



# Seasonal characteristics of surface water quality in the wastewater catchment system of an urbanizing basin

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Received: 15 May 2017 / Revised: 3 April 2018 / Accepted: 5 April 2018 / Published online: 19 April 2018  
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## Abstract

Vientiane, Lao PDR, has been subject to extensive and ongoing urbanization plans, including development of natural marshes and residentialization of paddy fields into suburban areas, despite natural marshes playing a vital role in treating wastewater from urban areas. Therefore, it is important to understand the current situation regarding the nutrient balance in these natural wastewater treatment systems to predict future conditions and design appropriate measures against water quality deterioration. However, limited data are available in Vientiane on the hydrological characteristics of water and nutrient runoff that flow into marshes through drainage canals. In this study, we conducted a periodic survey of drainage canals and Mak Hiao River in the wastewater catchment system surrounding Vientiane during the rainy and dry seasons. We monitored the discharge of surface water at 21 observation sites and analyzed water quality of nitrogen, phosphorus, and total organic carbon. These observations revealed that the concentrations of dissolved nitrogen and phosphorus were significantly higher at sites in urban areas, followed by sites in the main river basin and those in agricultural areas. Dissolved nitrogen and phosphorus concentrations varied with runoff discharge, especially in urban and river basin sites, with lower concentrations in the rainy season and higher concentrations in the dry season. On the other hand, we found no significant differences between the rainy and dry seasons in nutrient concentrations in the agricultural basin. Finally, we proposed measures to counteract the deterioration of water quality during dry seasons and simulated the impact of these measures.

**Keywords** Surface water quality · Wastewater · Urbanization · Land use · Marsh · Vientiane

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## Introduction

Target 6.3 of the Sustainable Development Goals aims to improve water quality by reducing pollution, with the aim of halving the proportion of untreated wastewater (United Nations 2015). In addition, the UNESCO International Hydrological Programme (IHP) aims to increase urban wastewater collection and treatment management as a global sustainable development goal relating to water (UNESCO-IHP 2014), and has proposed the establishment of integrated urban water management strategies for drinking water supply, wastewater treatment, and urban drainage and flood control systems; this constitutes the theme of the eighth phase of the IHP (UNESCO-IHP 2015), which aims to adequately

address sustainability challenges in the face of rapid urbanization and population growth.

Developing countries in Southeast Asia have received large investments from various countries to promote residential development and industrial urbanization. As a consequence, aquatic environments in these areas are facing threats associated with rapid economic growth, since urban development initially tends to introduce water supply systems early in the development cycle, with wastewater treatment systems being provided much later. Urbanization often occurs on natural marshes, which have a vital role in treating wastewater from urban areas (e.g., Liu and Diamond 2005; Xian et al. 2007). Paddy fields are another target of urbanization into suburban areas, which could drastically change the runoff characteristics of both surface water and nutrient pollutants.

In this study, we studied a drainage basin in Vientiane, Lao PDR. Vientiane is the capital city and center of administrative, cultural, management and economic activities in Lao PDR. It also has a high concentration of private businesses in the finance, investment, sales promotion, and management sectors. As the epicenter of Laos' economy, and as an area showing continued economic and population growth, employment opportunities are concentrated in Vientiane (JICA et al. 2015). The GDP of Laos has increased rapidly, from 473 USD in 2005 to 1077 USD in 2010 and 1850 USD in 2015 (UNSD 2017). In addition, the population of Vientiane is estimated to grow dramatically from 761,000 in 2010 to 1,540,000 in 2025 (United Nations Population Division 2015). Laos has a tropical climate influenced by southeast monsoons, which generate significant rainfall and high humidity, and has two distinct seasons that determine the rainfall and runoff characteristics: a rainy season from May to October and dry season from November to April. Vientiane has mean rainy and dry season precipitation of 1498 and 151 mm, respectively, based on the data from 1961 to 1990 (UNSD 2017).

According to a rapid assessment conducted by the Water and Sanitation Program of the World Bank, more than 95% of households and buildings in the survey area have sanitary facilities consisting of a septic tank or soak pit. In addition, desludging of septage from these systems is often not conducted properly or in a timely manner. Moreover, these facilities receive only sewage and domestic wastewater is discharged without treatment, which is the major source of water contamination in drainage canals (WSP 2015). Discharged wastewater in Vientiane flows through drainage channels into marshes, finally merging with the Mekong River after a long retention period. One of these marshes is That Luang Marsh, which has an area of roughly 20 km<sup>2</sup> (Gerrard 2004). In other words, wastewater disposal relies completely on the natural purification function of the marshes, for example via trapping and settling sediment,

denitrification, and nutrient uptake by plants. Since the early 1990s, the drainage network in Vientiane has improved with the assistance of various donors. These drainage canals originate from irrigation and drainage canals in suburban paddy field areas. However, the water quality in drainage canals and marshes has deteriorated and the quantity of water has been increasing due to the increased discharge of domestic wastewater from urban areas as a result of improved living standards, as well as rapid economic and population growth (JICA 2013). The inadequate drainage system is considered to be one of the major environmental problems in Vientiane, along with the fact that most sewage and stormwater are discharged directly into rivers and marshes without treatment (Ichiki and Mixay 2009). Although a quantitative evaluation of the purification function of the marshes in Vientiane has not yet been conducted, some reports have raised concerns that rapid shrinkage of these marshes severely reduces their purification capacity, altering the natural ecosystem and causing numerous environmental problems in downstream areas (Inkamseng 2010; Southichak 2013).

Before determining appropriate countermeasures for water quality deterioration in natural wastewater disposal systems such as marshes, it is important to understand the present inputs and outflows of nutrients in the system, as well as the characteristics of the runoff and the pollutant load in the basin. Presently, there is insufficient information on surface water quality in Vientiane, which has the subject to ongoing large-scale urbanization plans and is also experiencing unprecedented population growth. The survey conducted by Ichiki and Mixay (2009), which focused on a small tributary channel of That Luang Marsh, revealed that chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) showed much higher values during the dry season, possibly due to domestic wastewater, and decreased in the rainy season due to stormwater. Ribolzi et al. (2011) conducted a field survey along a tributary of the Mekong River in northern Laos and confirmed the negative effect of storm flow events on sediment loading and water quality. A Technical Cooperation Project (TCP) of the Japan International Cooperation Agency (JICA) conducted in Laos involved a precise research survey of Vientiane in a 2009–2011 'master plan' study. The survey included periodic collection of surface water samples at several sites in urban drainage canals flowing into Mak Hiao River, a tributary of the Mekong River, and analyzed water quality indices (JICA et al. 2011). The TCP reported that the water flowing in the drainage canals was predominately domestic and commercial wastewater, with high ammonium nitrogen (NH<sub>4</sub><sup>+</sup>-N) concentrations that were considerably lower at the monitoring sites along Mak Hiao River; meanwhile, no variation in nitrite nitrogen concentrations among the monitoring sites was observed. However, in addition to

the results of the aforementioned surveys, continuous collection of hydrological data and further discussions of the relationship between pollutants in runoff water and various parameters (e.g., land use, population, season, etc.) are still needed.

