

**HYDROGRAPH-SEPARATION-BASED
NON-POINT SOURCE POLLUTION
MODELLING IN THE
PINGQIAO RIVER BASIN, CHINA**

Han XUE

2017

**HYDROGRAPH-SEPARATION-BASED
NON-POINT SOURCE POLLUTION MODELLING
IN THE PINGQIAO RIVER BASIN, CHINA**

(中国平橋川流域を対象にした流出ハイドログラフ
成分分離法による非点源汚染モデリングの研究)

by

Han XUE

A dissertation

**Submitted in partial fulfillment of the requirements for the
Degree of Doctor of Engineering**

Department of Civil and Earth Resources Engineering

Kyoto University, Japan

2017

Acknowledgments

“Hydrograph-separation-based non-point source pollution modelling in the Pingqiao River Basin, China” has been conducted in Professor Takara’s Laboratory (Innovative Disaster Prevention Research Technology and Policy Research Laboratory), Disaster Prevention Research Institute (DPRI), Kyoto University, Japan.

My deepest gratitude goes first to my supervisor Professor Kaoru TAKARA who accepted me as his student from master course. He is a gentleman in providing me constant guidance, continuous support and comprehensive cultivation. Since October 2012 I enrolled in the Global Survivability Studies (GSS) Program which is supported under the ‘Leading Graduate Schools Program’ of MEXT. Professor TAKARA, as the leader of GSS Program, provided me various opportunities and cultivations for leadership, multidisciplinary and integrated academic knowledge in this 5-year graduate education course.

My special thanks goes to Associate Professor Takahiro SAYAMA who is from our laboratory. He is kind and skillful in helping each student to achieve their full potential. I learned a lot from him through countless discussions and conversations on my doctoral research and private issues as well. I still clearly remembered the days we discussed and revised the journal paper and doctoral thesis that made a fast growth of my academic ability.

I wish to express my gratitude for professors, faculties and students from GSS Program. They provided me various opportunities and full support for interdisciplinary communications, field work and practical activities through variety of courses and research activities.

I also extend my gratitude to Mrs. Sono INOUE and Mrs. Kaori SAIDERA for their kind support on administrative tasks with their nice smile.

My doctoral research originated from an industry-university collaborative project which is one of the research activities of GSS Program in collaboration with Horiba, Limited and the Chinese Academy of Sciences. I received assistant, support, understanding and advice from my partnership and supervisors. I would like to express my heartfelt gratitude to Mr. Takeshi KOBAYASHI and Mr. Kinta SEKIGUCHI from Horiba, Limited who provided me strong technical support on water quality item measurement and valuable suggestions for my water quality model development. I would like to sincerely appreciate Professor Bin HE, Assistant Professor Weili DUAN, Ms. Huifang MENG, Mr. Kaiyan ZHAO and Miss Chaojie YANG from the Chinese Academy of Sciences and Miss Heli ZHAO from the Nanjing University of Information Science and Technology. They provided me full local assistance and support for field investigation, continuous water quality observation, material collection and data exchange.

In Chapter 4 of this thesis, we conducted a testing study in Kiryu Experimental Watershed and compared our simulation results with the previous tracer hydrology results. In this study, I received full support from Associate Professor Masanori KATSUYAMA who is from GSS faculties on field investigation, data exchange and discussions with constructive suggestions. Additionally, I received valuable suggestions from Professor Yasuyuki KONO who is my GSS Secondary Academic Supervisor based on his regional research experiences in China. I would like to express my sincere gratitude to them and the collaborative platform provided by GSS Program.

I would like to give my gratitude to Prof. Ismail ABUSTAN and Dr. Mohd Remy Rozainy bin Mohd Arif Zainol from University Sains Malaysia which is the partnership of the GSS international cooperation project. They provided me valuable opportunity and experience of practical application of hydrological model for real world problem solution.

I also owe my sincere gratitude to my laboratory members who helped me during difficult course and finally I am indebted to my family for supporting me always.

Abstract

Background

Non-point source pollution (NPS) contributions became major causes of water quality degradation in Chinese rivers and lakes. Lake Taihu (2338 km²), which is located in the Yangzi River Delta, is the third largest freshwater lake in China. In the past 20 years, with rapid social and economic development, Lake Taihu has been suffering severe water quality deterioration and eutrophication problems. With recent effective abatement of point source pollution, it was estimated that at least more than 50% of the total pollution loads were generated by NPS in the Taihu Basin.

As improvement of water quality has become urgent and imperative for Chinese people, in the National Twelfth Five-Year Plan, the Chinese Government gave high priority and attached great importance on watershed hydrology and water quality simulation technology and targeted watershed management. The Taihu Basin Authority of Ministry of Water Resources is making vigorous efforts on promoting the integrated management of small and middle-scale river basins to respond to the national policy.

Our study area, the Pingqiao River Basin, is a small-scale river basin located in the upstream of the Taihu Basin. The water quality of the Pingqiao River Basin is closely related to the drinking water safety of Liyang City and the sustainable development of local economies of the Taihu Basin

Literature review

The NPS model is an important tool and effective technique for quantitative control and management of NPS. Various NPS models have been proposed in the past decades. Research into NPS modelling in China started in the early 1980s, developed from empirical modelling (e.g. statistic model, Export Coefficient Model (ECM)) to distributed water quality models.

Statistical models use monitoring data in typical experimental plots to build statistical relationships between precipitation, runoff and water quality. Statistical models have been applied in some basins in China, however, they were based on large quantities of measured data, available only in some specific areas. In addition, with the basin underlying surface condition changing, the reliability of the simulation results will be reduced.

ECM has been in general use because of simplicity and robustness. It assumes that the nutrient load exported from a watershed is equal to the sum of the losses from individual sources, such as land-use, livestock, rural life, etc. However, the choice of an export coefficient from the literature is subject to be with considerable uncertainty because of the difference in agricultural land management practices in China.

The distributed water quality models have been also applied in China in some river basins, reservoirs and lakes with satisfactory results. Among them, SWAT, AnnAGNPS and NSPF models are the most common ones and well applied. However, due to the large number of parameters, requirements for a large body of input data and limited available information, it is difficult to calibrate and validate these models, limiting their applications in China.

Objectives

As a result, in order to improve water quality problems of Lake Taihu, this study aims to quantitatively study the NPS issues of the upstream river basin through:

- 1) Proposing a NPS modelling based on hydrograph separation by a distributed hydrological model and Time-Space Accounting Scheme (T-SAS) as an alternative method which falls between ECM and fully physically-based models.
- 2) Verifying the applicability and reliability of hydrograph separation approach (T-SAS) through a testing study at a data-sufficient experimental basin.
- 3) Exploring the NPS export features in terms of different spatial zones (land-uses)

and temporal periods (short term and long term) according to our simulation results in target study area.

4) Proposing targeted and appropriate countermeasures for NPS control and management based on our simulations and the local conditions and limitations.

Originality

This proposed NPS modelling outputs time series of NPS nutrient loads exported from different spatial zones that is useful for targeted quantitative analysis; the hydrological model used in this study is fully physically-based while the water quality sub-model is more empirical based thus it has simpler calculation process and lower demand of data than distributed water quality models; in addition, our calculation basis of NPS nutrients i.e. source runoff concentration, is based on field measurement or inversely estimated. Therefore, the proposed approach may be suitable to conduct simulation with acceptable reliability in a watershed without enough water quality information.

Method

In this study we consider that the NPS nutrient loads in stream is a mixing of NPS nutrient loads from each spatial zone. This model simulates the NPS nutrient loads exported from each spatial zone and the NPS nutrient concentrations in streams. The spatial zone is considered as three land-use types (urban, agriculture and forest) and the stream runoff is mixed by runoff originated from each land-use. Our model simulates spatially exported NPS nutrient loads by estimating flow discharge contribution rates from different spatial zones and source runoff concentrations of nutrients for each spatial zone. The flow discharge (or contribution rate) is estimated from hydrograph separation results (in terms of spatial zones) by a distributed hydrological model and T-SAS. The source runoff concentrations can be estimated by field measurement or an inverse approach based on multiple stream flow samples.

Research processes and results

Firstly, a testing application of hydrograph separation in terms of source components

(surface flow, subsurface flow and groundwater flow) was conducted at the Kiryu Experimental Watershed which has sufficient observation data and previous studies results to verify the applicability and reliability of our hydrograph separation approach. We firstly developed a hydrograph-separation-based groundwater representing hydrological rainfall-runoff model and applied at the Kiryu Experimental Watershed with the streamflow discharge representing bedrock groundwater effects well validated. Then we used the T-SAS to separate hydrograph by source components and compared the results (groundwater contribution) with previous analyzed results by End-member mixing analysis (one approach of hydrogeochemical study). Our simulation results showed considerable contributions of bedrock groundwater (27% ~ 60%) to rainfall-runoff generation processes and increased groundwater contributions when upscaling basin scale. The consistence of groundwater contributions and dynamics with previous end-member mixing analysis results indicated the acceptable reliability of our model and applicability of T-SAS.

Then we applied our NPS model at the Pingqiao River Basin which is an upstream sub-basin of Lake Taihu for a storm event and a long-term study. In the event study, source runoff concentrations were inversely estimated and in the long-term study the continuously and regularly measured ones were used. In the two applications, stream discharge hydrograph was separated by different spatial zones (land-uses) as urban, agricultural area and forest.

In the storm event simulation, the inversely estimated source runoff concentrations showed satisfactory agreement with field measurement in the near period. The analysis suggested that this area (22.3 km²) exported about 2,630 kg of total nitrogen (TN) during the investigated storm event, and the urban area (5.3% of total area) contributed 18.5% of TN and 80.1% of ammonia nitrogen.

The one-year simulation (2014/12/1 ~ 2015/11/30) estimated 79,010 kg of TN and 1,670 kg of total phosphorus (TP) export. Simulated stream nutrient concentrations showed satisfactory agreement with the observations as the RMSE and RE of total nitrogen is 0.77 mg/L and 19.6% and the RMSE and RE of total phosphorus is 0.051

mg/L and 34.3% in summer. Our results well reflected the effects of runoff and farming activities on the seasonal nutrient load characteristics. 50.6% and 27.3% of TN were contributed in summer and spring, and 45.2% and 33.8% of TP were contributed in summer and autumn. Comparison of the two studies showed that the TN loads based on estimated source runoff concentration had about 30% overestimation than the results based on measured source runoff concentration.

The targeted countermeasures were proposed based on simulation results and local conditions. The drainage system and sewage treatment improvement were given the first priority because the urban area (5.3% of total area) had the highest contribution rate of NPS in both event (TN (18.5%), ammonia nitrogen (80.1%)) and long-term (TN (15.3%), TP (26.9%)) simulations. For the agricultural area, 30% reduction of current chemical fertilizer use was estimated to reduce 9,576 kg of TN export in the selected year. Forest suffering severe deforestation and soil erosion contributed 44.3% of TN and 36.6% of TP, thus afforestation on steep slopes is considered necessary and urgent.

Future work

Among various sources of uncertainty, the current study lacks the detailed validation of hydrograph separation results (particularly separation results by spatial source), the timely water sampling data for the inverse source runoff concentration estimations and more detailed land-use classifications and source runoff investigations. The testing application also highlighted the necessity of improving groundwater level (surface) reflection in our model.

Contents

Chapter1 Introduction.....	1
1.1 Background	1
1.2 Objectives.....	3
1.3 Brief contents	4
 Chapter 2 Study area	 6
2.1 Lake Taihu and the Taihu Basin	6
2.2 Lake Tianmu and the Tianmu Basin	8
2.3 The Pingqiao River Basin	10
2.4 Field investigation.....	11
2.4.1 Basic information	11
2.4.2 Water quality of Lake Tianmu	13
2.4.3 Water quality of upstream rivers.....	16
2.4.4 Pollution source investigation	19
 Chapter 3 Methodology	 22
3.1 Outline.....	22
3.2 Rainfall-Runoff-Inundation model.....	22
3.2.1 Model structure overview	22
3.2.2 Two-dimensional surface and subsurface flow model.....	24
3.2.3 One-dimensional river routing model.....	28
3.2.4 Interactions of water between slope and river	28
3.3 Time-Space Accounting Scheme	30

3.4 Mass conservation equations	33
3.5 Source runoff concentration estimations.....	34
3.5.1 Field measurement.....	34
3.5.2 Inversely estimation by statistical method	35
3.6 Hydrograph separation in terms of source components.....	35
3.6.1 Outline	36
3.6.2 The RRI model	36
3.6.3 Groundwater model	37
3.6.4 Improved T-SAS	39
3.6.5 End-member mixing analysis	41
Chapter 4 Testing the hydrograph-separation method at an experiment basin.....	43
4.1 Introduction.....	43
4.2 Study area.....	45
4.3 Simulation conditions	49
4.4 Results.....	51
4.4.1 Calibration and validation	51
4.4.2 Hydrograph separation	55
4.5 Discussions.....	58
4.5.1 Groundwater contributions to rainfall-runoff generation processes.....	58
4.5.2 Groundwater contribution increase of upscaling sub-basins H (M, A) to basin K	60
4.5.3 Groundwater contribution change of upscaling sub-basin R to basin K	61
4.5.4 Surface flow contributions	62

4.6 Summary	64
Chapter 5 NPS model application on a storm event study using inverse statistical approach	65
5.1 RRI model calibration	65
5.2 Hydrograph separation by T-SAS	65
5.3 Source runoff concentration estimations.....	68
5.4 NPS nutrient load simulation	71
Chapter 6 Long-term study of NPS and targeted countermeasure discussions	73
6.1 RRI model calibration	73
6.2 Hydrograph separation by T-SAS	74
6.3 NPS observations in stream	75
6.4 Source runoff concentration observations.....	76
6.5 Stream NPS nutrient concentration simulation	79
6.6 NPS nutrient load simulation	81
6.7 Comparison between event study and long-term study	85
6.8 Model features and limitations.....	87
6.8.1 Main features	88
6.8.2 Advantages and limitations.....	88
6.9 Targeted countermeasure proposal and discussions	89
Chapter 7 Conclusions.....	92
References	95

List of Tables

Table 2.1: Main water quality items of Lake Tianmu and outlets of rivers	15
Table 4.1: Geomorphic information of the five basins	46
Table 4.2: Annual precipitation and specific discharge of each basin	46
Table 4.3: Characteristics of the selected storm events	50
Table 4.4: Summary of groundwater contributions to runoff generation	59

List of Photos

Photo 2.1: Basic images of Lake Tianmu and three upstream rivers	12
Photo 2.2: Typical land-uses of the Tianmu Basin	13
Photo 2.3: Appearance changes of the upstream rivers in raining and non-raining days	17
Photo 2.4: Investigation of NPS pollution sources	21

List of Figures

Figure 2.1: Location information of Lake Taihu and surrounding areas	7
Figure 2.2: Location information of the Taihu Basin and the Tianmu Basin	9
Figure 2.3: Topographic and land-use conditions of the Pingqiao River Basin	11
Figure 2.4: Sampling points of Lake Tianmu and the three upstream rivers.....	14
Figure 2.5: Water quality spatial distribution map of Lake Tianmu and outlets of rivers	15
Figure 2.6: Longitudinal view of water quality changes of the three upstream rivers .	19
Figure 3.1: Schematic diagram of the RRI model	23
Figure 3.2: Schematic diagram of surface/subsurface flow conditions	28
Figure 3.3: Schematic diagram of the hydrograph separation by temporal classes (left) and spatial zones (right) of rainwater sources	30
Figure 3.4: Storage water separation in distributed hydrological model	32
Figure 3.5: Algorithm of T-SAS	33
Figure 3.6: Information of source runoff concentration field measurement.....	35
Figure 3.7: Flowchart of the testing study	37
Figure 3.8: Schematic diagram of the groundwater model.....	39
Figure 3.9: Schematic diagram of the hydrograph separation by source components .	40
Figure 3.10: End-members mixing analysis diagram	42
Figure 4.1: Basic information of the five basins.....	47
Figure 4.2: Hydrographs of the five basins during 2010 to 2012	48

Figure 4.3: Topography information	49
Figure 4.4: Basic concept of source component simulation in grid cells	49
Figure 4.5: Calibration and validation results	54
Figure 4.6: Hydrograph separation results in terms of source components	57
Figure 4.7: Summary of contributions of source components to runoff generation ...	58
Figure 4.8: Schematic diagram of groundwater level increase and groundwater exfiltration	63
Figure 5.1: Calibration results of the RRI model.....	66
Figure 5.2: Hydrograph separation results by T-SAS at Point A (near the outlet)	67
Figure 5.3(a): Flow discharge contribution rates of five representative points (b): Longitudinal views of stream water quality changes	68
Figure 5.4: Estimated source runoff concentrations (event-based) and measured source runoff concentrations in winter (2014/12/30 ~ 2015/2/24)	70
Figure 5.5: Validation of stream flow water quality by estimations.....	70
Figure 5.6: Simulation of NPS nutrient loads in the selected storm event	72
Figure 6.1: Calibration results of the RRI model.....	74
Figure 6.2: Hydrograph separation results by T-SAS at Point A (near the outlet)	75
Figure 6.3: TN and TP concentration changes at Point A (near the outlet).....	76
Figure 6.4: Source runoff concentration observations	77
Figure 6.5: Stream NPS nutrient concentration simulation and validation.....	80
Figure 6.6: Long term simulation of NPS nutrient loads.....	83
Figure 6.7: Summary of temporal and spatial contributions of NPS nutrients	85
Figure 6.8: Summaries of NPS nutrient amount.....	87

Chapter1 Introduction

1.1 Background

Water pollution and water quality have become significant issues of China during the rapid economic development recently. Although China has made great efforts in water environmental protection and water quality improvement over the past decades, analysis reveals that water pollution is still not controlled sufficiently, with a number of surface waters suffering varying degrees of pollution currently¹⁾.

Lake Taihu (2,338 km²), which is located in the Yangzi River Delta, is the third largest freshwater lake in China. The Taihu Basin (36,900 km²), with high population density, urbanization rate and economic development, is the most industrialized area in China²⁾. In the past two decades, with the rapid social and economic development, Lake Taihu has been suffering severe water quality deterioration and eutrophication problems^{3), 4)}.

In late May, 2007, a drinking water crisis occurred in Wuxi City, Jiangsu Province of China. A massive bloom of the toxin producing cyanobacteria *Microcystis* spp. occurred in Lake Taihu and approximately two million people suffered drinking water shortage for at least one week⁵⁾.

As improvement of water quality has become urgent and imperative for Chinese people, in the National Twelfth Five-Year Plan, the Chinese Government gave high priority and attached great importance on watershed hydrology and water quality simulation technology and targeted watershed management⁶⁾. The Taihu Basin Authority of Ministry of Water Resources is making vigorous efforts on promoting the integrated

management of small and middle-scale river basins to respond to the national policy⁷⁾.

With effective control of point source pollution during recent decades, non-point source pollution (NPS) contributions became major causes of water quality degradation in Chinese rivers and lakes⁸⁾. The previous investigation and study suggest that the pollutants generated by NPS comprises more than 50% of the total pollution loads in the Taihu Basin⁷⁾.

Because it is difficult to monitor, control and manage NPS lead by its characteristics such as complex mechanisms and processes, wide range, random occurrence and uncertainties¹⁰⁾, many previous researchers have made great efforts to develop various NPS models to quantitatively simulate and study it for effective control and management of NPS⁹⁾.

The NPS models quantitatively describe the complicated pollution generating process of the entire basin, analyze spatial and temporal features of NPS, help identifying the main source contribution and migration path, simulate NPS loads and the environment impact and estimate effects of land-use management and technical countermeasures. Therefore, the NPS model is an important tool and effective technique for quantitative control and management of NPS¹⁰⁾.

Various NPS models have been proposed in the past decades. Research into NPS modelling in China started in the early 1980s and developed from empirical modelling (e.g. statistic model, Export Coefficient Model (ECM)) to distributed water quality models¹⁰⁾.

Statistical models use monitoring data in typical experimental plots to build statistical relationships between precipitation, runoff and water quality¹¹⁾. Statistical models have been applied in some basins in China with satisfactory results, however, they were based on large quantities of measured data, available only in some specific areas. In addition, with the basin underlying surface condition changing, the reliability of the estimation results will be reduced subsequently¹⁰⁾.

ECM has been in general use because of simplicity and robustness¹⁰⁾. It assumes that the nutrient load exported from a watershed is equal to the sum of the losses from individual sources, such as land-use, livestock, rural life, etc. However, the choice of an export coefficient from the literature is subject to be with considerable uncertainty because of the difference in agricultural land management practices in China^{12), 13)}.

The distributed water quality models have been also applied in China in some river basins, reservoirs and lakes with satisfactory results. Among them, SWAT, AnnAGNPS and NSPF models are the most common ones and well applied. However, due to the large number of parameters, requirements for a large body of input data and limited available information, it is difficult to calibrate and validate these models, limiting their applications in China^{14), 15)}.

1.2 Objectives

In order to improve water quality problems of Lake Taihu, this study aims to quantitatively study the NPS issues of the upstream river basin through:

1) Proposing a NPS modelling based on hydrograph separation by a distributed hydrological model and Time-Space Accounting Scheme (T-SAS)¹⁷⁾ as an alternative method which falls between ECM and fully physically-based models.

This method outputs time series of NPS nutrient loads exported from different spatial zones. The hydrological model used in this study is fully physically-based while the water quality sub-model is more empirical based thus it has simpler calculation process and lower demand of data than distributed water quality models. In addition, our calculation basis of NPS nutrients i.e. source runoff concentration, is based on field measurement or statistically inverse estimation. Therefore, the proposed approach may

be suitable in a watershed without enough water quality information in China.

2) Verifying the applicability and reliability of hydrograph separation approach (T-SAS) through a testing application at a data-sufficient experimental basin.

3) Exploring the NPS export features in terms of different spatial zone (land-use) and temporal period (short term and long term) according to our simulation results in the target study area.

4) Proposing targeted and appropriate countermeasures for NPS control and management based on our simulations and the local features and limitations.

1.3 Brief contents

Chapter 1 is the introduction of this study.

Chapter 2 introduced the basic information of our study area (the Pingqiao River Basin) which is the upstream river basin of Lake Taihu. The current situation of study area was also introduced based on our field investigation in terms of water quality measurement and pollution source investigation.

Chapter 3 described the hydrograph-separation-based NPS modelling as our main methodology. Firstly, a distributed hydrological model (Rainfall-Runoff-Inundation model) and Time-Space Accounting Scheme were introduced as the basic tools for hydrograph simulation and separation. Then the mass conservation equation and source runoff concentration were introduced as basic concept and calculation basis of this method respectively. Finally, hydrograph separation approach in terms of source components which was used in a testing study (Chapter 4) to verify the performance of T-SAS approach were introduced individually.

Chapter 4 validated the applicability of hydrograph separation approach (T-SAS) in terms of source components (surface flow, subsurface flow and groundwater flow) at the Kiryu Experimental Watershed of Shiga Prefecture, Japan. As this well-studied basin has sufficient observation data and previous studied results, the applicability and reliability of our approach was tested and verified.

Chapter 5 conducted a NPS simulation for a storm event study (short term) using inversely estimated source runoff concentration.

Chapter 6 conducted a NPS simulation for a one-year study (long term) using field measured source runoff concentration. NPS nutrient loads were simulated and the spatio-temporal characteristics of NPS export were summarized. Finally targeted and appropriate countermeasures were proposed based on simulation results and local conditions.

Chapter 7 concluded the main findings and unsolved issues of this study.

Chapter 2 Study area

The Pingqiao River Basin which is the upstream river basin of Lake Tianmu is our target study area with detailed information introduced in Section 2.3. The Tianmu Basin is located in the upstream area of the Taihu Basin. The Taihu Basin and the Tianmu Basin are introduced in Section 2.1 and 2.2 for providing more background information.

2.1 Lake Taihu and the Taihu Basin

Lake Taihu is the third largest freshwater lake in China with a surface area of 2,338 km² and a basin area of 36,895 km² ²¹⁾. It is located in the Yangtze River Delta in eastern China (Figure 2.1). Lake Taihu is characterized by its shallowness with average water depth of 1.9 m ²⁾.

The Taihu Basin belongs to the subtropical monsoon climatic area with abundant precipitation, distinct four seasons and hot summer. The annual average temperature is 14.9°C ~ 16.2°C and the annual average total precipitation is 1,177 mm. About 60% of precipitation concentrates during May to September⁷⁾.

The total water resource in the Taihu Basin is 17.6 billion m³ and 398 m³ for per capita. The total area of water surface of the Taihu Basin is 5,551 km² with 189 lakes of water surface area more than 0.5 km². 228 rivers access in Lake Taihu, the total length of these rivers is about 120,000 km and the river density is 3.3 km/km² ⁷⁾.

The Taihu Basin is the most industrialized area in China with high population density (1,552/km²), urbanization rate and economic development²⁾. Besides the mega city Shanghai, this area has seven more large and medium-sized cities and rapid developing

rural areas. This area covers 0.4% of the total area of China, however, it has population of 59.93 million which accounts for 4.4% of the total population and provides GDP of 6,305.5 billion CNY (930.4 billion USD) which accounts for 9.9% of the National GDP (in 2014). The GDP Per capital of the Taihu Basin is as 2.2 times as the national average¹⁹⁾.

Lake Taihu is the key water source for agriculture, industry and major drinking water for surrounding cities (such as Shanghai, Suzhou, Wuxi, and Huzhou) and it is also important for tourism, aquaculture and flood control²⁾. However, with rapid social and economic development, Lake Taihu has been suffering severe water quality deterioration and eutrophication problems during the past two decades^{3), 4)}. In 2013, water quality of 73.9% of total area of Lake Taihu was under Class V which is the minimal class according to the Chinese Surface Water Quality Standard (GB3838-2002)²⁰⁾.

During recent decades with effective abatement of point source pollution, NPS become the primary pollution sources of Lake Taihu²⁾. The Implementation Plan of Comprehensive Control of Water Environment in the Taihu Basin of Jiangsu (2013) reported that the pollutants generated from agricultural NPS account for 44.9% and 68.2% for total nitrogen (TN) and total phosphorus (TP) and pollutants generated from urban areas account for 24.5% of TN and 25.2% of TP respectively⁷⁾.



Figure 2.1: Location information of Lake Taihu and surrounding areas

The west and southwest hilly areas are the main runoff areas (Figure 2.2), within which some reservoirs provide drinking water source for downstream residents.

2.2 Lake Tianmu and the Tianmu Basin

Lake Tianmu (12 km²), which is also called Shahe Reservoir, is located in the western hilly area of the Taihu Basin. It was built in 1960 as a multifunctional reservoir for drinking water, irrigation, tourism and fisheries. According to the survey in 2001 and 2002, the maximum water depth of Lake Tianmu was 14 m and the largest water storage capacity was 110 million m³¹⁸⁾. It is also the National AAAAA Level Scenic Spot (the highest level) and the Provincial Nature Reserve. It is said to be the “last clean water body” in the Yangtze River Delta economic circle¹⁵⁾. Lake Tianmu is one of the two drinking water sources for Liyang City (located in downstream) with population of 0.76 million in 2015 (another one is the Daxi Reservoir with the basin area of 90 km²).

The Tianmu Basin, with area of 148.5 km², is a sub-basin of the Taihu Basin. In the upstream areas of Lake Tianmu, three main rivers flow from south to north. They are the Pingqiao River, the Xiasong River and the Zhongtian River. Figure 2.2 shows the location information of the Taihu Basin and the Tianmu Basin.

The Tianmu Basin belongs to subtropical monsoon climatic area with abundant precipitation and sunshine and distinct four seasons. The annual average temperature is 15.7°C, the average annual total precipitation is 1169.3 mm and the precipitation concentrates during April to September¹⁵⁾. This area has a variety of landforms such as low mountains, hills and plains with elevation ranging from -22 m to 542 m.

The main land-use type of this area is agriculture (e.g. paddy field, farmland, tea plantation and orchard), urban (town) and forest. Forest is concentrated in the upstream hills and low mountains. As the population density of the Tianmu Town (within which is the Tianmu Basin) is about 326/km² in 2014, the total population of this area is speculated as around 48 thousand. The primary industry is agriculture, tea production

and tourism.

The water quality of the Tianmu Basin is closely related to the drinking water safety of Liyang City and the sustainable development of local economies of the Taihu Basin. With the recent economic growth, development of tourism, tea production and livestock and poultry cultivation, pollutants have been increasingly produced and discharged into rivers and lake, resulting in water quality degradation in Lake Tianmu. Recent investigation (2006) showed that the average concentration of TN and TP increased as 2.7 times and 2.0 times than the average level during 2001 to 2002²²⁾. With effective abatement of point source pollution, NPS contributions became major sources of TN and TP loads^{14), 15)}.

1) Excessive use of pesticides and chemical fertilizers, 2) Primitive livestock and poultry cultivation, 3) Untreated domestic sewage and waste, 4) Increased tourism development, 5) Surface erosion and nutrients delivered with sediments; were reported to be the main causes of NPS in this area^{14), 15), 22)}.

