along the Chao Phraya and the ratio of BOD/COD. BOD values at the 0.5 m depth were higher than at 2.0 m at the sampling sites with households nearby. A low BOD/COD ratio implies the river was contaminated with chemical substances. A ratio of less than 0.10 reveals the presence of a large portion of hard-biodegradable organic compounds (Samudro and Mangkoedihardjo, 2010). The BOD/COD ratios at 0.5 m were mostly greater than 0.1 and higher than those at 2.0 m. A low BOD/COD ratio was found in agricultural areas (A1, A2, A3), a residential area (R6) and an industrial area (I). At sampling point R6, a low BOD/COD was found because there was oil and grease contamination in the river, originating from a restaurant.



(a)



(b)

Figure 23. E. coli at 0.5 m and 2 m depths (a) in the upper and middle parts of the river (b) in the lower part of the river

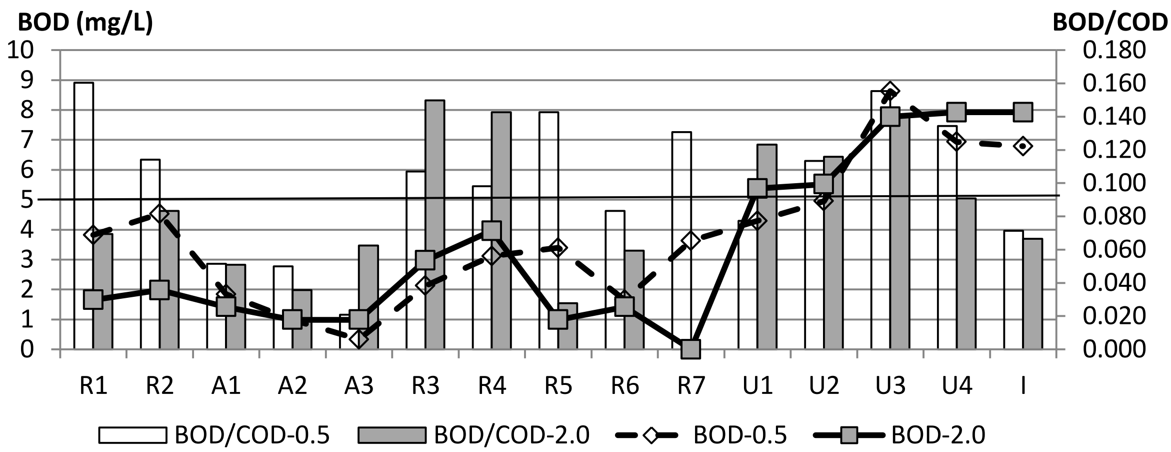


Figure 24. BOD values and BOD/COD ratios from different depths at sampling sites

Total Kjeldahl nitrogen (TKN) and total phosphorus in the river show the same trend as BOD. Total phosphorus in the water was highest in the lower part of the river (Figures 25-26). These enter the river water from human and animal wastes, fertilizer runoff and industrial effluents. Most TKN concentrations at 0.5 m were lower than at 2.0 m in residential areas (R1, R4-R7) and urban areas (U1-U3). Total phosphorus concentrations at different water depths did not differ much.

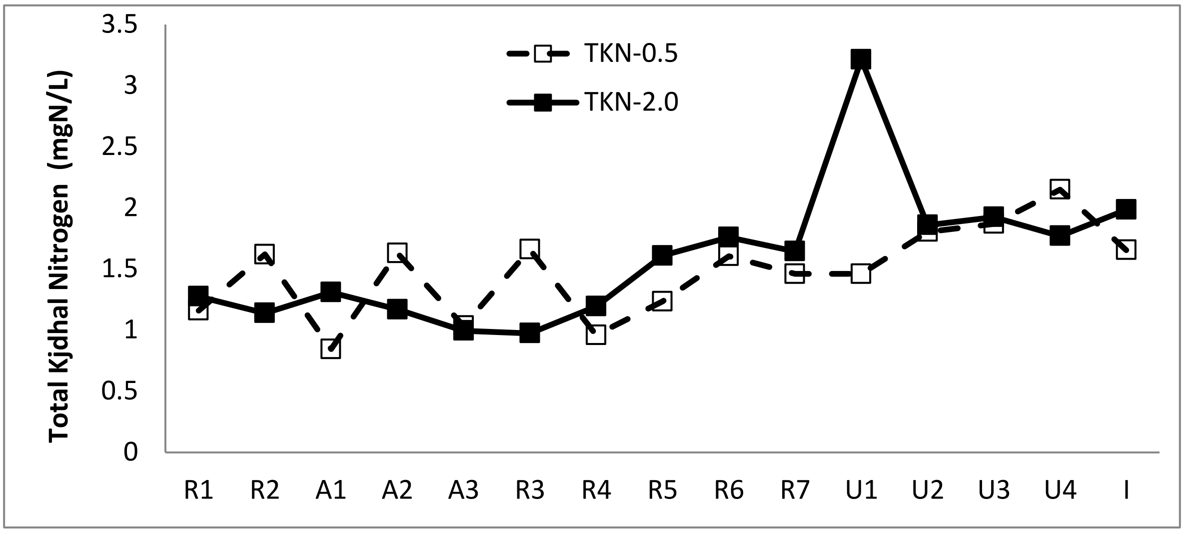


Figure 25. TKN concentrations from different water depths at sampling sites

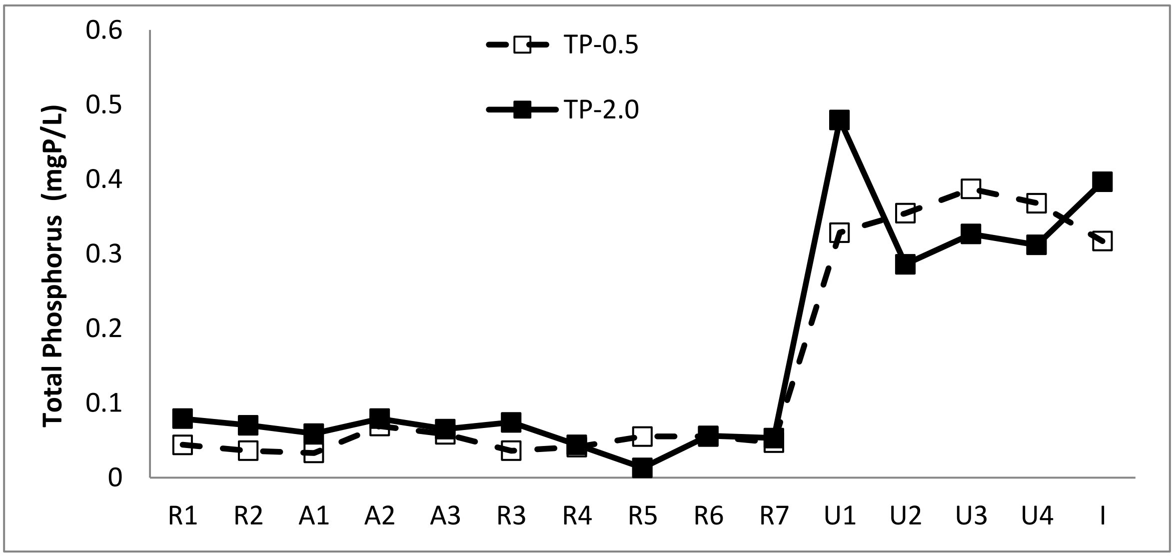


Figure 26. Total phosphorus concentrations from different water depths at sampling sites

3.3.2 Effects of seasonal changes and land use changes on river water quality

Effects of wet and dry seasons on river water quality were investigated for the four different land uses, residential, agricultural, urban and industrial. The dry season in Thailand occurs from November through May. The long period of dry weather is followed, in the upper Chao

Phraya (R, A), by heavy rain and storms in April. The amount of rainfall in the wet season during the period under study was also low compared to previous years.

From this study, the ranges of DO in the dry and wet seasons along the Chao Phraya were 3.55-7.30 and 2.60-6.56 mg/L, respectively (Figure 27a). It can be seen that there was a problem of organic pollution during the wet season due to rainfall washouts from the land. High pollution was found in urban areas located in the lower part of the river, particularly the stretch passing through the Bangkok metropolis. The pH values were also low in urban and industrial areas during the wet season. These fell in the range of 7.25-7.73 and 6.49-7.74 in the dry and wet seasons respectively (Figure 27b).

Suspended solids in the dry season along the Chao Phraya were in the range of 16.0-85.5 mg/L, lower than in the wet season (22.0-95.0 mg/L) (Figure 27c). The low amount of rainfall during the wet season in 2014-2015 did not affect the water turbidity for water supply production. However, the dryness led to a low river flow and caused the problem of saltwater intrusion from the Gulf of Thailand. An electrical conductivity (EC) value of 15.03 was found at the last sampling point in the dry season (Figure 27d). Chloride concentrations in excess of about 250 mg/L can give rise to a detectable taste in water. When chloride concentrations were analyzed, the concentration at the U1 sampling point within Bangkok city was 530 mg/L, and was 2,487 mg/L at sampling point I. Bangkok city is located 25 km from the sea. The altitude of the city does not exceed 2 m. The average altitude is 1.1 m which means that it is approximately 0.8 m above the average level of the Chao Phraya River. The water drought in Thailand during these 2 years were believed the worst in the past 100 years. High dissolved solids and EC affected the water supply production and water plants. Tap water in some Bangkok areas became unpalatable with a brackish taste. To overcome this problem, the Metropolitan Water Works Authority and Irrigation Department diverted water from the Mae Khlong River to the Chao Phraya River.