In this study, we examined the seasonal characteristics of surface water quality in a wastewater catchment system that included urbanizing areas and marshes in Vientiane, Laos. We conducted periodic field surveys of flow discharge and collected surface water samples at various monitoring stations located in the drainage channels. In addition, we classified all monitoring stations based on the land use of the catchment area. Water quality (e.g., nitrogen, phosphorus, and organic carbon) was analyzed in a laboratory. From these data, we determined: (1) the relationship between precipitation and runoff, (2) the seasonal fluctuations in the analyzed water quality parameters, (3) variations in fluxes of pollutant load along the main stream of Mak Hiao River, and (4) the characteristics of the pollutant load in runoff water according to the land use of the catchment area. Based on a comparison of the measured results with environmental quality standards, we proposed measures to counteract the deterioration of water quality.

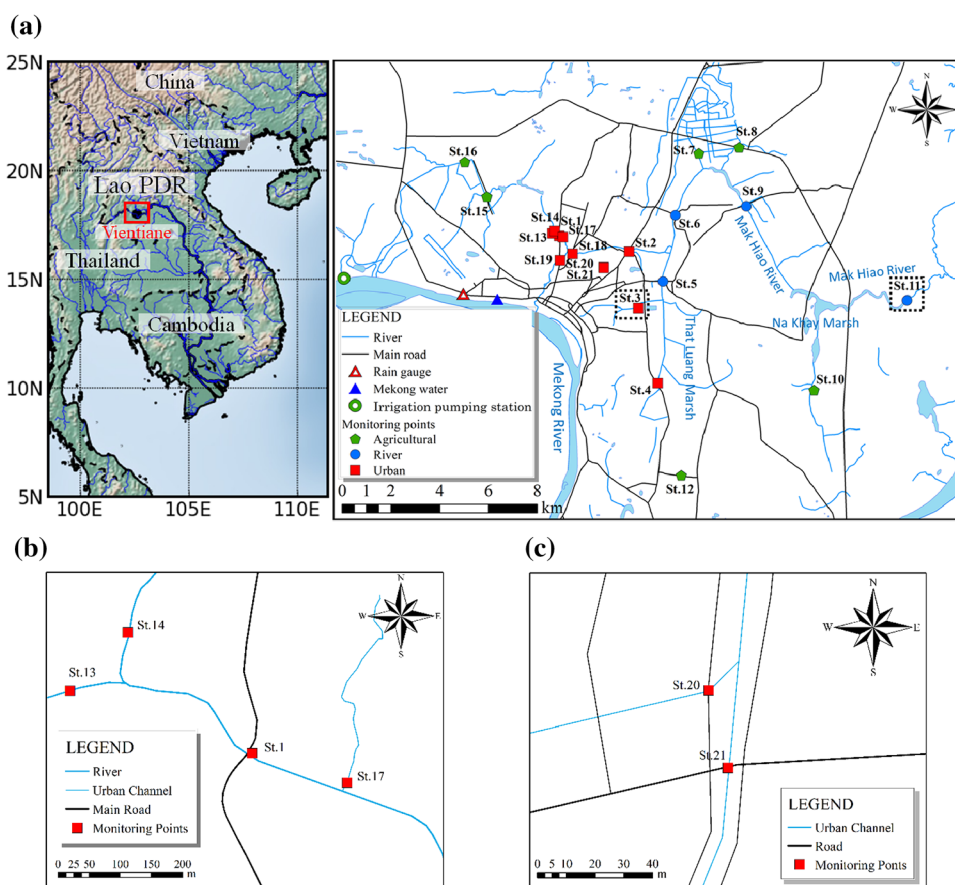
## Methods

### Study area

The study area is located in the upper watershed of Mak Hiao River (Fig. 1), which is one of the tributaries of the Mekong River and the outlet of the target basin (St.11) was located at a bridge in Nahai Village. Mak Hiao River receives water from That Luang Marsh, which gathers drainage water from Vientiane, flows eastward while gathering agricultural drainage water, and finally merges with the Mekong River. Mak Hiao River is about 65 km long and the upstream section has been developed and is partly covered with concrete in urban areas, while the downstream part remains in its natural state.

The drainage canals in Vientiane, including the Mak Hiao River, originally flowed southward and merged directly with the Mekong River. However, urban drainage projects aided by foreign countries, conducted since the 1960s, have closed off the outlets of the canals and built levees along the Mekong River to protect the urban area of Vientiane city from Mekong River floods (JICA 1990). Since then, the flow direction of the drainage canals has been reversed and discharged wastewater has taken a detour along the Mak

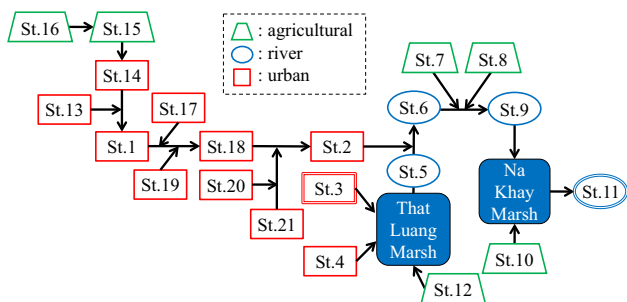
**Fig. 1** Locations of target area and monitoring stations (the monitoring points enclosed by dot lines indicate where the hourly water depth data were monitored continuously)



Hiao River to the Mekong River, due to the mild slope of the canals.

We placed 21 monitoring stations (St.1–21) in the study area (Fig. 1) and classified them based on the characteristics of the basin. Figure 2 shows a schematic diagram of the flow direction between the stations in the catchment system. Station locations were placed to cover the major inflow drainage channels into the main river. First, we defined the outlet (St.11) of the target area, which is located in the Mak Hiao River downstream of Na Khay Marsh, and identified the major inlets to That Luang Marsh (St.3, 4 and 12), Mak Hiao River (St.2, 7 and 8), and Na Khay Marsh (St.10). Three representative checkpoints along the Mak Hiao River were also selected as monitoring stations: the outlet of That Luang Marsh (St.5), the outlet from an urbanized area in Vientiane (St.6), and the inlet to Na Khay Marsh (St.9). While the drainage canals at St.2, 3 and 4 gather urban wastewater, the sub-basin of St.2 contains upstream and drained water from paddy fields that flows into the urban drainage system. Therefore, we set up two monitoring stations (St.15 and 16) at the outlet from the paddy area and three stations (St.14, 1 and 18) along the urban drainage canal. The major pumping station, which carries irrigation water from the Mekong River to paddy areas, is located on the west side of the study area, as illustrated in Fig. 1. Additionally, five monitoring stations (St.13, 17 and 19–21) were placed at representative inlets to the urban drainage canal. Consequently, there were four stations along the main stream of Mak Hiao River, six stations in agricultural drainage areas, and eleven stations in urban drainage areas. Hereafter, these station categories are referred to as “river,” “agricultural,” and “urban” stations, respectively.

Table 1 summarizes the characteristics of the monitoring stations. We defined the catchment area of each monitoring station using elevation and field survey data. We also obtained population data for every village in Vientiane from the results of the 2005 Population and Housing Census (Lao DECIDE Info Project 2016). Because precise data regarding



**Fig. 2** Schematic diagram of flow direction between monitoring stations in the study area (the monitoring points enclosed by double lines indicates where the hourly water depth data were monitored continuously)

village boundaries were not available, we assumed that the boundary line between any two adjacent villages follows a perpendicular bisector of the line connecting the center points of the two villages. The population of the catchment area was calculated as the sum of the population fraction in each village proportional to the area of that village included in the catchment area, assuming that the population distribution within each village is uniform.

