Performance of pond–wetland complexes as a preliminary processor of drinking water sources

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ABSTRACT

Shijiuyang Constructed Wetland (110 hm²) is a drinking water source treatment wetland with primary structural units of ponds and plant-bed/ditch systems. The wetland can process about 250,000 tonnes of source water in the Xincheng River every day and supplies raw water for Shijiuyang Drinking Water Plant. Daily data for 28 months indicated that the major water quality indexes of source water had been improved by one grade. The percentage increase for dissolved oxygen and the removal rates of ammonia nitrogen, iron and manganese were 73.63%, 38.86%, 35.64%, and 22.14% respectively. The treatment performance weight of ponds and plant-bed/ditch systems was roughly equal but they treated different pollutants preferentially. Most water quality indexes had better treatment efficacy with increasing temperature and inlet concentrations. These results revealed that the pond–wetland complexes exhibited strong buffering capacity for source water quality improvement. The treatment cost of Shijiuyang Drinking Water Plant was reduced by about 30.3%. Regional rainfall significantly determined the external river water levels and adversely deteriorated the inlet water quality, thus suggesting that the “hidden” diffuse pollution in the multitudinous stream branches as well as their catchments should be the controlling emphases for river source water protection in the future. The combination of pond and plant-bed/ditch systems provides a successful paradigm for drinking water source pretreatment. Three other drinking water source treatment wetlands with ponds and plant-bed/ditch systems are in operation or construction in the stream networks of the Yangtze River Delta and more people will be benefited.

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Introduction

Protecting drinking water sources, especially focusing on reducing nitrogen (N) and phosphorus (P) pollution, plays an essential role in guaranteeing drinking water safety and reducing the post-treatment cost (Bergman, 2011). Clearly, protecting water at the source is a fundamental way to ensure the health of humans, ecosystems and economies, and thus becomes the first important barrier in a “multi-barrier approach” to ensuring safe drinking water (Pollution Probe, 2004). Over the last decade, constructed wetland (CW) technology has evolved into a much broader range of treatment application

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worldwide in pretreating and polishing source water or effluents before they enter the waterworks or receiving water (Reilly et al., 2000; Shi et al., 2004; Juang and Chen, 2007; García et al., 2010; Zheng et al., 2014; Zhang et al., 2015). CWs are artificially enhanced engineering systems that have been designed to simulate natural processes among wetland vegetation, soils, and associated microbial communities and are being utilized for removal of a wide range of pollutants (Kadlec and Wallace, 2009; Sundaravadivel and Vigneswaran, 2001). We used the commonly accepted terminology of CWs for systems that are generally regarded as within the scope of the treatment wetland field (Kadlec and Wallace, 2009). Specifically, constructed ponds without plants or with seasonally implanted floating aquatic plants are also included in the discussion scope of CWs, since they have natural wetland analogs, but they are generally differentiated as pond systems. Characterized as cost-effective and eco-friendly, CWs have become popular worldwide for removing nutrients, organic matter, metals, pathogens, or other emerging pollutants from source/waste water (Mander and Mitsch, 2009; Fuchs et al., 2011; Zhang et al., 2015). Correspondingly, the performance of water quality improvement associated with nutrient and micropollutant attenuation in CWs has been extensively studied and documented (Reilly et al., 2000; Ayaz and Akça, 2001; Lee et al., 2010, 2014; Kadlec et al., 2010, 2011; García-Lledó et al., 2011; Zhang et al., 2014).

Although numerous CWs were built along polluted rivers (Reilly et al., 2000; Mitsch et al., 2005; Juang and Chen, 2007), engineering-scale offline riverine CWs with direct water supply for drinking water plants had not been previously reported at home and abroad. Shijiyang Constructed Wetland (SJY-CW) has established a successful paradigm to relieve the source water pollution in Jiaxing City. SJY-CW covers 110 hm² and is known as the first large-scale drinking water source treatment wetland in China. Every day, about 10% of the discharge (250,000 tonnes) across the contaminat-ed river enters SJY-CW through bypass flow pathways, and the outflow is supplied to the drinking water plant (SJY-DWP) in Jiaxing City. The regulation of inflow gates may achieve the outflow is supplied to the drinking water plant (SJY-DWP) in Jiaxing City. The regulation of inflow gates may achieve the switching of water sources (Xincheng River, Beijiao River) for emergent extreme events. Furthermore the wetland stores up to 1,200,000 tonnes of pretreated raw water to buffer an emergency for about 72 hr in case both water sources are impaired. The design of SJY-CW is protected by three Chinese invention patents. The adopted functioning core technologies are constructed root channel technology (Wang et al., 2012b) and enhanced plant-bed/ditch systems (Wang et al., 2012b; Zheng et al., 2012). SJY-CW has multiple eco-environmental and social values as habitat for biotic communities and a recreation site for residents (Yin et al., 2010). Nonetheless the water quality performance is always the focus, receiving great attention from authorities and the public.