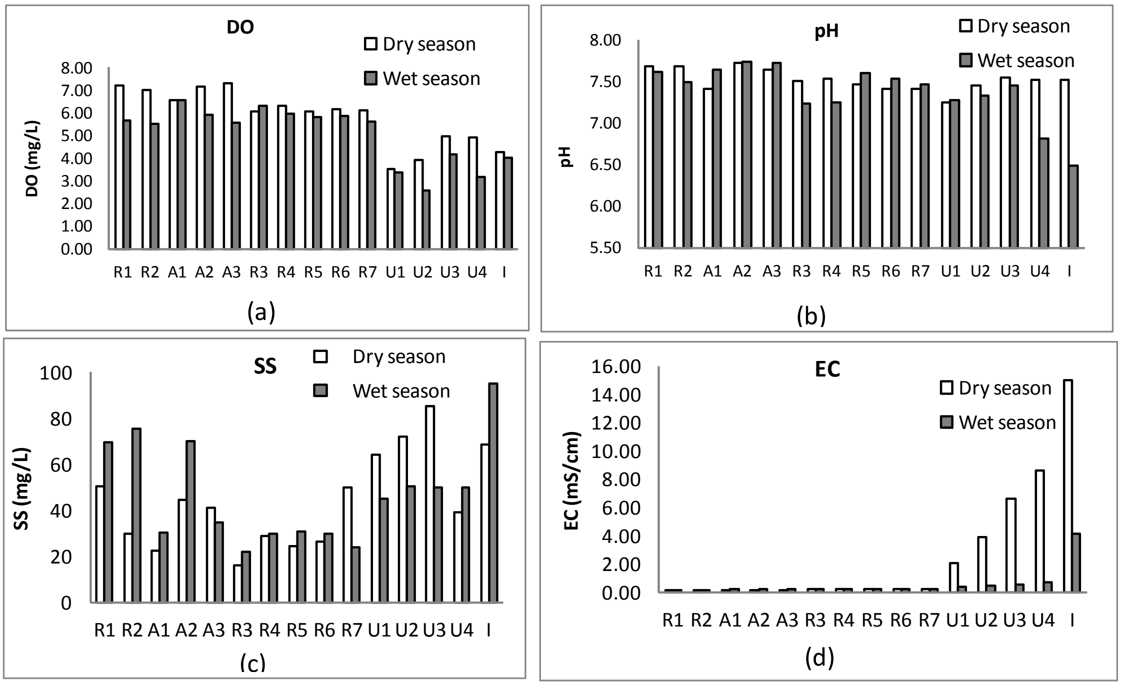


Figure 27. Effect of season on water quality along the Chao Phraya River

Table 18 shows the recommended criteria for characteristics of surface water in Thailand, according to land use, for pH, DO, BOD and TCB. Table 19 displays the mean value of water quality for each area. Organic pollution was the main form of pollution along the Chao Phraya with BOD values exceeding the criteria for all land uses. High TCB and E. coli indicate the pollution comes from households, particularly in urban and industrial areas.

These two area types make up the economic center of Thailand, whose myriad activities include the commercial, the industrial and services. Here many canals connect to the river; these act as sewers for receiving the discharge of wastewater in most areas because the centralized wastewater treatment plants can not cover all parts of the city. Because of this, wastewater is discharged without treatment into public sewers which drain into the canals.

Table 18. Criteria for water surface characteristics classified by land use

Parameters	Residential area	Agricultural area	Urban area	Industrial area
pH	5.00-9.00	5.00-9.00	5.00-9.00	5.00-9.00
DO (mg/l)	$\geq$ 6.00	$\geq$ 4.00	$\geq$ 2.00	$\geq$ 2.00
BOD (mg/l)	$\leq$ 1.50	$\leq$ 2.00	$\leq$ 4.00	$\leq$ 4.00
TCB (MPN/100ml)	$\leq$ 5,000	$\leq$ 20,000	-	-

Table 19. Mean values for river water quality in different land use areas

Parameters	Season	Residential area	Agricultural area	Urban area	Industrial area
DO	Wet	5.81	6.03	3.34	4.00
	Dry	6.41	7.00	4.34	4.25
pH	Wet	7.46	7.70	7.22	6.49
	Dry	7.53	7.60	7.44	7.53
EC	Wet	0.24	0.21	0.55	4.14
	Dry	0.22	0.18	5.32	15.03
SS	Wet	40.29	45.17	48.88	95.00
	Dry	32.36	36.00	65.25	68.50
TKN	Wet	1.30	1.74	2.18	2.44
	Dry	1.39	1.17	1.82	1.66
TP	Wet	0.08	0.10	0.30	0.40
	Dry	0.04	0.05	0.30	0.31
BOD	Wet	1.71	1.56	4.11	7.26
	Dry	3.18	1.05	6.20	6.79
TCB	Wet	140,785	82,564	316,223	373,940
	Dry	27,079	5,900	263,480	173,290
E.coli	Wet	23,193	7,493	22,197	12,104
	Dry	393	285	10,040	1,250

Wet season water quality is worse than in the dry season because of the surface runoff after a rainfall. Thailand’s climate is affected by two tropical weather patterns during its “rainy” season: the southwestern monsoon that originates in the Indian Ocean, and tropical storms that originate in the Pacific. The monsoons are the primary driver of rainfall during the rainy season, from June to October (Thai Meteorological Department, 2012).

3.3.3 Effects of extreme events and land use on river water quality

The Thai Meteorological Department (2014) reported that for 2014 all months except January and February were warmer than what was normal for the 1981-2010 period. No tropical cyclones hit Thailand in 2014, leaving rainfall 4% below normal at 1520.4 mm. A large contribution to the annual rainfall total usually comes from the monsoon trough and the southwest monsoon, accompanied by several cyclones dissipating near the country.

As the water quality of the Chao Phraya is so dependent on the climate, water sampling was done in wet and dry seasons in the agricultural area A3 in Singburi Province. This province is located in the central plain of the country. With no large water reservoir in the province, it must rely on dams upstream to the north. During the period studied in 2014-2015, Thailand faced long periods of water drought due to the El Nino phenomenon, which reduced rainfall, consequently altering typical farming activities. Rice farmers delayed cultivation and some refrained from planting a second crop, switching to plants needing less water. Figures 28-29 show runoff, numbers of rainy days and rainfall amounts during rice cultivation.

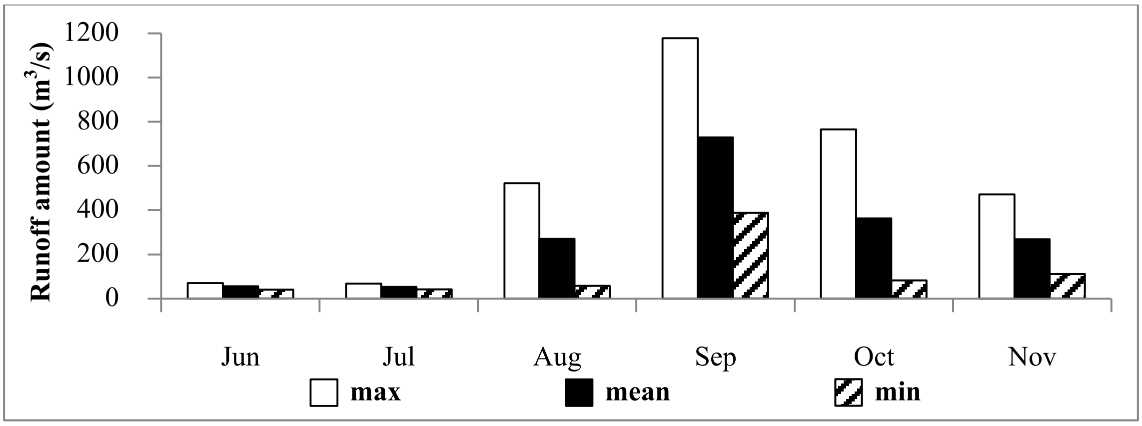


Figure 28. Runoff amount in the Chao Phraya River in Singburi Province

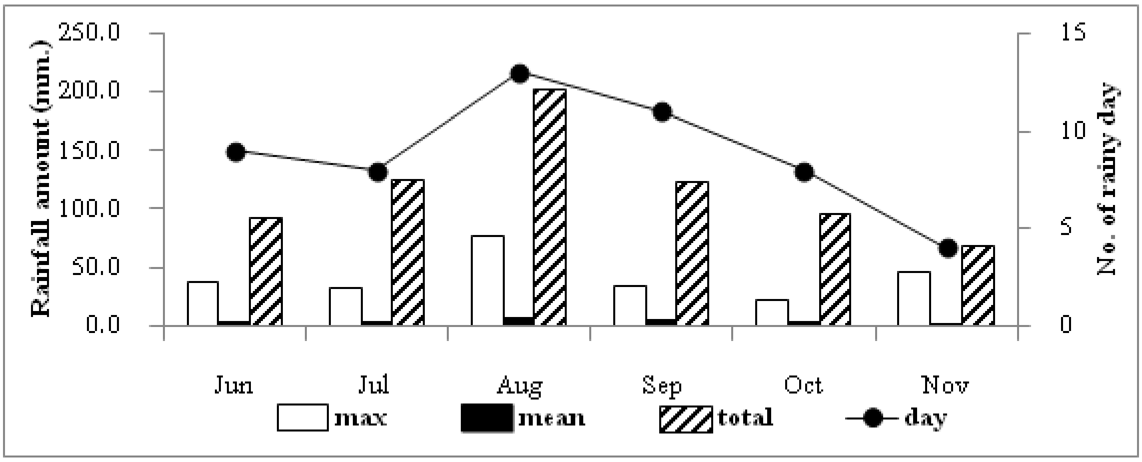


Figure 29. Rainfall amount and number of rainy days during cultivation periods in Singburi Province