From the beginning of the rainy season in 2015 to the end of the dry season in 2016, field surveys were conducted five times, on 8–10 July, 15–16 August, 9–11 October, and 12–14 December, 2015, and 8–11 February, 2016. We measured hourly precipitation in 0.5-mm increments during the survey using a tipping bucket-type rain gauge installed at the field observation site at the Vientiane Department of Meteorology and Hydrology. The location of the field observation site is indicated in Fig. 1.

## Discharge measurements

Flow discharge measurements at St.1–11 were conducted during the surveys conducted in August, October, and December 2015 and February 2016. For safety reasons, we adopted the float method to measure the stream flow discharge at St.1 and 3–11. The cross-sectional area was divided into several sections considering the surroundings, such as structures and topography. Width, water depth, and the average velocity of stream flow were measured at each section, and the partial discharge was calculated by multiplying these three parameters. The average velocity was given as the surface velocity multiplied by 0.85 (Gordon et al. 2004). Finally, the discharge of flow through the cross-section was calculated as the sum of the partial discharges. We calculated discharge assuming that the water depth at the measurement point was equal to the critical depth at St.2, where a free over-fall structure was installed. The critical depth was given as an average of the overflow depth measured at several points along the cross-section.

In addition, we monitored hourly water depth at St.3 and St.11, which we considered to be representative of the runoff characteristics from the urban area and whole catchment system, respectively. St.3 was located at one of the urban drainage outlets to That Luang Marsh, and its catchment basin was one of the most densely populated areas among the target stations. Meanwhile, St.11 was located at the final outlet of the study basin. We used water level loggers (HOBO U20; Onset Computer Co., Bourne, MA, USA) to collect the water depth data. The discharges of the two stations were calculated from the monitored water depth using stage-rating curves, which showed the relationship between water depth and flow discharge according to regression curves adjusted to field survey data. The stage-rating curves at St.3 and 11 were based on observed data of discharge

**Table 1** Characteristics of the catchment, topography of canal and data sampling terms for each monitoring station

Station number	Category*	Catchment area (km <sup>2</sup> )	Population density (persons km <sup>-2</sup> )	Topography**	Observation month			Max. cross-sectional area (m <sup>2</sup> )***
					Jul-2015	Aug-2015	Oct-2015	
1	Urban	57.53	992	Tr·Co	✓	✓	✓	18.6
2	Urban	70.11	1241	Re·Co	✓	✓	✓	4.2
3	Urban	9.30	3812	Tr·Co	✓	✓	✓	5.2
4	Urban	15.40	1943	Na·Ea	✓	✓	✓	1.6
5	River	56.89	1462	Na·Ea	✓	✓	✓	7.2
6	River	141.13	1361	Na·Ea	✓	✓	✓	17.3
7	Agricultural	18.78	1271	Na·Ea	✓	✓	✓	7.2
8	Agricultural	19.35	267	Na·Ea	✓	✓	✓	11.6
9	River	201.56	1242	Na·Ea	✓	✓	✓	26.8
10	Agricultural	15.57	141	Na·Ea	✓	✓	✓	1.7
11	River	260.92	1156	Na·Ea	✓	✓	✓	51.0
12	Agricultural	7.59	861	Na·Ea	✓	✓	✓	
13	Urban	7.33	2054	Tr·Co	✓	✓	✓	
14	Urban	50.08	836	Tr·Co	✓	✓	✓	
15	Agricultural	26.70	827	Na·Ea	✓	✓	✓	
16	Agricultural	20.45	841	Tr·Ea	✓	✓	✓	
17	Urban	5.64	2319	Na·Ea	✓	✓	✓	
18	Urban	64.82	1185	Tr·Co	✓	✓	✓	
19	Urban	1.65	4027	Tr·Co	✓	✓	✓	
20	Urban	0.73	3437	Re·Co	✓	✓	✓	
21	Urban	0.61	4204	Na·Ea	✓	✓	✓	

\*River, agricultural and urban indicate the stations located along the main stream of Mak Hiao River, at agricultural drainage stream and at urban drainage canal, respectively

\*\*Re, Tr and Na indicate the shape of canals which represent rectangular, trapezoidal and natural river shape, respectively. Ea and Co indicate the type of canals which represent earth canal and concrete-lined canal, respectively

\*\*\*Maximum values among the measured cross-sectional areas during the survey



and water depth that were assumed to follow a power function, with coefficients of determination of 0.878 and 0.992, respectively. The discharge data (unit:  $\text{m}^3/\text{s}$ ) were converted to runoff depth data (unit:  $\text{mm}/\text{h}$ ) by dividing each area of the catchment basin (unit:  $\text{km}^2$ ) and multiplying by 3.6. The data were collected on 8 July–12 December, 2015, at St.3 and 8 July–24 October, 2015, and 17 December, 2015, to 7 February, 2016, at St.11.

### Water quality measurements

Water samples were collected at the stations and analyzed for quality. Table 1 lists the quality parameters that we collected and analyzed. In addition, water was sampled from the Mekong River as a reference for nearby Vientiane, indicated in Fig. 1 as “Mekong water,” during each field survey, except that in July 2015. A bucket tied to a rope was used to draw water, with water being sampled directly from the canal where possible. The bucket was rinsed twice with the sample water before collection of water samples. At each station, we collected a 250-mL sample in polyethylene sampling bottles, ensuring that the bottles were completely filled with the sampled water to prevent oxidation of ammonium and other constituents. The samples were preserved by refrigeration as soon as possible after sampling and for as much time as possible during transportation to avoid alteration of water quality. All samples were filtered using glass fiber filters and analyzed for concentrations of TN, nitrate and nitrite nitrogen ( $\text{NO}_3^-/\text{NO}_2^--\text{N}$ ),  $\text{NH}_4^+-\text{N}$ , TP,  $\text{PO}_4^{3-}-\text{P}$ , and total organic carbon (TOC) in a laboratory at the University of Tokyo, Japan, as soon as possible after transport. The sampled water was frozen prior to being analyzed for quality, if analysis could not be completed within 2 weeks of sampling. TN,  $\text{NO}_3^-/\text{NO}_2^--\text{N}$ , and  $\text{NH}_4^+-\text{N}$  were measured to detect pollution from human excrement and fertilizer, while TP and  $\text{PO}_4^{3-}-\text{P}$  were included to study pollution from detergents and fertilizer. TOC was measured to estimate pollution from excrement and other domestic wastewater. The analyzed water quality parameters, adopted analytical methods, and equipment are listed in Table 2.