The present study has provided extensive day-based data analyses on the water quality performance of SJY-CW during its initial two year operation period (28 months). The objectives are: (1) to examine the effectiveness of multiple ponds and wetland treatment systems; and (2) to probe into the interactive relationships between water quality indexes and other environmental variables.

1. Materials and methods

1.1. Site description

1.1.1. Physical geography of Jiaxing City
Jiaxing City (120°17′20″–121°16′02″ E and 30°19′35″–31°01′56″ N) is situated in the stream networks of the Yangtze River Delta (YRD), one of the most population-dense and economically developed areas in China. The city’s area is 3915 km², comprising plain 3564 km², hills 40 km², and waters 311 km². Jiaxing City is in a typical plain river system with a distributional density of streams 3.5 km/km² and a ratio of stream networks of 9.13% (Fig. 1a). It belongs to the subtropical monsoon zone with a clear distinction between the four seasons. The annual average values of air temperature, precipitation and evaporation are 16.0°C, 1100–1260 mm, and 910 mm respectively.

1.1.2. Water quality dilemma of Jiaxing City
Water shortage due to deteriorated water quality in Jiaxing City has long buffeted the local authorities and people. It is a big challenge for us to protect our precious water resources. Here we adopted the comprehensive pollution index of water quality (K) (Appendix A Eq. (S1)) (Guin, 1980) to assess the river water quality trends of Jiaxing City in recent years (Appendix A Fig. S1). It was indicated that the average K (years 2002–2008) reached up to 2.40 (the red line in Appendix A Fig. S1), which was far higher than the limit value (1.0) of “heavily polluted”. There were gradual increasing and decreasing trends of K for the periods of 2002–2006 and 2006–2008 respectively. However, the general levels of K are quite worrying.

1.1.3. Micropollution of Xincheng River and the way out
The Xincheng River, as a raw water supply for the largest drinking water plant at present (SJY-DWP) in Jiaxing City, has suffered from organic and ammonia pollution for a long time (Yin et al., 2010). The biennial average concentrations of ammonia nitrogen (NH₃-N), total nitrogen (TN), total phosphorus (TP), and permanganate index (COD₅₅) of this river were about 1.3 mg/L, 4.3 mg/L, 0.4 mg/L, and 5.8 mg/L respectively. To protect the drinking water source, Jiaxing City has adopted a series of control measures, including setting up gates to stop ship navigation, implementing water interchange, building two water sources, and establishing first-class, second-class and third-class source water protection areas. These practices have achieved some discernible effects. However, the annual average IV grade of source water according to the Chinese national environmental quality standards for surface water (GB 3838–2002) (SEPA, 2002a) still threatens the drinking water supply safety. Some further safeguard mechanisms must be established in addition. The previously proposed optional solutions seem impractical, costly and yet provide no guarantee of success. For example, (1) to control all sources in the short term is very hard because of multiple sources, crisscrossed waterways, complex flows, and partly external pollution; (2) further increase of the intensity of O₃-AC treatment in the waterworks will involve considerable expense and yet give rise to BrO₃⁻ secondary
pollution; (3) trans-valley water diversion such as drawing water from faraway Chun’an 1000-Islet (Qiandao) Lake (ca. 200 km) and Taihu Lake (ca. 40 km) would encounter a series of problems such as high cost, potential algal blooms, and urban area impact, and in addition the water quality is not guaranteed, so this controversial plan was rejected.