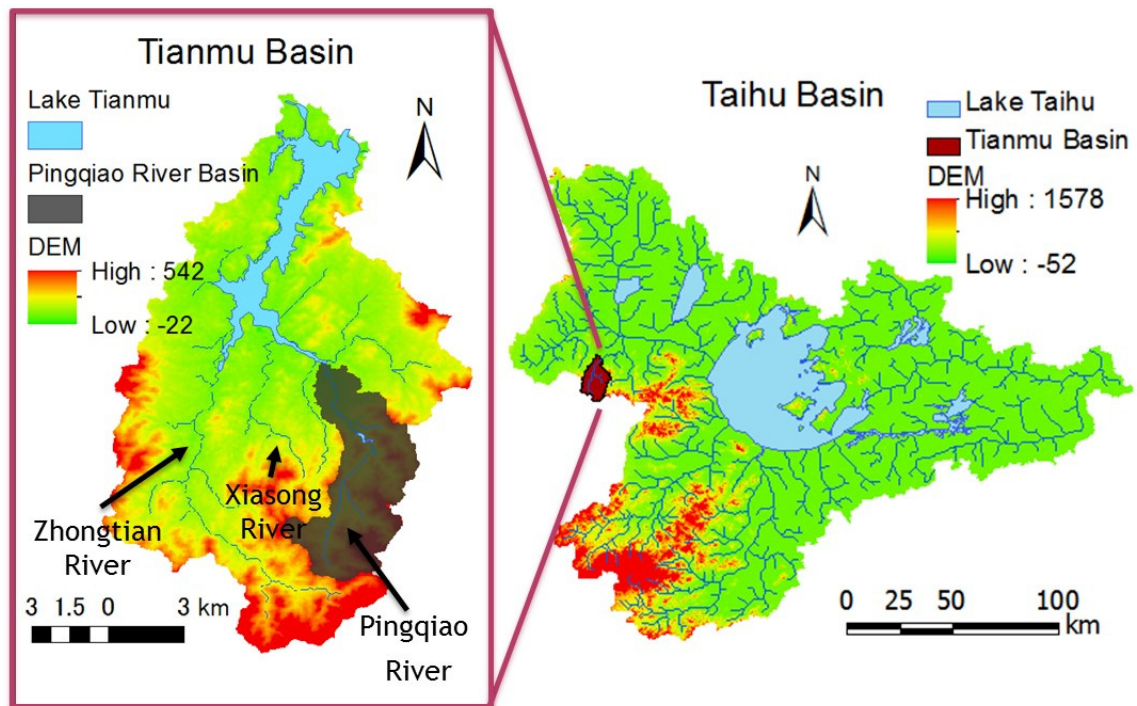


Figure 2.2: Location information of the Taihu Basin and the Tianmu Basin

2.3 The Pingqiao River Basin

The Pingqiao River is one of the three upstream rivers of the Tianmu Basin and the Pingqiao River Basin is our target study area. It is an area of 22.3 km² with elevation ranging from 5 m to 437 m above sea level. It is a typical small-scale hilly basin of the Taihu Basin with landforms of nearly half hills and half plains. It has forest concentrated in the upstream hills, agricultural land distributed in low areas and a town (urban) located in the downstream near the outlet as figure 2.3 shows.

In order to well study the NPS in such small-scale river basins, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences started the water quality sampling and measurement from November 2014 and provided strong technical support for this research.

Figure 2.3 shows the topographic and land-use conditions of the Pingqiao River Basin. The topographic data is based on ASTER GDEM V2 with 30-m resolution. Land-use was manually extracted from the Google Earth images (2016/1/7) and classified into four types: urban (5.3%), agriculture (31.3%), forest (62%) and water body (1.4%). Soil type was assumed to be uniform as loamy sand by referring previous research at an adjacent river basin¹⁴⁾.

For observations, precipitation has the temporal resolution of six hours from OGIMET and the daily resolution from Chinese Academy of sciences; discharge data was discontinuously measured for 27 times during a period between 2016/5/27 and 2016/7/6. For water quality observations, nine points in the stream flow (2014/11/25 ~ 2015/11/27) and three points of source runoff (2014/12/30 ~ 2015/11/27) were sampled on the weekly basis (monthly basis for forest source runoff point). Discharge and water quality observations were provided by Chinese Academy of Sciences. Source runoff observation points is to be introduced in Section 3.4 for details.

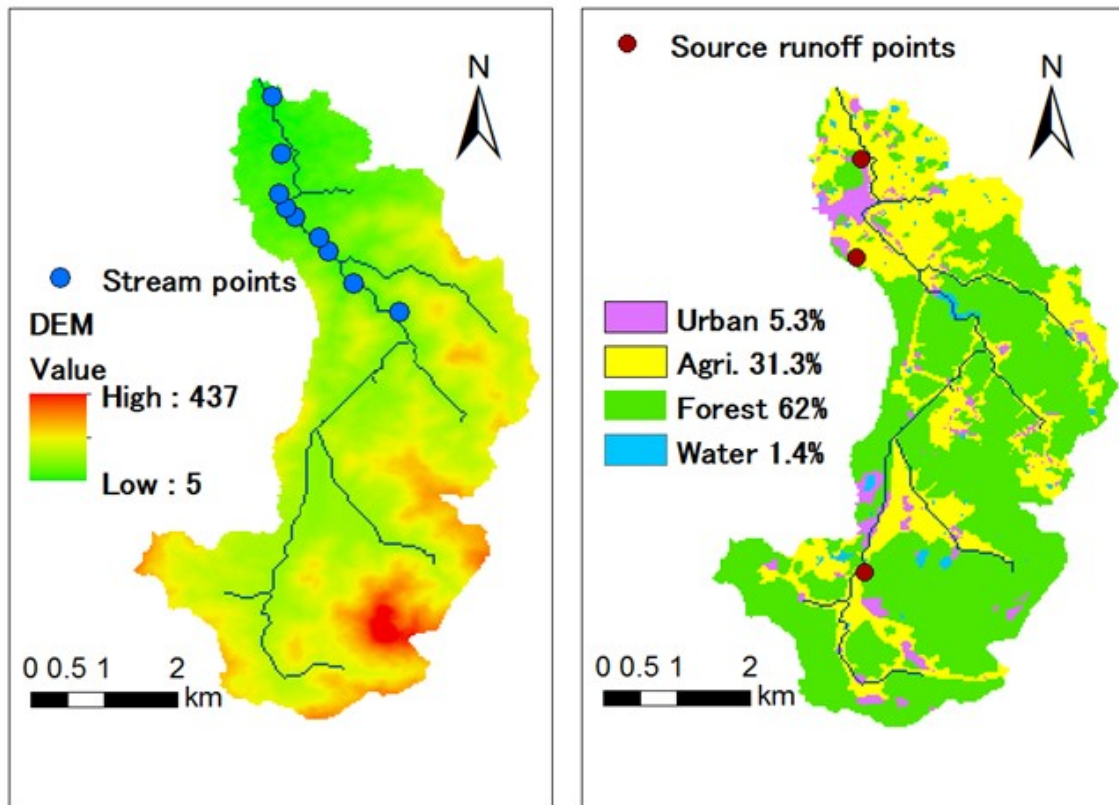


Figure 2.3: Topographic and land-use conditions of the Pingqiao River Basin

2.4 Field investigation

In order to well grasp the current situation of this study area, a field investigation has been conducted in the Tianmu Basin from 2014/11/19 to 2014/12/18 including water quality measurement and pollution source investigation. This investigation was collaborated with the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences and the HORIBA, Limited. The Chinese Academy of Sciences provided full local assistance and data exchange, the HORIBA, Limited provided technical support for water quality item measurement.

2.4.1 Basic information

Photo 2.1 shows the basic images of Lake Tianmu and the three upstream rivers.

Generally, this area has beautiful views and clean water visually.



Photo 2.1: Basic images of Lake Tianmu and three upstream rivers

In the upstream areas, the Xiasong River Basin and the Zhongtian River Basin are relatively uniformly consisted of forest and agricultural land and the Pingqiao River Basin is consisted of forest, agricultural land and a small proportion of urban area (the Pingqiao Town) located near its outlet. In the downstream areas, lands near Lake Tianmu are used for agriculture production particularly for tea plantation. Areas surrounding Lake Tianmu (particularly in the northern half) is concentrated with hotels and resorts for tourism. Photo 2.2 shows typical land-uses of the Tianmu Basin.



Photo 2.2: Typical land-uses of the Tianmu Basin

2.4.2 Water quality of Lake Tianmu

We have sampled and measured 17 points of water quality surrounding Lake Tianmu and 18 points in the upstream rivers. The sampling point selection is comprehensively based on considering certain and regular intervals, accessibility and reflection of tributary and land-use changes. Figure 2.4 shows the location information of each sampling point. Water quality of Lake Tianmu shown in Table 2.1 indicated that it did not achieve the drinking water source standard (Class II by Chinese Surface Water Quality Standard (GB3838-2002)) and the exceeded items were COD, TN and TP as highlighted.

Figure 2.5 shows the water quality spatial distribution map of Lake Tianmu in terms of TN and TP. 17 sampling points surrounding the lake (measured on 2014/11/20, sunny) and three points at or near outlets of upstream rivers (measured on 2014/12/12, sunny) were plotted on these maps. The average concentration of TN at (or near) outlets of upstream rivers are 2.4 times higher than the lake average and the average concentration of TP of river outlets (or near outlets) are 38% of the lake average. That upstream rivers have higher TN concentrations than lake indicates that upstream rivers

have certain NPS contributions to the lake. On the other hand, upstream rivers have lower TP concentrations, however, as phosphorus nutrients less dissolve in water, they are gradually delivered and accumulated in the lake, causing higher concentrations in lake after a long period. Also, the delivery of NPS nutrients is closely related with the hydrological process (runoff) and this issue is discussed in the next section.

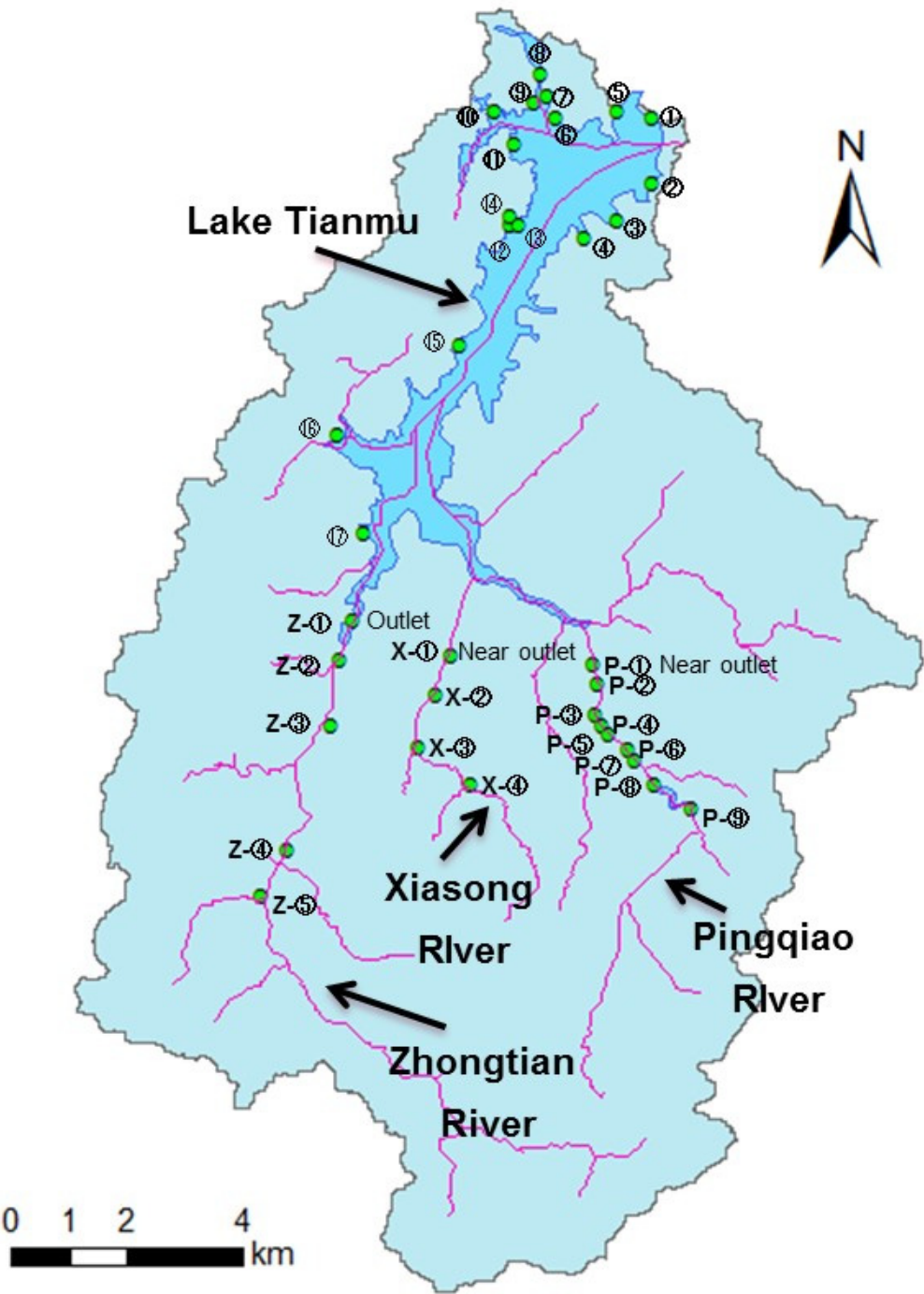


Figure 2.4: Sampling points of Lake Tianmu and the three upstream rivers

Table 2.1: Main water quality items of Lake Tianmu and outlets of rivers

Sampling points	pH	DO	COD Mn	NH ₄ -N	TP	TN
Lake Tianmu_1	6.71	8.5	6.2	0.077	0.084	1.014
Lake Tianmu_2	7.19	10.1	6.856	0.136	0.092	1.015
Lake Tianmu_3	7.4	9.84	7.512	0.081	0.059	0.955
Lake Tianmu_4	7.35	10.2	6.12	0.108	0.100	0.968
Lake Tianmu_5	7.42	10.2	6.064	0.087	0.010	0.995
Lake Tianmu_6	7.32	10.24	8.96	0.041	0.084	0.896
Lake Tianmu_7	7.37	9.85	6.728	0.074	0.059	0.842
Lake Tianmu_8	7.9	8.76	6.04	0.060	0.067	0.786
Lake Tianmu_9	7.57	10.2	5.856	0.049	0.067	0.872
Lake Tianmu_10	7.81	10.28	5.88	0.052	0.051	0.875
Lake Tianmu_11	7.76	9.91	5.752	0.043	0.051	0.899
Lake Tianmu_12	7.77	8.97	6.256	0.065	0.092	0.919
Lake Tianmu_13	7.94	9.25	5.12	0.132	0.149	0.982
Lake Tianmu_14	7.95	9.41	5.08	0.088	0.133	0.945
Lake Tianmu_15	7.68	9.32	5.056	0.059	0.149	0.900
Lake Tianmu_16	7.32	8.95	6.072	0.082	0.248	0.790
Lake Tianmu_17	8.1	10.41	6.584	0.048	0.207	0.740
Outlet_Pingqiao	8.2	12.88	0.88	0.318	0.079	3.236
Near outlet_Xiasong	8.33	13.95	0.64	0.033	0.022	1.218
Near outlet_Zhongtian	8.04	12.52	1.68	0.045	0.013	2.090
Chinese Surface Water Quality Standard						
I (Source water)	6~9	≥7.5	≤2	≤0.15	≤0.01	≤0.2
II (Drinking water source)	6~9	≥6	≤4	≤0.5	≤0.025	≤0.5
III (Drinking water source)	6~9	≥5	≤6	≤1.0	≤0.05	≤1.0
IV (Industry water)	6~9	≥3	≤10	≤1.5	≤0.1	≤1.5
V (Agriculture water)	6~9	≥2	≤15	≤2.0	≤0.2	≤2.0

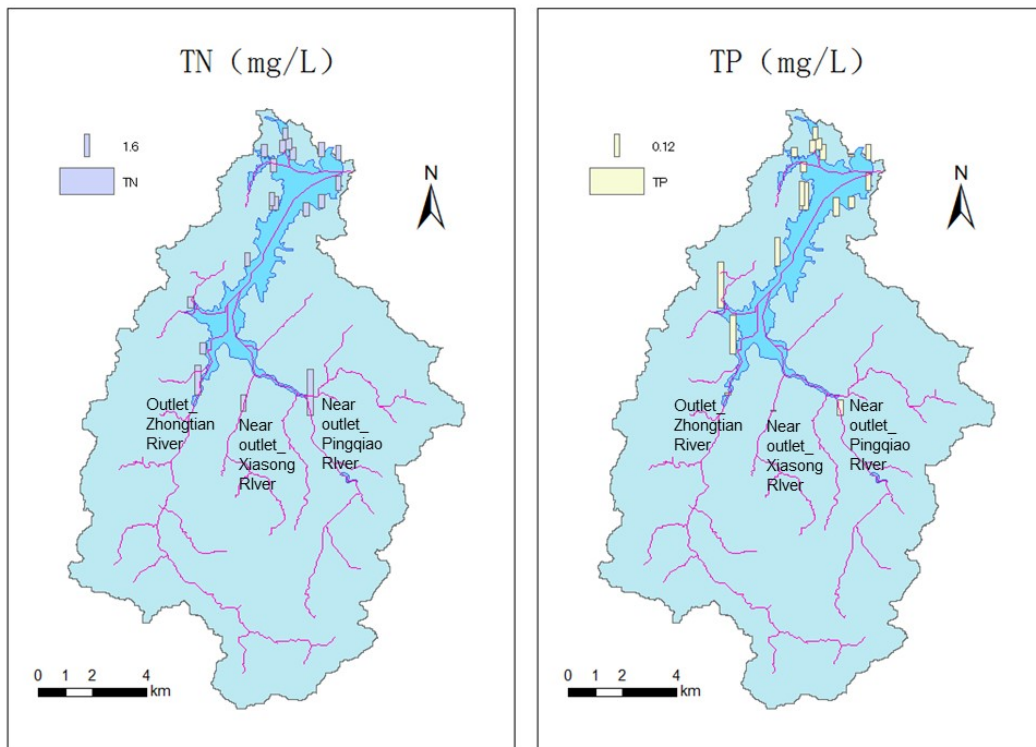


Figure 2.5: Water quality spatial distribution map of Lake Tianmu and outlets of rivers (per unit length of the bars represent 1.6 mg/L of TN concentration and 0.12 mg/L of TP concentration)

2.4.3 Water quality of upstream rivers

As NPS nutrients are considered to be contributed from upstream rivers and closely related with the hydrological process (runoff), we measured the water quality of the three upstream rivers in two days under different weather conditions (2014/11/25, rainy and 2014/12/12, sunny). Sampling points locations are illustrated in Figure 2.4 and results are shown in Figure 2.6. Photo 2.3 shows the visual changes of the three rivers in these two days at the same locations.

Figure 2.6 is the longitudinal view of stream water quality of the three rivers in terms of TN, TP, nitrate nitrogen (NO_3^- -N) and ammonia nitrogen (NH_4^+ -N) respectively. The purple line represents water quality measured in a raining day (2014/11/25) and red line represents that measured in a non-raining day (2014/12/12). It is obvious that nutrients in that raining day had higher concentrations than the non-raining day for all the items and almost all the points.

For the Pingqiao River, points P-①, P-② and P-③ located near urban areas had higher NPS nutrient concentrations than other points (particularly for NH_4^+ -N and TP). The longitudinal water quality changes of the Xiasong River and the Zhongtian River were relatively smooth because the land-uses of the two rivers are uniformly consisted of forest and agricultural land thus they have less urban effects. These data sets well reflected the runoff and land-use effects on NPS concentration changes.

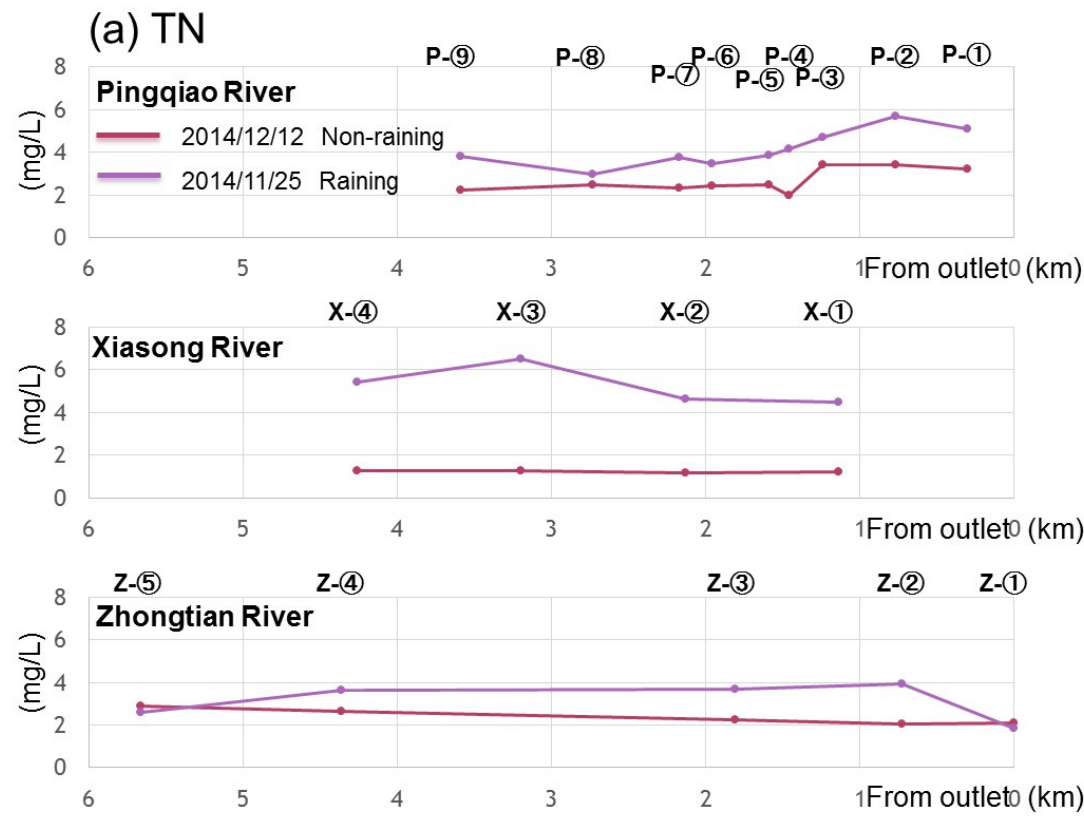
Additionally, the NPS concentration amplification of the Xiasong River in raining day was obviously larger than the other two rivers (except some points near the Pingqiao River's urban area, e.g. Points P-①, P-② and P-③). It is considered that because the Xiasong River is the smallest one among the three, its water quality is easily affected relatively.

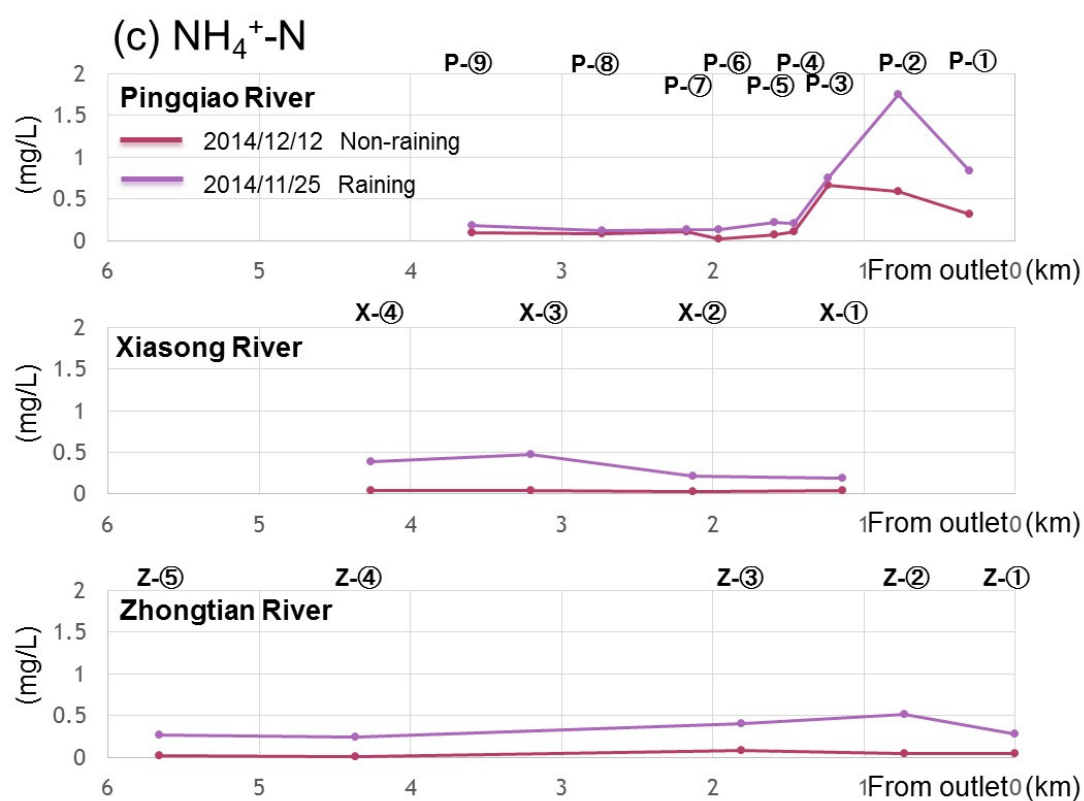
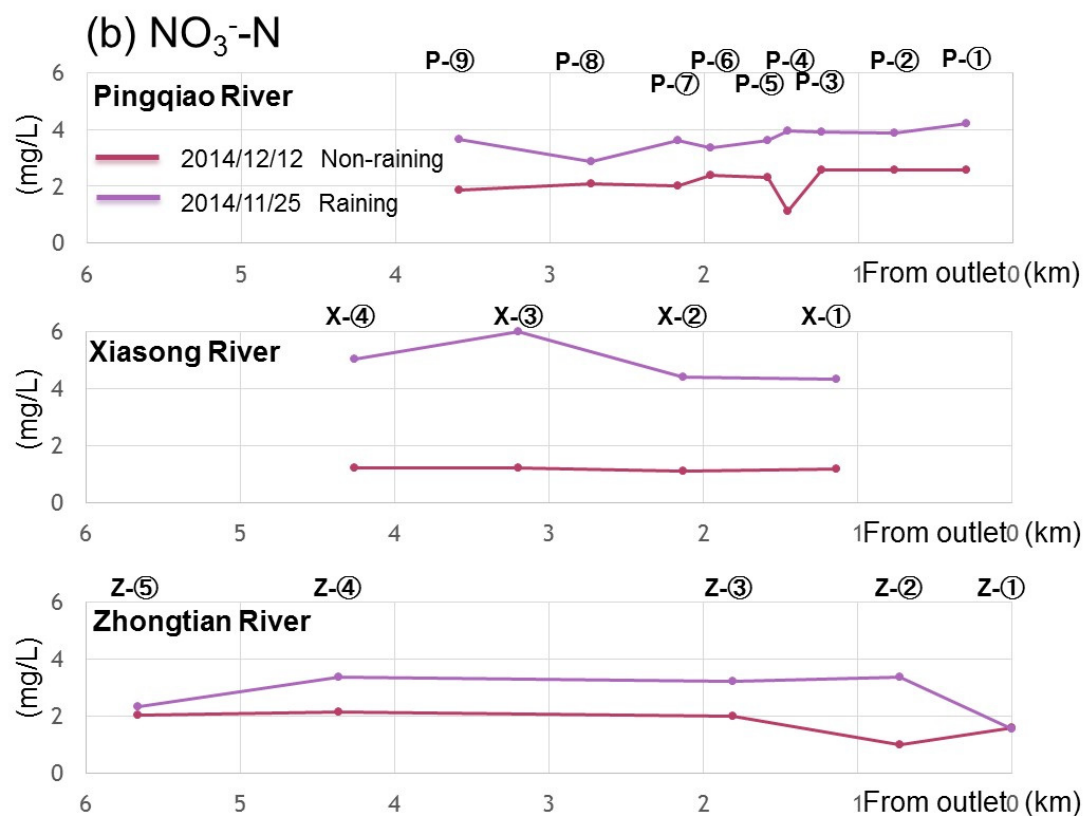
As mentioned above, the average TP concentration of river outlets (or near outlets) were lower than the lake, however, the river average TP concentration under runoff

process (in raining day) was 2.2 times higher than the lake average, meaning a large amount of phosphorus nutrients were flushed into the lake through runoff process rather than non-raining days.



Photo 2.3: Appearance changes of the upstream rivers in raining and non-raining days





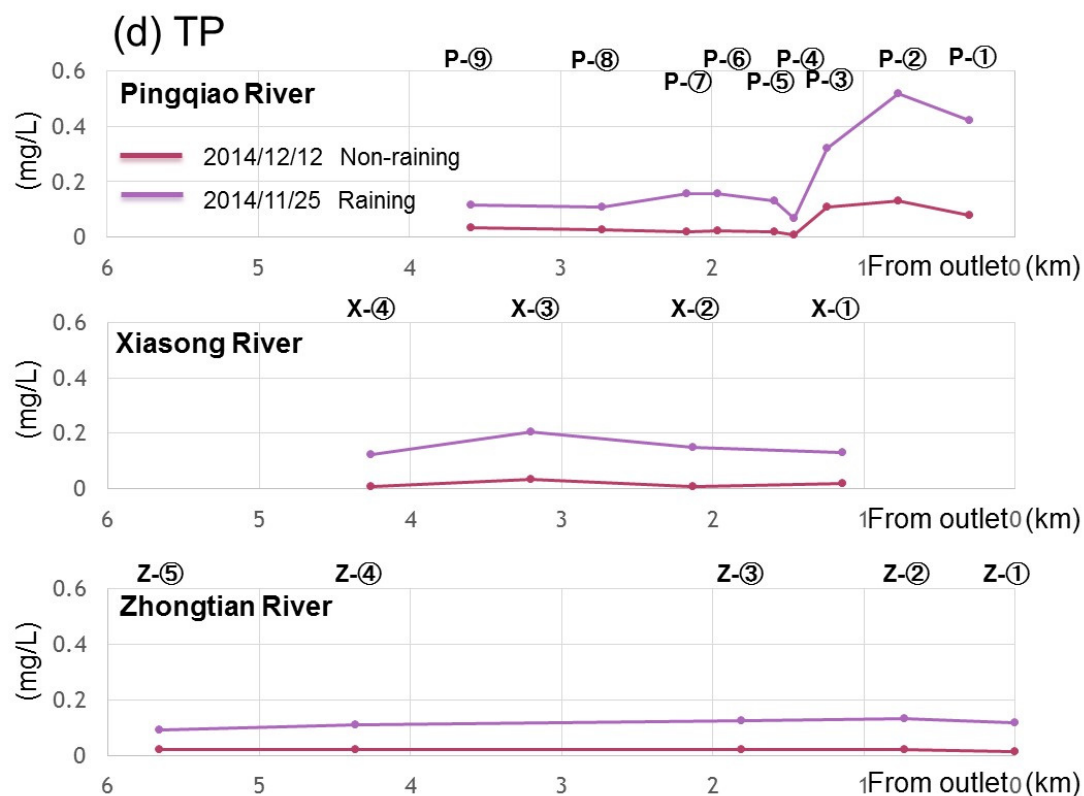


Figure 2.6: Longitudinal view of water quality changes of the three upstream rivers
(a) TN, (b) NO_3^- -N, (c) NH_4^+ -N, (d) TP

2.4.4 Pollution source investigation

We have investigated the upstream areas for NPS pollution source and found consistency with the descriptions by previous studies. The images of the investigated fields are shown in Photo 2.4 with details described below:

1) Primitive livestock and poultry cultivation

The poultry cultivation in backyard is common for local households and the small-scale livestock cultivation is also well seen. The feces of livestock and poultry is untreated and directly discharged into the river.