Biological and chemical parameters of the Chao Phraya River during the wet and dry seasons for a one-day period are shown in Figures 30-34. The values of pH were in the range of 7.42-7.46 and 7.50-8.05 in the wet and dry seasons, respectively. Dissolved oxygen was lower during the wet season than the dry because of surface runoff from the land into the river. Rice cultivation consists of three main processes: land preparation, seeding/planting and harvesting. During rice planting, fertilizer and pesticides are applied. There are two periods for fertilizer application on rice paddy fields, the vegetative phase and the reproductive phase. Urea fertilizer (46-0-0) at the application rate of 10.5 kg/m^2 is used in the tilling stage to stimulate rice plant growth; the second application of chemical fertilizer (18-8-8) is for grain formation. In addition, some Thai farmers keep flocks of ducks in their rice paddies. Duck are a form of biocontrol of pests; their feeding in the paddies reduces the high expense of commercial feed as well. These activities contribute to water contamination by organic substances and coliform bacteria. Higher nutrients, organic substances and coliform bacteria were found in the wet season. However, the BOD/COD ratio in the dry season is lower than in the wet. Most parameters are higher in the morning, except nitrate concentrations in the wet season. This is related to the conversion of organic nitrogen from applied fertilizer. The increment of nitrate from the decomposition of urea fertilizer to ammonia and nitrate occurs as follows:

$$CO(NH_2)_2 \xrightarrow{\text{Ammonification}} NH_3 \xrightarrow{\text{Nitrosomonas}} NO_2^- \xrightarrow{\text{Nitrobacter}} NO_3^- \quad (1)$$