1.1.4. Local solution as an ideal selection
A local solution, namely controlling critical sources as far as possible and building treatment wetlands to pretreat the drinking source water, might be the best practical solution currently. This social and political need triggered an in-depth collaboration between Jiaxing City and the Chinese Academy of Sciences (CAS). The Jiaxing City government has adopted the source water protection ecological wetland scheme provided by the Research Center for Eco-Environmental Sciences (RCEES), CAS and built the first large-scale drinking water source protection wetland in China. The Xincheng River wetland treatment project is located in the northwestern corner of Jiaxing City. The whole planning area spans up to 5.59 km² with measures of treating the sewage water in rural areas, dredging the bottoms of polluted rivers, building ecological wetlands, constructing drinking water buffer zones and so on (Yin et al., 2010). The ecological wetland, named as the Shijiuyang Constructed Wetland, covers 110 hm² between 30°46′12.57″–30°47′02.31″ N and 120°41′52.43″–120°42′41.31″ E (Fig. 1b). The technical support was provided by the Research Center for Eco-Environmental Sciences, the Chinese Academy of Sciences. The Jiaxing Water Conservancy Bureau had organized a technical appraisal at an earlier stage. The engineering design was jointly completed by RCEES, CAS and the Water Resources and Hydraulic Prospecting and Design Research Institute of Jiaxing City. The engineering construction, operation and maintenance were carried out by the Jiaxing Water Conservancy Investment Limited Company. The direct engineering cost was about 8 million USD (exchange rate of that time) for the whole wetland, equivalent to 7.36 USD/m² by area and
32 USD/m³ by tonne water treatment capacity for facility construction. The operation cost is about 0.0043 USD/m³ by tonne water treatment. The treatment cost of Shijuyang Drinking Water Plant was reduced by about 30.3%. In July 2009, SJY-CW was formally approved as a Provincial Level Wetland Park (PLWP) by the Forestry Department of Zhejiang Province. SJY-CW was the first PLWP in Jiaxing City and the fourth PLWP in Zhejiang Province. In December 2011, SJY-CW was officially conferred the Chinese National Award for Best Practices to Improve the Living Environment by the Ministry of Housing and Urban–Rural Development of the People's Republic of China. The Shijuyang project has won the Dubai International Award for Best Practices to Improve the Living Environment in 2012 conferred by the Dubai Municipality, Dubai-United Arab Emirates and the United Nations Human Settlements Programme (UN-HABITAT). In December 2013, SJY-CW was approved as a National Urban Wetland Park by the Ministry of Housing and Urban–Rural Development of the People’s Republic of China.

1.1.5. Composition and technology cores of Shijuyang Constructed Wetland
SJY-CW is made up of 9 ponds, 62 ditches, 61 plant beds, 1 pretreatment channel, 1 open transfer channel, and several auxiliary systems including 1 pump station with 4 submerged pumps (maximum flow 6.6 m³/sec), 10 gates, 48 gravel choke plugs, 8 water flow checking points, 1 overflow weir, 1 pipe jack, 4 box culverts, 7 bridges, 3 docks and 3 service centers as well as 1 suite of monitoring and control systems (Fig. 1b and c, Appendix A Figs. S2-S11). The pond systems serve as important pretreatment, aeration, buffering and stabilization processors (Appendix A Figs. S5, S7, S9, and S10). The wetland systems are innovative plant-bed/ditch systems simulating the natural landscape in the largest freshwater lake — Baiyangdian Lake in North China (Appendix A Fig. S6) (Wang et al., 2012a). The plant-bed/ditch systems are composed of high water level small ditches (HD, inflow) and low water level small ditches (LD, outflow) connected with impervious gravel choke plugs (gate) on alternate ends of plant beds, as well as meandering large ditches (channel) running through them (Appendix A Figs. S6, S12, and S13). Artificial root channels formed by pre-buried plant straws are distributed under the subsurface layer of plant beds based on constructed root channel technology (Wang et al., 2012a). Hydraulic control with pumps and multiple gates (Fig. 1b and c) drives the water inflow passing through the functioning zones and interfaces of the wetland under a designed water fluctuation (30–40 cm once or twice every day). The water flow pathways extend for approximately 10 km with hydraulic residence time of about 4 days and hydraulic loading rate from 39.2 cm/day to 29.2 cm/day. The hydraulic residence times for pretreatment ponds, plant-bed/ditch systems (wetland root channel purifying zone), and post-treatment ponds (deep purifying zone) were 9.7 hr, 28.6 hr, and 56.4 hr respectively. The detailed parameters for the design of Shijuyang Constructed Wetland are listed in Appendix A Table S1. In particular, about 65% of inflow water passes through the large ditch (channel) directly, while the other 35% of inflow water flows into the high water level small ditch (HD) and is exuded through the subsurface root channel structure inside the plant bed (PB) into the low water level small ditch (LD). As for structural form and hydraulic operation mode, SJY-CW is classified as a semi-subsurface flow wetland. The various ponds and large ditches are always free surface flow (SF) wetlands, while alternate plant beds and small ditches generally serve as subsurface flow (SSF) wetlands to satisfy the better functioning of root channels within plant beds under moderate and low water level and as surface flow wetlands for short periods under extremely high water level. Initially 13 species of aquatic plants were artificially transplanted into SJY-CW. After a one year operation period, 49 vascular plant species were detected on the basis of a field survey (Zheng et al., 2011). After a two year operation period, 70 vascular plant species were recorded (Shen et al., 2011). No algal blooms occurred at any time in SJY-CW due to the mutual generation and restriction of aquatic life. For clarity, SJY-CW can be divided into four orientation areas: West, South, North, and East regions (Fig. 1b). Divided by the Beijiao River (the ancient Beijing-Hangzhou Grand Canal), the whole wetlands systems can be categorized into two large regions, i.e., West Region (upstream) and Great East Region (downstream). The SJY-CW project was launched in April 2007 and the Great East Region was completed and began a test run in July 2008 (first stage). The integrated systems, including the Great East Region and West Region, were jointly put into operation in January 2009 (second stage). Now the wetland systems have been smoothly operated for 7 years.