## Results and discussion

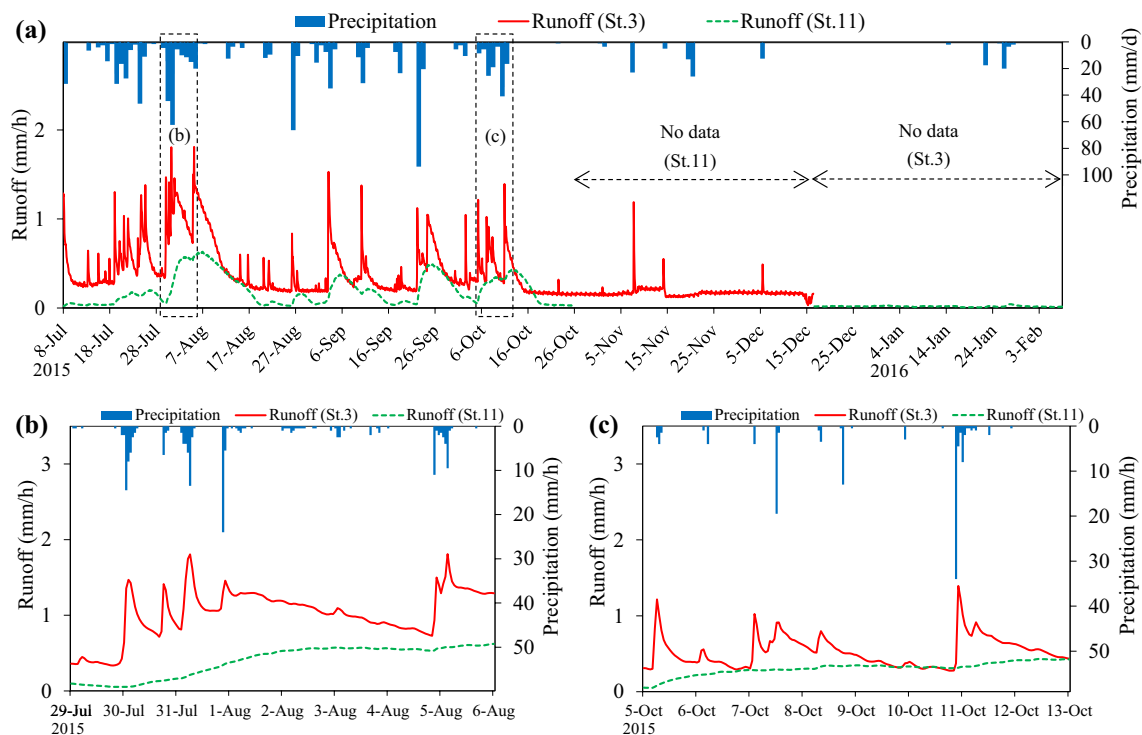
### Rainfall and runoff

The cumulative amount of rainfall from July 2015 to February 2016 was 1030 mm, nearly equivalent to the normal amount of 1001 mm during the same period in Vientiane (UNSD 2017). Figure 3 shows a hyetograph of the obtained precipitation data. Daily precipitation for the entire survey period is shown in Fig. 3a, while Fig. 3b, c shows the hourly precipitation for specific periods with several rainfall events. There were 19 rainfall events during the survey period. The hydrographs describing the runoff depth at St.3 and St.11 are also shown in Fig. 3. The decreasing curve of the hydrograph of St.11 exhibited lower and milder fluctuations, with a later runoff peak than that of St.3. These characteristics can be explained by the unique features of each watershed. For instance, since the catchment area of St.3 is located upstream of that of St.11 and has a steeper slope and much smaller area ( $9.30 \text{ km}^2$ ) than St.11 ( $260.92 \text{ km}^2$ ), the runoff at St.3 fluctuates more drastically than that of St.11. However, gradually decreasing curves were shown in the hydrograph from St.3 after some heavy rainfall events, e.g., on 1 August, 5 August and 4 September. This may be a result of the influence of backflow due to the mild slope of the topography, as described above. Therefore, the runoff depth at St.3 shown in Fig. 3 may be overestimated during such periods.

The total rainfall during the rainy season when we obtained the discharge data for St.3 and St.11 (8 July–24 October, 2015) was 870 mm and the cumulative runoff depths of St.3 and St.11 during the same period were 1150 and 530 mm, respectively. Thus, the runoff ratios of St.3 and St.11 during the observation period in the rainy season were 1.32 and 0.61, respectively. The total precipitation from 1 November to 12 December, when the discharge data of St.3 were collected in the dry season, was 80 mm, and the cumulative runoff depth of St.3 was 177 mm (runoff ratio: 2.21). In comparison, the total precipitation from 12 December, 2015, to 7 February, 2016, when the discharge data of St.11 were collected in the dry season, was 43 mm, and the

**Table 2** Analyzed water quality parameters and analytical methods

Parameters	Method	Japanese industrial standard	Equipment
TN	Continuous flow analysis	JIS K0170-3	STAT-2000, BL TEC K.K.
$\text{NO}_3^-/\text{NO}_2^--\text{N}$		JIS K0170-2	
$\text{NH}_4^+-\text{N}$	Indophenol blue absorptiometry	JIS K0102 42.2	V-630, JASCO
TP	Potassium peroxodisulfate decomposition method	JIS K0102 46.3.1	
$\text{PO}_4^{3-}-\text{P}$	Molybdenum blue absorptiometry	JIS K0102 46.1.1	
TOC	Continuous total carbon analysis	JIS K0805	TOC-L, SHIMADZU



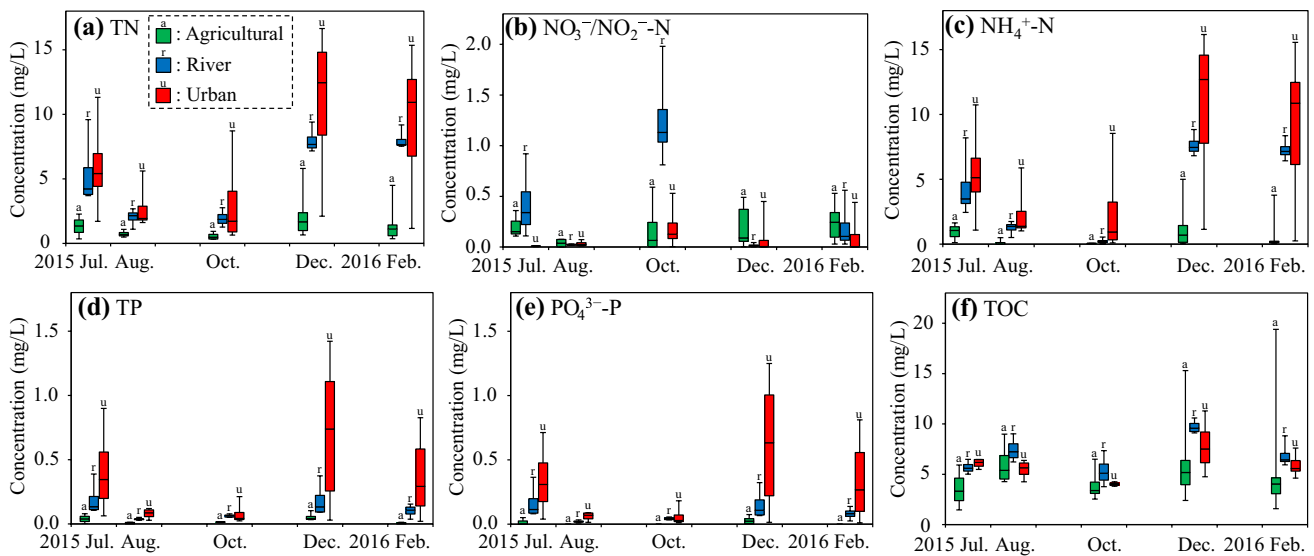
**Fig. 3** Hyetograph and hydrograph at St.3 and St.11