2) Untreated domestic sewage and waste

This area has poor drainage and sewage facilities. The most popularized domestic sewage system is the poorly equipped septic tank. Residents use it to produce manure

however it may flush out waste water through surface runoff.

Additionally, open and free dumped domestic wastes are well seen on vacant lands such as river banks.

Washing activities besides rivers are also common. Even worse, if the phosphorus containing detergents are well used, this will cause a large amount of phosphorus export into water body. Although the Taihu Basin has started the implementation to prohibit phosphorus containing detergent use, Chen and Hua (2004) indicated that the phosphorus containing detergent use is one important cause of NPS of the Taihu Basin²⁹⁾.

3) Increased tourism development

Superior hotels and resorts are concentrated surrounding Lake Tianmu, however, in the upstream areas, local residents managed a considerable number of family hotels for addition income. These increased family hotels may increase domestic waste and sewage discharge into rivers when without effective management and treatment.

4) Surface erosion and nutrients delivered with sediments

In some areas the severe deforestation and environmental damage are obvious. We have also found some sand factories exposed their sand materials without shelters. This may be flushed out and with the increased sediments by surface erosion, it will cause NPS nutrient burden to downstream areas.



Photo 2.4: Investigation of NPS pollution sources

Chapter 3 Methodology

3.1 Outline

In this study we consider that the NPS nutrient loads in stream is a mixing of NPS nutrient loads from each spatial zone. This method simulates the NPS nutrient loads exported from each spatial zone and the NPS nutrient concentrations in streams. The spatial zone is considered as three land-use types (urban, agriculture and forest) and the stream runoff is mixed by runoff originated from each land-use.

NPS nutrient loads exported from each spatial zone is the product of discharge and source runoff concentration of each spatial zone. The stream nutrient concentration is the summary of products of flow discharge contribution rate and source runoff concentration of each spatial zone.

Flow discharge (or contribution rate) from each spatial zone is estimated by a distributed hydrological model and T-SAS.

The source runoff concentration is the average NPS nutrient concentration of runoff originated from each grid of the same spatial zone and it can be estimated by field measurement or an inverse approach based on multiple stream flow samples.

3.2 Rainfall-Runoff-Inundation model

3.2.1 Model structure overview

The RRI model is a 2D grid cell-based hydrological model which simulates both rainfall runoff and flood inundation processes (Figure 3.1). This model has three main features as following:

1) The RRI model calculates flow based on 2D diffusive wave approximation for both hill slopes and flood plains.

2) This model simulates lateral subsurface flow and surface flow in terms of the discharge-hydraulic gradient relationship in mountainous areas and vertical infiltration based on the Green-Ampt model in flood plains for better representations of rainfall-runoff processes under different land conditions.

3) The model deals with slopes and river channels separately. The channel flow is computed with the built-in 1D diffusive wave model while the slope flow is calculated with the 2D diffusive wave model. The flow interaction between the river channel and slope is also estimated based on different position conditions of water-level and levee-height^{16), 52)}.

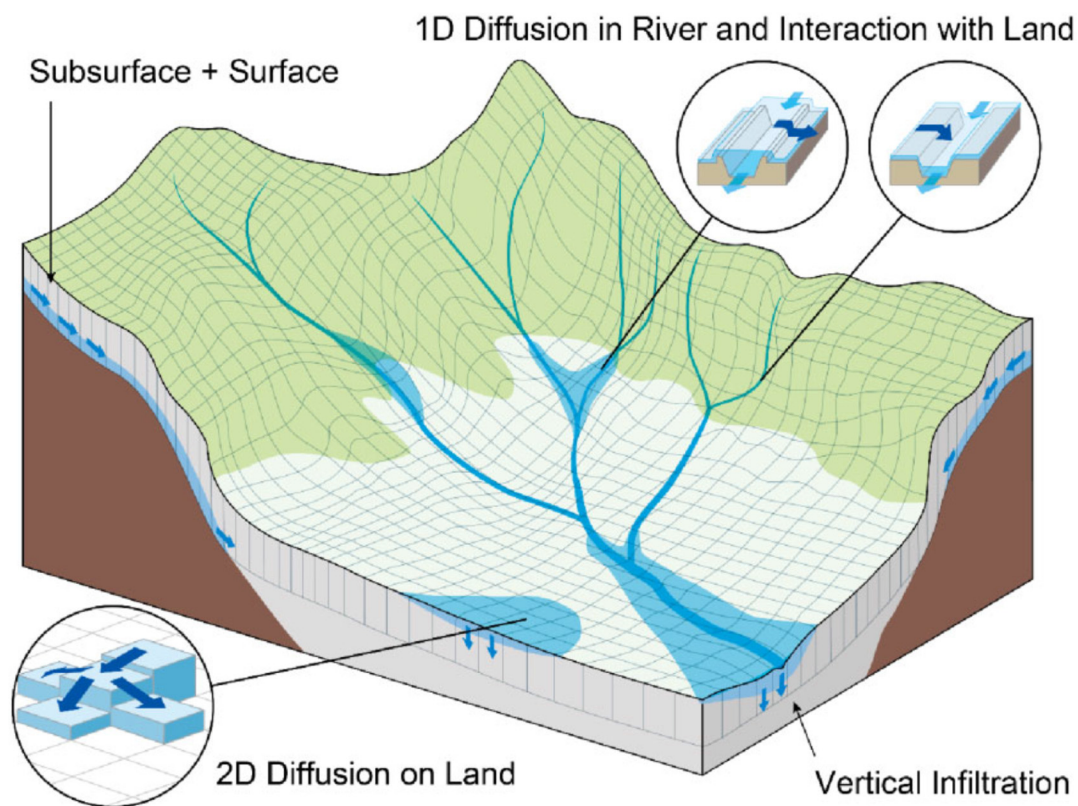


Figure 3.1: Schematic diagram of the RRI model
(figure form the Rainfall-Runoff-Inundation Model User's Manual⁵²⁾)

In this study, we use the RRI model as distributed hydrological model but did not implement the inundation simulation. This study area has three typical land-use types i.e. urban area, agricultural area and forest. In the RRI model parameter settings, we consider that the urban area has only overland flow (no infiltration loss nor subsurface flow); the agricultural land has vertical infiltration and infiltration excess overland flow and the forest has saturated subsurface flow and saturation excess overland flow (no unsaturated subsurface flow considered).

3.2.2 Two-dimensional surface and subsurface flow model

The model equations are derived based on the mass balance equation (1) and momentum equation (2) for gradually varied unsteady flow as following:

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = r - f \quad (1)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial u q_x}{\partial x} + \frac{\partial v q_x}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{\tau_x}{\rho_w} \quad (2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial u q_y}{\partial x} + \frac{\partial v q_y}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{\tau_y}{\rho_w} \quad (3)$$

where h is the height of water from the local surface, q_x and q_y are the unit width discharges in x and y directions, u and v are the flow velocities in x and y directions, r is the rainfall intensity, H is the height of water from the datum, ρ_w is the density of water, g is the gravitational acceleration, and τ_x and τ_y are the shear stresses in x and y directions. The second terms of the right side of equations (2) and (3) are calculated based on the Manning's equation:

$$\frac{\tau_x}{\rho_w} = \frac{gn^2 u \sqrt{u^2 + v^2}}{h^{1/3}} \quad (4)$$

$$\frac{\tau_y}{\rho_w} = \frac{gn^2 v \sqrt{u^2 + v^2}}{h^{1/3}} \quad (5)$$

where n is Manning's roughness parameter.

Under the diffusion wave approximation, the inertia terms (the left side terms of equations (2) and (3)) are neglected. Moreover, by separating x and y directions (i.e. ignoring v and u terms in equations (2) and (3), respectively), the following equations are derived as:

$$q_x = -\frac{1}{n} h^{5/3} \sqrt{\left| \frac{\partial H}{\partial x} \right|} \operatorname{sgn} \left(\frac{\partial H}{\partial x} \right) \quad (6)$$

$$q_y = -\frac{1}{n} h^{5/3} \sqrt{\left| \frac{\partial H}{\partial y} \right|} \operatorname{sgn} \left(\frac{\partial H}{\partial y} \right) \quad (7)$$

where sgn is the signum function.

The RRI model spatially discretizes mass balance equation (1) as follows:

$$\frac{dh^{i,j}}{dt} + \frac{q_x^{i,j-1} - q_x^{i,j}}{\Delta x} + \frac{q_y^{i-1,j} - q_y^{i,j}}{\Delta y} = r^{i,j} - f^{i,j} \quad (8)$$

where $q_x^{i,j}$, $q_y^{i,j}$ are x and y direction discharges from a grid cell at (i, j) .

Water depths and discharges are calculated at each grid cell for each time step by combining equations (6), (7) and (8). The RRI model uses different discharge-hydraulic gradient relationships to simulate both surface and subsurface flows with the same algorithm in mountainous areas. Equations (6) and (7) are replaced with the following equations (9) and (10) which were originally developed for a kinematic wave rainfall-runoff model considering both surface and subsurface flows⁵⁰. The water

surface slope is assumed as the hydraulic gradient by the RRI model as the hydraulic gradient was assumed to be equal to the topographic slope for the kinematic wave approximation. Equations (9) and (10) simulate both saturation excess overland flow and saturated subsurface flow with a single variable, h . The saturated subsurface flow is described based on Darcy's law when the depth of the lateral flow is within the soil depth times porosity ($h \leq d_a$), while the combination of the saturated subsurface flow and the surface flow are described once the depth of the lateral flow exceed the soil depth times porosity ($d_a < h$):

$$q_x = \begin{cases} -k_a h \frac{\partial H}{\partial x}, (h \leq d_a) \\ -\frac{1}{n} (h - d_a)^{5/3} \sqrt{\left| \frac{\partial H}{\partial x} \right|} \operatorname{sgn} \left(\frac{\partial H}{\partial x} \right) - k_a h \frac{\partial H}{\partial x}, (d_a < h) \end{cases} \quad (9)$$

$$q_y = \begin{cases} -k_a h \frac{\partial H}{\partial y}, (h \leq d_a) \\ -\frac{1}{n} (h - d_a)^{5/3} \sqrt{\left| \frac{\partial H}{\partial y} \right|} \operatorname{sgn} \left(\frac{\partial H}{\partial y} \right) - k_a h \frac{\partial H}{\partial y}, (d_a < h) \end{cases} \quad (10)$$

where k_a is the lateral saturated hydraulic conductivity and d_a is the soil depth times the effective porosity.

Additionally, equations (11) and (12) are used to simulate unsaturated subsurface flow, saturated subsurface flow and surface flow with the single variable, h .

$$q_x = \begin{cases} -k_m d_m \left(\frac{h}{d_m} \right)^\beta \frac{\partial H}{\partial x}, (h \leq d_m) \\ -k_a (h - d_m) \frac{\partial H}{\partial x} - k_m d_m \frac{\partial H}{\partial x}, (d_m < h \leq d_a) \\ -\frac{1}{n} (h - d_a)^{5/3} \sqrt{\left| \frac{\partial H}{\partial x} \right|} \operatorname{sgn} \left(\frac{\partial H}{\partial x} \right) - k_a (h - d_m) \frac{\partial H}{\partial x} - k_m d_m \frac{\partial H}{\partial x}, (d_a < h) \end{cases} \quad (11)$$

$$q_y = \begin{cases} -k_m d_m \left(\frac{h}{d_m}\right)^\beta \frac{\partial H}{\partial y}, (h \leq d_m) \\ -k_a(h - d_m) \frac{\partial H}{\partial y} - k_m d_m \frac{\partial H}{\partial y}, (d_m < h \leq d_a) \\ -\frac{1}{n}(h - d_a)^{5/3} \sqrt{\left|\frac{\partial H}{\partial y}\right|} \operatorname{sgn}\left(\frac{\partial H}{\partial y}\right) - k_a(h - d_m) \frac{\partial H}{\partial y} - k_m d_m \frac{\partial H}{\partial y}, (d_a < h) \end{cases} \quad (12)$$

Note that k_m is computed by $k_m = k_a / \beta$ to assure the continuity of the discharge change when $h = d_m$, so that k_m is not used as the model parameter.

It is suitable to apply these discharge-hydraulic gradient relationship equations to humid forest areas with a high permeable soil layer where a lateral subsurface flow is dominant. However, for relatively flat areas, the vertical infiltration during the first period of rainfall is more important to the large-scale flooding process. Here we treat the vertical infiltration as loss for event-based simulation and calculate the infiltration loss f with the Green-Ampt infiltration model.

$$f = k_v \left[1 + \frac{(\phi - \theta_i) S_f}{F} \right] \quad (13)$$

where k_v is the vertical saturated hydraulic conductivity, ϕ is the soil porosity, θ_i is the initial water volume content, S_f is the suction at the vertical wetting front and F is the cumulative infiltration depth⁵²).

In our study area, there are mainly three land-use types. They are urban, agricultural area and forest. The urban and agricultural area are almost located in flat areas and the forest is almost located in mountainous areas. In the RRI model application, we consider the urban area has only overland flow but without infiltration loss nor subsurface flow, thus we set both k_v and k_a equal to be zero. For the agricultural land, we consider it has vertical infiltration and infiltration excess overland flow but without subsurface flow, we set k_a equal to be zero. For the forest, we consider it has saturated subsurface flow and saturation excess overland flow but without vertical infiltration loss, we set k_v equal to be zero. In the study in the Pingqiao River Basin, simulation of forest

did not consider the unsaturated subsurface flow but in the testing study in the Kiryu Experimental Watershed, the unsaturated subsurface flow in forest was considered. The schematic diagram of surface/subsurface flow conditions are illustrated in Figure 3.2.

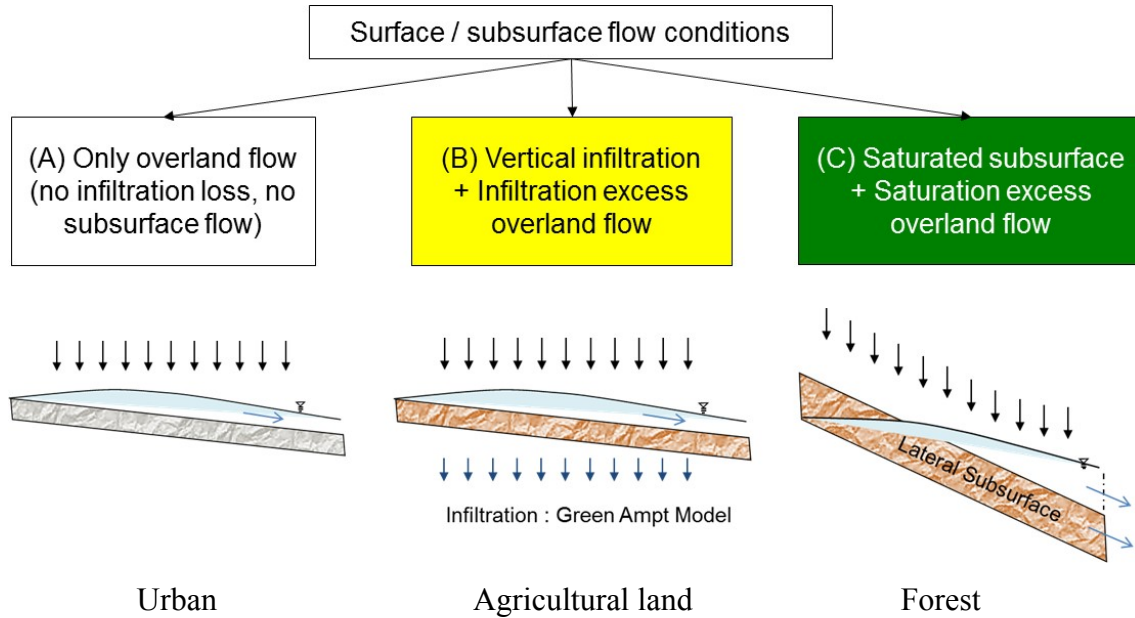


Figure 3.2: Schematic diagram of surface/subsurface flow conditions (figure form the Rainfall-Runoff-Inundation Model User's Manual⁵²)

3.2.3 One-dimensional river routing model

The RRI model calculates streamflow based on the diffusion wave approximation by ignoring the y direction in equations (6) and (8). The cross section of channel is assumed to be rectangle, whose geometries are defined by width, depth and levee height⁵²).

3.2.4 Interactions of water between slope and river

Water exchange between slope grid cell and river grid cell is estimated by the relative position relationships between the slope water level, river water level and levee height. To calculate the unit length discharge exchange from slope to river (q_{sr}) and the unit length discharge exchange from river to slope (q_{rs}), four different conditions are considered with different overtopping formulae applied.

1) When the slope water level is higher than the river water level, flow from slope to river is considered as the normal condition. The discharge from the slope into the river is calculated by the following formula:

$$q_{sr} = \mu_1 h_s \sqrt{g h_s} \quad (14)$$

where μ_1 is the constant coefficient (= 0.544) and h_s is the slope water depth.

2) When the river water level is higher than the slope water level but lower than the levee height, no flow exchange between slope and river is considered.

3) When the river water level is higher than both the levee height and the slope water level, overtopping flow from river to slope is considered. The overtopping flow exchange is calculated by the following formula:

$$q_{rs} = \mu_2 h_1 \sqrt{2g h_1} \quad (15)$$

where μ_2 is the constant coefficient (= 0.35) and h_1 is the difference between the river water level and the levee crown.

4) When the slope water level is higher than both the levee height and the river water level, overtopping flow from slope to river is considered. The overtopping flow exchange is calculated by the following formula:

$$q_{sr} = \mu_2 h_2 \sqrt{2g h_2} \quad (16)$$

where μ_2 is the constant coefficient (= 0.35) and h_2 is the difference between the river water level and the slope water level⁵²⁾.

3.3 Time-Space Accounting Scheme

T-SAS is a matrix-based time-space accounting scheme that tracks the ratio of flow contributed by rainwater originating from certain temporal classes and spatial zones. One of the objectives of T-SAS is to analyze the discharge (computed by RRI model) contributed by rainwater originating from when and where, i.e. T-SAS separates hydrograph in terms of different temporal classes and spatial zones of rainwater sources¹⁷⁾. Figure 3.3 illustrates the schematic diagram of the separation of the temporal and spatial hydrograph components.

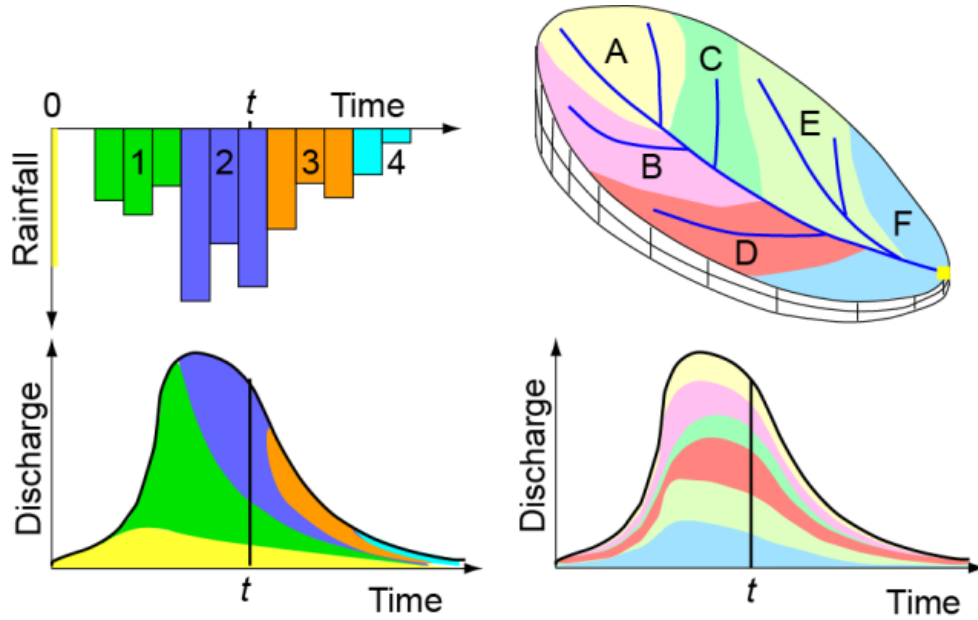


Figure 3.3: Schematic diagram of the hydrograph separation by temporal classes (left) and spatial zones (right) of rainwater sources

(figure from Takahiro SAYAMA and Jeffrey J. MCDONNELL, 2009¹⁷⁾)

For time source hydrograph separation (Figure 3.3(left)), we can divide rainfall into optional several temporal classes, in this example we used five temporal classes from 0 to 4. The 0 class represents pre-event water while the classes 1 to 4 represent event water in the different periods of the hyetograph. The colors in the hyetograph correspond to the colors in the hydrograph in Figure 3.3(left), indicating that at any time t , how much portions of discharge at the outlet of the basin are contributed by rainwater

from corresponding periods.

For spatial source hydrograph separation (Figure 3.3(right)), we can divide the basin into optional several spatial zones, in this example we divided into six spatial zones from A to F. The colors of the basin correspond to the colors in the hydrograph in Figure 3.3(right), illustrating that at any time t , how much portions of discharge at the outlet of the basin are contributed by rainwater from corresponding zones¹⁷⁾.

In this study, we used T-SAS for spatial source hydrograph separation in terms of different land-uses but without using the time source hydrograph separation.

In order to achieve the objective above, to separate the storage water in each element of distributed hydrological model based on time and spatial source is considered (Figure 3.4). The element of distributed hydrological model is a block within which storage water is considered as one state variable. In the RRI model, one slope grid cell or river grid cell is applicable for an element. For storage separation, it is assumed that water mixing between each element only occur through moving. Based on the assumption, storage water is separated by time updating computation of all the elements using the following mass balance equation:

$$\frac{dv_i}{dt} = \sum_j q_{ji} \frac{v_j}{V_j} - \sum_k q_{ik} \frac{v_i}{V_i} + r_i - e_i \frac{v_i}{V_i} \quad (17)$$

Where v_i is the separated storage water in element i . In order to receive all sources of storage, vectors used for v_i have the same dimensions of the number of sources. V_i is the total storage water in element i , it is the summary of each source of v_i . q_{ji} is the inflow from element j to element i , q_{ik} is the outflow from element i to element k . r_i is the precipitation with source information given, e_i is the loss from element i to outside of system by evapotranspiration or infiltration, and t represents the time.

In equation (17), the unknowns are v_i and v_j . By using the runoff model which sequentially tracks from upstream to downstream, the calculation order of mass balance

equation is from upstream to downstream therefore v_j becomes known. That means equation (17) becomes ordinary differential equation with one variable and can be analytically solved by proceeding computation from upstream to downstream. Based on the separated storage water in every element, the runoff discharge hydrograph can be separated by multiplying the contribution rate of each source (solved by each source of v_i) and the runoff discharge at the outlet element³⁵).

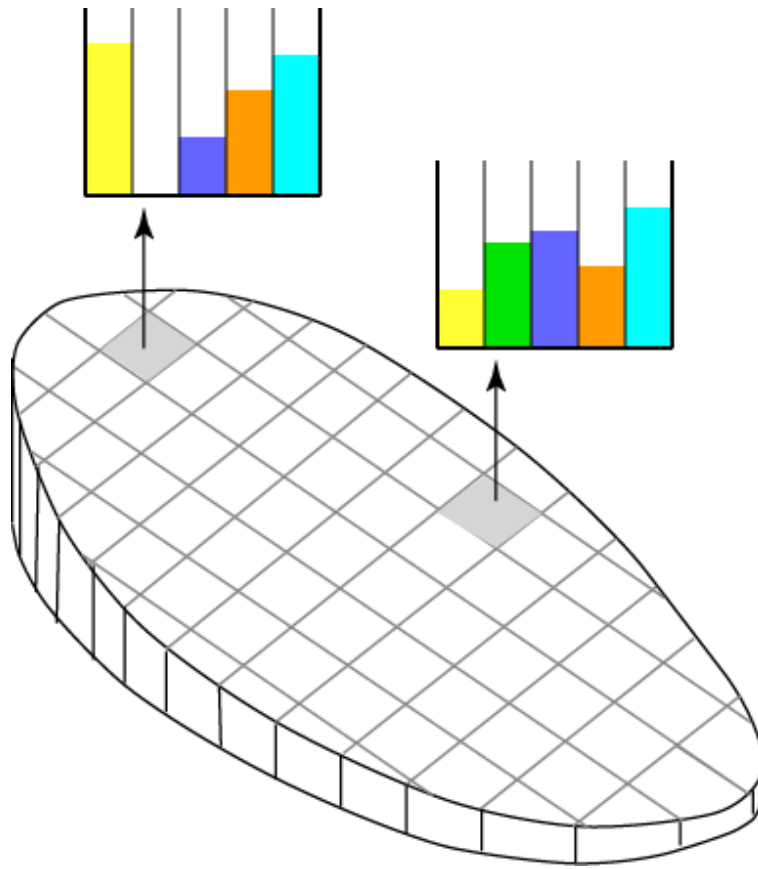


Figure 3.4: Storage water separation in distributed hydrological model
(figure from Takahiro SAYAMA et al., 2013³⁵)

The implementation of T-SAS follows the algorithm as Figure 3.5 shows:

- 1) Assign ID to every element in the distributed hydrological model (RRI model). The ID of the outlet element is listed as well.
- 2) Implement the RRI model and output the water storage, flux between elements,

precipitation and evapotranspiration (or infiltration) of each element at appropriate time step.

3) Use the condition filter to assign values to rainwater corresponding to specified temporal classes or spatial zones. In this study, spatial source hydrograph separation in terms of different land-uses (urban, agriculture and forest) is applied and we assign value 1, value 2 and value 3 to grid cells representing urban, agriculture and forest respectively.

4) Read the RRI model output and condition filter and calculate equation (17) with time updating to separate the storage water in each element.

5) Separate the runoff discharge at the outlet element by multiplying the contribution rate of spatial source (solved by each source of v_i) and the runoff discharge³⁵.

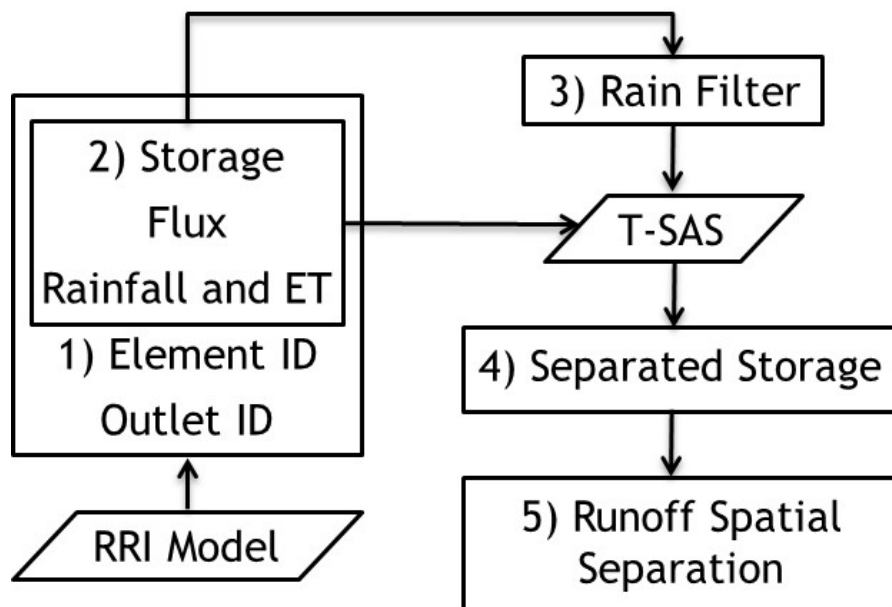


Figure 3.5: Algorithm of T-SAS

3.4 Mass conservation equations

Stream flow consists of runoff originated from multiple spatial zones at any time and location. If we assume that the source runoff concentration does not vary temporally within a short event nor by flow mixing as the biochemical reaction can be negligible due to the comparatively short travel time in streams, the following mass conservations should be satisfied:

$$\begin{aligned}
 f_{A1}C_A + f_{B1}C_B + \cdots + f_{Z1}C_Z &= C_{ST1} \\
 f_{A2}C_A + f_{B2}C_B + \cdots + f_{Z2}C_Z &= C_{ST2} \\
 &\vdots \\
 f_{An}C_A + f_{Bn}C_B + \cdots + f_{Zn}C_Z &= C_{STn}
 \end{aligned} \tag{18}$$

where f_{A1} is the contribution rate of flow discharge which originates from spatial zone A for sample 1; C_A is the source runoff concentration of NPS nutrient for spatial zone A; C_{ST1} is stream flow concentration of NPS nutrient for sample 1; A, B,, Z represent different spatial zones (e.g. A: urban, B: agriculture, C: forest; $n_Z=3$); n_Z is the number of spatial zones; 1, 2, 3,, n represent spatio-temporally different stream samples.

Among the equations above, discharge contribution rates (f_A , f_B , and f_C) are obtained from spatial-zone-based separated hydrograph by the RRI model and T-SAS. If the source runoff concentrations (C_A , C_B , and C_C) can be estimated, stream flow NPS nutrient concentrations (C_{ST}) can be solved. To obtain the source runoff concentration, two approaches are proposed in Section 3.5.