1.2. Water quality performance assessment

1.2.1. Monitoring frequency and indexes
After SJY-CW was constructed and put into trial operation, periodic monitoring for regular water quality indexes was established immediately according to the Chinese national environmental quality standards for surface water (GB 3838-2002). The sampling intervals are one day for most indexes and one or two weeks for a few others. Five long-term water sampling stations were selected in the critical nodes of functioning regions of the wetlands (Fig. 1b and c). The Great East Region includes four stations, i.e., SB: inlet of Great East Region, NE: end of multiple plant-bed/ditch systems, EE: outlet of Great East Region, IT: intake of drinking water plant (SJY-DWP). The West Region includes one station, WB: inlet of West Region. The collected samples were analyzed within 24 hr as far as possible and otherwise stored at 4°C. Water samples were measured for water temperature, pH, dissolved oxygen (DO), alkalinity, turbidity, color, taste and odor, visible substance, ammonia nitrogen (NH₄-N), nitrite nitrogen (NO₂⁻-N), total nitrogen (TN), total phosphorus (TP), permanganate index (COD₅₅), total iron (Fe), and total manganese (Mn) following the national standard methods (SEPA, 2002b). Regular water quality analyses were jointly conducted by the Hangzhou Water Quality Monitoring Station of National Urban Water Supply Monitoring Networks, Jiaxing Water Quality Monitoring Station of Zhejiang Province Urban Water Supply Monitoring Networks, and Shijuyang Drinking Water Plant. The water quality data in this study was mostly obtained from these stations.

1.2.2. Weighted comprehensive water quality index
A comprehensive water quality index is better to evaluate the water quality condition compared with a single water quality
index, and is becoming increasingly popular (Peng, 2004). For the sake of combining the comprehensive index with the water quality grade (GB 3838–2002), the weighted comprehensive index of water quality ($I_j$) (Eqs. (1) and (2)) (Liang and Jiang, 2002) was adopted in this study to assess the performance of wetland purification. DO, NH$_4$–N, COD$_{Mn}$, total Fe and total Mn were selected to calculate the $I_j$.

$$I_j = q_j + \rho \times \sum_{i=1}^{m} \frac{W_i \times C_i}{W_i^N}$$  \hspace{1cm} (1)$$

In which:

$$W_i = \frac{S_i}{S_n}$$ \hspace{1cm} (2)

where: $I_j$: the comprehensive index of $j$ station; $q_j$: the impact as 3 corresponding to water quality grade III; $\rho$: empirical factor, 0.45 at water quality grade III; $S_i$: the standard value of pollution index $i$ for grade I according to GB 3838–2002; $S_n$: the standard value of pollution index $i$ for grade V according to GB 3838–2002.

1.2.3. Removal rate and load reduction

The removal rate (RR, %) of a pollutant is calculated from the concentration difference between the outlet and inlet of the wetland (Eq. (3)). The pollution load reduction (LR, kg/day) is derived from the multiplication of the concentration difference between outlet and inlet and the treated water volume (Eq. (4)). The treated water volume data were taken from the historical records of daily operation. For the Great East Region, the outlet and inlet are EE and SB; for the integrated systems including also the West Region, the outlet and inlet are EE and WB respectively (Fig. 1b). The first initial operation stage includes only the Great East Region, and the subsequent second operation stage always includes the Great East Region and the West Region. Here we classify the region difference according to different operation stages.

$$RR = \frac{C_i - C_o}{C_i} \times 100\%$$ \hspace{1cm} (3)

where: $C_i$ (mg/L): inlet concentrations of pollutants; $C_o$ (mg/L): outlet concentrations of pollutants.

$$LR = (C_i - C_o) \times Q \times \frac{1}{1000}$$ \hspace{1cm} (4)

where: $Q$ (m$^3$): treated water volume.