cumulative runoff depth of St.11 was 23 mm (runoff ratio: 0.53). The runoff ratio of St.11, located at the outlet of the entire study area, was moderate in both the rainy and the dry seasons because a proportion of rainfall gradually returns to the atmosphere via evapotranspiration or percolates deep underground. However, the calculated runoff ratio of St.3 was considerably higher. This was likely caused by error in the discharge measurement due to the influence of backwater on the monitoring site of St.3 or by influent from municipal water. In terms of supply water, the consumption amount assumed and planned for was around 180 L/day/capita, and most households take more water from their shallow wells (Noda et al. 2017). For reference, assuming that the daytime population of the basin of St.3 is double that of its residents of about 35,000, as a result of population concentration during the day (calculated from Table 1), and assuming they use and discharge double the amount of water consumption that was planned for, the outflow rate is comparable to the runoff depth of 2.7 mm/day, which compensates for a large proportion of the difference between the cumulative precipitation and runoff depth at St.3 in both rainy and dry seasons.

### Water quality parameters

Figure 4 summarizes the results of the surface water quality analysis as box plots for each water quality parameter, including the classification of monitoring station and survey

terms. Standard statistical parameters, such as range, mean and variance of TN, TP and TOC are summarized in Table 3. The urban stations had the highest TN concentrations, followed by the river and agricultural stations (Fig. 4a), while the TN concentrations of Mekong water showed values ranging from 0.42 to 0.66 mg/L. TN concentrations were higher in the dry season than in the rainy season. Larger discharge during the rainy season was associated with lower TN concentrations and this trend was especially strong at the urban and river stations. This implied that the pollutants in wastewater from urban areas were diluted by runoff water in the rainy season and that the TN concentrations in the agricultural drainage area did not vary greatly among the seasons. The trend toward low concentrations was confirmed by the  $\text{NO}_3^-/\text{NO}_2^-$ -N concentrations (Fig. 4b), as well as a report by the JICA TCP that nitrate nitrogen was below 1.0 mg/L at most monitoring points, with no spatial or temporal variations (JICA et al. 2011). However, a dramatic increase in  $\text{NO}_3^-/\text{NO}_2^-$ -N at river stations was observed in October 2015. Considering that no significant increase in the concentration of urban and agricultural stations was confirmed at that time, it might have been the result of sediment flushing from the riverbed, which is discussed in greater detail in the next section.  $\text{NH}_4^+$ -N accounted for a large proportion of TN (Fig. 4c), indicating that little  $\text{NH}_4^+$ -N from human excrement and fertilizer was oxidized while flowing in the drainage channel and river, either because



**Fig. 4** Box plots of the surface water quality analysis results for each classification of monitoring station and survey term (the lower and upper end of whisker represent the minimum and maximum. The bot-

tom, top, and middle line of the box represent the first, third quartiles, and median, respectively)

the flow period was short or because the water was under reduction conditions.

Figure 4d, e shows the TP and PO<sub>4</sub><sup>3-</sup>-P concentrations. Both TP and PO<sub>4</sub><sup>3-</sup>-P concentrations followed nearly the same trends as those of TN. The urban stations showed slightly higher values than the river and agricultural stations. In addition, PO<sub>4</sub><sup>3-</sup>-P accounted for most of the TP. Finally, TOC did not exhibit any particular characteristics or trends (Fig. 4f).

Statistical analysis of the observed concentrations of TN, TP and TOC was conducted to elucidate the characteristics noted above. The data obtained from the surveys in July, August and October 2015 were classified into rainy season and those from December 2015 and February 2016 were sorted into dry season. Since water quality data can be assumed not to follow a normal distribution, non-parametric tests were employed for statistical analysis. The Mann–Whitney *U* test was applied for testing whether a significant difference exists between the rainy and dry seasons. According to the results of the test (Table 3), significant differences between rainy and dry seasons are present in TN and TOC at river stations, and in all parameters at urban stations. However, interestingly, there is no significant difference between seasons in any parameter observed at agricultural stations, which might be explained by assuming that the concentrations of pollutants do not vary remarkably in agricultural areas. Multiple comparison tests were also used to determine whether there are significant differences among catchment types in the water quality parameters obtained in each season. The Kruskal–Wallis *H* test was applied for multiple comparisons because the results of Bartlett’s test

showed that the samples of three catchment categories in both seasons were from populations with unequal variance at the significance level of 5%. According to the results of the *H* test (Table 3), there were significant differences among catchment types for TN and TP in both seasons and for TOC in the dry season.

According to the national environmental standards (Water Resources and Environment Administration 2010) of the Laos government, the standard concentrations of nitrate nitrogen and ammonia nitrogen in surface water are 5.0 and 0.2 mg/L, respectively. Our results showed that the NH<sub>4</sub><sup>+</sup>-N in most samples greatly exceeded the standard, especially in urban and river stations. The Water Resources and Environment Administration (2010) also cites 35 mg/L as the standard concentration of total Kjeldahl nitrogen (i.e., total organic nitrogen and NH<sub>4</sub><sup>+</sup>-N) in wastewater discharge from the urban area; this standard was not exceeded in any water samples. National standards define 1.0 mg/L as the general industrial wastewater discharge standard for phosphorus concentrations. According to Fig. 4d, some of the water samples taken at urban stations exceeded this value in the dry season.

### Pollutant load flux along the river stream

Since the river monitoring stations St.5, 6, 9, and 11 were located in the main stream of Mak Hiao River, the characteristics of the dynamics and spatiotemporal distribution of nutrients can be understood by comparing pollutant load fluxes at each plot. Figure 5 shows the calculated results of load fluxes obtained by multiplying the measured discharge



**Table 3** Results of statistical analysis on concentration of TN, TP and TOC

	Rainy seasons						Dry seasons						
	Number of samples	Min.(mg/L)	Max. (mg/L)	Mean (mg/L)	Variance (mg <sup>2</sup> /L <sup>2</sup> )	H value <sup>†</sup>	Number of samples	Min. (mg/L)	Max. (mg/L)	Mean (mg/L)	Variance (mg <sup>2</sup> /L <sup>2</sup> )	H value <sup>†</sup>	U value <sup>††</sup>
TN	Agricultural	11	0.33	2.28	0.84	0.34	15.8**	12	0.36	5.81	1.86	21.6**	33
	River	12	1.10	9.60	3.14	5.28		8	7.17	9.41	8.00		8**
	Urban	12	0.64	11.3	3.97	11.3		22	1.15	16.7	10.2	24.5	
TP	Agricultural	11	0.00	8.1 × 10 <sup>-2</sup>	1.8 × 10 <sup>-2</sup>	5.5 × 10 <sup>-4</sup>	15.7**	12	0.00	1.0 × 10 <sup>-1</sup>	2.9 × 10 <sup>-2</sup>	1.0 × 10 <sup>-3</sup>	57
	River	12	2.9 × 10 <sup>-2</sup>	3.9 × 10 <sup>-1</sup>	9.7 × 10 <sup>-2</sup>	9.8 × 10 <sup>-3</sup>		8	3.7 × 10 <sup>-2</sup>	3.7 × 10 <sup>-1</sup>	1.4 × 10 <sup>-1</sup>	1.1 × 10 <sup>-2</sup>	27
	Urban	12	2.5 × 10 <sup>-2</sup>	9.0 × 10 <sup>-1</sup>	1.9 × 10 <sup>-1</sup>	6.5 × 10 <sup>-2</sup>		22	2.1 × 10 <sup>-2</sup>	1.4 × 10 <sup>0</sup>	5.3 × 10 <sup>-1</sup>	1.9 × 10 <sup>-1</sup>	71*
TOC	Agricultural	11	1.42	8.94	4.55	4.59	5.52	12	1.55	19.3	6.21	29.5	61
	River	12	3.77	9.01	6.15	2.07		8	5.93	10.6	8.31	3.16	16*
	Urban	12	3.81	6.47	5.19	1.12		22	4.63	11.3	6.75	3.29	65*