3.5 Source runoff concentration estimations

3.5.1 Field measurement

In this study, we selected three typical source runoff points shown in Figure 3.6 to measure the water quality to grasp the source runoff concentration degrees. We sampled from a ditch near residence, a drainage near an agricultural land and the top upstream stream (almost surrounded by forest) to represent source runoff concentrations of urban, agriculture and forest zone respectively.

3.5.2 Inversely estimation by statistical method

The alternative approach is an inverse method in case the field observation cannot be obtained. If we have several stream flow observations (C_{ST}) and the observation number (n) equals to (or larger than) spatial zone numbers (n_z), the equations (or overdetermined equations) can be solved to estimate source runoff concentrations.

For a better calculation, to get corresponding numbers of spatio-temporally different stream samples with quantitatively significant difference at the beginning of runoff generation are expected¹⁷⁾.

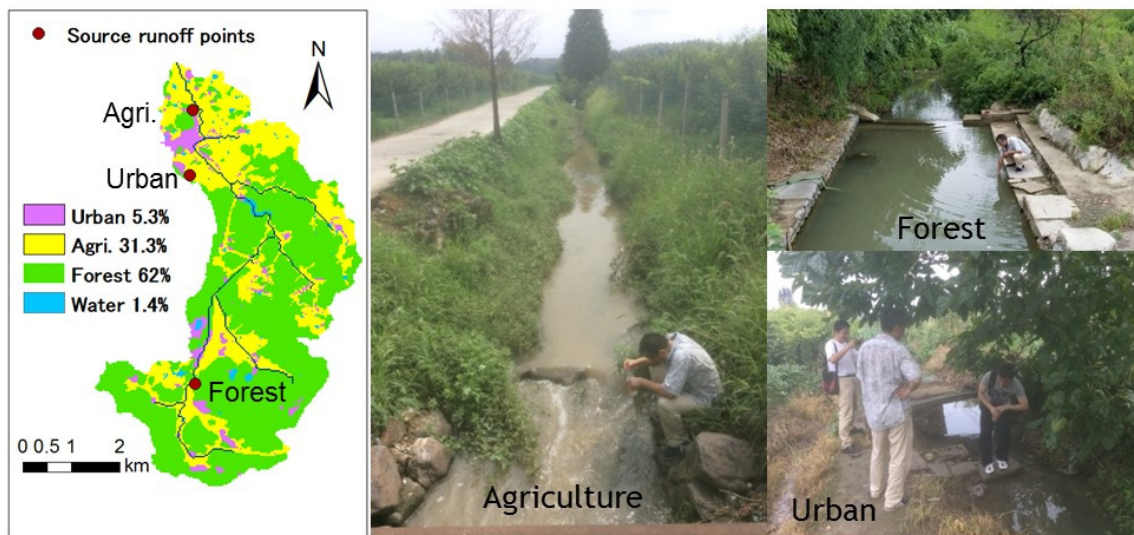


Figure 3.6: Information of source runoff concentration field measurement

3.6 Hydrograph separation in terms of source components

3.6.1 Outline

In order to verify the applicability and reliability of hydrograph separation approach (T-SAS), a testing application were conducted at the Kiryu Experimental Watershed. This application separated runoff discharge in terms of source components (surface flow, subsurface flow and groundwater flow) and the method is introduced in this section individually. This method has the following four steps as shown in the flowchart in Figure 3.7.

- 1) Apply a physically-based hydrological rainfall-runoff model representing mountainous groundwater (groundwater model incorporated to the RRI model) at our study area (a weathered granitic basin) to generate discharge hydrograph with groundwater effect into consideration.

- 2) Conduct calibration and validation with observation data.

- 3) Apply T-SAS on the simulation results to separate hydrograph in terms of source components (surface flow, subsurface flow and groundwater flow).

- 4) Summarize bedrock groundwater contributions and compare our simulation with previous results (Iwasaki et al., 2015³⁷⁾) by the end-member mixing analysis (EMMA) to study the groundwater contributions to rainfall-runoff generation process and improve our model.

3.6.2 The RRI model

The RRI model was introduced in Section 3.2. In this study, we use RRI model as distributed hydrological rainfall-runoff model without implementation of the inundation simulation. In the parameter setting, we consider this study area has uniform land-use of mountainous forest with unsaturated subsurface flow, saturated subsurface flow and saturation excess overland flow (surface flow). Groundwater flow is simulated by the

incorporated groundwater model that is introduced in the next section.

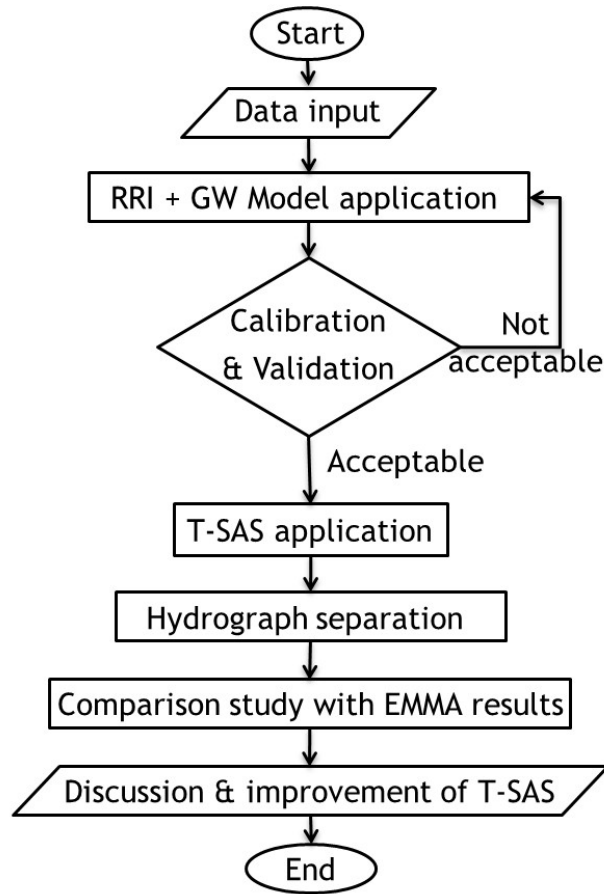


Figure 3.7: Flowchart of the testing study

3.6.3 Groundwater model

This groundwater model of mountainous slope³⁶⁾ (Figure 3.8) is incorporated to the RRI model with the following assumptions:

- 1) The vertical depth from soil-bedrock interface to groundwater surface is represented by variable z_g within grid cells.
- 2) The lateral groundwater discharge is vertically integrated based on the Dupuit-Forchheimer assumption.

3) The saturated hydraulic conductivity is assumed as vertically exponential decline, so that it can avoid defining the unknown bottom boundary of the aquifer.

4) If the groundwater is not saturated and the water depth in soil layer (h_s) is larger than 0, infiltration from soil to bedrock occurs with flow velocity r_{sg} .

5) Unsaturated zone of aquifer is not considered. Infiltrated water from soil to bedrock immediately recharge the bedrock groundwater.

6) If the groundwater surface is saturated by groundwater flow, water amount of $-z_g\gamma_g$ exfiltrate into soil layer and z_g is set to 0. Where γ_g is the bedrock effective porosity. In this model, exfiltrated bedrock groundwater flows into river grids through soil layer.

This groundwater model based on above assumptions is represented by the simultaneous equations of mass balance (19) and Darcy's law (20).

$$-\gamma_g \frac{\partial z_g}{\partial t} + \frac{\partial q_g}{\partial x} = r_{sg} - r_{gl} \quad (19)$$

$$q_g = - \int_{z_g}^{\infty} k_{g0} \exp(-f_g z) I_g dz = - \frac{k_{g0}}{f_g} I_g \exp(-f_g z_g) \quad (20)$$

$$r_{sg} = \begin{cases} k_{sg} & (h_s > 0, z_g > 0) \\ 0 & (h_s = 0) \end{cases} \quad (21)$$

where q_g is the unit width discharge of bedrock groundwater, k_{sg} is the vertical saturated hydraulic conductivity, k_{g0} is the lateral saturated hydraulic conductivity on top bedrock, f_g is the constant that defines the decline of saturated hydraulic conductivity vertically, I_g is the gradient of groundwater level, r_{gl} is the parameter representing outflow of bedrock groundwater outside the system³⁶⁾.

As a result, the simulation result is controlled by four parameters, i.e. γ_g , k_{sg} , k_{g0} and f_g .

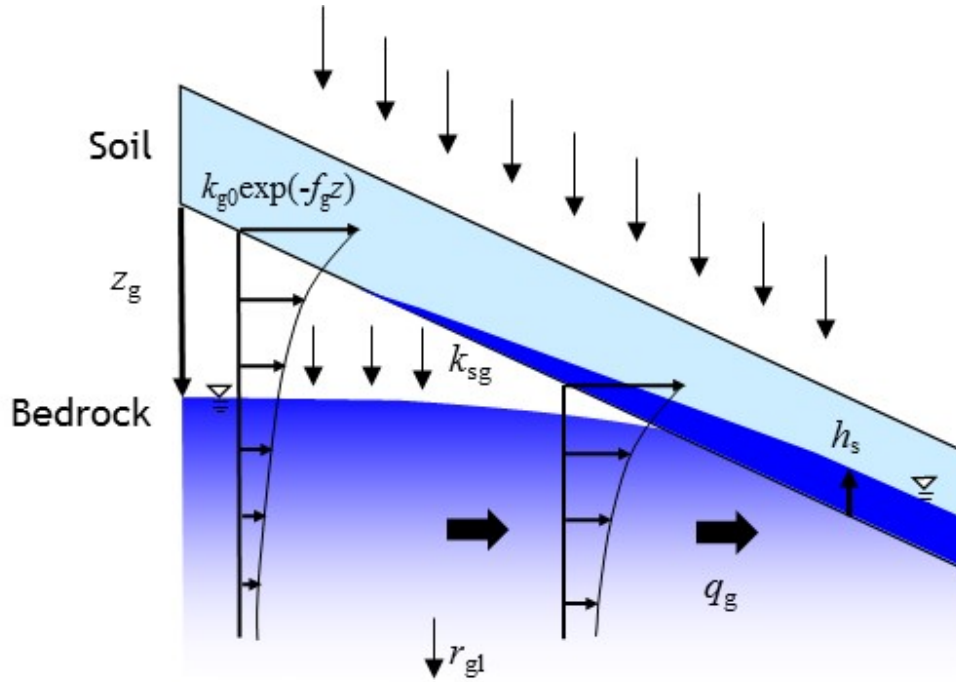


Figure 3.8: Schematic diagram of the groundwater model
(figure from Takahiro SAYAMA et al., 2015³⁶⁾)

3.6.4 Improved T-SAS

T-SAS was introduced in Section 3.3 as a matrix-based time-space accounting scheme that tracks the ratio of flow contributed by rainwater originating from certain temporal classes and spatial zones. In this study, T-SAS was improved to conduct hydrograph separation in terms of source components as Figure 3.9 shows. The hydrograph is expected to be separated into three parts: surface flow, subsurface flow and groundwater flow⁵¹⁾. In order to achieve this, we assigned four different values to rainwater through the runoff process according to different flowpaths.

- 1) Firstly, value 2 was assigned to the overall rainwater.

2) Value 3 was assigned to the initial storage.

3) Through the runoff simulation process, when rainwater infiltrated into bedrock, value 4 was assigned.

4) Through the runoff simulation process, when rainwater exceeded surface, value 1 was assigned.

Therefore, values 1, 2, 3, 4 were assigned to runoff and represented surface flow, subsurface flow, initial storage and groundwater flow respectively. Since the initial storage was almost consisted of subsurface flow in this study, hydrograph separation in terms of three parts (surface flow, subsurface flow and groundwater flow) was achieved.

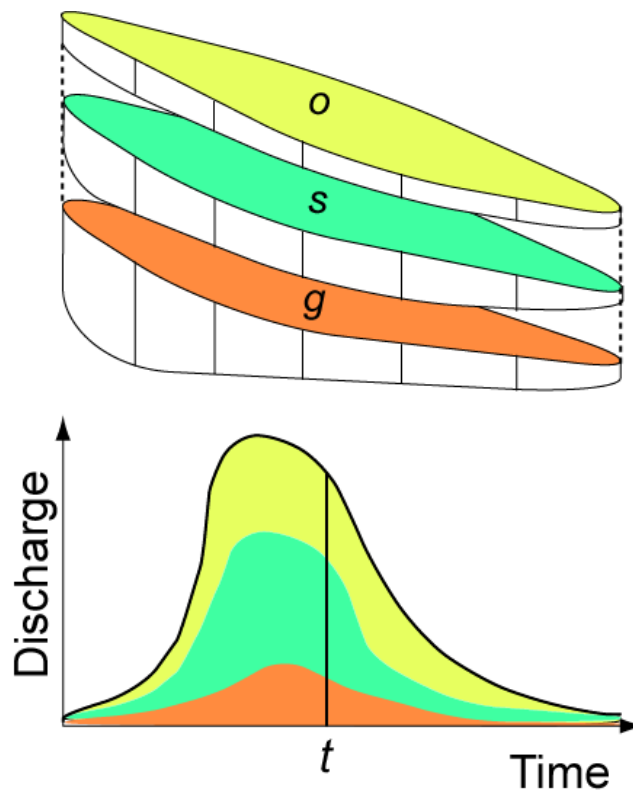


Figure 3.9: Schematic diagram of the hydrograph separation by source components ((overland) surface flow, subsurface flow and groundwater flow) (figure from Takahiro SAYAMA et al., 2016⁵¹⁾)

3.6.5 End-member mixing analysis

EMMA is a technique that links soil water chemistry to stream water chemistry by assuming that the stream water is a mixture of source water (source components)⁴⁹⁾. These source water are called end-members because they form the chemical boundaries of possible stream water observations⁴⁸⁾.

Selection of end-members are determined when those source water concentrations 'bounded' the stream water concentrations for all pairwise combinations of the solutes; that is, in a two-dimensional plot of one solute against another, the stream water concentrations lay inside the triangle whose vertices are the three end-member concentrations⁴⁸⁾ as Figure 3.10 shows.

EMMA has the following assumptions: solute concentration is invariant in time and space; solutes are mix conservatively; there are differences in concentration between the end-members⁴⁸⁾.

Based on the end-member mixing diagram (Figure 4.7), hydrograph of stream water is possibly separated by the contribution rates of end-members (source components). The contribution rate of end-member is calculated by solving mass balance equations (22).

$$f_1 C_{A1} + f_2 C_{A2} + \cdots + f_3 C_{A3} = C_{Ast}$$

$$f_1 C_{B1} + f_2 C_{B2} + \cdots + f_3 C_{B3} = C_{Bst}$$

$$f_1 + f_2 + f_3 = 1 \quad (22)$$

where f is the contribution rate of end-member, 1, 2, 3 represent three end-members, C_A and C_B are concentrations of solute A and solute B, st represents stream water.

In this area, hydrograph separation by source components based on EMMA in three selected storm events have been studied by Iwasaki et al. (2015)³⁷⁾. Our study is to represent the three events by T-SAS approach and compare our hydrograph separation results with the EMMA approach.

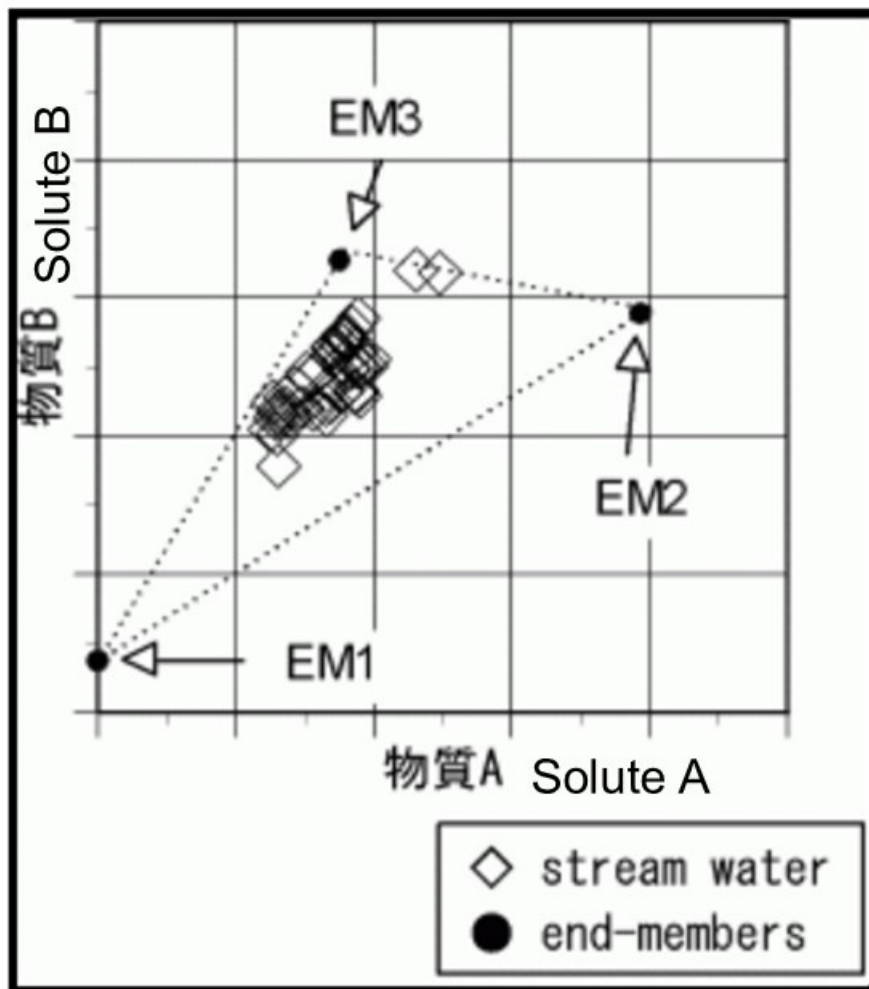


Figure 3.10: End-members mixing analysis diagram
(figure from <http://www.bluemoon.kais.kyoto-u.ac.jp/katsu/EMMA.html>)

Chapter 4 Testing the hydrograph-separation method at an experiment basin

As our study area (the Pingqiao River Basin) lacks the detailed validation data of hydrograph separation results, this chapter tested our hydrograph-separation method performance at the Kiryu Experimental Watershed (Shiga Prefecture, Japan) which has sufficient observation data and previous results for model validation and comparison study. The hydrograph separation was based on source components (surface flow, subsurface flow and groundwater flow). This was one challenge of our hydrograph separation approach and the applicability and reliability was verified. This chapter is relative independent with its own study area introduced in Section 4.2 and methods introduced in Section 3.6.

4.1 Introduction

Understanding a discharge hydrograph is essential for flood prediction, water resources management, and chemical and ecological material transport³⁹⁾. Recently developed process-based hydrological models provide useful tools to generate discharge hydrograph representing surface and subsurface flow. These models have succeeded to some extent in application in humid forest areas as lateral subsurface runoff is the dominate runoff generation process⁴⁰⁾. However, complete agreement between simulation and observation has rarely been achieved and this generally attributed to 1) uncertainty in surface conditions (e.g. Manning's roughness parameter) and soil properties (e.g. thickness, hydraulic conductivity); 2) ignoring the bedrock groundwater contribution⁴¹⁾.

Many of existing hydrological models assume impermeable bedrock in computing flow dynamics at mountainous slope grid cells³⁶⁾. However, the importance of bedrock groundwater has been emphasized in controlling the dynamics of subsurface flow in soil layer through piezometric and tensiometric responses, sprinkler and tracer experiments, hydrogeochemical studies and intensive bedrock groundwater monitoring^{37), 39), 40), 41)}. Additionally, recent studies have revealed that bedrock groundwater affects the upscaling of baseflow runoff processes^{42), 43)} and storm-runoff generation processes⁴¹⁾.

Sayama et al. (2015) developed a groundwater model for mountainous bedrock aquifer incorporated to a distributed hydrological model (Rainfall-Runoff-Inundation (RRI) model) and the simulation results in Rokko catchment involving the groundwater component showed the significant improvement for representing the observed hydrograph characteristics³⁶⁾. However, the groundwater contribution was unsolved in this model.

Sayama et al. (2009) developed a matrix-based time-space accounting scheme (T-SAS) that tracks the ratio of flow contributed by rainwater originating from certain temporal classes and spatial zones¹⁷⁾. The improved T-SAS that deals with flowpath of rainwater makes hydrograph separation based on source components (e.g. groundwater) become possible⁵¹⁾.

On the other hand, hydrochemical studies of forest hydrology and tracer hydrology have been conducted to separate hydrograph source components through e.g. end-member mixing analysis (EMMA). EMMA was performed to identify the potential source components of stream water and to calculate the contributions of each end member (source component) by solving the mass-balance equations⁴¹⁾.

As a result, this study aims to develop a hydrograph-separation-based groundwater representing hydrological model that is consisted of groundwater model incorporated to a distributed hydrological rainfall-runoff model and the improved T-SAS to represent the flow discharge dynamics with bedrock groundwater effects and the bedrock groundwater contributions to rainfall-runoff generation processes. The bedrock

groundwater contributions based on hydrograph separation are comparatively studied with the previous results by EMMA to verify and improve our model.

4.2 Study area

The study area is at the Kiryu Experimental Watershed (KEW; Figure 4.1) which is located in the southern part of Shiga Prefecture of Japan with elevation ranging from 190 m to 255 m above the mean sea level. The climate is warm with peaking rainfall in summer but little snowfall in winter. The mean annual precipitation and the mean air temperature from 2010 to 2012 were 1902.1mm and 13.4 °C by a local meteorological observation³⁷⁾.

The vegetation of KEW is uniform and is mainly consisted of *Chamaecyparis obtuse* Sieb. et Zucc. (Japanese cypress), which was planted in 1959 for afforestation. About 100 years ago, some stonemasonry dams were constructed to prevent sediment loss caused by deforestation and soil erosion of KEW. After the reforestation, soil erosion and sediment movement were reduced, leaving these high permeable dams that do not prevent passing water³⁷⁾.

KEW is underlain by Cretaceous biotite granite. Katsura et al. (2006) indicated that the soil and the weathered bedrock had clearly distinguishable hydraulic properties in this basin⁴⁵⁾.

KEW is classified into basin K (5.99 ha), which corresponds to the entire KEW, and four sub-basins (R: 1.75 ha; M: 0.68 ha; H: 0.40 ha; and A: 0.086 ha). Basin K is a second-order basin, sub-basin R is a first-order sub-basin, and sub-basins M, H, and A are zero-order sub-basins. Five hydrological observation nests within the KEW were established to investigate the rainfall-runoff generation processes by observing precipitation, discharge and conducting hydrochemical measurements as shown in Figure 4.1. The geomorphic information of the five basins are shown in Table 4.1.

Hydrological characteristics of the five basins are different. The stream flow was perennial in basin K and sub-basins R, M, and A but ceased during dry season with little rainfall in sub-basin H. Sub-basin H has larger annual bedrock infiltration and shorter mean residence time (MRT) of stream water while sub-basins R and A and basin K have less annual bedrock infiltration and longer MRT of stream water⁴³⁾.

The runoff responses to rainstorms also varied significantly among the five basins. Table 4.2 shows the annual specific discharge and Figure 4.2 shows the hydrograph at the outlet of each basin from 2010 to 2012 (grey shading indicates periods with data unavailable). Basin K has larger annual specific discharge and hydrological response to rainstorms than sub-basins H and M but smaller annual specific discharge and hydrological response than sub-basins A and R. Sub-basin R has the largest peak specific discharge while sub-basin M was observed the smallest hydrological responses to rainstorms under wet conditions. Sub-basin H has the smallest baseflow which even ceased during the dry winter season. The hydrological responses of sub-basin H were smaller under drier conditions but became similar to or larger than the other basins under wet conditions³⁷⁾.

Table 4.1: Geomorphic information of the five basins

	K	R	M	H	A
Area (ha)	5.99	1.75	0.68	0.4	0.09
Basin order	2	1	0	0	0
Channel length (m)	320	125	12	5	15
Mean slope angle (°)	25.3	22.7	21.4	26.5	23
Mean soil depth (cm)	64.9	65.4	146.3	50.6	80.6

(data from Iwasaki, Katsuyama et al., 2015³⁷⁾)

Table 4.2: Annual precipitation and specific discharge of each basin

Year	Precipitation (mm)	Specific discharge (mm)				
		K	R	M	H	A
2010	1909.3	970.7	-	656.3	383.0	1386.1
2011	1905.2	972.9	1231.5	712.2	335.4	-
2012	1892.0	909.0	1118.0	684.4	412.4	-

(data from Iwasaki, Katsuyama et al., 2015³⁷⁾)

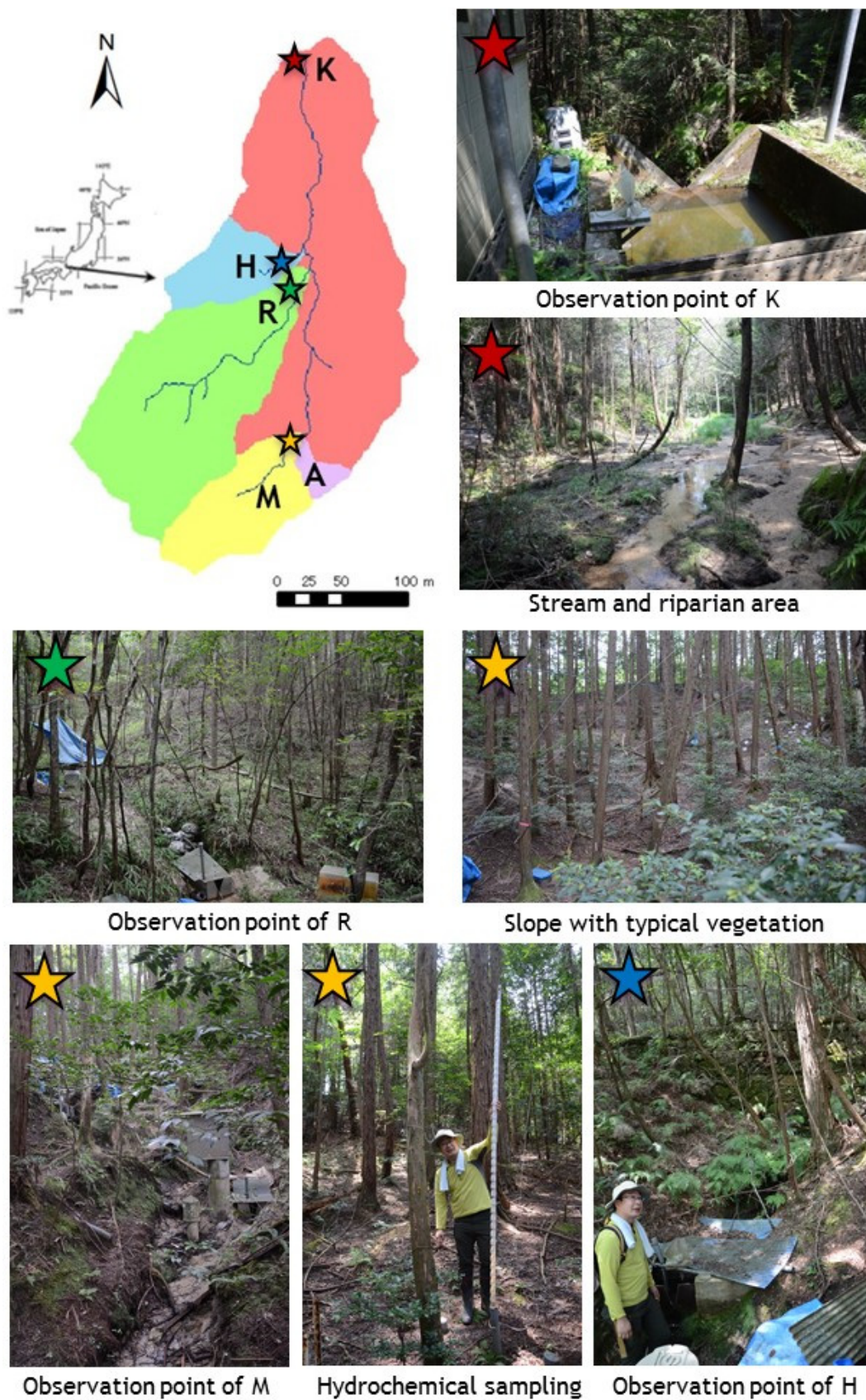


Figure 4.1: Basic information of the five basins

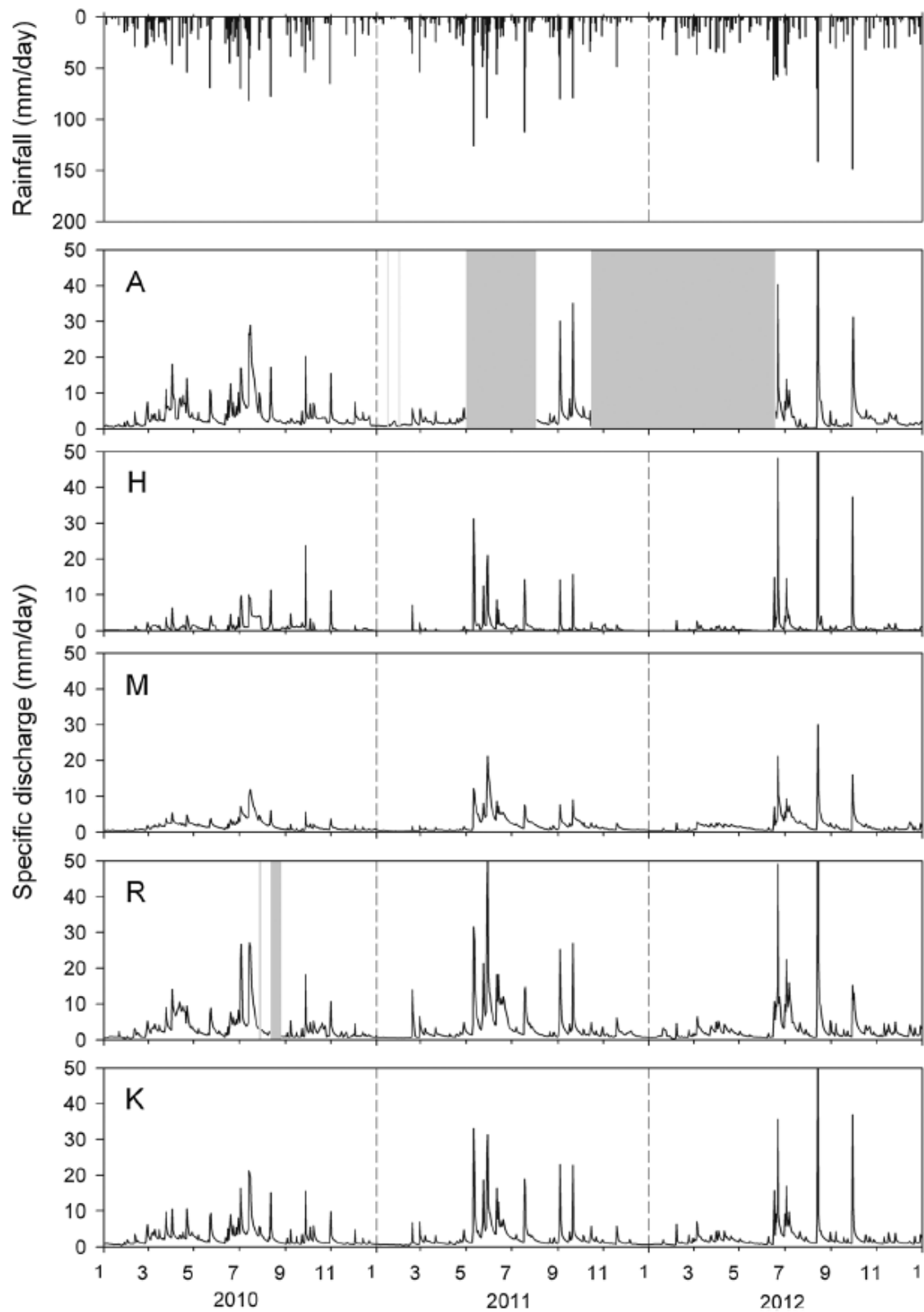


Figure 4.2: Hydrographs of the five basins during 2010 to 2012
(figure from Iwasaki, Katsuyama et al., 2015³⁷⁾)

4.3 Simulation conditions

Figure 4.3 shows the topography information. The topographic data is of 3-m resolution; and the land-use and the soil property are uniformly considered. Precipitation data and discharge data of five basins were measured from 2000/1/1 to 2015/1/1 with hourly temporal resolution. Basic data were provided by Associate Professor Katsuyama MASANORI from Kyoto University.