1.2.4. Local seasonal classification

For distinguishing the seasonal patterns of water quality purification by the constructed wetlands, suitable season division is made according to the commonly accepted climatological rules rather than the astronomical methods. Combining the five-day moving average temperature (i.e., pentad temperature) with the growth and activities law of plants or animals reflecting the coming of seasons, four seasons are divided accordingly (Pei et al., 2009). When the pentad temperature is above 10°C and lower than 22°C, it is spring; greater than 22°C, summer; between 22°C and 10°C, autumn; and lower than 10°C, winter. Based on this dividing principle, the four seasons in Jiaxing City are defined as follows: Spring: from the middle third of March to the middle third of May, 71 days; Summer: from the last third of May to the first third of October, 143 days; Autumn: from the middle third of October to the last third of November, 51 days; and Winter: from the first third of December to the first third of March, 100 days.

1.2.5. Robust and resistant technique

In order to avoid some extreme values (potential outliers), which may greatly affect the overall evaluation, the robust and resistant technique is used. The trimean ($M$) is a good measure of central tendency, almost as resistant to extreme scores as the median and less subject to sampling fluctuations than the arithmetic mean in extremely skewed distributions (Tukey, 1977). Trimean is defined as the weighted average of the median and the two quartiles, and the calculation formula can be found in Eq. (5).

$$M = \frac{1}{4} \times Q3 + \frac{1}{2} \times M + \frac{1}{4} \times Q1$$ \hspace{1cm} (5)

where: $M$: trimean; Q3: 75% quartile; M: 50% quartile (i.e., median); Q1: 25% quartile.

1.2.6. Grey relational analysis

Grey relational analysis (GRA) has been frequently utilized to analyze the relationships in behavior or boundary among objects where there is uncertainty in mechanisms, incomplete data, etc. (Deng, 1984). In this study, we used grey relational grade (GRG) to compare the relationships between some environmental data. The GRA was conducted under MATLAB 5.3 (R11).

1.3. Statistical procedures and drawing

The SAS System for Windows 9.2 (2002–2008) was adopted to analyze the environmental data and unless otherwise noted, all significant differences met the probability criterion of $p \leq 0.05$. Parametric methods are preferably selected for data following normal distribution as tested by PROC UNIVARIATE, and reverse nonparametric methods are well suited for situations where little is known about the distribution under study. Parametric one-way ANOVA was performed by PROC ANOVA to handle only balanced ANOVA designs to determine if significant differences existed between the treatment groups. Parametric one-way GLM was performed by PROC GLM to handle complicated ANOVA for unbalanced data. Nonparametric one-way ANOVA was performed by PROC NPAR1WAY using Wilcoxon scores (Kruskal–Wallis test). The DUNCAN option performs Duncan’s multiple range test on all main effect means given in the MEANS statement. PROC REG was performed to obtain a simple complete model fit to the data, and the selection method STEPWISE option was used to optimize the model, while the Cp statistic was used as the criterion for model selection. Parametric Pearson product–moment correlation was performed by PROC CORR to measure the association for two variables. Nonparametric Spearman rank-order correlation was performed to measure the association based on the ranks of the data values. PROC UNIVARIATE was performed to create histograms for each variable listed in the HISTOGRAM statement and to examine
Wetland during both operation stages. Regardless of the significant differences between the outlet and inlet of the single water quality index (Liang and Jiang, 2002). It showed and reliable integrated water quality index as compared to the water from the Xincheng River (Tables 1 and 2). The weighted SJY-CW had a considerable treatment performance for source water passed only the Great East Region at the first stage. It existed between inlets or outlets at both stages. This reflected the performance of the relative stability of inflow or outflow in SJY-CW as far as the data distribution. Wavelet analysis, which is applied in Fourier Transform Infrared spectroscopy, was implemented in the SAS/IML wavelet functions to obtain the wavelet smoothing of water quality data and to analyze detailed temporal patterns of temperature and removal rate signals over temporal scales (Kang and Lin, 2007). The statistical drawings were derived by PROC BOXPLOT, PROC GPLOT and PROC UNIVARIATE directly from SAS for Windows 9.2 (Friendly, 1991).