\**p* < 0.05, \*\**p* < 0.01

†Kruskal–Wallis *H* test was used for multiple comparison testing whether the samples of agricultural, river and urban stations originate from the same distribution

††Mann–Whitney *U* test was used for significance test between rainy and dry seasons

and concentration of water quality. The TN, TP, PO<sub>4</sub><sup>3-</sup>-P, and TOC results indicated a gradual increase towards the stream in the rainy season and a decrease downstream of St.6 in the dry season. The former was possibly caused by both pollutant inflow from tributaries and the flushing out of settled sediment by high runoff. In contrast, the latter was considered to be the result of the settlement of sediment or the purification effect during flow of the Mak Hiao River, since the calculated load fluxes decrease downstream, although total pollutant load fluxes must increase downstream due to mixing with discharged wastewater in the tributaries. Interestingly, the NH<sub>4</sub><sup>+</sup>-N load flux in October 2015 showed a decrease from St.6, as well as during the dry season, and the NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>-N load flux in October 2015 was significantly higher than that in the rainy season and increased with increasing distance downstream. This result may have been caused by deposition of eroded sediment onto the riverbed and oxidation of nitrogen compounds, considering that there was less rainfall around the survey period in August 2015 and that the survey in October 2015 was conducted immediately after a heavy rainfall event; in addition, the NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>-N concentrations at agricultural and urban stations exhibited lower values relative to river stations in October 2015 (Fig. 4b). Nitrogen oxidation may have been activated by the supply of fresh water containing high dissolved oxygen concentrations from rainwater. However, further investigations and evidence are needed to support this hypothesis.

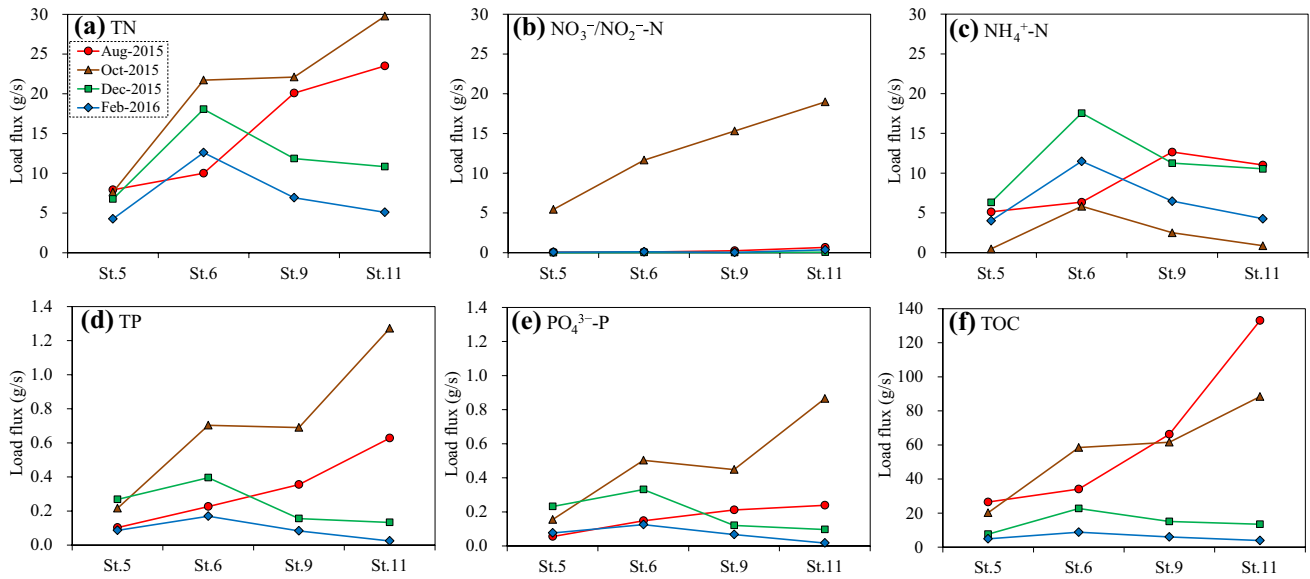
### Discharge and water quality

Figure 6a–c shows the results of the relationship between the measured discharge and TN, TP, and TOC concentrations. Table 4 shows the coefficient of regression curve and the coefficient of determination assuming the power math function as Eq. (1):