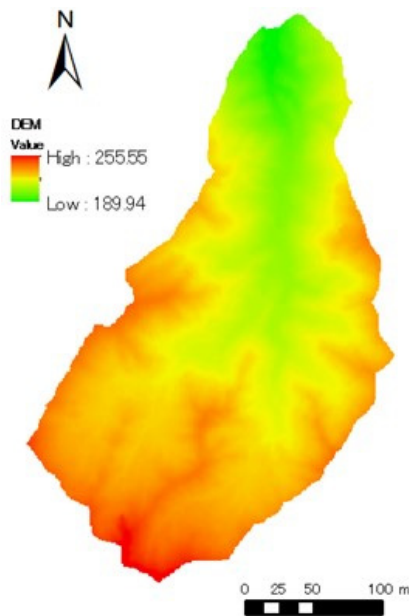


Figure 4.3: Topography information

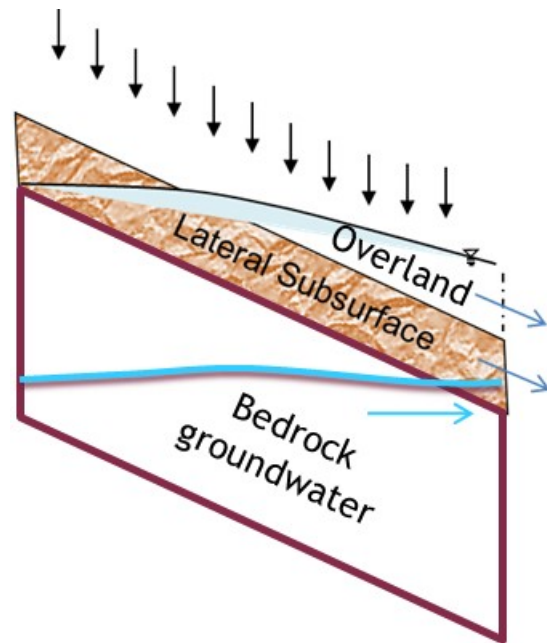


Figure 4.4: Basic concept of source component simulation in grid cells

Figure 4.4 shows the basic concept of source component simulation in grid cells. Grid cell was divided into two layers, the soil and the bedrock. The surface flow (overland flow), subsurface flow and groundwater flow were simulated simultaneously by the RRI model incorporated with the groundwater model. Moreover, within the soil layer, unsaturated subsurface flow and saturated subsurface flow were both simulated.

Three storm events with distinct durations, total amount and intensities were selected for study. Event 1 (total 67.4 mm in two days) was caused by a seasonal rain front,

Event 2 (total 180.7 mm in eight days) was caused by a typhoon and Event 3 (total 272.3 mm in eight days) was caused by a combination of a typhoon and a seasonal rain front. The total rainfall of 272.3 mm was the largest 8-day precipitation recorded in the last 5 years at KEW. Characteristics of the three events are summarized in Table 4.3.

Table 4.3: Characteristics of the selected storm events

	Event 1	Event 2	Event 3
Study period	2011/6/10-11	2011/9/1-8	2012/6/15-22
Total amount (mm)	67.4	180.7	272.3
Maximal intensity (mm/h)	17.4	14.9	20.9

Hyetograph of the three storm events are shown in Figure 4.5. Event 1 represents a short concentrated rainfall with about 60 mm in 9 hours, Event 2 represents a persistent rainfall with one peak in the middle and Event 3 performs as a combination of three small sub-events.

Hydrograph separation by EMMA of the three events have been conducted³⁷⁾ and the results were used for comparison study.

Application of the RRI model incorporated with the groundwater model has four steps:

1) Set the global initial groundwater depth z_g to be -10 m (10m below the soil-bedrock interface) as the approximate low boundary of groundwater level by referring the groundwater level monitoring results⁴⁴⁾ and observation well depth³⁷⁾.

2) Run the first simulation from one month before each event with the initial groundwater level of Step 1 to increase the groundwater level following topography and obtain the natural 3D groundwater level distribution. The first simulation periods were: 2011/5/10 ~ 2011/6/12 for Event 1, 2011/8/1 ~ 2011/9/9 for Event 2 and 2012/5/15 ~ 2012/6/23 for Event 3.

3) We assumed that the groundwater level when (at time t) groundwater starts to exfiltrate into the outlet of basin K (corresponding to the entire KEW) represents the actual groundwater surface distribution to contribute baseflow of basin K. We selected the groundwater level (surface) at time t of Event 2 as initial condition for the next simulation.

4) We input the initial groundwater level of Step 3 and start the second simulation from an antecedent precipitation event before our target event for more realistic reflection of the initial changes of groundwater level. The second simulation periods were: 2011/5/29 ~ 2011/6/12 for Event 1, 2011/8/24 ~ 2011/9/9 for Event 2 and 2012/6/8 ~ 2012/6/23 for Event 3.

4.4 Results

4.4.1 Calibration and validation

We applied the RRI model incorporated with the groundwater model at the KEW and output discharges representing bedrock groundwater effects at outlets of the five basins. Simulation results of the five basins for the selected three events were calibrated and validated with available observations. Calibration was based on basin K (corresponding to the entire KEW) of Event 2 as Event 2 had simple precipitation pattern and moderate amount among the three events. The same parameter settings were applied on other sub-basins (R and H) of Event 2, basin K and sub-basins R and H of Event 1, basin K and sub-basins R, H and M of Event 3 for validations. Calibration and validation results are shown in Figure 4.5.

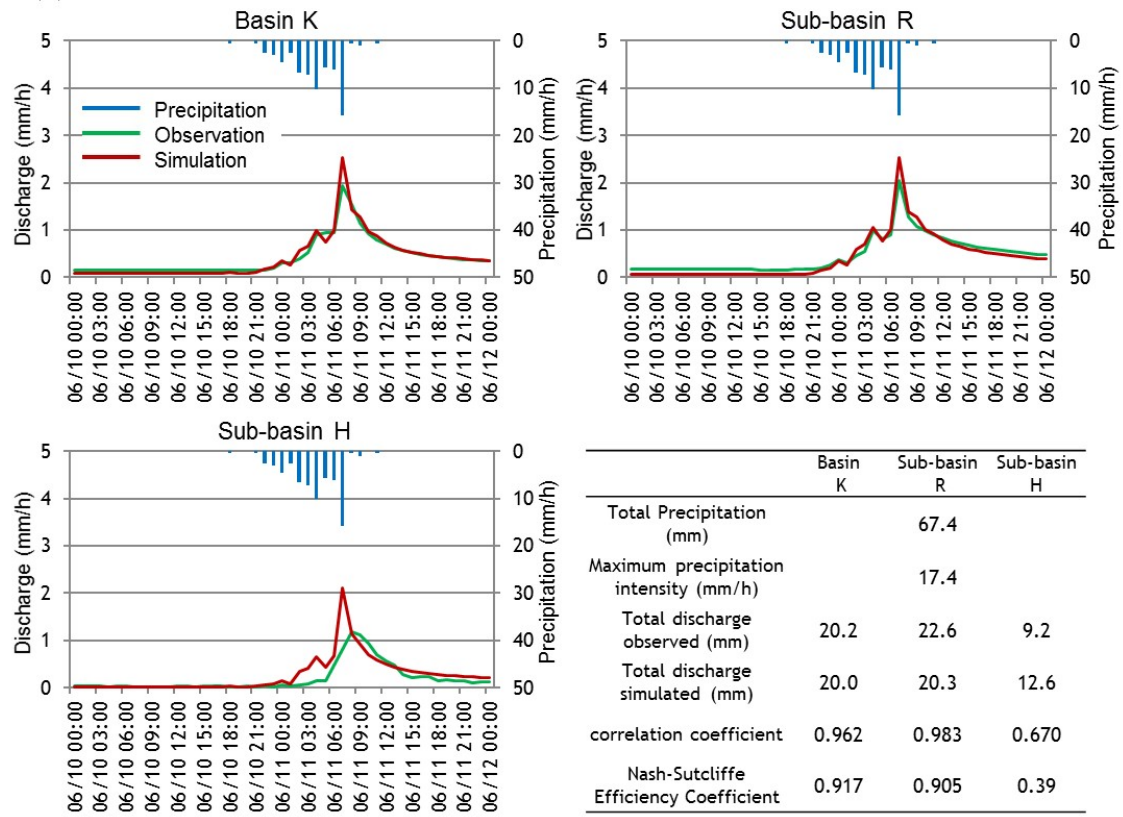
Event 2 had the most satisfactory agreement with observations among the three events. The Nash-Sutcliffe Efficiency Coefficient (NSE) of basin K, sub-basin R and sub-basin H were 0.82, 0.933 and 0.688 respectively.

Basin K and sub-basin R of Event 1 had satisfactory agreement as NSE showing 0.917 and 0.905 but sub-basin H performed considerably overestimated with NSE of 0.390.

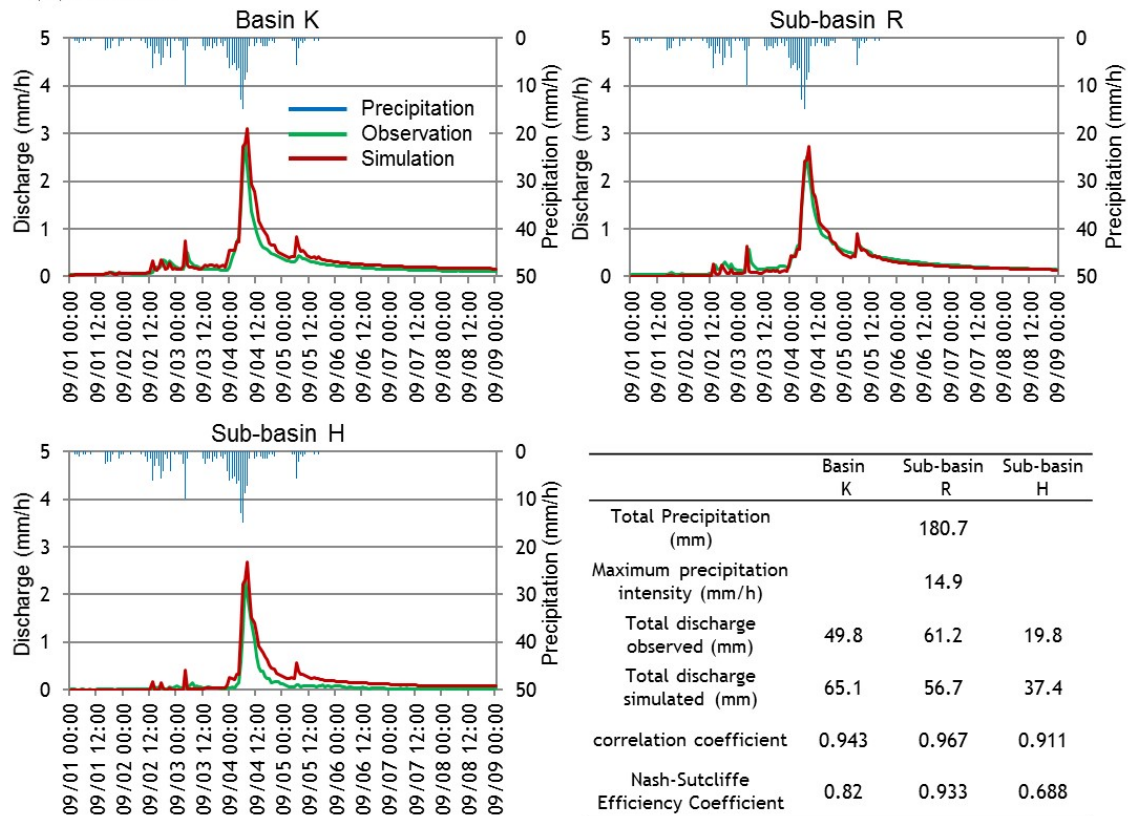
Event 3 had special rainfall pattern and this was reflected in the validation uncertainties as well. Event 3 was considered as a combination of three sub-events. The soil moisture well affected the runoff response to rainstorm as observations showed. The first sub-event and the last sub-event had similar rainfall pattern, total amount (101.3 mm and 114.5 mm) and maximum intensity (19.9 mm/h and 20.9 mm/h), however, the runoff response to the last sub-event was obviously higher than the first sub-event. Particularly for sub-basin R, the peak specific discharge of the last sub-event was about 6.9 mm/h but the peak specific discharge of the first sub-event was 2.0 mm/h. This was speculated that for the first sub-event, soil was under dry condition (unsaturated) and certain amount of rainfall was absorbed and stored in soil layer before saturated, causing smaller hydrological response. As a result, we set parameters representing the unsaturated soil zone and then simulation results have been improved as different hydrological responses to the two sub-events were reflected to some extent. NSE of basin K, sub-basins R, H and M were 0.792, 0.784, 0.808 and 0.030 respectively.

According to the annual discharge characteristics described in Section 4.2, sub-basin R and basin K had larger annual discharge than sub-basins H and M. Sub-basin R had the largest peak discharge and sub-basin M had the smallest hydrological response under wet condition. Both observations and simulations of the three events performed approximately consistent in terms of the annual characteristics of these basins.

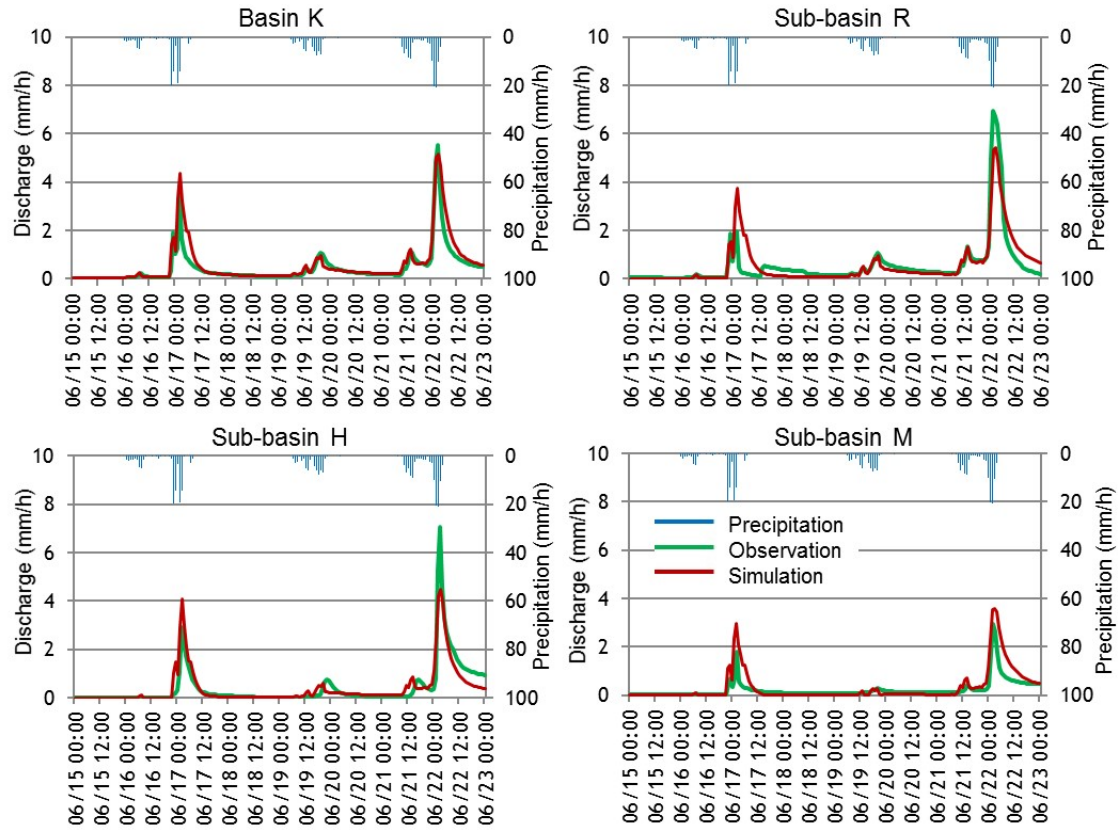
(a) Event 1



(b) Event 2



(c) Event 3



	Basin K	Sub-basin R	Sub-basin H	Sub-basin M
Total Precipitation (mm)		272.3		
Maximum precipitation intensity (mm/h)		20.9		
Total discharge observed (mm)	88.2	104.7	77.6	43.6
Total discharge simulated (mm)	109.6	108.0	75.3	61.9
correlation coefficient	0.892	0.785	0.808	0.852
Nash-Sutcliffe Efficiency Coefficient	0.792	0.784	0.808	0.03

Figure 4.5: Calibration and validation results
(a) Event 1, (b) Event 2, (c) Event 3

Approximately, basin K had better validation than other sub-basins because parameter was globally set and the calibration was based on basin K. Performances of other sub-basins can be theoretically improved by local setting of parameters but in this study, we consider the validation results without local parameter setting were acceptable as NSE indicated.

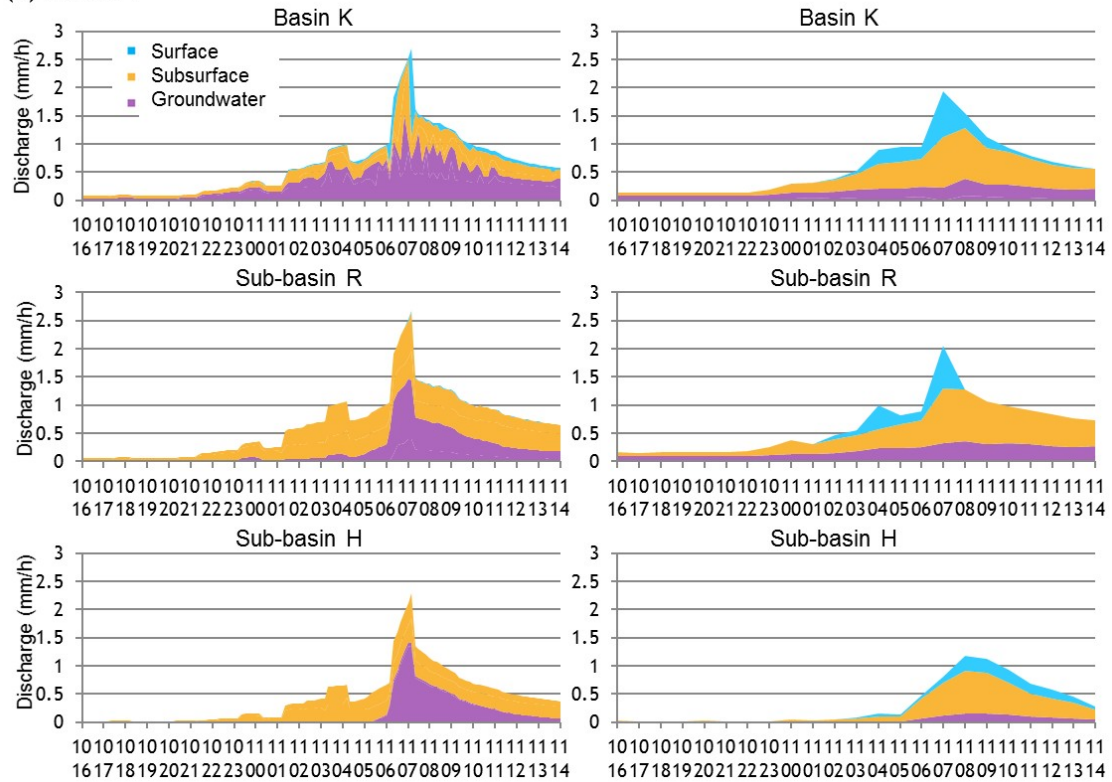
4.4.2 Hydrograph separation

Hydrograph were successfully separated in terms of source components and results are shown in Figure 4.6 for the three selected events and five basins. Left side represents our simulation results and right side shows the separation results by EMMA³⁷⁾. Event 1 and Event 2 have only basin K, sub-basins R and H studied in corresponding with the available EMMA results. Color blue, orange and purple represent surface flow, subsurface flow and groundwater flow respectively.

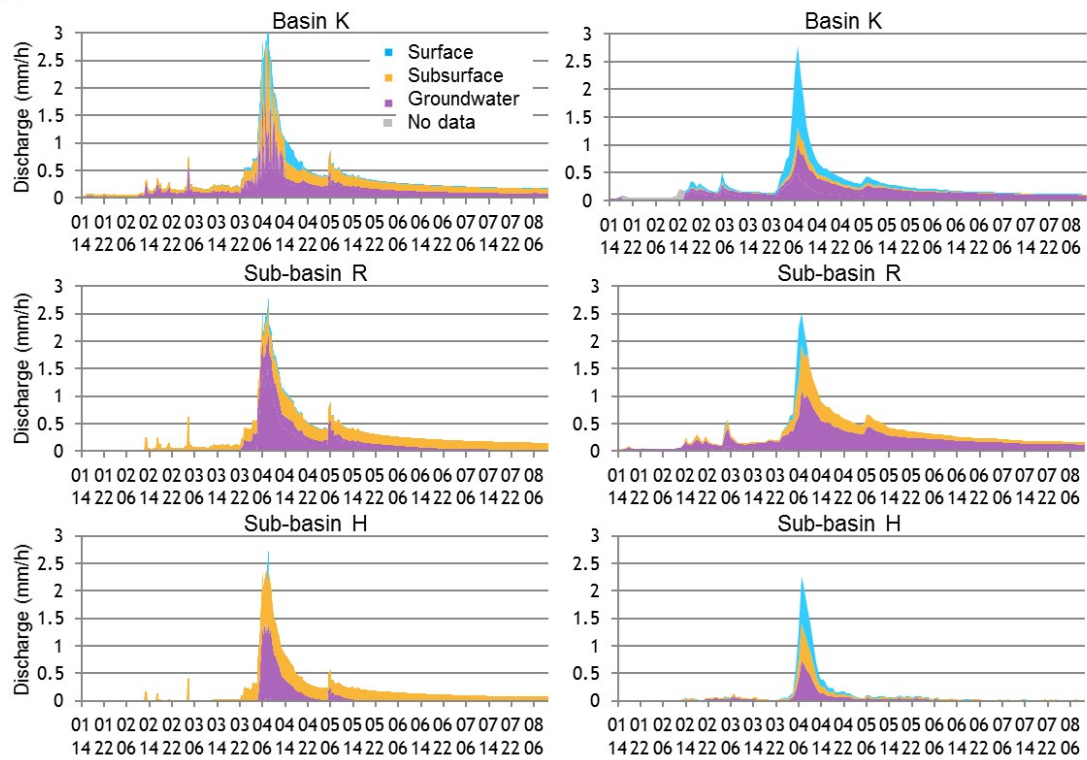
Separated hydrograph by T-SAS and EMMA had similar distribution patterns of the three source components for Event 1 and Event 2. But for event 3, in our simulation, sub-basins R, H, M and A had no groundwater flow exfiltration for the first sub-event, while results by EMMA showed that the exfiltration of groundwater appeared from the first sub-event for these sub-basins.

Another difference between results of T-SAS and EMMA is the contributions of each source component. Basically our results showed less surface flow contributions and more groundwater flow contributions. We will have detailed discussions in the next section.

(a) Event 1



(b) Event 2



(c) Event 3

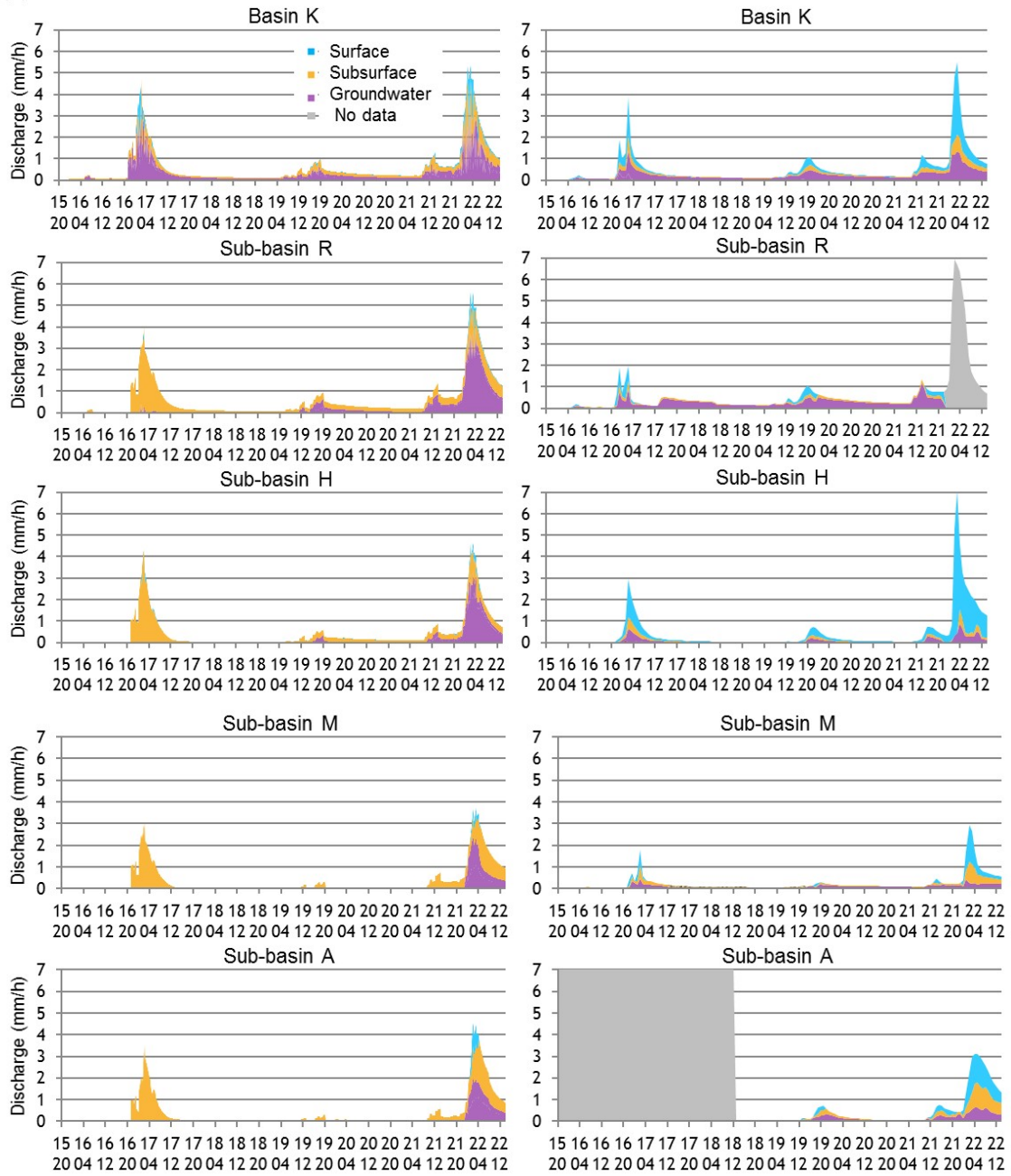


Figure 4.6: Hydrograph separation results in terms of source components
(a) Event 1, (b) Event 2, (c) Event 3

4.5 Discussions

4.5.1 Groundwater contributions to rainfall-runoff generation processes

Contributions of source components were summarized in Figure 4.7. Color blue, orange and purple represent surface flow, subsurface flow and groundwater flow respectively. The left side is based on our simulation results and the right side is based on results of EMMA approach. Among the EMMA results, basin K of Event 2, sub-basins R and A of Event 3 had some periods with data unanalyzed. Because our focus is on the rainfall-runoff generation process, if the unanalyzed period was during baseflow process (e.g. basin K of Event 2 and sub-basin A of Event 3), we considered the effect was negligible when we do not take it into the overall summarization. While sub-basin R of Event 3 lacks data of the runoff process thus we did not summarize this case for comparison study.