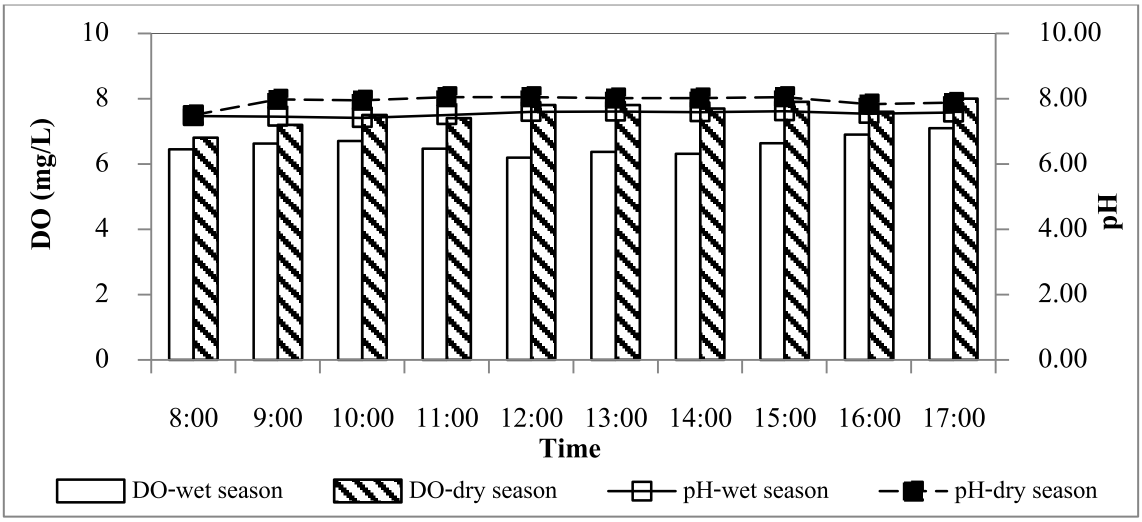


Figure 30. Hourly pH and dissolved oxygen (DO) values in agricultural area A3

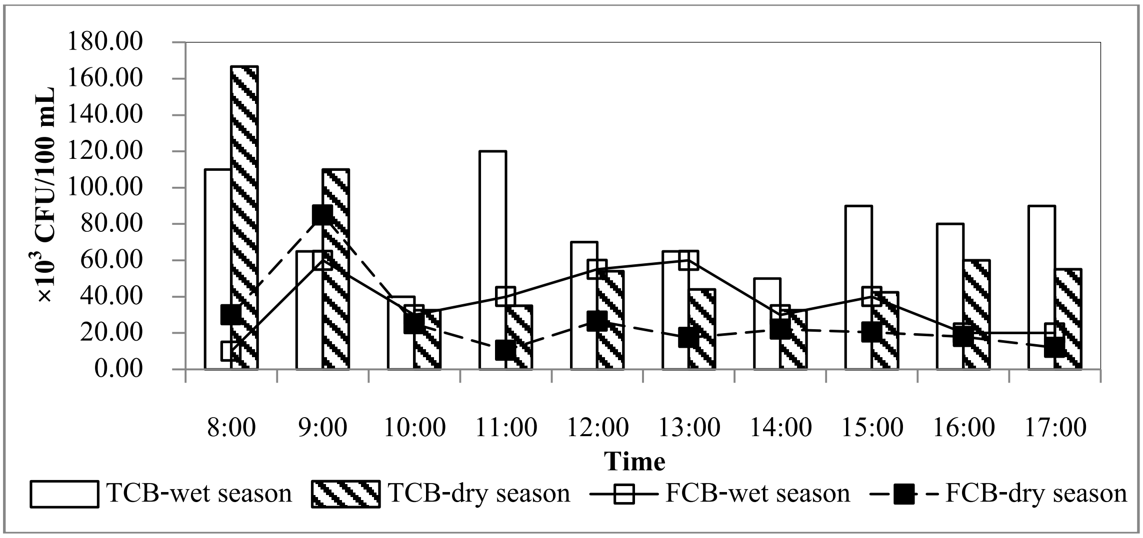


Figure 31. Hourly TCB and FCB values in agricultural area A3

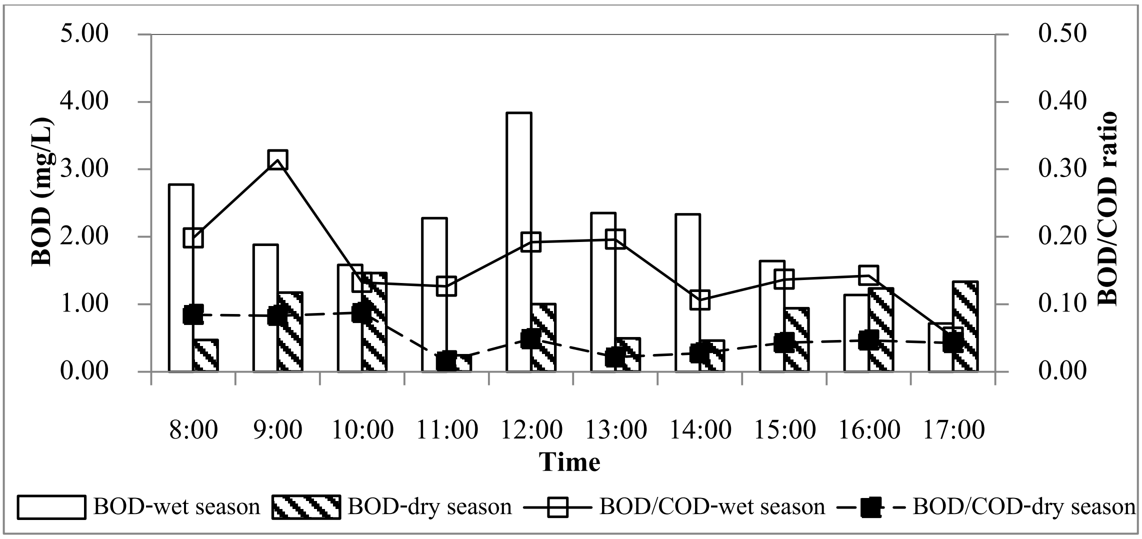


Figure 32. Hourly BOD and BOD/COD values in agricultural area A3

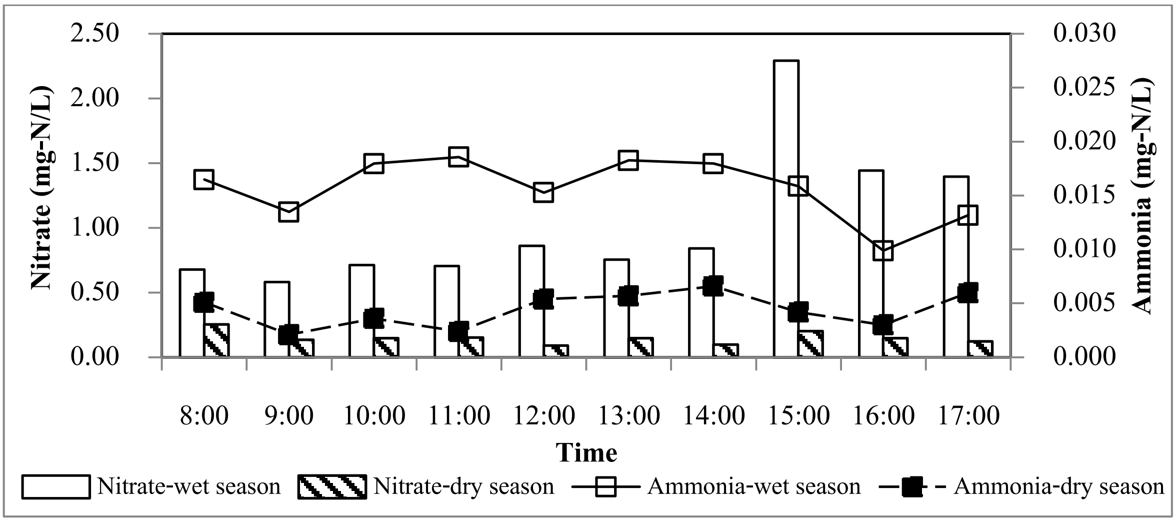


Figure 33. Hourly nitrate and ammonia values in agricultural area A3

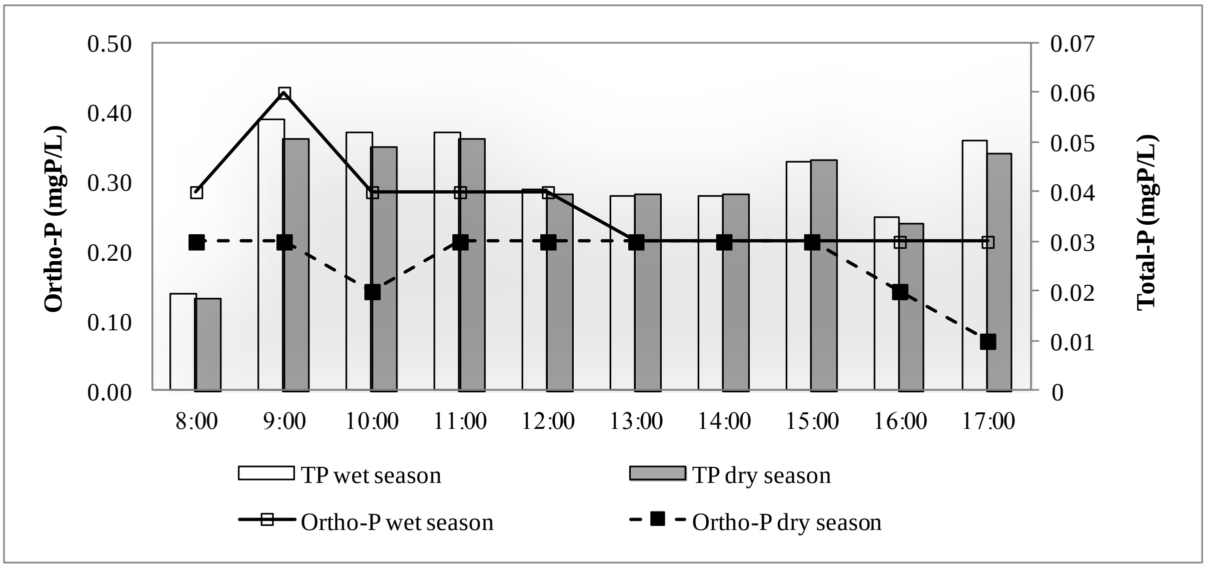


Figure 34. Hourly total phosphate and orthophosphate values in agricultural area A3

The main contaminants in the river water are organic substances and coliform bacteria, particularly in the wet season. Water samples in different area types (residential, agricultural and urban areas) during the wet season (in September) were collected hourly. The rainfall amounts and river water flow rates for each area type are shown in Table 20. There was no rain in the upper part of the Chao Phraya in the residential and agricultural areas on the sampling date. The monthly rainfall amounts in each area were also low.

Table 20. Rainfall amounts and river flow rates in areas studied during the wet season

Area	Rainfall amount (mm)		River flow (m^3/s)
	on sampling date	Monthly	
Residential	0	130.7	845
Agricultural	0	4.1	730
Urban	4	188.0	786

The BOD, TCB and FCB values for each land use area are shown in Figure 35. BOD values did not differ from morning to afternoon for all land uses. River water in residential and urban areas was collected near a wastewater treatment plant (WWTP), thus BOD in the river was diluted. The effluents of the treatment plant consisted of treated wastewater, and were released all day. BOD removal efficiency for WWTP-R was higher than for WWTP-U, as shown in Table 21. However, coliform bacteria in the residential area was high because of contamination with sewer water. It can be seen that higher TCB and FCB values were found in the afternoon in residential and urban areas. Such human activities that result in the discharge of wastewater directly into the sewer tend to be higher in the afternoon.

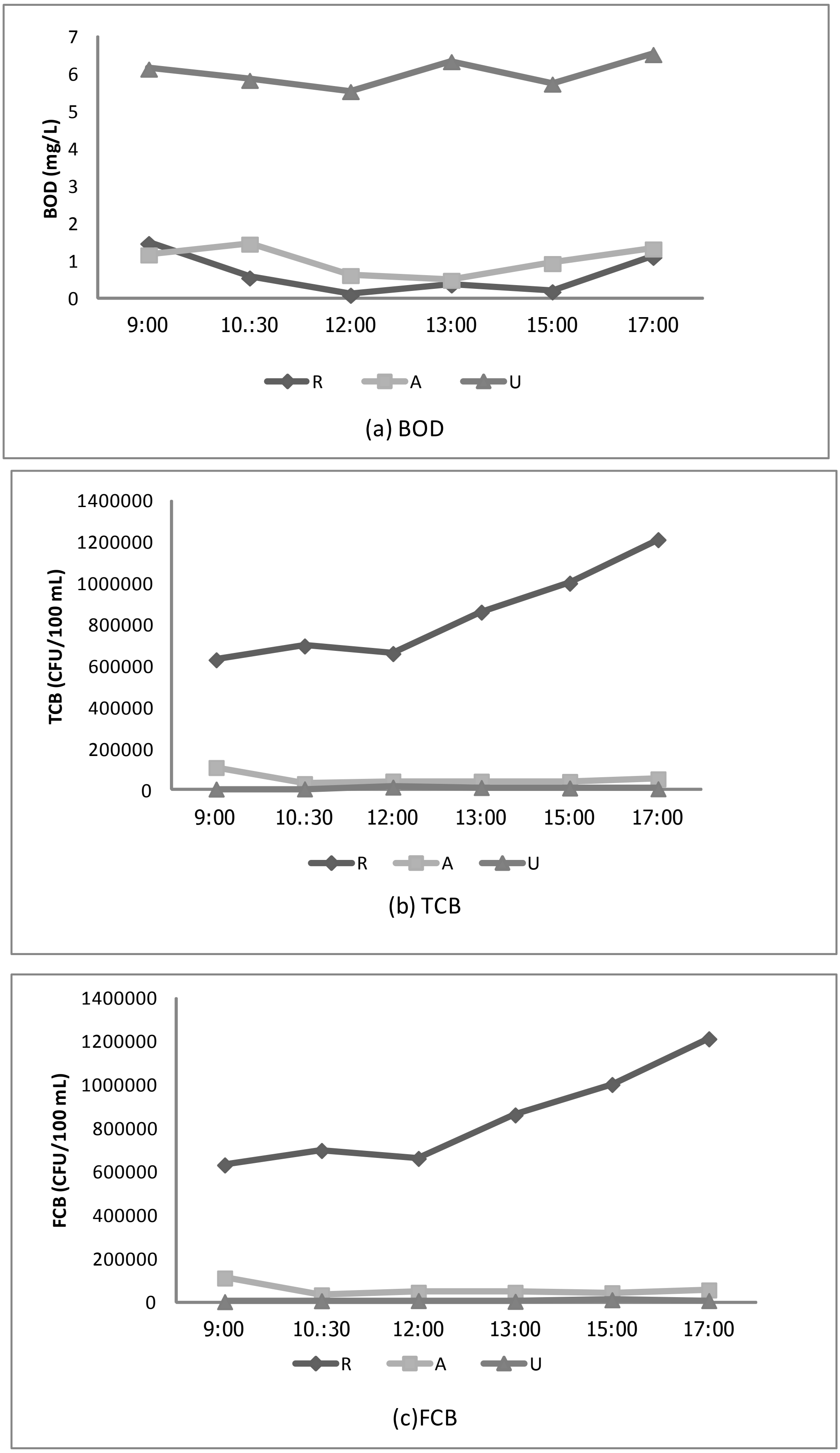


Figure 35. Comparison of daily BOD, TCB and FCB values in the river in different land use areas