2. Results and discussion

2.1. Weighted comprehensive index of water quality

SJY-CW had a considerable treatment performance for source water from the Xincheng River (Tables 1 and 2). The weighted comprehensive index of water quality ($I_j$) is a robust, sensitive and reliable integrated water quality index as compared to the single water quality index (Liang and Jiang, 2002). It showed significant differences between the outlet and inlet of the wetland during both operation stages. Regardless of the stages, the $I_j$ of the outlet was significantly lower than that of the inlet ($Table$ 1, $p < 0.0001$). The $I_j$ at inlet and outlet at the second stage was both significantly lower than that at the first stage. This showed that the quality of source water from Xincheng River was improved gradually under the various source control efforts of local government, corresponding to the variation trend from 2006 to 2008 in Appendix A Fig. S1. These results are a little different from those in Table 2. This can possibly be explained by the dramatic difference in sample sizes ($n = 381-416$ in Table 1, $n = 14$ in Table 2) and the higher sensitivity and robustness of the $I_j$ index than the single water quality index. In any case, SJY-CW exhibited a relatively stable purification level at both stages ($I_j$ reduction by 0.3, Table 1). On the whole, SJY-CW can improve the source water quality by one grade (Table 1, $I_j$ grade from IV to III) according to GB 3838-2002.

2.2. Single water quality index

Robust values for various water quality indexes and removal rates (RRs) at both operation stages based on the trimean (Eq. (5)) are listed in Table 2. The DO saturation degree at the outlet (49.3%-56.9%) was significantly higher than that at the inlet (34.3%-27.2%), and the concentrations of most pollution indexes at the outlet were significantly lower than those at the inlet at both stages. This reflected the performance of the multiple pond and wetland systems in SJY-CW, which was consistent with the results in Table 1. No significant differences in the removal rates were detected between the two stages except for the increase in DO saturation. When inflow water passed through the integral systems, including the West Region and Great East Region at the second stage, the DO saturation degree increased by 115.9%, which was significantly higher than the opposite situation (by 47.2%) when the water passed only the Great East Region at the first stage. It should be pointed out that in general no statistically significant differences for the values of selected indexes existed between inlets or outlets at both stages. This reflected the relative stability of inflow or outflow in SJY-CW as far as

### Table 1 – Weighted comprehensive index of water quality ($I_j$).

| Classification | n   | Mean  | Std.  | Minimum | Maximum |
|----------------|-----|-------|-------|---------|---------|
| 1st-inlet      | 416 | 4.01  | 0.22  | 3.46     | 4.87    |
| 1st-outlet     | 416 | 3.70  | 0.19  | 3.25     | 4.35    |
| 2nd-inlet      | 381 | 3.94  | 0.18  | 3.54     | 4.58    |
| 2nd-outlet     | 399 | 3.62  | 0.16  | 3.12     | 4.15    |

$n$: sample size; Std: standard deviation. The data sources for two stages correspond to (1) 1st, from August 2008 to September 2009, whose inlet and outlet were SB and EE respectively; and (2) 2nd, from October 2009 to November 2010, whose inlet and outlet were WB and EE respectively. The different letters in the Mean column indicate significant differences (nonparametric test, followed by Kruskal-Wallis test, and Duncan’s multiple range test for ranks under GLM procedure).

### Table 2 – Trimean of single water quality index and removal rate.

| Items          | 1st-inlet | 1st-outlet | 2nd-inlet | 2nd-outlet | 1st-RR | 2nd-RR |
|----------------|-----------|------------|-----------|------------|--------|--------|
| DO saturation (%) | 34.3%     | 49.3%      | 27.2%     | 56.9%      | 47.2%  | 115.9% |
| Turbidity (NTU) | 42.41     | 26.80      | 32.69     | 23.88      | 37.7%  | 31.0%  |
| NH$_3$-N (mg/L) | 1.09      | 0.63       | 1.23      | 0.60       | 41.7%  | 49.6%  |
| UIA (mg/L)     | 0.013     | 0.008      | 0.010     | 0.005      | 29.3%  | 42.4%  |
| NO$_2$-N (mg/L) | 0.15      | 0.13       | 0.15      | 0.11       | 8.8%   | 13.7%  |
| COD$_{an}$ (mg/L) | 5.99     | 5.53       | 5.43      | 5.13       | 7.1%   | 5.7%   |
| Total Fe (mg/L) | 1.36      | 0.80       | 0.90      | 0.59       | 39.3%  | 33.5%  |
| Total Mn (mg/L) | 0.28      | 0.21       | 0.27      | 0.23       | 22.3%  | 17.3%  |
| TN (mg/L)      | 4.06      | 3.28       | 4.24      | 3.67       | 17.6%  | 15.9%  |
| TP (mg/L)      | 0.41      | 0.31       | 0.44      | 0.32       | 25.2%  | 26.2%  |