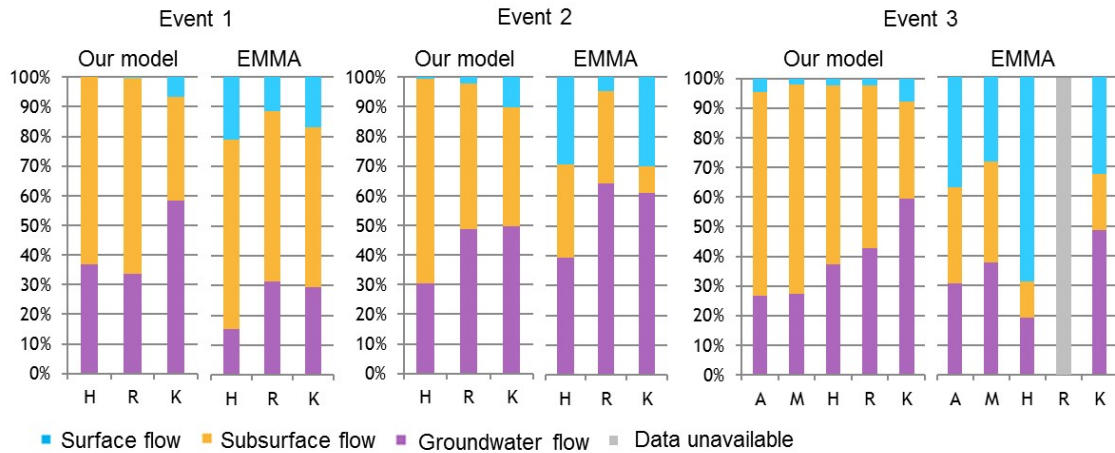


Figure 4.7: Summary of contributions of source components to runoff generation

Our simulation indicated that the bedrock groundwater had considerable contributions to storm runoff generation and the contributions were consistent with the EMMA estimations. Groundwater were estimated to contribute approximate 27% ~ 60% of total runoff for the overall events and basins. While the EMMA approach estimated that about 15% ~ 64% of runoff were contributed by groundwater. The two approaches

estimated similar groundwater contributions in terms of basin order as well. The second-order basin K had groundwater contributions of 49.6% ~ 59.5% by our model while 29.3% ~ 61.1% by EMMA. The first-order sub-basin R had groundwater contributions of 33.5% ~ 48.6% by our model while 31.3% ~ 64.2% by EMMA. The zero-order sub-basins H, M and A had groundwater contributions of 26.7% ~ 37.3% by our model while 15.3% ~ 39.3% by EMMA. As Iwasaki et al. (2015) concluded that the contributions of bedrock groundwater increased as the basin scale became larger in this area³⁷⁾, our simulation results well reflected this trend in general. The detailed groundwater contributions to runoff generation were summarized in Table 4.4.

Table 4.4: Summary of groundwater contributions to runoff generation

Event 1					
Sub-basin H		Sub-basin R		Basin K	
Our model	EMMA	Our model	EMMA	Our model	EMMA
37.0%	15.3%	33.5%	31.3%	58.4%	29.3%
Event 2					
Sub-basin H		Sub-basin R		Basin K	
Our model	EMMA	Our model	EMMA	Our model	EMMA
30.6%	39.3%	48.6%	64.2%	49.6%	61.1%
Event 3					
Sub-basins A, M, H		Sub-basin R		Basin K	
Our model	EMMA	Our model	EMMA	Our model	EMMA
26.7% ~ 37.3%	19.1% ~ 37.7%	42.7%	-	59.5%	48.7%

When focusing on rainfall events, Event 2 and Event 3 showed better consistence between our results and the EMMA estimations in terms of groundwater contributions. For Event 1, our model had larger estimation of groundwater contribution as sub-basin H had groundwater contribution of 37% by our estimation while 15.3% by EMMA, basin K had groundwater contribution of 58.4% by our estimation while 29.3% by EMMA. Our simulation started from an antecedent rainfall event of the target event to take more realistic reflection of the initial groundwater level changes. Event 1 had a larger antecedent event (161 mm) than the other two events (Event 2: 33 mm; Event 3: 39 mm) and the initial groundwater level was probably overestimated by a lower declining speed of groundwater level after the antecedent event (in our model), causing

a larger groundwater contribution estimated.

4.5.2 Groundwater contribution increase of upscaling sub-basins H (M, A) to basin K

Increased groundwater contributions when upscaling from zero-order sub-basins (H, M, A) to second-order basin (K) were found in both our simulations and EMMA results. The reason is illustrated in Figure 4.7(a) and (b).

Figure 4.8(a) shows the schematic diagram of assumed conditions and processes representing the real situation while Figure 4.8(b) shows the simulation conditions in our model. Blue dot line represents the initial groundwater level and the blue solid line represents the changed (increased) groundwater level. Purple star marks represent outlets of basins. Note that zero-order sub-basins (H, M, A) are located at higher positions or on relative steeper slopes than the second-order basin (K). We assumed that the initial groundwater level reached the outlet of basin K because it had perennial stream baseflow as figure 4.8(a) shows. After rain began, groundwater level rose and groundwater flow recharged the runoff at the outlet of basin K. The rain lasted and when the risen groundwater level reached the outlet of sub-basins H (M, A), groundwater exfiltrated at the outlet and recharged the runoff of sub-basins H (M, A). This indicated that basin K had longer exfiltration duration than sub-basins H (M, A), resulting in higher contribution of groundwater to runoff generation process.

This assumption could be proved from the EMMA side. When looking at Figure 4.6(right), the basin K had groundwater recharging for the whole period, while sub-basins H (M, A) had a shorter period of groundwater exfiltration. Although the EMMA results are not observation data in the strict sense, we considered it represented the real situation to some extent when without more reliable observations.

On the other hand, our model represented different initial groundwater level that reached the outlet of basin K with a certain distance below the soil-bedrock interface (as topography also) as Figure 4.8(b) shows. However, the mechanism and process of

groundwater level increase and groundwater exfiltration were well represented and reflected by our model, resulting in similar increasing trend of groundwater contributions when upscaling from zero-order sub-basins (H, M, A) to second-order basin (K) that also proved our assumption of the real situation.

From Figure 4.6(left), the simulation results showed obvious increased groundwater exfiltration periods of upscaling from sub-basins H (M, A) to sub-basin R to basin K. This also explained that why sub-basins R, H, M and A had not groundwater exfiltration in the first sub-event of Event 3 because the increased groundwater level did not reach the outlets before enough accumulation.

4.5.3 Groundwater contribution change of upscaling sub-basin R to basin K

Differences between our results and EMMA have also been found, i.e. our results show the increased groundwater contributions when upscaling from the first-order sub-basin (R) to the second-order basin (K), however, groundwater contributions of sub-basin R and basin K by EMMA results performed similar. The reason is illustrated in Figure 4.8(c) and (d). Figure 4.8(c) shows the schematic diagram of assumed conditions and processes representing the real situation while Figure 4.8(d) shows the simulation conditions in our model.

The basic difference between the first-order sub-basin (R) and the zero-order sub-basins (H, M, A) is that sub-basin R is located at higher position than basin K but not as high as sub-basins M and A nor on a relative steeper slope as sub-basin H. Under this situation, the assumed real initial groundwater surface probably followed the topography closely as Figure 4.8(c) shows. When rain began, the groundwater level rose and groundwater exfiltrated and recharged the runoff at the outlets of basin K and sub-basin R at nearly the same time, causing similar groundwater contribution of the two basins.

From the EMMA results (Figure 4.6(right)), basin K and sub-basin R had groundwater exfiltration from the beginning for the whole periods of all events,

indicating the rationality of our assumption.

On the other hand, our model did not reflect the initial groundwater surface as the assumed real condition. The similar process with Figure 4.8(b) was represented and shown in Figure 4.8(d), i.e. the groundwater level rose after rain began and the groundwater recharged runoff of sub-basin R only after the groundwater level reached its outlet, resulting in shorter exfiltration duration of sub-basin R and lower groundwater contributions than basin K.

As a result, the relative positional relationship changes of groundwater level and the outlets of basins determine the groundwater exfiltration period and contributions. The 3D groundwater level (surface) change of real situation can be well reflected or not determines the reliability of simulation results.

4.5.4 Surface flow contributions

Our results showed obvious differences of surface flow contributions when comparing with the EMMA results. Particularly for Event 3, the EMMA results showed much higher surface flow contributions than our simulations. In our model, we considered that the lateral subsurface flow was dominant runoff generation mechanism in humid forest areas with a high permeable soil layer, the surface flow was contributed by the saturated excess overland flow. However, under real situation of less undergrowth and humus, infiltration excess overland flow may occur and contribute into surface flow, causing higher contribution of surface flow than simulation results.

4.6 Summary

This study developed a hydrograph-separation-based groundwater representing hydrological rainfall-runoff model and applied it at the KEW successfully.

The simulated streamflow discharge representing bedrock groundwater effects showed satisfactory agreement with observations.

Hydrograph were successfully separated by T-SAS in terms of source components and the separated results (groundwater contributions) were compared with the previous results separated by EMMA. Our simulation indicated that groundwater contributed 27% ~ 60% to rainfall-runoff generation for overall selected events and basins. Our results also showed groundwater contributions of 49.6% ~ 59.5% for the second-order basin (K), 33.5% ~ 48.6% for the first-order sub-basin (R) and 26.7% ~ 37.3% for the zero-order sub-basins (H, M, A), indicating increasing groundwater contributions of upscaling basin scale. The consistence of groundwater contribution and changing trend with EMMA results indicated acceptable reliability of our model.

As the reflection of real 3D groundwater level (surface) is the key factor to determine the reliability of simulation results, our model well reflected the increasing trend of groundwater contributions of upscaling sub-basins H (M, A) to basin K because groundwater level dynamics were represented as real case. However, our model did not well reflect the groundwater contribution change of upscaling sub-basin R to basin K because the initial groundwater level and dynamics showed some gap between model and the real case.

Chapter 5 NPS model application on a storm event study using inverse statistical approach

This chapter applied the NPS modelling at the Pingqiao River Basin to conduct the event study of NPS. We selected a storm event from 2014/11/23 12:00 to 2014/11/26 12:00 with 70 mm precipitation in 72 hours. The source runoff concentrations were inversely estimated by multiple stream flow samples. Finally, the time series of spatially separated NPS nutrient loads were simulated and output.

5.1 RRI model calibration

Figure 5.1 shows the simulated and observed stream flow discharges during the calibration period (2016/5/25 0:00 ~ 2016/7/6 0:00). Since the discharge measurement was not continuous and mostly limited to be after flow peaks, it is difficult to evaluate the model performance with Nash efficiency. The Root Mean Square Error (RMSE) of the simulation was 13.0 m³/s and we confirmed that the simulated discharge showed the similar variation ranges with the observations. However, it is possible that our simulation results underestimated the runoff discharge, this may cause the underestimation of the simulated NPS nutrient loads subsequently but it has little effect on the flow discharge contribution rate and source runoff concentration estimations.

5.2 Hydrograph separation by T-SAS

Figure 5.2 illustrates the hydrograph separation results by T-SAS application at Point

A (see Figure 5.3(b)) in the selected storm event (2014/11/23 12:00 ~ 2014/11/26 12:00, 70 mm in 72 hours). We merged the results from water body into agriculture because it covers only 1.4 % and mainly the ponds are located in the agricultural areas. As shown in Figure 5.2, hydrograph was separated into the three parts contributed from urban, agriculture and forest land-uses. Generally, the runoff contributed from urban, agriculture and forest account for about 9%, 24% and 67% of the total runoff respectively.

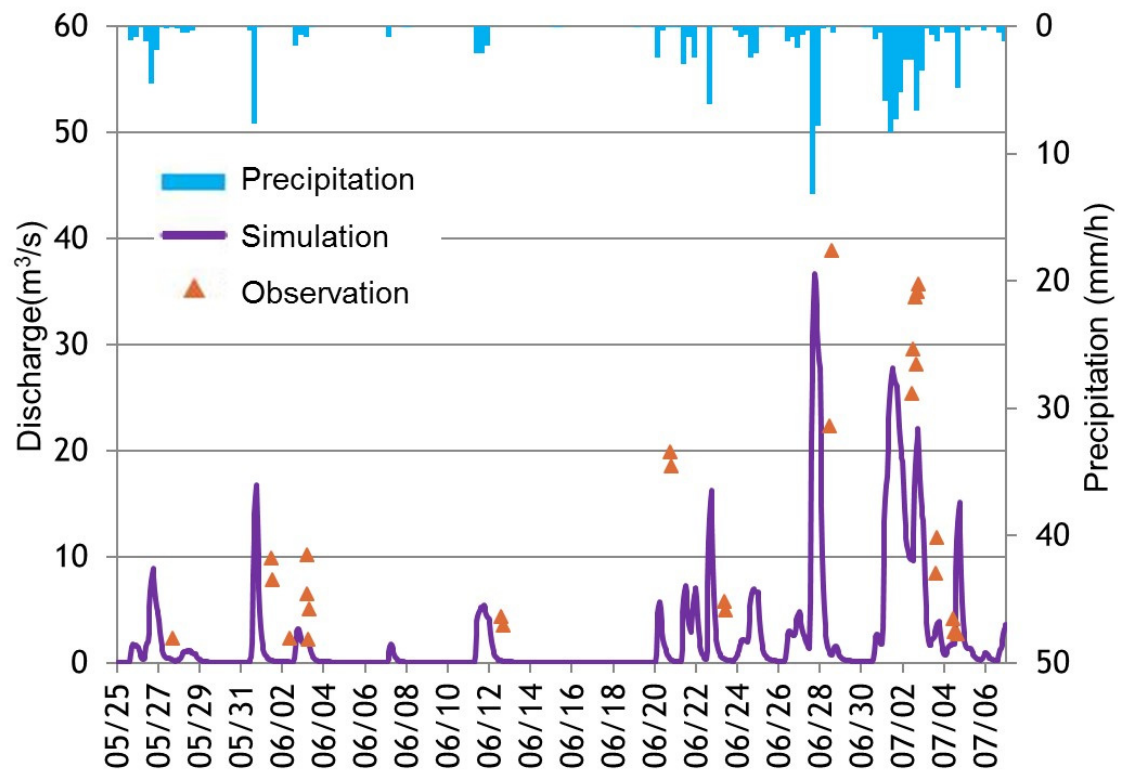


Figure 5.1: Calibration results of the RRI model

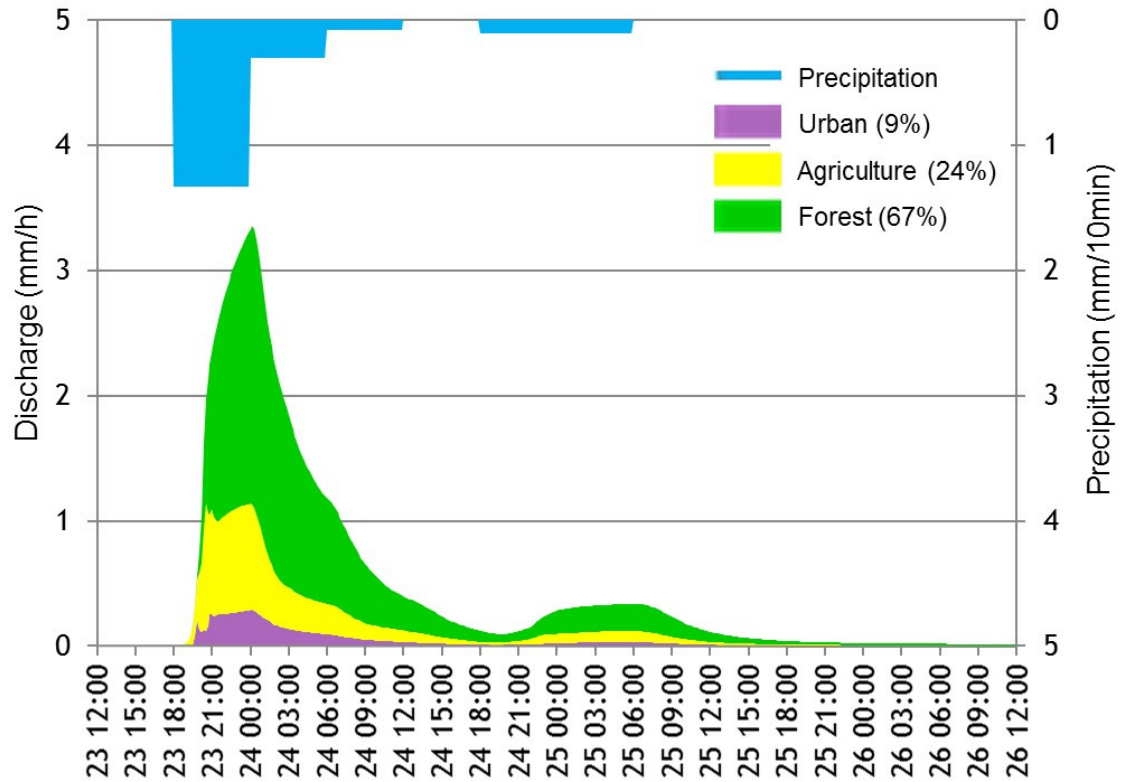


Figure 5.2: Hydrograph separation results by T-SAS at Point A (near the outlet)
(number in the % indicates the proportion of runoff contributed by each land-use to the total runoff)

Figure 5.3(a) shows the time series of discharge contribution rates of each land-use by hydrograph separation results at five representative points. At the initial runoff generation stage, the discharge contribution rates have obvious and significant difference among different locations due to the different timing of arrival of water from each land-use. Particularly, the initial runoff is contributed comparatively high percentage of agriculture and urban areas for downstream points because agriculture and urban areas are located in the lower part of the basin.

Figure 5.3(b) is the longitudinal view of stream water quality (TN, NO_3^- -N and NH_4^+ -N, respectively) along the Pingqiao River. The blue line represents water quality of nine points measured in a raining day (2014/11/25) and red dashed line represents that measured in a non-raining day (2014/12/12). Not only NPS nutrient in the raining day has obvious higher concentration than the non-raining day, but also points A, B and

C located near urban areas have higher nutrient concentrations than other points. These data sets well reflected the runoff and land-use effects on NPS nutrient loads.

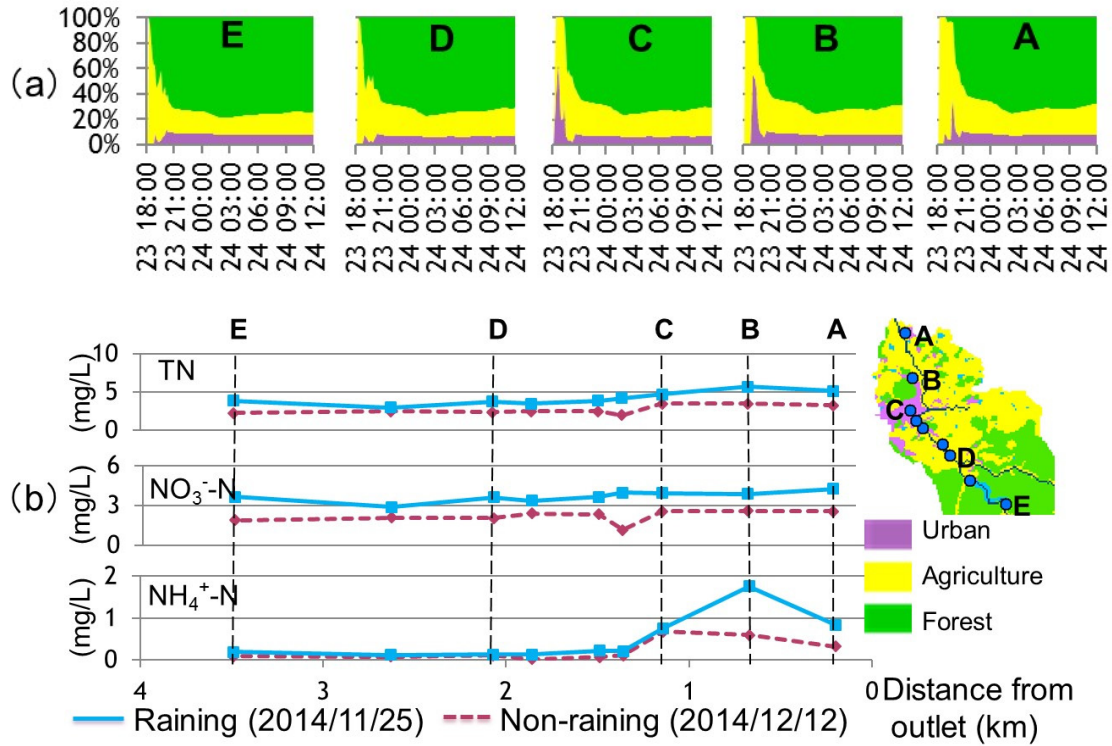


Figure 5.3(a): Flow discharge contribution rates of five representative points
(b): Longitudinal views of stream water quality changes

When comparing Figure 5.3(a) with Figure 5.3(b), discharge contribution rates correspond with stream water quality change, in particular the changes of contribution rates of urban area are positively correlated with the stream water quality changes of NH_4^+ -N and TN.

5.3 Source runoff concentration estimations

By using the above relationships, we demonstrate here the statistical method to inversely estimate the source runoff concentrations by solving the set of equation (18). We used nine points of stream water quality data and built overdetermined ternary

equations with nine equations. We focused on the average contribution rates during 2014/11/23 19:00 to 20:00 to take the advantage of high spatial variations. As for the water quality data, since the sampling was not conducted exactly at the beginning of the event, we used the closest sampling time measured on 2014/11/25.

For better understanding, Figure 5.4 shows the estimated source runoff concentrations as well as the measured values from each contributing land-use. Note that these source runoff concentrations were measured at the small streams or ditches dominated only from each land-use. The measured source runoff concentrations were selected from 2014/12/30 to 2015/2/24 to indicate the winter level. Straight full line (dashed line) represents the estimated (adjusted) source runoff concentration and the marker line represents measured ones. Generally, the estimated source runoff concentrations had good agreement with the observed ones, however, urban source runoff concentration (C_A) of TN, agriculture source runoff concentration (C_B) of NO_3^- -N and urban source runoff concentration (C_A) of NH_4^+ -N showed some overestimations.

In addition, if the inversely estimated value is out of the physically reasonable range (e.g. minus) or unbalance between each nutrient (e.g. $C_{TN} \leq C_{\text{NO}_3^-} + C_{\text{NH}_4^+}$), we estimated the adjusted values to a certain level by referring the observations and considering the balance of each nutrient for the further applications.

Then we used equation (18) to estimate the stream flow NPS nutrient concentrations by using estimated source runoff concentrations. Comparison between estimation and observation is shown in Figure 5.5. The estimated results had good agreement with observations as the estimations well represented the water quality change trend of observations particularly the increasing trend near urban areas (the first three points from the outlet). Although the maximum and minimum estimation values (between 2014/11/23 19:00 and 20:00) had some degree of deviation, particularly for NH_4^+ -N near the urban area, the average values fit the observations as the red line shows.

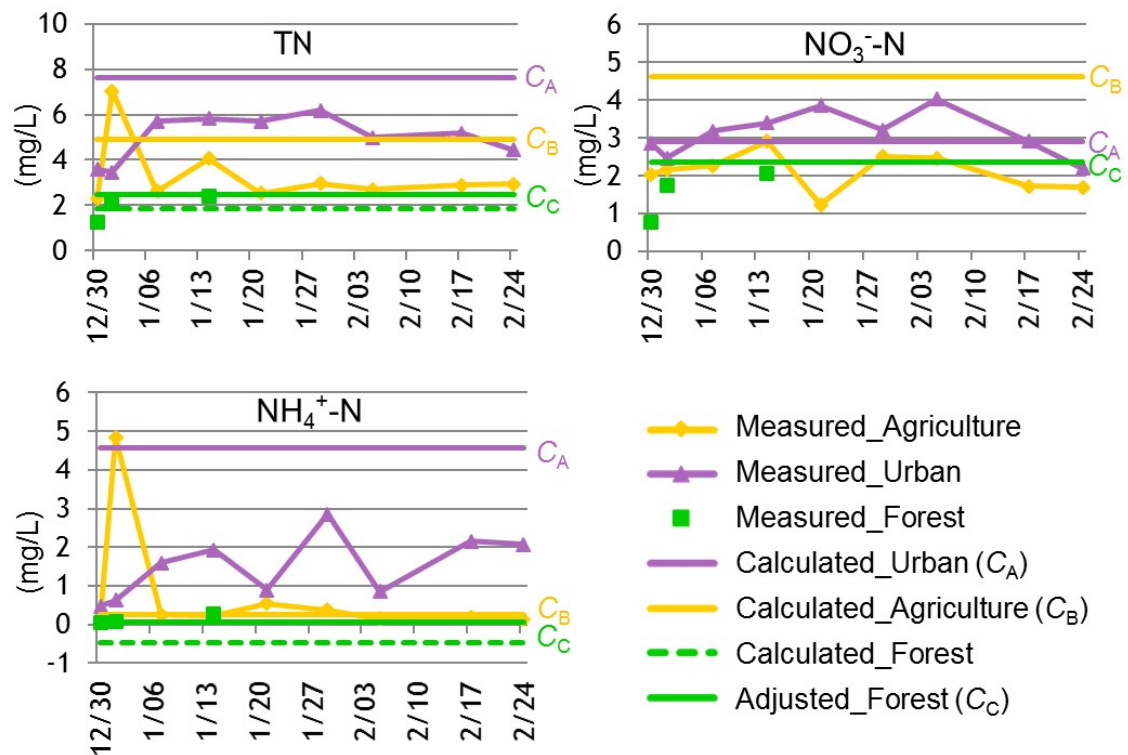


Figure 5.4: Estimated source runoff concentrations (event-based) and measured source runoff concentrations in winter (2014/12/30 ~ 2015/2/24)

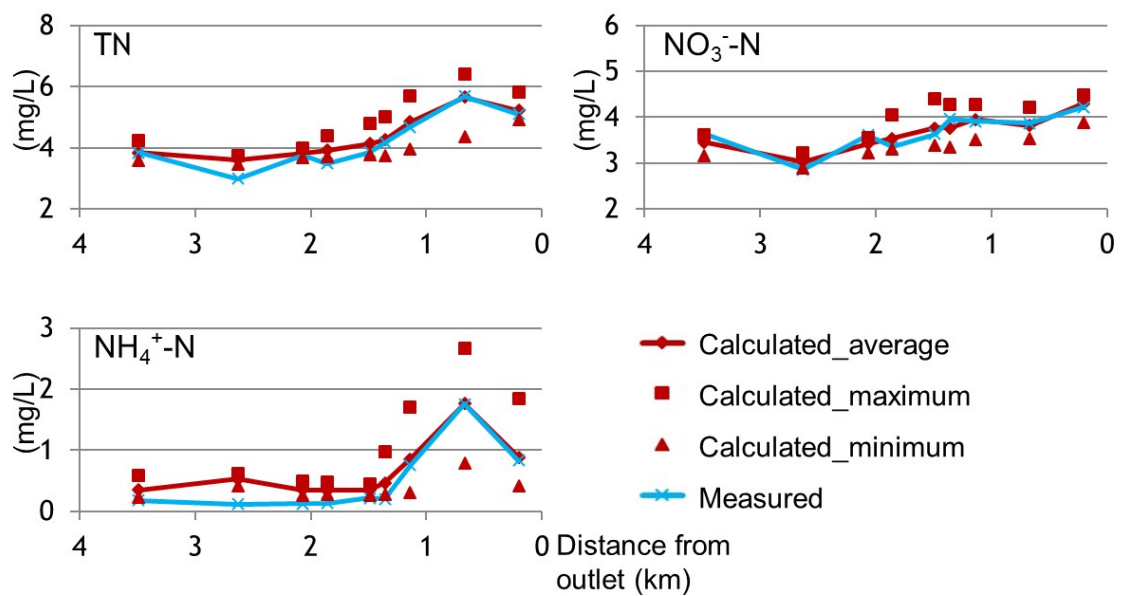


Figure 5.5: Validation of stream flow water quality by estimations

5.4 NPS nutrient load simulation

By using the simulated time series of separated discharges and estimated source runoff concentrations, we computed the time series of spatially separated NPS nutrient loads and summarized the contributions of each land-use as shown in Figure 5.6.

In this short event (70 mm precipitation in 72 hour) 2,630 kg of TN, 2,330 kg of NO_3^- -N and 360 kg of NH_4^+ -N nutrients were delivered.

For agricultural land, it contributed 24% of runoff but 34.7% of TN and 38.6% of NO_3^- -N export. This is considered as the effects of pesticides and chemical fertilizers use.

For the urban area, it accounts for 5.3% of total area but contributed 18.5% of TN and the most NH_4^+ -N (80.1%). Based on our field investigation, this urban area has poor drainage and sewage facilities. The poorly equipped septic tank may flush out waste water through surface runoff, causing a large amount of NH_4^+ -N export. Additionally, flushed domestic waste (open and free dump) is also considered as another important cause of nitrogen nutrients from urban areas.

Note that the TN contributions by urban and agricultural land, the NO_3^- -N contributions by agricultural land and the NH_4^+ -N contributions by urban are probably overestimated as the overestimation of the source runoff concentrations when comparing with the measured values in the nearby period as Figure 5.4 shows.