Table 21. Influent and effluent of wastewater treatment plants in wet and dry seasons

		Season	BOD (mg/L)	COD (mg/L)	DO (mg/L)	TP (mgP/L)	NH_3 (mgN/L)	pH
WWTP-R	Influent	Wet	26.80	135.2	3.08	0.31	0.03	7.2
		Dry	32.00		2.86	0.70		7.1
		Average	29.40	135.0	2.97	0.51		7.1
	Effluent	Wet	0.31	47.6	4.90	0.15	0.02	7.1
		Dry	1.80		4.56	0.30		6.8
		Average	1.06	47.6	4.73	0.15	0.02	6.9
	% removal	Wet	98.84	64.8		51.61	33.33	
		Dry	94.38			57.14		
		Average	96.61	64.8		54.38	33.30	
WWTP-U	Influent	Wet	23.87	59.2	2.70	1.86	10.75	6.7
		Dry	34.93	69.03	2.20	1.75	9.81	6.8
		Average	29.40	64.1	2.45	1.81	10.28	6.8
	Effluent	Wet	4.32	27.9	5.96	1.11	2.47	6.8
		Dry	5.90	23.0	6.27	0.96	1.37	7.0
		Average	5.11	25.4	6.12	1.04	1.92	6.9
	% removal	Wet	81.90	53.0			77.02	
		Dry	83.11	66.7			86.03	
		Average	82.51	59.8			81.53	

3.4 Conclusions

This study found that climate and land use changes affect water quality, particularly during the wet season in urban and residential areas. Runoff from the land leads to an increase in bacteria numbers and in organic pollution, which indicates higher health risks from direct water use. Coliform bacteria accumulated in the bottom sediments of the river, and could be suspended when disturbed by watercraft. Full-day observations of water quality in agricultural areas showed high coliform bacteria levels in the morning, while BOD and nitrates were higher in the afternoon. Coliform bacteria levels were higher in the afternoon in residential and urban areas. It is human activities that have the greatest effect on water quality.

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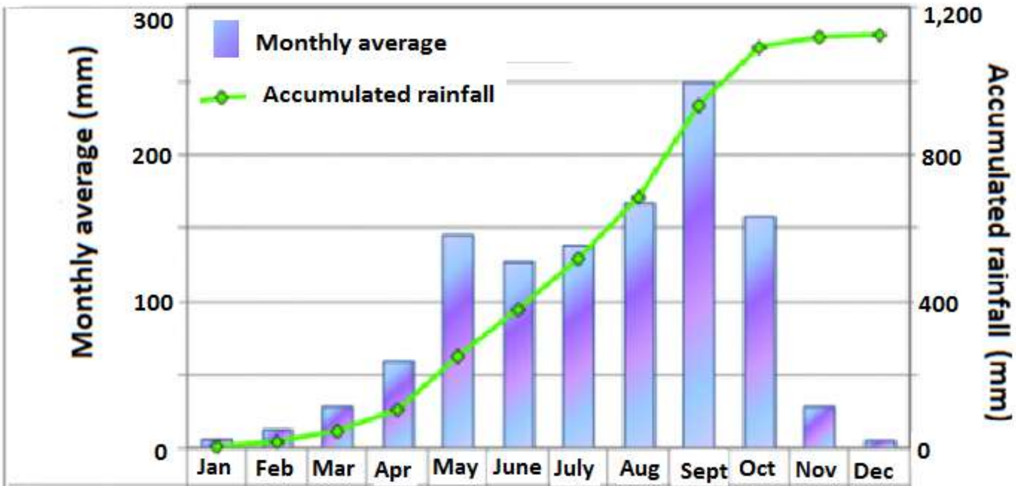
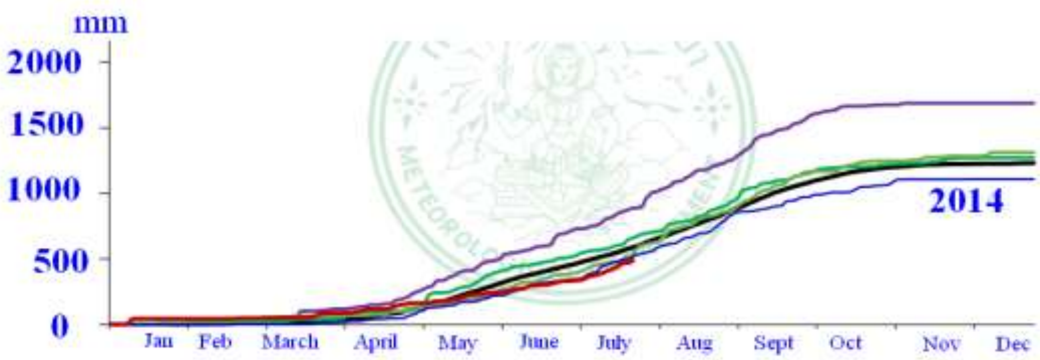
Appendix

Average rainfall 1992-2012

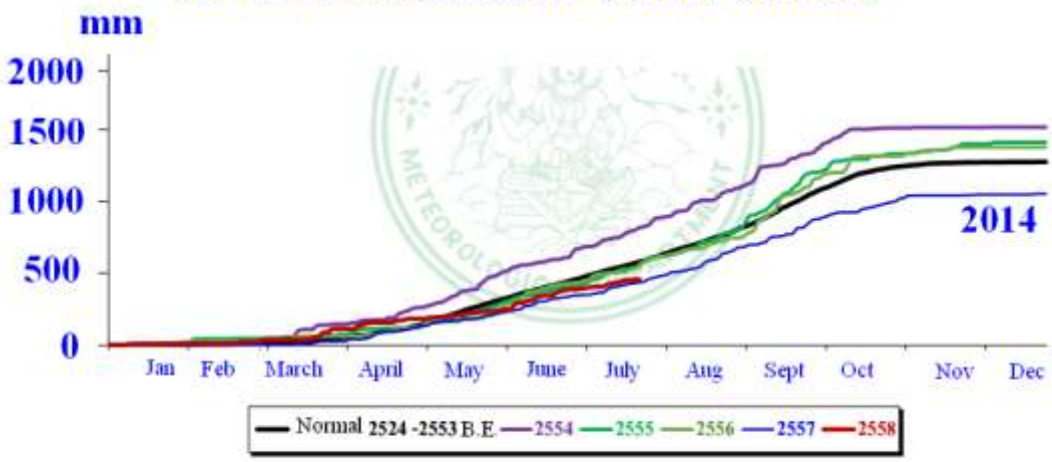


	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly average	6	13	28	59	146	127	138	167	249	158	28	5
accumulated rainfall	6	19	47	106	252	518	579	685	934	1093	1121	1127

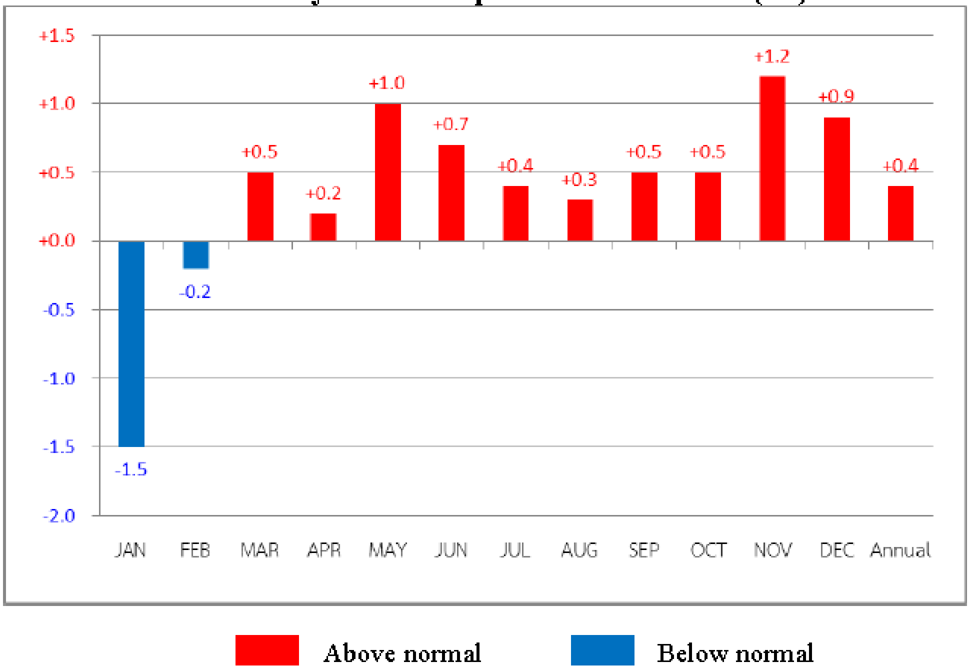
Accumulated Rainfall in Northern Thailand