Data were calculated on the basis of monthly mean ($n = 14$ months for each stage). UIA: un-ionized ammonia; RR: removal rate; DO: dissolved oxygen. DO saturation (%) is the ratio of DO concentration (mg/L) to the maximum dissolved oxygen concentration saturation (mg/L) in freshwater at the corresponding temperature. The RR for DO saturation is calculated from ($C_p/C_i$) / $C_i = 100\%$, which reflects the increase rate of DO saturation. All others are derived from Eq. (1). The data sources for two stages correspond to (1) 1st, from August 2008 to September 2009, whose inlet and outlet were SB and EE respectively; and (2) 2nd, from October 2009 to November 2010, whose inlet and outlet were WB and EE respectively. The different letters beside the concentrations or saturation indicate significant differences of values among inlets and outlets (parametric test).
the single water quality index was concerned. At the same time, it was suggested that the single water quality index was not as sensitive as the weighted comprehensive index of water quality (I) in reflecting the integrated water quality condition (Tables 1 and 2).

Of all the water quality indexes that affect aquatic life, ammonium is the most important criterion after oxygen, especially in intensive systems, while un-ionized ammonium is about 100 times more toxic to fish than ionized ammonium (Guan et al., 2010; Chen et al., 2012). The average UIA levels (mean ± S.D., 0.009 ± 0.008 mg/L) in SJY-CW were lower than the generally accepted safety threshold of 0.02 mg/L (SEPA, 1989) for aquatic life, although the total ammonia nitrogen levels were more than 1.0 mg/L (Table 2), corresponding to grade III (GB 3838–2002). SJY-CW exhibited considerable removal rates for UIA (29.3%–42.4%). In healthy ponds and lakes, un-ionized ammonia levels should always be nearly zero. Anytime the UIA is higher than 0.05 mg/L, the fish are being damaged (Emerson et al., 1975). As the concentration rises above 0.05 mg/L, it causes more and more damage. At 2.0 mg/L, the fish will die. Based on the above discussion, the water in SJY-CW was relatively healthy as far as the average UIA was concerned. Nonetheless, the uncommon maximum UIA value of 0.077 mg/L at some occasional specific times and places is very likely to be an underlying problem, and corrective measures should be taken to similar occurrences immediately.

The grey relational analysis results indicated that removal rates of most water quality indexes were related with each other and had GRGs of more than 0.6 (results not shown). It is necessary to point out that the GRGs between DO and other indexes (NH$_3$–N, NO$_2$–N, TN, COD$_{Mn}$, Fe, Mn) were significant (0.6040–0.6933, n = 28). Dissolved oxygen is critically important for the health of aquatic ecosystems and for the transformation of many pollutants. In many permits in the United States, a minimum DO of 5 mg/L is specified (Kadlec and Wallace, 2009). The DO levels in SJY-CW varied over a broad range (0.3–10.7 mg/L). The average DO levels at the inlet and outlet were 3.00 mg/L and 5.06 mg/L respectively, and 88.6% of values at the inlet and 54.8% of values at the outlet were less than 5.00 mg/L respectively. Due to the complexity of oxygen transfer, production and consumption, wetlands are not particularly efficient at obtaining oxygen in sufficient quantities to deal with heavy pollutant loads, and several techniques such as compressed air bubblers or alternating fill and draw might be necessary to supplement the natural aeration processes (Kadlec and Wallace, 2009).