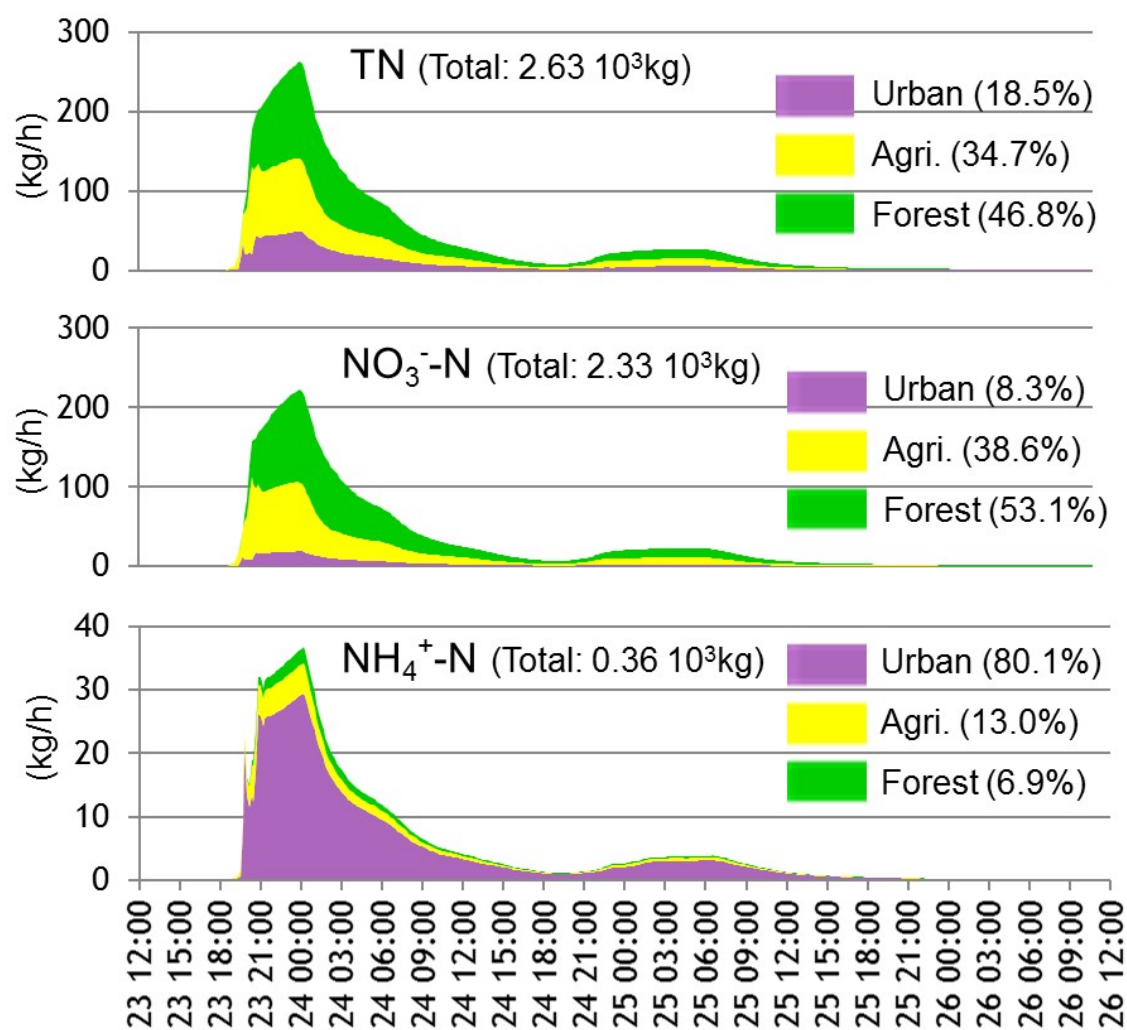


Figure 5.6: Simulation of NPS nutrient loads in the selected storm event

Chapter 6 Long-term study of NPS and targeted countermeasure discussions

In Chapter 5, we used the inversely estimated source runoff concentration to generate the NPS nutrient simulation of a selected storm event. This chapter used the field measured source runoff concentration to conduct a one-year simulation as a long-term study.

Three points of source runoff were sampled from 2014/12/30 to 2015/11/27 on the weekly basis (monthly basis for forest source runoff point). Our simulation periods were from 2014/12/1 20:00 to 2015/11/30 20:00 for the long-term study and from 2016/5/25 0:00 to 2016/7/6 0:00 for the model calibration.

In the event study, we assumed that the source runoff concentration was invariant temporally and mix conservatively as the biochemical reaction can be negligible due to the comparatively short travel time in streams. In the long-term study, as the changes of source runoff concentration cannot be neglected, we conducted a weekly basis measurement to reflect the source runoff concentration changes. Consequently, we assumed the source runoff concentration kept invariant within one week's period.

6.1 RRI model calibration

For the long-term application, 3 arc-seconds (about 90 m) resolution and daily precipitation data were used to save the computational time of the T-SAS approach.

Figure 6.1 shows the simulated and observed stream flow discharges during the

calibration period. Since the discharge measurement was not continuous and mostly limited to be after flow peaks, it is difficult to evaluate the model performance with Nash efficiency. The Root Mean Square Error (RMSE) of the simulation was $10.3 \text{ m}^3/\text{s}$ and we confirmed that the simulated discharge showed the similar variation ranges with the observations. However, it is possible that our simulation results underestimated the runoff discharge, this may cause the underestimation of the simulated NPS nutrient loads subsequently.

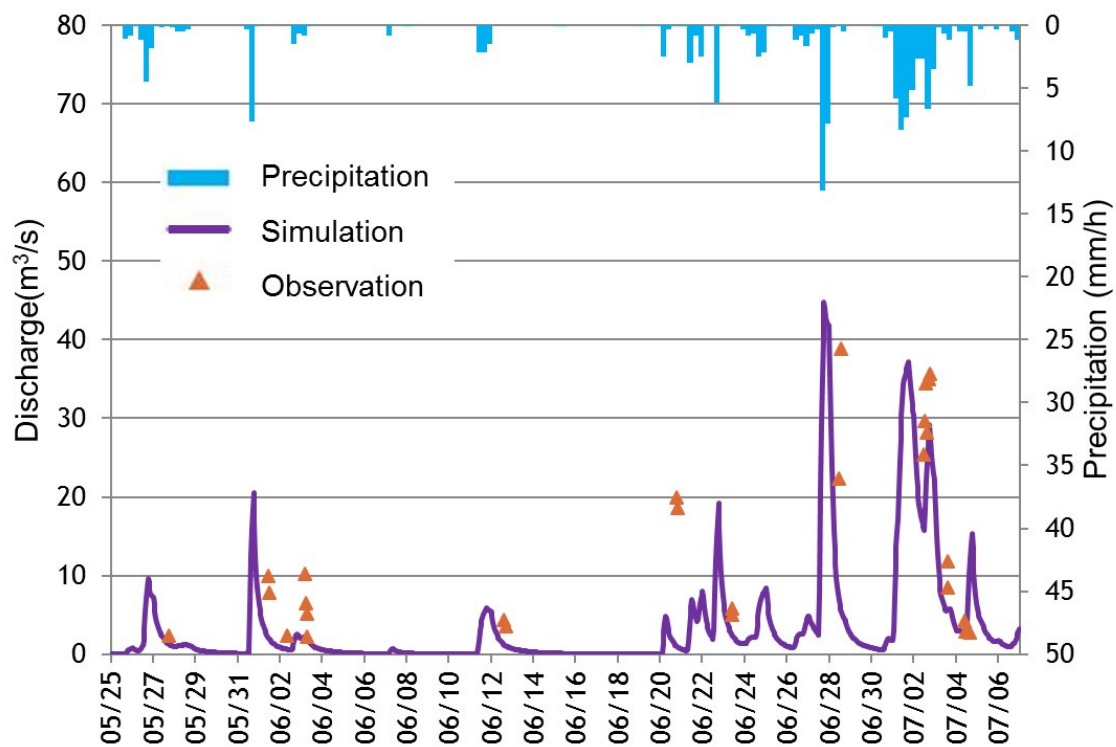


Figure 6.1: Calibration results of the RRI model

6.2 Hydrograph separation by T-SAS

Figure 6.2 illustrates the hydrograph separation results by T-SAS application at Point A (near the outlet, see Figure 5.3(b)) from 2014/12/1 20:00 to 2015/11/30 20:00. We merged the results from water body into agriculture as the event study did in Section 5.2. As shown in Figure 6.2, hydrograph was separated into three parts contributed from

urban, agriculture and forest land-uses. Generally, the runoff contributed from urban, agriculture and forest account for about 9%, 37% and 54% of the total runoff respectively.

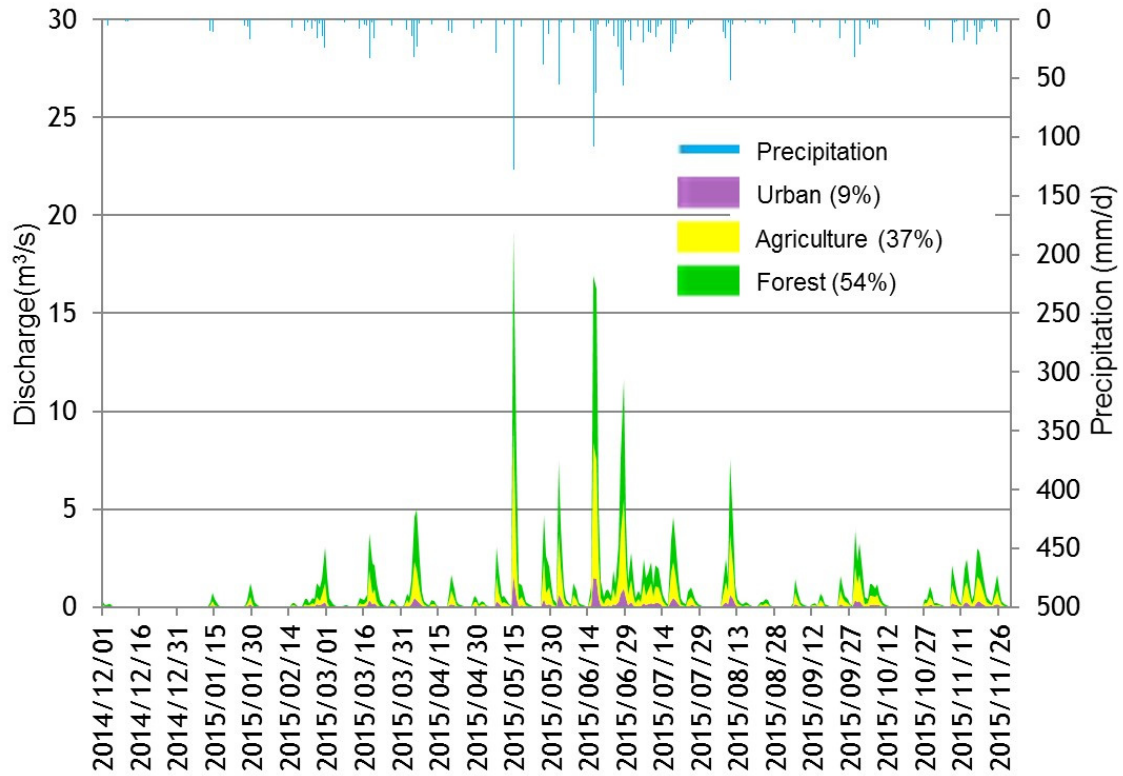


Figure 6.2: Hydrograph separation results by T-SAS at Point A (near the outlet) (number in the % indicates the proportion of runoff contributed by each land-use to the total runoff)

6.3 NPS observations in stream

Figure 6.3 represents the TN and TP concentration changes at Point A within the selected year by weekly basis measurement.

TN has annual average concentration of 3.36 mg/L and standard deviation of 0.79 mg/L. The higher concentrations (more than average value) appeared in January, February, April, May, June, July and October, indicating spring, summer, middle

autumn and late winter.

TP has annual average concentration of 0.097 mg/L and standard deviation of 0.089 mg/L. The higher concentrations appeared in January, May, July, August, September and October, indicating late spring, summer, early autumn and early winter.

Note that the above descriptions do not represent the seasonal features of these NPS items by the limited observation period of one year.

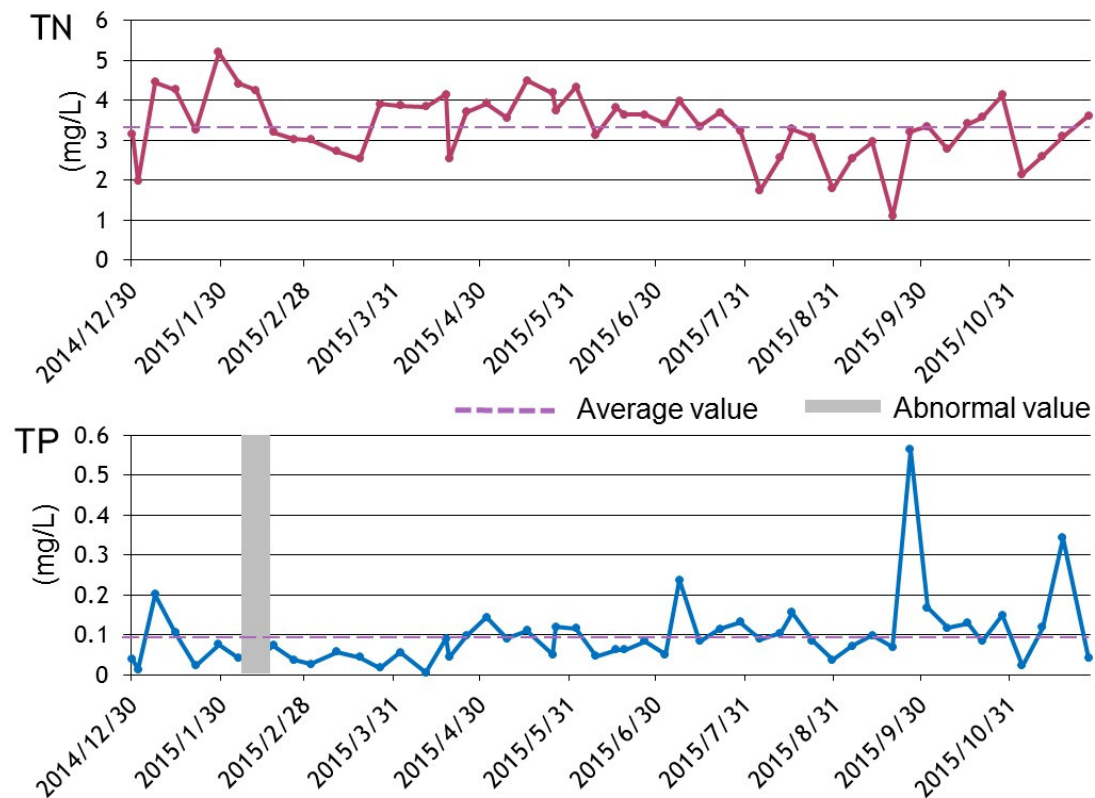


Figure 6.3: TN and TP concentration changes at Point A (near the outlet)

6.4 Source runoff concentration observations

Figure 6.4 represents the source runoff concentration changes within the selected year by weekly basis measurement (monthly basis for forest source runoff). The purple

marker line, yellow marker line and green markers represent source runoff concentrations of urban, agricultural land and forest respectively.

It is obvious that three land-use types have their own source runoff concentration level, indicating different degrees of NPS contributions. For TN, urban area has the highest level of source runoff concentration with average concentration of 4.81 mg/L. In contrast, agricultural area has the average concentration of 3.08 mg/L and forest has the average concentration of 2.51 mg/L. For TP, the average source runoff concentrations of urban, agriculture and forest are 0.207 mg/L, 0.056 mg/L and 0.083 mg/L.

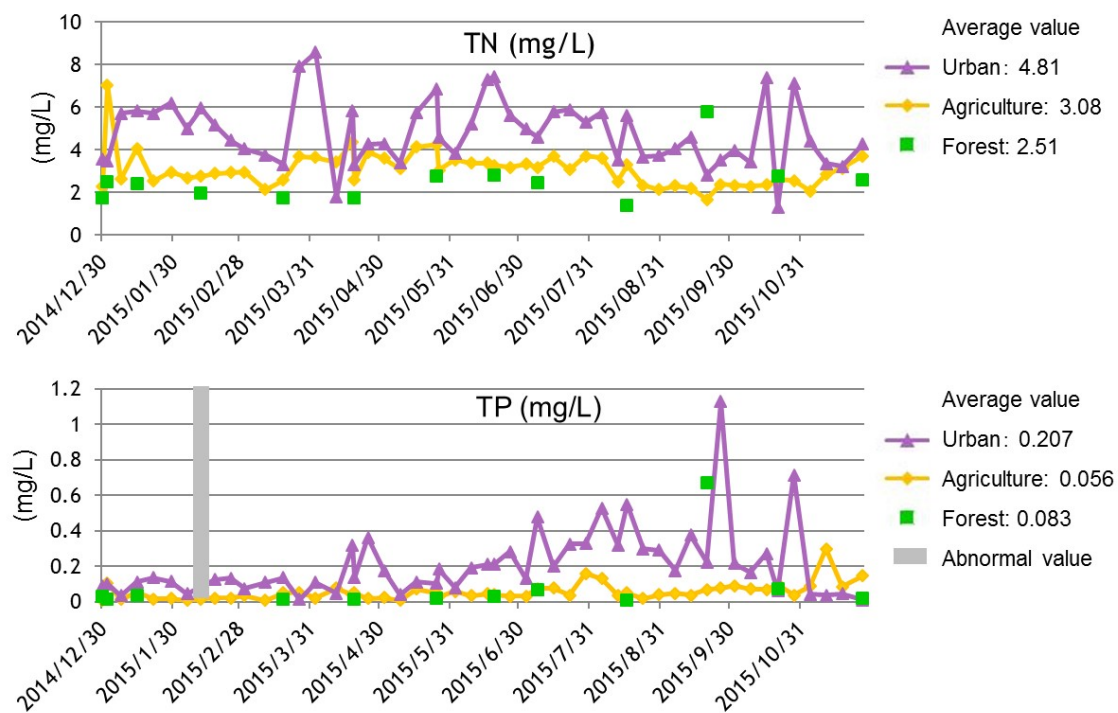


Figure 6.4: Source runoff concentration observations

Generally, that runoff generated from urban area has the highest NPS concentration is considered as the severe and concentrated effects by domestic sewage and waste. Agricultural land is expected to have higher NPS concentration than forest because of the pesticides and chemical fertilizers uses. This speculation was proved by the TN observations but not represented by the TP observations. The main reason to cause forest has higher concentration of TP than agricultural land is the high value measured

on 2015/9/20 for forest. Without this date, the average TP concentration of forest becomes 0.030 mg/L which is lower than the agriculture average (0.056 mg/L). However, it is not easy to confirm whether this date just comes from an occasional event or represents the seasonal trend realistically. In this study, we kept this date effective and require future confirmation after longer observation period and accumulation of data.

Another finding is the different fluctuation of each source runoff concentration. Source runoff concentrations of urban have the largest degree of dispersion, on the other hand, the fluctuations of agriculture and forest source runoff concentrations perform more smooth. The urban source runoff concentration was measured in a ditch near residential houses, the human activities are considered more complex than the other two land-uses and it was well reflected in our measurement. For TN, standard deviations of urban, agriculture and forest are 1.53 mg/L, 0.85 mg/L and 1.10 mg/L. For TP, standard deviations of urban, agriculture and forest are 0.197 mg/L, 0.049 mg/L and 0.186 mg/L. Obviously, urban areas have the largest standard deviations for both TN and TP, indicating a larger amount of variation to the mean.

The source runoff concentration changes also reveal seasonal characteristics. For TN, the higher source runoff concentrations of urban appear in late spring, summer, middle autumn and winter which is similar with the stream observations. The higher source runoff concentrations of agricultural land concentrate in spring and summer which is considered as the farming season with pesticides and chemical fertilizers use intensively. The higher source runoff concentrations of forest appear in summer and winter. For TP, the higher source runoff concentrations of urban concentrate in summer and autumn. The changes of source runoff concentrations of agricultural land and forest (except the high value in 2015/9/20) appear smooth when comparing with the urban area.

In summary, the high concentrations of NPS nutrients mainly concentrate in spring and summer (autumn and winter for some cases) for both stream and source runoff samples. The cause of increase of NPS release is preliminarily considered as the effects of intensive human activities, farming season and temperature effects.

6.5 Stream NPS nutrient concentration simulation

Based on the flow discharge contribution rates (estimated by the RRI model and T-SAS) and source runoff concentrations of each land-use (field measured), the stream NPS nutrient concentrations were calculated (refer Section 5.3).

For a reasonable estimation, we separated the source runoff concentrations measured in 52 times into two types (runoff and baseflow) based on the daily precipitation in the measured day and treat them separately. We assumed that the days with daily precipitation more than 10 mm are runoff days and the others are baseflow days. The source runoff concentrations measured in runoff days (or up to no more than one day after that runoff day) respond to rainfall events calculation and the source runoff concentrations measured in baseflow days respond to baseflow calculation respectively. Moreover, we classified the source runoff concentrations of runoff days according to the precipitation intensities and thus we have totally four classes of source runoff concentrations:

Class 1: daily precipitation $< 10\text{mm}$, source runoff concentration for baseflow

Class 2: $10\text{mm} \leq \text{daily precipitation} < 25 \text{ mm}$, source runoff concentration for moderate rain;

Class 3: $25 \text{ mm} \leq \text{daily precipitation} < 50 \text{ mm}$, source runoff concentration for heavy rain;

Class 4: $50 \text{ mm} \leq \text{daily precipitation}$, source runoff concentration for extreme heavy rain.

As a result, among the 52 observations, we have 39 observations of source runoff concentrations fall into Class 1, 9 observations fall into Class 2, 2 observations fall into Class 3 and 2 observations fall into Class 4.

As supplementary explanation, in our field investigation we have found that the NPS concentrations of upstream rivers have obvious increase in a raining day than a non-raining day (see Section 2.4.3). However, the NPS concentrations and precipitation did not reveal significant correlations based on the long-term observations.

The calculation process is simply described as below. For a selected day, we check its daily precipitation and determine which class it falls into. Then we search the nearest measured source runoff concentration beforehand which falls into the same class. Finally, this source runoff concentration is used for the calculation of equation (18).

After we repeated these procedures for the whole 365 days, time series of stream NPS nutrient concentrations of this selected year were calculated and plotted on Figure 6.5. The red dots represent the observations and the green lines represent the simulation results.

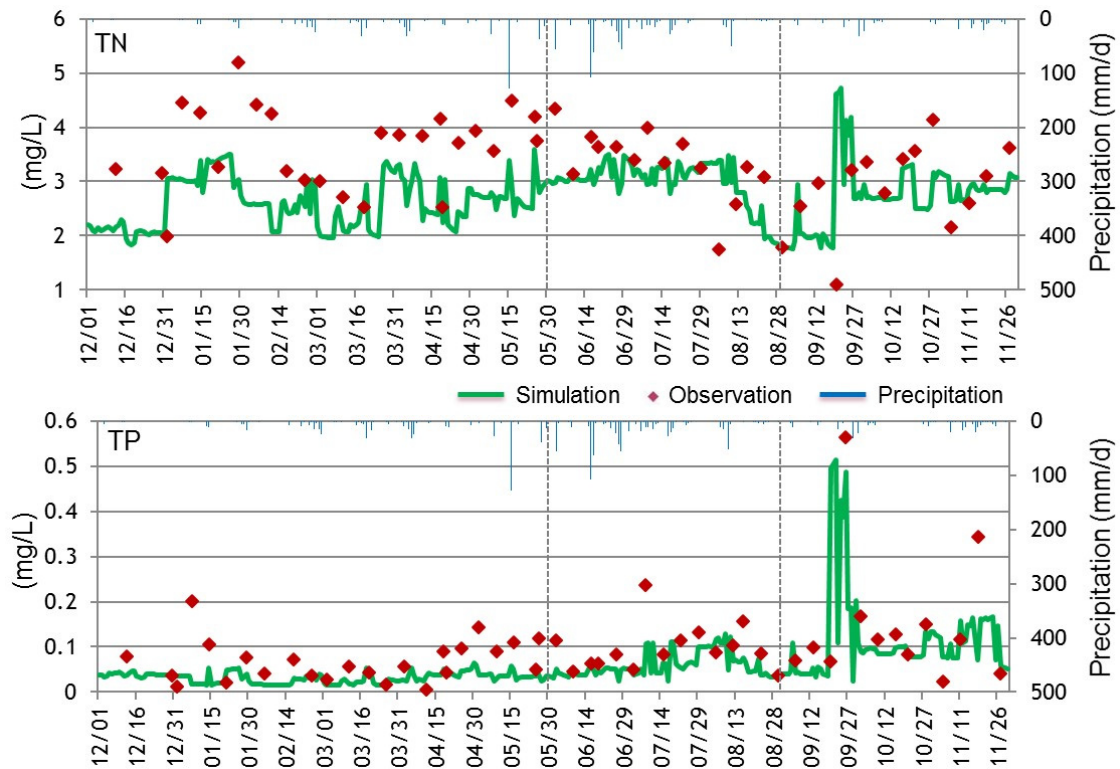


Figure 6.5: Stream NPS nutrient concentration simulation and validation

Our simulation results have acceptable agreement with the observations as the RMSE and Relative Error (RE) of TN is 1.06 mg/L and 28.7% and the RMSE and RE of TP is 0.087 mg/L and 68.1%. When focusing on summer duration (June, July and August, within the dashed grey lines), our simulation results become more satisfactory as the RMSE and RE of TN is 0.77 mg/L and 19.6% and the RMSE and RE of TP is 0.051 mg/L and 34.3%. This is because we applied the source runoff concentrations into the nearest days with corresponding precipitation intensity and this improved the accuracy of simulation results particularly for rainfall events. This consequently improved the accuracy of simulation results in precipitation concentrated summer. As about 50% of the NPS nutrients are estimated to be delivered in summer (see Section 6.6), simulation performance of summer has significant effect on the overall simulation results and reliability.

6.6 NPS nutrient load simulation

Using the time series of discharge and source runoff concentration of each land-use, time series of spatially separated NPS nutrient loads were simulated and the contribution rate of each land-use was summarized in Figure 6.6.

In this one-year simulation (2014/12/1 ~ 2015/11/30), 79,010 kg of TN and 1,670 kg of TP were delivered. It is obvious that the NPS nutrient export is closely related with the runoff process thus the NPS loads have similar changing patterns with precipitations. According to the Implementation Plan of Comprehensive Control of Water Environment in Taihu Basin of Jiangsu (2013), the annual export coefficients of TN and TP of the Taihu Basin in 2010 were 4,258 kg/km² and 247 kg/km². While the annual export coefficients of TN and TP of our study area (the Pingqiao River Basin) in 2015 were estimated to be 3,543 kg/km² and 75 kg/km². Simulation results indicated that the Pingqiao River Basin had lower export rates of TN and TP than the level of the Taihu Basin, however it is also necessary to attract high attention for water quality improvement.

For the urban area, it accounts for 5.3% of total area but contributed 15.3% of TN and 29.6% of TP loads, indicating that urban areas are important sources of NPS loads. As analysis in Section 5.4, the untreated domestic sewage and free dumped domestic waste were considered as important causes of concentrated NPS nutrient export. Another reason to cause high contribution rate of TP in urban area is speculated as the phosphorus-containing detergent use. According to the previous investigation, the contribution rate of detergent-phosphorus to the total phosphorus load was about 16.1% in the Taihu Basin³²⁾, 17.6% in the Yili River Basin of the Taihu Basin³¹⁾ and 13.6% in the Hefei region of Lake Chao³³⁾.

For the agricultural land, it accounts for 31.3% of total area and contributed 40.4% of TN and 33.8% of TP loads. On the other hand, forest accounts for 62% of total area and contributed 44.3% of TN and 36.6% of TP loads. Agricultural land has higher NPS contribution rates than forest and this attributes to the effects of pesticides and chemical fertilizers use.

The simulated NPS loads were validated with the observed NPS loads. The observed NPS loads were calculated by multiplying the observed stream NPS concentrations and the simulated discharges and plotted as red dots shown in Figure 6.6. The simulated NPS loads had satisfactory agreement with the observed loads for both TN and TP. Particularly in the precipitation and discharge concentrated summer (shown within the grey dashed lines), our simulation results well represented the observations. From December 2014 to February 2015 the simulated stream NPS nutrient concentrations had less satisfactory agreement with the observations, however, in this period the discharge was comparably lower, indicating less effects on the simulated NPS loads as Figure 6.6 shows.