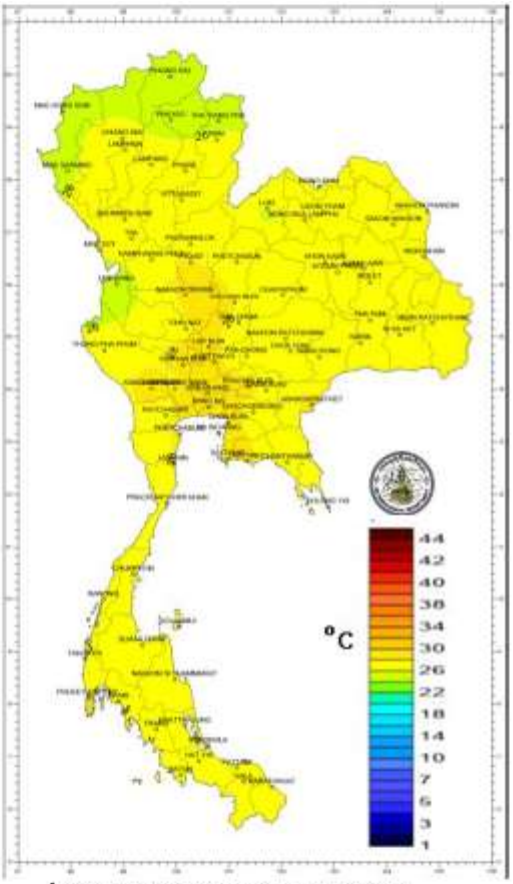


Accumulated Rainfall in Central Thailand



Thailand's monthly Mean temperature anomalies (°C) in 2014





Mean temperature 2014
Max. = 29.9 °C
Min. = 24.1 °C

Thailand's monthly rainfall

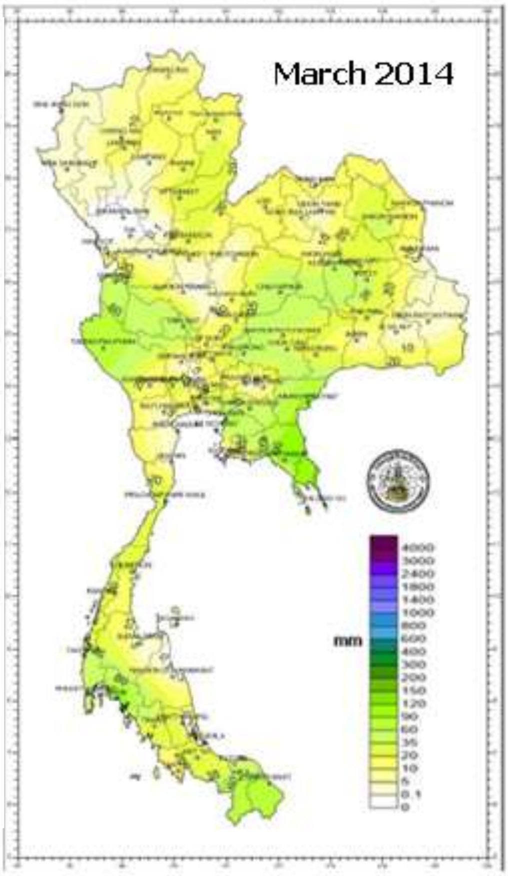
March 2014: Max. = 158.6 mm, Min. = 0.0 mm

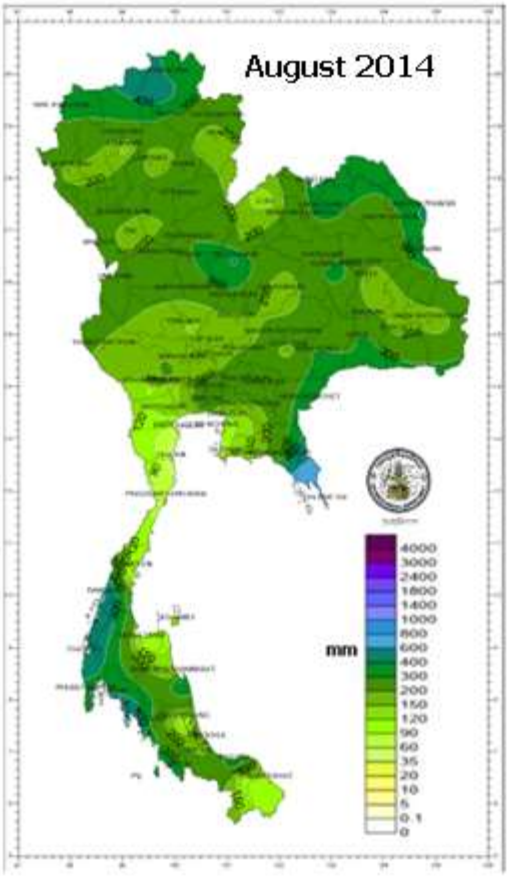
Aug. 2014: Max. = 1077.3 mm, Min. = 39.3 mm

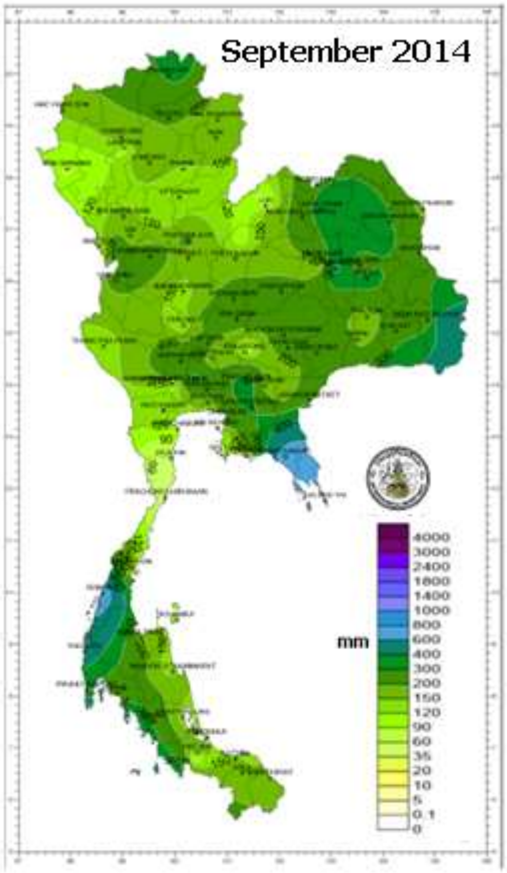
Sept. 2014: Max. = 893.3 mm, Min. = 40.8 mm

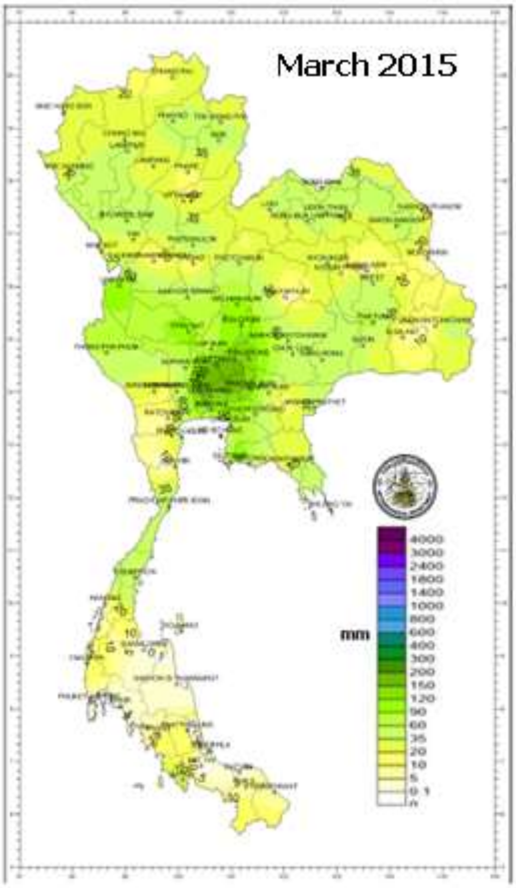
March 2015: Max. = 187.3 mm, Min. = 0.0 mm