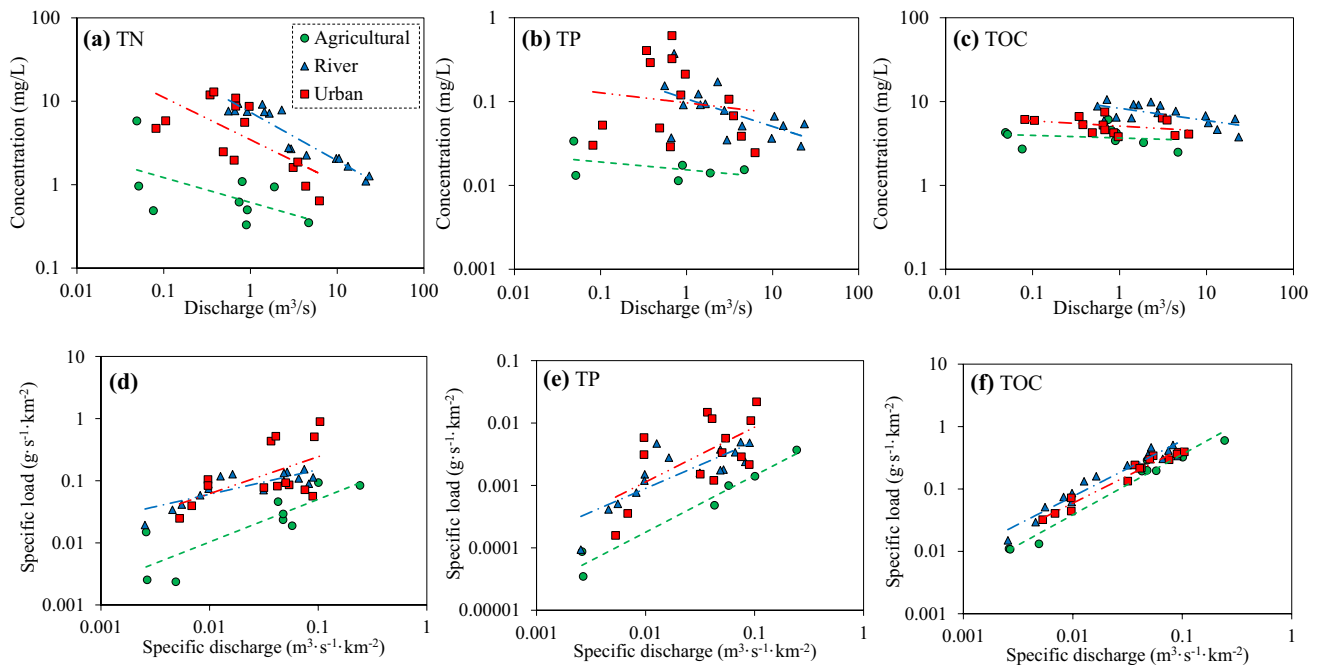
$$C = aQ^b \tag{1}$$

where *C* is concentration (mg/L), *Q* is discharge (m<sup>3</sup>/s), and *a* and *b* are constant coefficients. The coefficient *b* implies the degree of dilution of dissolved matter. If *b* = 0, the concentration is constant regardless of the discharge. The results for TN and TP were correlated negatively with discharge and the degree of correlation was stronger for TN than for TP. The gradient of the regression curve in the logarithmic graph of TN (Fig. 6a) was less than that of TP (Fig. 6b), as indicated by coefficient *b* (Table 4). The agricultural stations showed lower values than the river and urban stations for both TN and TP. However, TOC concentration showed less dependence on discharge and was relatively constant with respect to discharge.

A discussion of load per unit area would generally be helpful for elucidating the characteristics of pollutants in



**Fig. 5** Pollutant load fluxes at the monitoring stations along the main stream of Mak Hiao River



**Fig. 6** Discharge and concentration of TN (a), TP (b) and TOC (c), and specific discharge and specific load of TN (d), TP (e) and TOC (f)

r runoff water, regardless of the wide variation in catchment area among the stations. Figure 6d–f shows the relationship between the specific discharge and specific load of TN, TP, and TOC. The specific load, which represents the outflow rate of the pollutant load per unit area per unit time, was calculated by multiplying the discharge and concentration of water quality, and then dividing by the catchment area of each station. The specific discharge was calculated by

dividing discharge by the catchment area. Table 5 shows the coefficients of the regression curves and the coefficients of determination when assuming the power math function as in Eq. (2):

$$L = aq^b \quad (2)$$

where  $L$  is the specific load ( $\text{g s}^{-1} \text{km}^{-2}$ ) and  $q$  is the specific discharge ( $\text{m}^3 \text{s}^{-1} \text{km}^{-2}$ ). Here, the coefficient  $b$  represents

**Table 4** Coefficient of regression curves and coefficient of determination for relationship between discharge and concentration of TN, TP and TOC

Water quality parameter	Category	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>
TN	Agricultural	0.61	−0.30	0.32
	River	7.36	−0.58	0.87
	Urban	3.45	−0.51	0.45
TP	Agricultural	0.015	−0.09	0.21
	River	0.108	−0.33	0.36
	Urban	0.097	−0.12	0.02
TOC	Agricultural	3.68	−0.03	0.04
	River	8.32	−0.15	0.41
	Urban	5.11	−0.06	0.13

**Table 5** Coefficient of regression curves and coefficient of determination for relationship between specific discharge and specific load of TN, TP and TOC

Water quality parameter	Category	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>
TN	Agricultural	0.25	0.69	0.72
	River	0.38	0.40	0.65
	Urban	0.96	0.59	0.31
TP	Agricultural	0.012	0.91	0.96
	River	0.029	0.75	0.66
	Urban	0.066	0.88	0.41
TOC	Agricultural	3.37	0.97	0.97
	River	4.74	0.90	0.94
	Urban	3.39	0.88	0.96

the characteristics of load runoff from the basin. If  $b > 1$ , the load runoff from the basin is of washout type because the concentration of the component increases according to specific discharge. If  $b = 1$ , the concentration is constant regardless of the specific discharge. If  $b < 1$ , the concentration is decreasing according to specific discharge, representative of dilution, which can be determined by dividing Eq. (2) by  $q$  and deriving an expression of the  $C$ – $q$  relationship. As indicated by the results in Table 5, the pollutant runoff exhibited characteristics of dilution, in the order of TN, TP, and TOC, as well as the order of river, urban, and agricultural with regard to TN and TP runoff. Moreover, there were differences in the coefficients of determination between Tables 4 and 5, implying that the  $L$ – $q$  relationship has a stronger correlation than the  $C$ – $Q$  relationship. TOC showed less dependence on discharge and station category and, as a result, the values of the power number of regression curves  $b$  were close to 1.

The conclusions drawn from these results are as follows. The TN and TP loads per unit area from urban drainage were several times higher than those of agricultural drainage. TN

was diluted by runoff water, but TP and TOC were not sensitive to discharge volume, especially in the agricultural and urban catchment areas.

We estimated the outflow rate of pollutants using the results of the relationship between specific discharge and specific load. Figure 7 shows a hyetograph and variations in nutrient load flows at St.3 and St.11. The results were obtained by converting the time series discharge data into specific discharge, substituting them with Eq. (1) and then multiplying by the catchment area. There was a significantly larger runoff of pollutants in the rainy season than in the dry season. The cumulative outflows of TN, TP, and TOC during the data observation period of the rainy season (8 July–24 October, 2015) were 23, 0.9, and 46 t at St.3 and 270, 7.7, and 847 t at St.11, respectively.