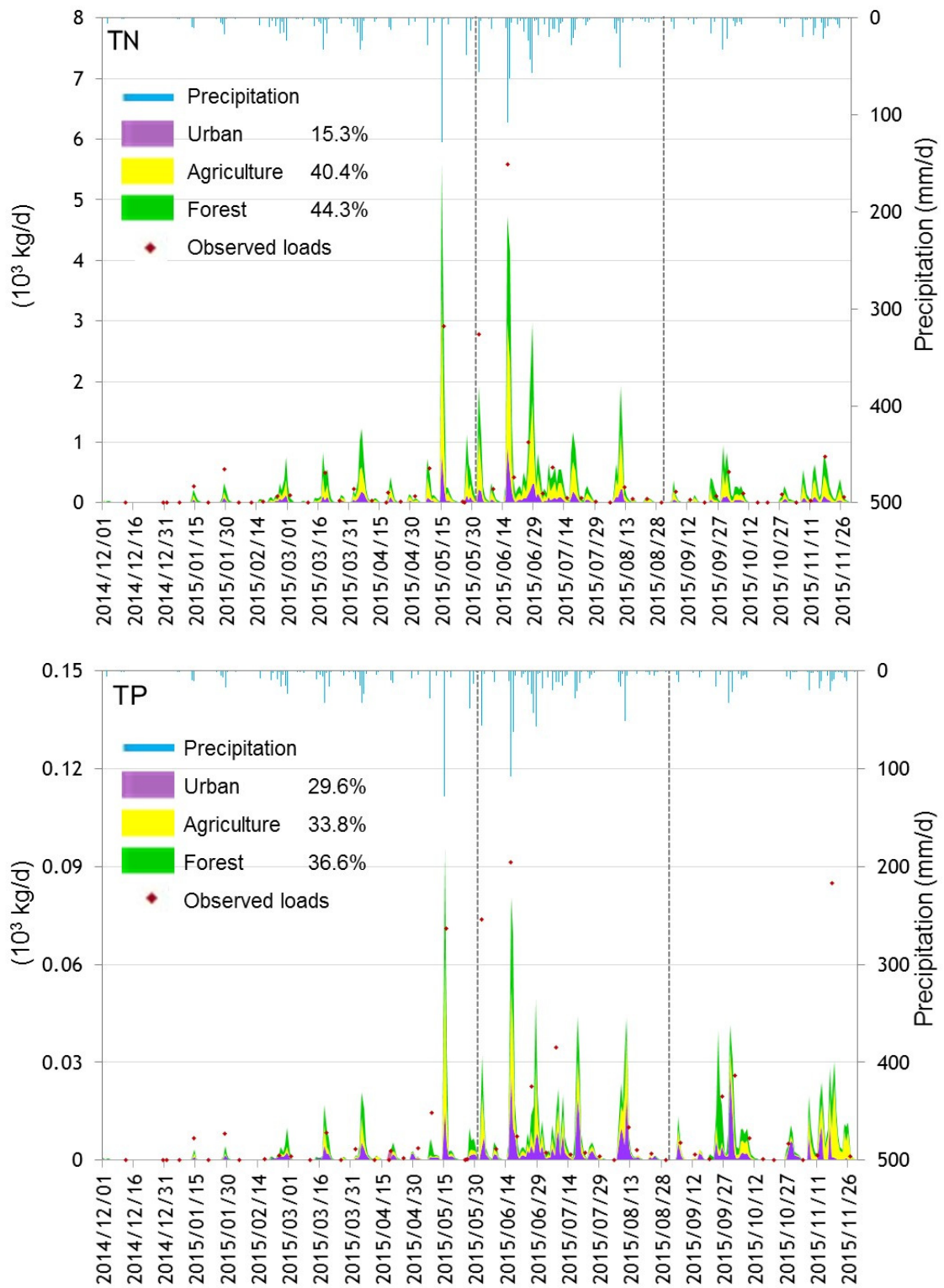


Figure 6.6: Long term simulation of NPS nutrient loads
(numbers in % indicates the proportion of NPS load contributed by each land-use to the total load)

Figure 6.7 summarized the NPS nutrient loads and the spatial and temporal contributions. Summer and spring contributed 50.6% and 27.3% of annual TN loads and summer and autumn contributed 45.2% and 33.8% of annual TP loads. Summer had the most NPS contributions and this directly attributes to the concentrated rainfall events in summer. The Taihu Basin has three distinct rainy seasons, they are spring rain in April and May, plum rain in June and July and the Typhoon rain in August and September²⁶. In this selected year, the seasonal runoff performs as summer (48.8%) > spring (28.1%) > autumn (18.2%) > winter (4.9%). Our simulation results show substantial agreement with this trend. Also, the concentrated farming activities in spring and summer lead to a large amount of chemical fertilizers use. The overused fertilizer particularly nitrogen fertilizer with high solubility are dissolved and discharged into water body, causing large TN export in spring and summer. Simulation results of TP in autumn were somehow affected by the observation of occasional high value in 2015/9/20 and we do not conclude the seasonal characteristic before more reliable data analyzed.

The observed NPS export amount was summarized as the red cross shows. The observed NPS amount was calculated by summarizing the observed NPS loads which is products of observed stream NPS nutrient concentrations and simulated discharges. The observed stream NPS nutrient concentrations were simplified to be constantly considered within the observation basis. Our simulation results showed 13.5% underestimation of observed total export amount of TN and 44.6% underestimation of observed total export amount of TP. The underestimation rates in summer were 12.5% for TN and 37.0% for TP, both of which showed relatively less than other seasons, indicating better simulation agreement in precipitation concentrated periods.

In addition, we selected 13 days with daily precipitation more than 25 mm and summarized the TN and TP contributions. These 13 days with heavy rainfall contributed 36.1% of TN and 26.7% of TP of the annual loads.



Figure 6.7: Summary of temporal and spatial contributions of NPS nutrients

6.7 Comparison between event study and long-term study

In the event study in Chapter 5, source runoff concentrations were statistically inversely estimated by multiple spatially different stream flow samples. This approach has no demand of source runoff concentration measurement but the inversely estimated values probably face statistical problems (i.e. out of reasonable range). As storm event has relatively short period, the source runoff concentration can be used as constant by neglecting the biochemical effects in stream traveling.

For long-term simulation, the changes of source runoff concentrations cannot be neglected. As a result, continuously and regularly measured source runoff concentrations become necessary to reflect the changes. More intensive observations

lead to higher accuracy of simulation results subsequently but cause more labor and cost. In this study, we used the measured source runoff concentrations on weekly basis to strike the balance.

To test the performance, we applied four cases with different conditions and summarized the NPS loads (total and spatially-separated) in Figure 6.8:

(a) with the estimated source runoff concentrations for the selected storm event (Figure 6.8(a));

(b) with the average measured source runoff concentrations in winter (2014/12/30 ~ 2015/2/24) for the above storm event (Figure 6.8(b));

(c) with the estimated source runoff concentrations from the above event and conducted a one-year simulation (2014/12/1 20:00 ~ 2015/11/30 20:00) (Figure 6.8(c));

(d) with the regularly measured source runoff concentrations and conducted a one-year simulation (2014/12/1 20:00 ~ 2015/11/30 20:00) (Figure 6.8(d)).

Generally, the total amount of NPS nutrients based on estimated source runoff concentrations (Figure 6.8(a) and Figure 6.8(b)) performs 20% ~ 69% overestimation than the results based on measured ones (Figure 6.8(c) and Figure 6.8(d)). This is because of the overestimation of source runoff concentrations of TN of urban and agricultural land, NO_3^- -N of agricultural land and NH_4^+ -N of urban as Section 5.4 discussed.

For the left side (Figure 6.8(a) and Figure 6.8(c)), results of event and long-term have similar distribution pattern because we used the same estimated source runoff concentrations for both. When comparing Figure 6.8(c) with the long-term results based on measured source runoff concentrations (Figure 6.8(d)), distribution pattern become different because the estimated source runoff concentration was used as non-varied for one-year simulation in Figure 6.8(c) and this is different with the real observations.

Theoretically, the least requirement for simulation is one set of source runoff concentrations (estimated or measured). It can be applied for both event simulation and long-term simulation. However, when considering the long-term change of source runoff concentrations, more sets of data lead higher accuracy and reliability of results. This also makes research more flexible to combine the local conditions.

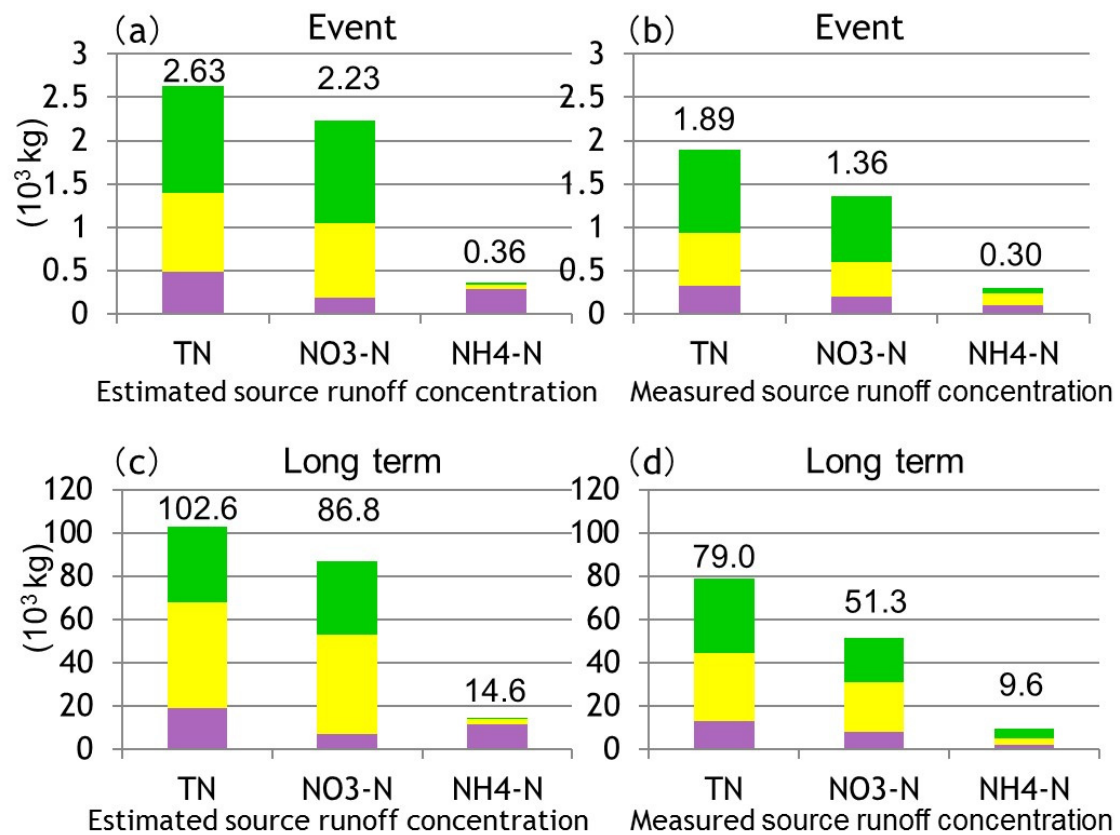


Figure 6.8: Summaries of NPS nutrient amount of (a) event simulation by estimated source runoff concentrations; (b) event simulation by average measured source runoff concentrations; (c) one-year simulation by estimated source runoff concentrations; (d) one-year simulation by measured source runoff concentrations.

6.8 Model features and limitations

6.8.1 Main features

1) Our model outputs time series of spatially separated NPS nutrient loads and it is useful for targeted quantitative analysis.

2) The calculation basis (e.g. source runoff concentration) is based on field measurement or inversely estimated using corresponding numbers of stream water samples.

3) The hydrological model used is fully physically-based while the water quality sub-model is more empirical based thus it has simpler calculation process and lower demand of data.

6.8.2 Advantages and limitations

1) This method has acceptable reliability because the hydrological model used is fully physically-based and the calculation basis is field measurement based.

2) This model is expected to be applicable for most watersheds in China as the geography information of China is somehow enriched (applicable for hydrological model) but water quality data are limited (applicable for empirical based water quality sub-model).

3) As the model feature described, the simulation results of NPS loads are temporally continuous and spatially separated. It is useful for targeted and detailed analysis.

4) The validation of hydrograph separation results has not been conducted and this requires future concerns.

5) For inverse estimation of source runoff concentration, special requirements (e.g. corresponding numbers, spatially or temporally different, at the beginning of runoff generation) of stream samples are needed. This may limit its application when these

requirements are not met.

6.9 Targeted countermeasure proposal and discussions

1) Excessive use of pesticides and chemical fertilizers, 2) Primitive livestock and poultry cultivation, 3) Untreated domestic sewage and waste, 4) Increased tourism development, 5) Surface erosion and nutrients delivered with sediments; are reported to be the main NPS sources in this area. This section is to conduct targeted analysis and discussion of improvement countermeasures by combining our simulation results and local conditions.

1) Excessive use of pesticides and chemical fertilizers

The previous study showed that the recommended nitrogen fertilizer amount for paddy field of the Taihu Basin was 225 ~ 285 kg/ha, the recommended phosphate fertilizer amount for paddy field was 30 ~ 60 kg/ha¹⁵⁾. Nitrogen fertilizer amount with more than 360 kg/ha is considered as excessive use. Referring the adjacent basin (the Zhongtian River Basin), more than 70% of farmers have exceeded this standard (360 kgN/ha) and 24% of them have used more than 1000 kgN/ha. For the overall agriculture, the chemical fertilizer use of the Zhongtian River Basin was 410 kgN/ha and the recommended amount was 280 kgN/ha¹⁵⁾. It is estimated that at least 40% of nitrogen fertilizers were exceeded. If countermeasure of reducing about 30% of current nitrogen fertilizer use achieved, 9,576 kg of TN loads are estimated to be reduced in this selected year.

Besides the reduction of fertilizer use, to intercept and absorb the lost nutrients is another effective countermeasure. In the past attempts, to build ecological ridges (isolation belts) and constructed wetland, and restore the natural river bank are proved to be effective for water quality purification³⁴⁾.

Among the agricultural lands, different crops have corresponding NPS contribution rates. For example, tea plantation is said to have large NPS contribution as it is usually planted on the hill slopes (causing more sediments than plains) and has large amount of fertilizer use (489.6 kgN/ha)¹⁵⁾. In this study, we measured the agricultural source runoff concentration without considering different crops separately. At the present stage, the investigations and researches on NPS contributions by different crops particularly tea plantation of this area is under processing. By combining these results, our study is expected to be more refined in future.

2) Primitive livestock and poultry cultivation

Livestock and poultry cultivation is another important NPS source when the feces untreated. Liu et al. (2010) summarized that the livestock and poultry cultivation contributed the most (34% of TN and 58% of TP) among the total NPS in the Taihu Basin²⁸⁾. Certainly, this result contains the large scale livestock and poultry cultivation which rarely exists in our study area, however, contribution of small and middle-scale cultivations cannot be neglected.

As the livestock and poultry cultivation in this area is common and decentralized, this causes difficulties for effective control and management. The basic principle of countermeasure is to divide areas and implement corresponding appropriate management. Cultivation in areas near streams and rivers are strictly limited and controlled, the other areas are managed with loose policy. To strengthen education and reward system to encourage autonomy of residents is also considerably necessary. From the technical perspective, composting and construction of biogas digesters can have efficient reuse of feces and transform it into benefit. The above techniques are also applicable for human excrement in rural areas (residents in agricultural land and forest).

In this study, livestock and poultry cultivation effect has not been separately simulated. In future, with more detailed land-use data and investigation information, livestock and poultry cultivation is possible to be contained, making our results more targeted.

3) Untreated domestic sewage and waste

As simulation results showed, urban area has the largest NPS contribution rate than the other land-uses for both event study and long-term study. This attributes to the untreated domestic sewage, free dumped domestic waste and phosphorus-containing detergent use as discussed in Section 6.6.

Correspondingly, improvement of the drainage system and sewage treatment is of the first importance with considering the future population growth. Free dumped domestic waste and phosphorus-containing detergent use should be forbidden particularly in areas near streams and rivers. To conduct the mandatory management and education simultaneously is recommended.

4) Increased tourism development

The minus effects caused by increased tourism development are similar with urban areas. Countermeasures should be focused on sewage and domestic waste treatment and management as well.

5) Surface erosion and nutrients delivered with sediments

Farming on slopes and deforestation cause surface erosion and nutrients delivered with sediments. Our simulation shows that forest has certain contributions of NPS nutrients (44.3% of TN and 36.6% of TP). The tea plantation, arable land and bare land with slope more than 15° are suggested to be afforested. The afforestation can be mixed planting of protection forest and economic forest to minimize the loss of farmers. Based on our investigation, we have found some sand factories exposed their sand materials without shelters. For these sand factories, materials should be covered and protected to reduce the discharged sediments during runoff process.

Chapter 7 Conclusions

A hydrograph-separation-based NPS model was proposed and applied at the Pingqiao River Basin in China. This model uses flow discharge contribution rates and source runoff concentrations of NPS nutrients from different spatial zones (land-uses) to simulate the NPS concentrations and loads in stream flow. The method has the following features:

- 1) It outputs time series of spatially separated NPS nutrient loads and it is useful for targeted quantitative analysis.
- 2) The source runoff concentration can be field measured or inversely estimated using corresponding numbers of stream water samples.
- 3) The hydrological model used is fully physically-based while the water quality sub-model is more empirical based thus it has simpler calculation process and lower demand of data.

Based on our field investigation, the observed data revealed that some water quality items e.g. TN, TP, COD of Lake Tianmu (downstream of the Pingqiao River) did not satisfy the local drinking water source standards. The upstream rivers had certain NPS contributions and the nutrient export was closely related to the runoff process.

Simulations for an event study (72 hours) and a long-term study (one year) were conducted. In the event study, source runoff concentrations were inversely estimated and the long-term study used the continuously and regularly measured ones.

In the storm event simulation (70 mm precipitation in 72 hours), the inversely estimated source runoff concentrations showed satisfactory agreement with the field

measurement in the near period. The analysis suggested that this area (22.3 km²) exported about 2,630 kg of TN, in which the urban area (5.3% of total area) contributed 18.5% of TN and 80.1% of NH₄⁺-N. This result is consistent with local situation reasonably based on our field investigation of pollution sources.

In the long-term study (2014/12/1 ~ 2015/11/30), simulation results of stream nutrient concentrations showed satisfactory agreement with the observations. Particularly in the precipitation concentrated summer, the RMSE and RE of TN were 0.77 mg/L and 19.6% and the RMSE and RE of TP were 0.051 mg/L and 34.3%. Results suggest that 79,010 kg of TN and 1,670 kg of TP were delivered in this selected year. 50.6% and 27.3% of TN were contributed in summer and spring, and 45.2% and 33.8% of TP were contributed in summer and autumn. These results well reflected the effects of runoff and farming activities on the seasonal nutrient load characteristics.

By comparing the two studies, the TN loads based on estimated source runoff concentrations showed about 30% overestimation than the results based on measured source runoff concentrations.

For the proposed targeted countermeasures, we gave the first priority on the drainage system and sewage treatment improvement because the urban area has the highest contribution rates of TN and TP according to both event and long-term simulations. Urban area accounts for 5.3% of total area but contributed 15.3% of TN and 29.6% of TP loads in the selected year. For the agricultural area, 30% reduction of current nitrogen chemical fertilizer use was estimated to reduce 9,576 kg of TN export in this year. Our simulation results showed the forest area suffering severe deforestation and soil erosion contributed 44.3% of TN and 36.6% of TP loads, therefore, afforestation on steep slopes are considerably necessary and urgent.

Among various sources of uncertainty, the current study lacks the detailed validation of hydrograph separation results, the timely water sampling data for the inverse source runoff concentration estimations and more detailed land-use classifications. Further study is recommended with more investigation and detailed field data.

In the testing application of hydrograph separation in terms of source components (surface flow, subsurface flow and groundwater flow) in the Kiryu Experimental Watershed, simulation results showed considerable contributions of bedrock groundwater (27% ~ 60%) to rainfall-runoff generation processes and increased groundwater contributions when upscaling basin scale. The consistence of groundwater contributions and dynamics with previous results by EMMA approach indicated the acceptable reliability of our model and applicability of T-SAS. As we concluded that the reflection of real 3D groundwater level (surface) was the key factor to determine the reliability of simulation results, our model well reflected the groundwater level and dynamics for some basins (zero-order and second-order) as results showed, however, simulation results of the first-order sub-basin indicated gap from real situation and pointed out future improvement directions.

References

- 1) Qu, J. H. and Fan, M. H. : The current state of water quality and technology development for water pollution control in China, *Critical Reviews in Environmental Science and Technology*, Vol. 40, No. 6, pp. 519-560, 2010.
- 2) Qin, B. Q., Xu, P. Z., Wu, Q. L., Luo, L. C. and Zhang, Y. L. : Environmental issues of Lake Taihu, China, *Hydrobiologia*, Vol. 581, No. 1, pp. 3-14, 2007.
- 3) Ministry of Environmental Protection of the People's Republic of China : China Environmental Status Bulletin 2014, in Chinese.
- 4) Ministry of Environmental Protection of the People's Republic of China : China Environmental Status Bulletin 2015, in Chinese.
- 5) Qin, B. Q., Zhu, G. W., Gao, G., Zhang, Y. L., Li, Wei., Paerl, H. W. and Carmichael, W. W. : A drinking water crisis in Lake Taihu, China: linkage to climatic variability and lake management, *Environmental Management*, Vol. 45, No. 1, pp. 105-122, 2010.
- 6) The State Council of the People's Republic of China : The Twelfth Five-year Plan for national economic and social development of the People's Republic of China, 2011, in Chinese.
- 7) Jiangsu Province of China : Implementation plan of comprehensive control of water environment in the Taihu Basin of Jiangsu, 2013, in Chinese.
- 8) Yang, S. J., Zhang, A. P., Yang, S. Q. and Yang, Z. L. : Status analysis of agriculture non-point source pollution and advances in domestic and overseas, *Chinese Journal of Agrometeorology*, Vol. 30, pp. 82-85, 2009, in Chinese, with English abstract.
- 9) Edwin, D. O., Zhang, X. L. and Yu, T. : Current status of agricultural and rural non-point source pollution assessment in China, *Environmental Pollution*, Vol. 158, No. 5, pp. 1159-1168, 2010.
- 10) Shen, Z. Y., Liao, Q., Hong, Q. and Gong, Y. W. : An overview of research on agricultural non-point source pollution modelling in China, *Separation and*

Purification Technology, Vol. 84, No. 9, pp. 104-111, 2012.

- 11) Chen, X. P. : Rainfall-agricultural runoff-pollutant model of the Three Gorges Reservoir, *China Environmental Science*, Vol. 12, No. 1, pp 48-52, 1992, in Chinese.
- 12) Johnes, P. J. : Evaluation and management of the impact of land-use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient approach, *Journal of Hydrology*, Vol. 183, No. 3-4, pp. 323-349, 1996.
- 13) Li, H. E. and Zhuang, Y. T. : The export coefficient modelling approach for load prediction of nutrient from non-point source and its application, *Journal of Xi'an University of Technology*, Vol. 19, No. 4, pp. 307-312, 2003, in Chinese, with English abstract.
- 14) Li, Y. : Study on hydrology and water quality process simulation based on HSPF model: a case study in Zhongtian River watershed, Master thesis of Nanjing Agriculture University, 2013, in Chinese, with English abstract.
- 15) Wu, M. W. : Simulation of agricultural non-point source pollution in Zhongtianhe Catchment based on AnnAGNPS model, Master thesis of Nanjing Agriculture University, 2012, in Chinese, with English abstract.
- 16) Sayama, T., Ozawa, G., Kawakami, T., Nabesaka, S. and Fukami, K. : Rainfall-Runoff-Inundation analysis of Pakistan Flood 2010 at the Kabul River Basin, *Hydrol. Sci. J.*, Vol. 57, No. 2, pp. 298-312, 2012.
- 17) Sayama, T. and McDonnell, J. J. : A new time-space accounting scheme to predict stream water residence time and hydrograph source components at the watershed scale, *Water Resource Research*, Vol. 45, W07401, 2009.
- 18) Huang, Q. F., Zhang, Y. L., Chen, W. M. and Dong, Y. W. : Hydrological characteristic changes of Lake Tianmu and its impact on ecological environment of upstream wetlands and lakes, *Wetland Science*, Vol. 5, No. 1, pp. 51-57, 2007, in Chinese.
- 19) Taihu Basin Authority of Ministry of Water Resources : Taihu Basin and southeast rivers water resources bulletin, 2014, in Chinese
- 20) Taihu Basin Authority of Ministry of Water Resources : Taihu Basin and southeast rivers water resources bulletin, 2013, in Chinese
- 21) Taihu Basin Authority of Ministry of Water Resources : The health status report of

- Taihu Lake, 2015, in Chinese
- 22) He, R. R. : Study on occurrence mechanism of eutrophication in Tianmu Lake, Master thesis of Nanjing Agriculture University, 2009, in Chinese, with English abstract.
 - 23) Li, H. E. : Mean concentration method for estimation of nonpoint source load and its application, *Acta Scientiae Circumstantiae*, Vol. 20, No. 4, pp. 397-400, 2000, in Chinese, with English abstract.
 - 24) World Meteorological Organization : Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation, Climate Data and Monitoring WCDMP-No. 72.
 - 25) Gao, Y. X., Zhu, G. W., He, R. R. and Wang, F. : Variation of water quality and trophic state of Lake Tianmu, *Environmental Science*, Vol. 30, No. 3, pp. 673-679, 2009, in Chinese, with English abstract.
 - 26) Li, Z. F. and Yang, G. S. : Research on non-point source pollution in Taihu Lake Region, *Journal of Lake Sciences*, Vol.16 Suppl., pp. 83-88, 2004, in Chinese, with English abstract.
 - 27) Wang, M. C., Liu, X. Q. and Zhang, J. H. : Evaluate method and classification standard on lake eutrophication, *Environmental Monitoring in China*, Vol. 18, No. 5, pp. 47-49, 2002, in Chinese, with English abstract.
 - 28) Liu, Z., Li, W. X., Zhang, Y. M., Zhang, L. J., Zhang, H. L., Li, Y., Cai, J. B., Zhuang, W. and He, F. : Estimation of non-point source pollution load in Taihu Lake Basin., *Journal of Ecology and Rural Environment*, Vol. 26, pp. 45-48, 2010, in Chinese, with English abstract.
 - 29) Chen, H. S. and Hua, Y. Q. : Non-point source pollution control and governance in Taihu Basin, *Water Resources Protection*, Vol. 1, 2004, in Chinese.
 - 30) Zhong, Chu. Lei. : Study on the correlation between eutrophication indexes of inland rivers and precipitation, *occupation and health*, Vol. 18, No. 2, pp. 107-108, 2002, in Chinese.
 - 31) Huang, W. Y., Shu, J. H. and Xu, P. Z. : The contribution of phosphorus in detergents from the catchment of Yili to Lake Tai, *Transactions of Oceanology and Limnology*, Vol. 4, pp. 20-25, 2000, in Chinese, with English abstract.
 - 32) Huang, W. Y., Shu, J. H. and Gao, X. Y. : Study on contribution of phosphorus in

- detergents to Lake Taihu, *Guizhou Environmental Protection Science and Technology*, Vol. 6, No. 3, pp. 29-32, 2000, in Chinese.
- 33) Jin, Q. H., Zhu, S. J., Huang, W. Y., Shu, J. H., Zhong, P. and Cheng, J. S. : Detergent-phosphorus' contribution in Hefei region of the Chao Lake, *Environmental Pollution and Control*, Vol. 23, No. 6, pp. 320-322, 2001, in Chinese, with English abstract.
- 34) Li, Z. F., Liu, H. Y. and Li, H. P. : Impact on nitrogen and phosphorous export of wetlands in Tianmu Lake Watershed, *Environmental Science*, Vol. 33, No. 11, pp. 3753-3759, 2012, in Chinese, with English abstract.
- 35) Sayama, T., Tatebe, Y., Fujioka, S., Ushiyama, T. and Tanaka, S. : Analysis on spatio-temporal sources of large-scale flooding, *Journal of Japan Society of Civil Engineers*, Ser. B1 (Hydraulic Engineering), Vol. 69, No. 4, pp. I_463-I_468, 2013, in Japanese, with English abstract.
- 36) Sayama, T., Kosugi, K. and Iwami, Y. : Development of a distributed Rainfall-runoff model simulation for mountainous groundwater, *Journal of Japan Society of Civil Engineers*, Ser. B1 (Hydraulic Engineering), Vol. 71, Issue 4, pp. I_331-I_336, 2015, in Japanese, with English abstract.
- 37) Iwasaki, K., Katsuyama, M. and Tani, M. : Contributions of bedrock groundwater to the upscaling of storm-runoff generation processes in weathered granitic head water catchments, *Hydrological Processes*, Vol. 29, No. 6, pp. 1535-1548, 2015.
- 38) Cash, J. R. and Karp, A. H. : A variable order Runge-Kutta method for initial value problems with rapidly varying right-hand sides, *ACM Trans. on Math. Software*, Vol. 16, No. 3, pp. 201-222, 1990.
- 39) Kosugi, K., Fujimoto, M., Katsura, S., Kato, H., Sando, Y. and Mizuyama, T. : Localized bedrock aquifer distribution explains discharge from a headwater catchment, *Water Resource Research.*, Vol. 47, No. 7, W07530, 2011.
- 40) Sayama, T., McDonnell, J.J., Dhakal, A. and Sullivan, K.: How much water can a watershed store?, *Hydrological Processes*, Vol. 25, No. 25, pp. 3899-3908, 2011.
- 41) Katsura, S., Kosugi, K., Mizutani, T., Okunaka, S. and Mizuyama, T. : Effects of bedrock groundwater on spatial and temporal variations in soil mantle groundwater in a steep granitic headwater catchment, *Water Resource Research.*, Vol, 44, No. 9, W09430, 2008.

- 42) Shaman, J., Stieglitz, M. and Burns, D. : Are big basins just the sum of small catchments?, *Hydrological Processes*, Vol. 18, No. 16, pp. 3195-3206, 2004.
- 43) Katsuyama, M., Tani, M. and Nishimoto, S. : Connection between streamwater mean residence time and bedrock groundwater recharge/discharge dynamics in weathered granite catchments, *Hydrological Processes*, Vol. 24, No. 16, pp. 2287-2299, 2010.
- 44) Katsuyama, M., Ohte, N. and Kabeya, N. : Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment, *Water Resources Research*, Vol. 41, No. 1, W01010, 2005.
- 45) Katsura, S., Kosugi, K., Yamamoto, N. and Mizuyama, T. : Saturated and unsaturated hydraulic conductivities and water retention characteristics of weathered granitic bedrock, *Vadose Zone Journal*, Vol. 5, No. 1, pp. 35-47, 2006.
- 46) Christophersen, N. and Hooper, R. P. : Multivariate analysis of streamwater chemical data: The use of principal components analysis for the endmember mixing problem, *Water Resources Research*, Vol. 28, No. 1, pp. 99-107, 1992.
- 47) Hooper, R. P. : Diagnostic tools for mixing models of streamflow chemistry, *Water Resources Research*, Vol. 39, No. 3, pp. 1055-1067, 2003.
- 48) Hooper, R. P., Christophersen, N. and Peters, N. E. : Modelling streamwater chemistry as a mixture of soilwater end-members - an application to the Panola Mountain catchment, Georgia, U.S.A, *J. Hydrol.*, Vol. 116, No. 1-4, pp. 321-343, 1990.
- 49) Christophersen, N., Neal, C., Hooper, R. P., Vogt, R. D. and Anderson, S. : Modelling streamwater chemistry as a mixture of soilwater end-members - a step towards second-generation acidification models, *J. Hydrol.*, Vol. 116, No. 1-4, pp. 307-320, 1990.
- 50) Takasao, T. and Shiiba, M. : Incorporation of the effect of concentration of flow into the kinematic wave equations and its applications to runoff system lumping. *Journal of Hydrology*, Vol. 102, pp. 301-322, 1988.
- 51) Sayama, T., Itokazu, T., Kosugi, K. and Takara, K. : Estimation of bedrock groundwater contribution from a mountainous catchment with a distributed rainfall-runoff model and time-space accounting scheme, *Proceedings of 7th International Conference on Water Resources and Environment Research*, CD-ROM, 2016.

52) Sayama, T. : Rainfall-Runoff-Inundation Model User's Manual ver. 1.4.2.