Sept. 2015: Max. = 939.8 mm, Min. = 67.7 mm








March 2015
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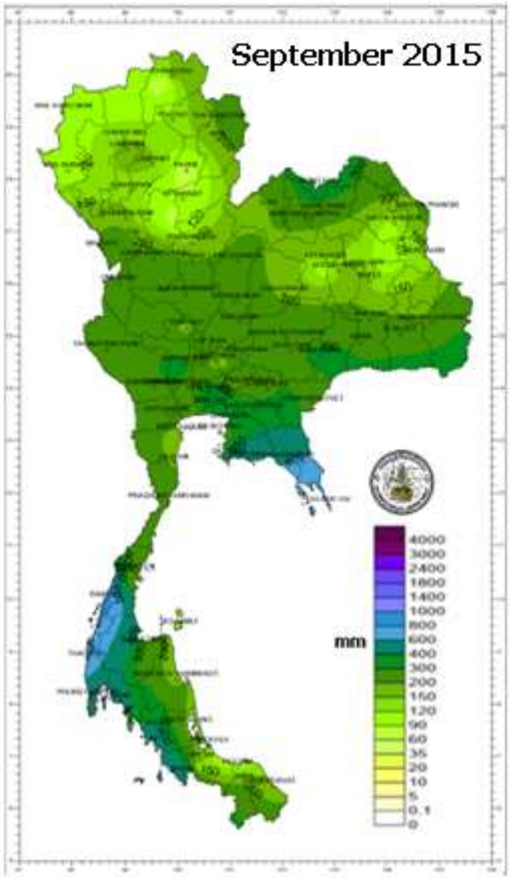
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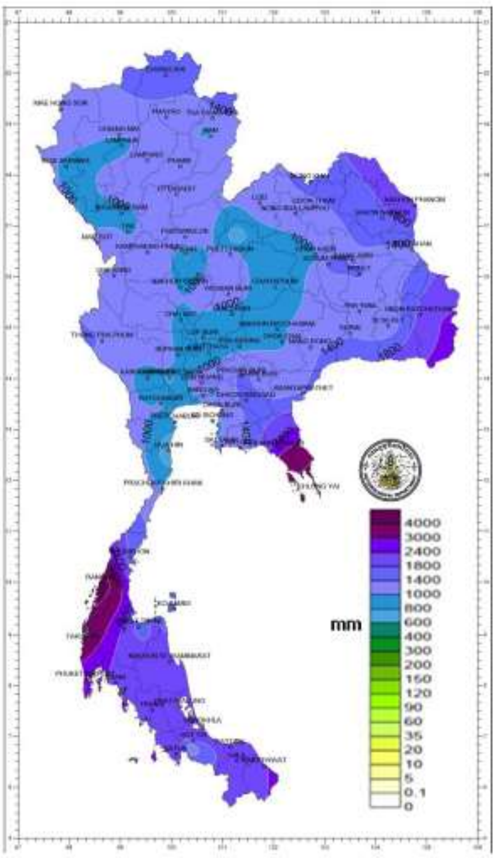
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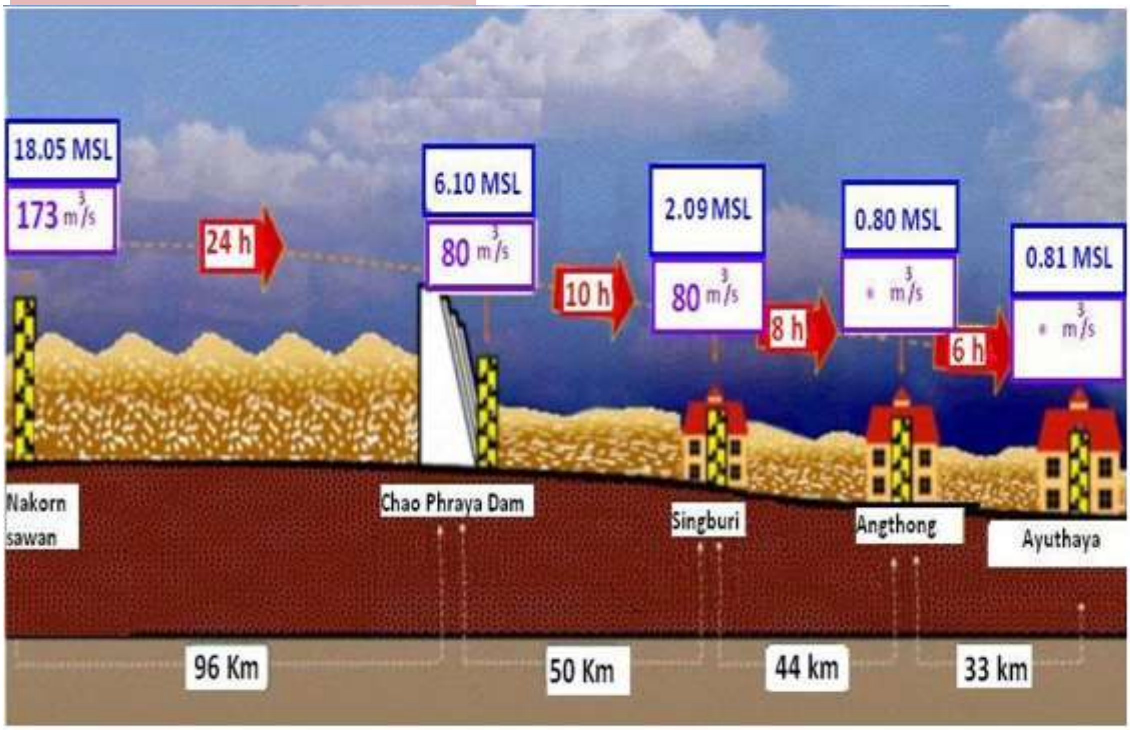
Thailand's rainfall for 2014 by areas (max. = 5143.90 mm, min. = 610.30 mm)

Distance, mean sea level and river flow rate of the Chao Phraya River

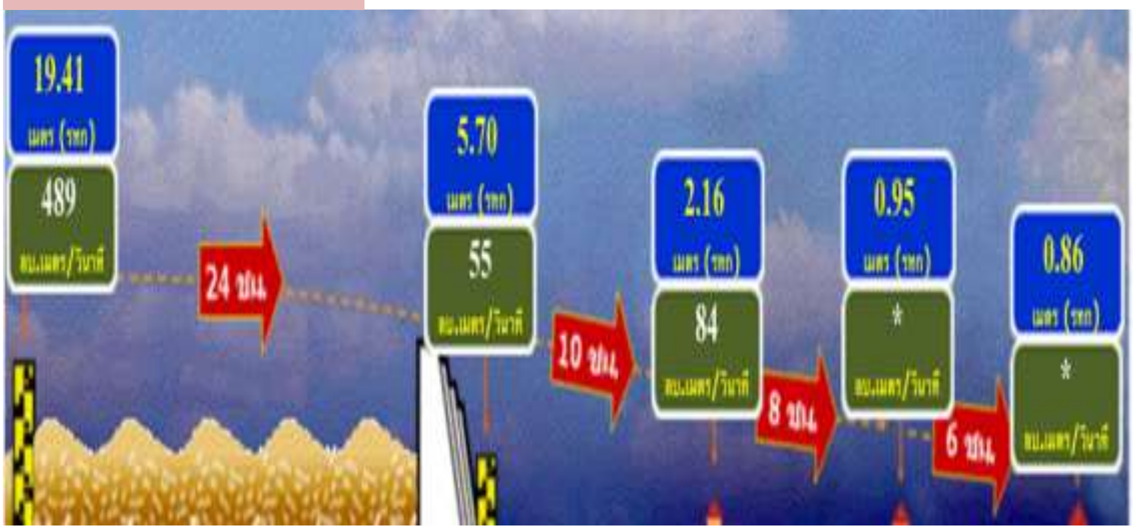
Dates of sampling: Dry season: 6-7th April 2014, 28-29th March 2015