### Countermeasure against water quality deterioration

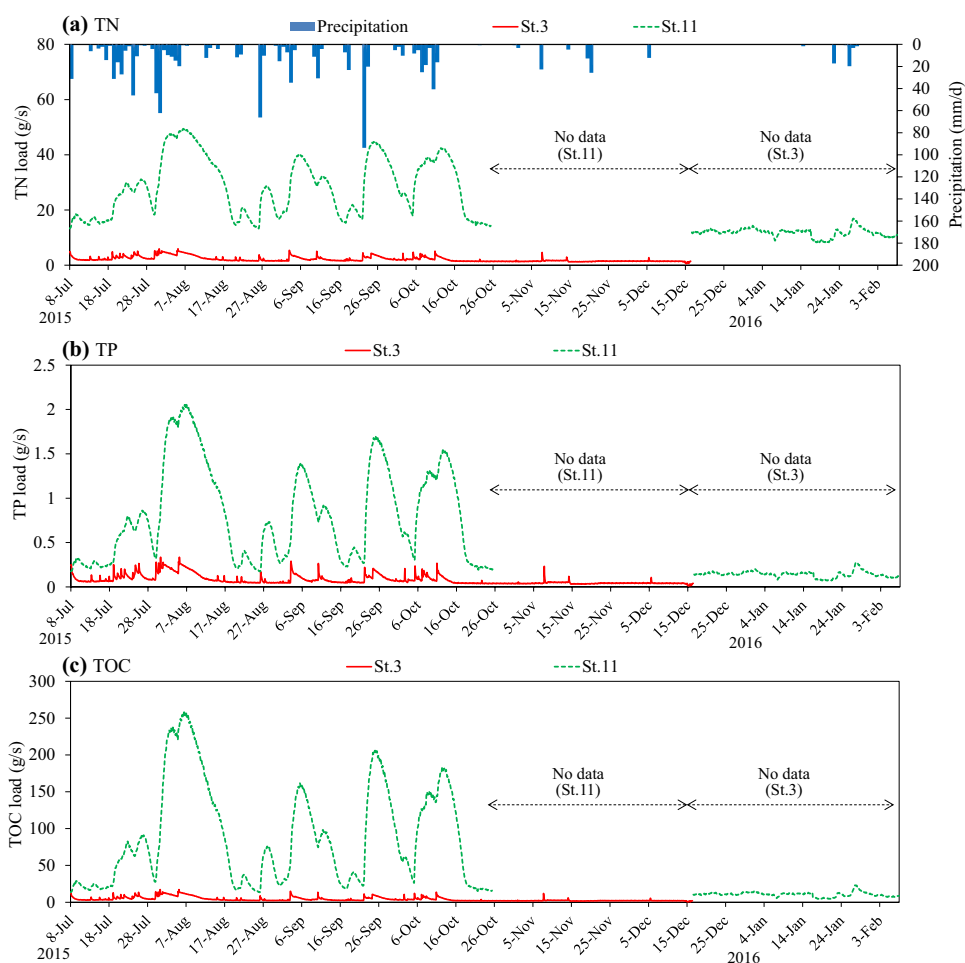
Considering the results above, one possible method of lowering the pollutant concentrations in the marsh in the dry season is to dilute the drainage water by adding a relatively minimal amount of polluted water. For example, water from the Mekong River can be pumped into the marsh through the drainage canal in the dry season as a practicable countermeasure against water quality deterioration. The measured TN concentration of the Mekong River water remains constant around 0.5 mg/L throughout all seasons. Therefore, we compared the simulated TN concentration at St.11 with and without pumping of 1 m<sup>3</sup>/s of Mekong River water, containing 0.5 mg/L TN, into the marsh in the dry season. In the case without pumping [case (a)], we adopted Eq. (3), the parameters of which we determined by reference to Table 4, to estimate the variations in TN concentration derived from the observed discharge data.

$$C = 7.36Q^{-0.58} \quad (3)$$

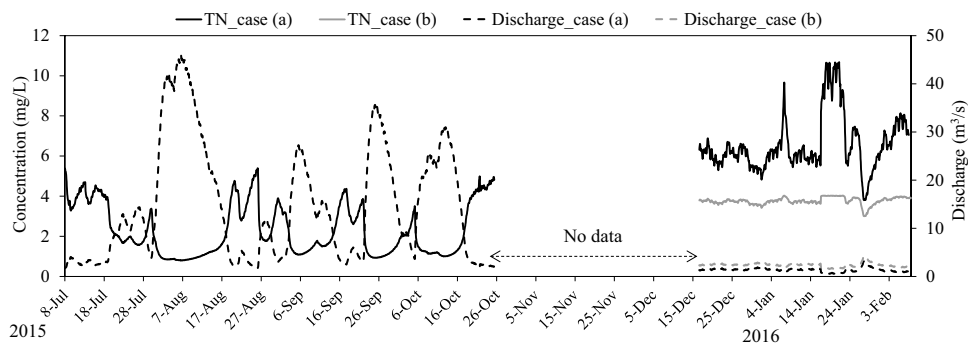
In the case with pumping [case (b)], we added 1 m<sup>3</sup>/s of water containing 0.5 mg/L TN to the simulated concentration of case (a) and calculated the concentration using a weighted average. Figure 8 shows the results of the TN concentration and discharge of cases (a) and (b), which showed that the TN concentration at St.11 in the dry season could be reduced to below 5 mg/L by pumping water from the Mekong River through the marsh, which is a much lower value than the case without pumping.

Of course, this dilution procedure does not directly reduce the absolute quantity of nutrient pollutants present. However, canals and rivers themselves have self-purification functions, which can be understood as the capacity for storing, recycling or purifying a certain amount of organic and inorganic human waste through dilution, assimilation and chemical or biological re-composition processes (de Groot et al. 2002). This self-purification capacity is often

**Fig. 7** Hyetograph and estimated nutrient load of TN (a), TP (b) and TOC (c) at St.3 and St.11



**Fig. 8** Calculated results of TN concentration of runoff at St.11 (“case (a)” indicate the result obtained by using the observed data and “case (b)” shows the simulated results when  $1 \text{ m}^3/\text{s}$  of Mekong River water is pumped up into the marsh in the dry season)



reported to be affected by the environment (Vagnetti et al. 2003; Mbuligwe and Kaseva 2005; Ostroumov 2005). For example, Wei et al. (2009) revealed that dam construction drastically reduced the self-purification capacity of the downstream river, possibly due to the decreased amounts of flooding and discharge, which led to lower dissolved oxygen. Considering the other possible effects described above, the proposed countermeasure of water dilution can have an additional positive impact on water quality. Since only simulated results of concentration dilution are shown in the present

paper, further investigation or field experiments, including the enhanced self-purification function of Mekong River water addition, are needed in the future.

### Concluding remarks

In this study, we surveyed surface water discharge for variations in nitrogen, phosphorus, and TOC concentrations in both rainy and dry seasons at various monitoring stations

in the wastewater catchment system around Vientiane, the capital of Lao PDR. Several key seasonal characteristics of surface water quality in the basin were observed. Especially in urban and river basin areas, dissolved nitrogen and phosphorus concentrations varied with runoff discharge, showing lower concentrations in the rainy season and higher concentrations in the dry season while there was no significant difference between the seasons in nutrient concentrations obtained at agricultural stations. The highest values were observed in the urban stations, followed by the main river basin and agricultural land stations. The  $\text{NH}_4^+\text{-N}$  and phosphate phosphorus ( $\text{PO}_4^{3-}\text{-P}$ ) accounted for the largest proportions of TN and TP, respectively, in both runoff water and outflow from the marsh. TOC concentrations did not vary greatly, regardless of discharge volume. To counteract deteriorating water quality, we suggest reducing high nutrient concentrations in the dry season by dilution via pumping water from the Mekong River into the marsh and simulated the reduced concentrations at urban and river stations when this measure was applied.

The results of this study can be used to support future research on the impact of land use changes, related to urbanization, on runoff mechanisms of pollutants, as well as the purification capacity of marshes. However, additional surveys are required to quantify more precisely the purification effect of natural wastewater catchment systems, such as That Luang Marsh. Since the main scope of this paper was to determine the runoff characteristics of the pollutant load in the drainage basin around Vientiane, these topics were beyond the scope of this study and further analysis respect to population, livestock, land use, and unit load of pollutant will be performed in future research.

**Acknowledgements** This research was supported by Green Network of Excellence-environmental information funded by the Ministry of Education, Culture, Sports, Science and Technology, Japan and the Environment Research and Technology Development Fund (1E-1104), KAKENHI Grant Nos. 26220202 and 17K17662 from the Japan Society for the Promotion of Science (JSPS), and the Environment Research and Technology Development Fund (S-10, S-14) of the Ministry of the Environment, Japan.

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