Wet season: 8-9th August 2014, 8-9th August 2015

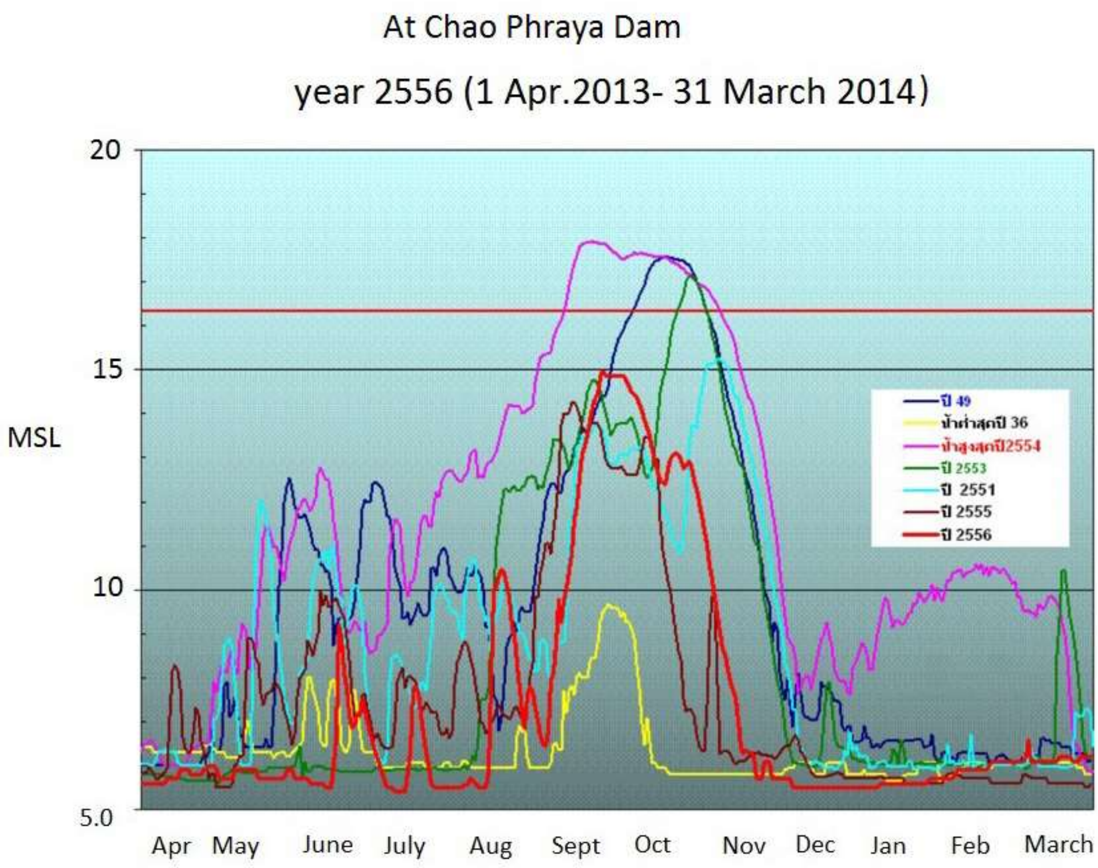
Dry 2014



Wet 2014



		Nakhon Sawan	Chao Phraya Dam	Singburi	Angthong	Ayuthaya
Dry 2015	Water level (MSL)	17.83	5.84	1.97	0.77	0.94
	Water Flow (m^3/s)	186	65	68	-	-
Wet 2015	Water level (MSL)	18.48	5.96	2.05	0.86	0.57
	Water Flow (m^3/s)	351	75	78	-	-



Abstract of the SCI Paper: *Water* (2015), *7*(12), 6892-6909. doi:10.3390/w7126665

Assessment on Hydrologic Response by Climate Change in the Chao Phraya River Basin, Thailand

The Chao Phraya River in Thailand has been greatly affected by climate change and the occurrence of extreme flood events, hindering its economic development. This study assessed the hydrological responses of the Chao Phraya River basin under several climate sensitivity and greenhouse gas emission scenarios. The Soil and Water Assessment Tool (SWAT) model was applied to simulate the streamflow using meteorological and observed data over a nine-year period from 2003 to 2011. The SWAT model produced an acceptable performance for calibration and validation, yielding Nash-Sutcliffe efficiency (NSE) values greater than 0.5. Precipitation scenarios yielded streamflow variations that corresponded to the change of rainfall intensity and amount of rainfall, while scenarios with increased air temperatures predicted future water shortages. High CO_2 concentration scenarios incorporated plant responses that led to a dramatic increase in streamflow. The greenhouse gas emission scenarios increased the streamflow variations to 6.8%, 41.9% and 38.4% from the reference period (2003–2011). This study also provided a framework upon which the peak flow can be managed to control the nonpoint sources during the wet season. We hope that the future climate scenarios presented in this study provide predictive information for the river basin.

Keywords: hydrology; Chao Phraya; SWAT

Abstracts of Six Proceedings

Effects of Water Depth, Season and Land Use on the Microbial Numbers along the Chao Phraya River

This study examined the microbial quality in the Chao Phraya River during a dry season (April 2014) and a wet season (August 2014). Water samples were collected at depths of 0.5 and 2 meters from the water surface. Impacts of different land uses was determined for total coliform bacteria (TCB), fecal coliform (FCB), fecal streptococcus (FS) and *Escherichia coli* (E. coli). The highest number of TCB was 5.96 log MPN/100 ml in residential areas and the highest number of E. coli was 4.45 log MPN/100 ml in urban areas during the wet season. High levels of BOD and low levels of DO were found in residential and industrial areas, indicating the effect of the numbers and activities of the population on pollutant contamination of the river. The spread of bacteria in the river could be affected by river velocity since the number of E. coli at 40% of the distance from the river bank was higher than at 20% of the distance from the bank. Moreover, results from high FCB/FS and low TCB/E. coli ratios revealed that contamination from municipal wastewater was a major source of water pollution. The highest ratio of FCB/FS was 299 in residential areas while the lowest TCB/E. coli ratio was 5 in industrial areas.

Keywords: Chao Phraya River; land use; coliform

Effect of Drought on Water Resources: A Case Study of the Chao Phraya River

This research aims to assess the changing physical and chemical water quality of the Chao Phraya River in drought conditions resulting from climate change. Chemical and physical parameters were evaluated by using the data from fifteen water sampling sites along the river under different land uses. The highest BOD, of 6.78 mg/L, was found in Prapadaeng district. During periods of low flow and drought, high chloride and total dissolved solids (TDS) concentrations of 2487 and 9080 mg/L, respectively, were found. The relationship

between chemical and physical parameters revealed that electrical conductivity (EC) can be used to evaluate TDS and chloride concentration through linear regression.

Keywords: Chao Phraya River; water drought; surface water; water quality

Water Quality in irrigated Field and Surface Water

Human activities, particularly in paddy fields occur widely and it are a major cause of eutrophication in surface water. The purpose of this study was to investigate the water quality in paddy fields and nearby surface waters during rice cultivation in Inburi district, Singburi Province. Water samples were taken from paddy fields, canals and the Chao Phraya River and were analyzed for pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), organic nitrogen (Org-N), nitrate (NO_3^-), ammonia (NH_3), total phosphate (TP) and orthophosphate (ortho-PO_4^{3-}). Results showed the pH of all samples in the range of 6.7-7.9. The concentrations of TKN, NO_3^- and NH_3 in paddy fields have a tendency to decrease during rice growth because of uptake by rice plants. However, they were high following fertilizer application. Drainage of water from irrigated paddy fields affected the BOD and DO concentrations in canals and the river. BOD and DO concentrations in the river during rice cultivation in the wet season were 2.45-4.25 and 5.6-6.7 mg/L, respectively, while they were 0.33 and 7.1 mg/L, during the dry season. High BOD concentration results from decaying organic matter in the soil and organic fertilizer accumulation. Organic N from fertilizer remaining in the field brought the concentration to 1.72 mg N/L. It can change to nitrate by the nitrification process and leach [nto surface water and groundwater. The proper water quality management in paddy fields is therefore necessary to reduce the pollution loads in the surface water.

Water Quality and Organic Loads along the Chao Phraya River in Nakhon Sawan Municipality

The purpose of this research is to study the water quality in the Nakhon Sawan municipality. Four sampling points along the Chao Phraya River and one sampling point on the Ping River were analyzed for biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO) and pH between 9.00 am - 7.00 pm. Results revealed that BOD and COD concentrations fluctuated during the daytime. The highest daily BOD and COD concentrations, 9.64 and 61mg/L, respectively, were found at Dechatiwong Bridge, arising from drainage here of wastewater from residential areas. Organic pollution increased two times after a rainfall, with BOD and COD loads of 8.09 and 57.47 kg/capita/day, respectively. The pH of the Chao Phraya and Ping rivers were in the range of 7.0-7.5. The DO values for all sampling points were in the range of 5.0-7.0 mg/L. Therefore, proper wastewater management is needed to improve the water quality to meet the class-II surface water quality standard, for which the value of BOD must be ≤ 1.5 mg/L and DO ≥ 6.0 mg/L.

Impact of Climate and Land Use on *Escherichia coli* in the Chao Phraya River

This study examines effects of land use on the microbial quality of the Chao Phraya River in April, 2014. Water samples were collected at the depths of 0.5 and 2 meters along the river, including its upper, middle and lower sections. Total coliform bacteria (TCB) and E. coli were determined following the EPA method Colilert. The highest amounts of TCB and E. coli were found in the lower part of the Chao Pharya. TCB was more than 2.42×10^5 MPN/100 mL and E. coli was 1.95×10^4 MPN/100 mL at Chong Nonsi, a residential and commercial area in Bangkok. This indicates nonpoint source pollution from the city. We found high BOD resulting in high E. coli levels occurred especially in residential and urban areas. The fact that TCB/E. coli values are lower for such areas would indicate pollution in the river from fecal matter of warm-blooded animals and humans.

Keywords: Chao Phraya River; coliform; E. coli; water quality

Investigation of Nutrient and Coliform Bacteria from Nonpoint Sources on the Chao Phraya River Banks in the Dry Season

This research investigated the effects of waterfront buildings, houses and wastewater treatment plants on the banks of the Chao Phraya River in the dry season. Water samples from the Chao Phraya banks were collected during the daytime and analyzed for coliform bacteria and nutrients. A mean daily total coliform bacteria (TCB) of 566×10^4 CFU/100mL was found 25 m from the river bank near waterfront housing. The high TCB and fecal coliform bacteria (FCB) from urban areas contaminating the river pose risks for human users. Focused water resources management is needed to ameliorate such health risks using a sustainable, long-term approach.

Keywords: Chao Phraya River; coliform bacteria; dry season; nonpoint source; nutrient