### 2.3. Spatial variation of water quality index

Major water quality indexes varied significantly for the representative stations in SJY-CW (Fig. 2). It was shown that the DO saturation increased significantly with an abrupt step after the inflow water passed from Station 1 to Station 4 ($p < 0.0001$). In contrast to DO, NH$_3$–N and total Mn exhibited a gradual decreasing trend from Station 1 to Station 4 (for both, $p < 0.0001$). These results together demonstrated the effectiveness of purification processes in the functioning zones of pond and wetland combined systems. The functioning zones between Station 1 and Station 2 are pretreatment river channel, pretreatment ponds, plant beds and ditches, and buffering pond with gravitational flow mode (Fig. 1b and c). The functioning zones between Station 2 and Station 3 are pumping and free overfall flow area (SB in Fig. 1b), multiple plant beds and ditches, and buffering ponds with power plug-flow mode. The functioning zones between Station 3 and Station 4 are two consecutive deep purifying ponds (post-treatment ponds). These zones all played their parts in the removal of pollutants from river source water. Ponds and wetlands as well as their combination are widely adopted treatment elements in ecological engineering, and their treatment performance has been extensively examined and discussed (Tanner and Sukias, 2003; Kadlec, 2003, 2005). The generally accepted opinion was that wetland is more efficient in removing most pollutants, especially total suspended solids (TSS), and ponds should be commonly placed as the presetting element (Kadlec, 2003, 2005; Kadlec and Wallace, 2009). However, the dispersive ponds (pretreatment pond, buffering pond, aeration pond, post-treatment pond) in SJY-CW played their key complementary roles in water quantity buffering and water quality purification. In particular, the post-treatment pond could further purify and stabilize the outflow water quality and provide a huge space (600,000 tonnes) for storing the purified raw water and buffering an emergency for about 72 hr for the drinking water plant. In addition, the pretreatment channel (ca. 1.2 km) before the pretreatment pond was essential to the presetting function and preliminary purification of TSS, NH$_3$–N, TP, and COD$_{Mn}$, which significantly lessened the treatment load of the pretreatment pond. Practice has proved that the modified nearly abandoned channel as a pretreatment element made significant sense to wetland treatment. The periodic sediment dredging of the pretreatment channel (about once every two or three years) rather than the pretreatment pond might easily and effectively move the contaminants from the aquatic system to the terrestrial system.

However, there are returning peaks for COD$_{Mn}$, total Fe, and turbidity at Station 2, and then a gradual decrease trend from Station 2 to Station 4 (Fig. 2). The outflow water from the West Region was drawn into the Great East Region through the submerged pipe jacking in the Beijiao River by the pumping systems in the Great East Region. According to irregular detailed samples from the West Region, this region itself also showed considerable performance for the major water quality indexes (data not shown). A possible explanation for the peaks in Fig. 2 was that there existed a lateral oozing or mixed pumping from the Beijiao River, since it crossed the whole SJY-CW in the longitudinal direction. According to 10 successive days of monitoring results for Beijiao River in November 2008, the Beijiao River contained 46.50 NTU of turbidity and 1.67 mg/L of total Fe on average, which were significantly higher ($p = 0.0234$ and $p = 0.0048$ respectively) than those in Xincheng River (35.58 NTU turbidity, 1.33 mg/L total Fe) at the same period. Further tracer evidence for the peaks in Fig. 2 is still under study.

### 2.4. Temperature effect and temporal variation

Water temperature is one of the important cyclic stimuli in a large number of wetland driving forces that follow an annual cycle (Kadlec and Reddy, 2001). The removal rates of major
water quality indexes in SJY-CW varied linearly with temperature (Table 3). The observed wetland removals may have different temperature dependence (Kadlec and Reddy, 2001; Lee et al., 2010). The increase rate of DO and removal rates of NH$_4^+$-N and total Mn increased significantly with temperature, especially DO ($R^2 = 0.7176$, GRG = 0.9082) and NH$_4^+$-N ($R^2 = 0.8712$, GRG = 0.9382). Conversely, the removal rates of turbidity, COD$_{Mn}$ and total Fe decreased significantly with temperature. The GRGs between major water quality indexes and temperature ranged from 0.7111–0.9382 (Table 3), which provides more evidence of the role of temperature in determining the treatment efficiency of SJY-CW.

Fig. 2 – Spatial variation of water quality index. WestB: inlet of West Region; SouthB: inlet of Great East Region; NorthE: end of multiple plant-bed/ditch systems; EastE: outlet of Great East Region. n: sample size; DO sat.: DO saturation; Ammonia: NH$_4^+$-N; COD(Mn): permanganate index. The meaning of box plot is the same as in Appendix A Fig. S1. Box width varies with the group size n. In addition, the notches measure the significance of the difference between two medians. The medians of two box plots are significantly different at approximately the 0.95 confidence level if the corresponding notches do not overlap. The different letters beside the boxes indicate significant differences (nonparametric test, followed by Kruskal-Wallis test, and Duncan’s multiple range test for ranks under GLM procedure).

Table 3 – Regression model between trimean of removal rate and temperature.

| Linear regression equation | n  | $R^2$ | p         | RMSE  | GRG   |
|----------------------------|----|-------|-----------|-------|-------|
| RR DO = 0.0826 + 0.0419 * T | 30 | 0.7176| <0.0001   | 0.2353| 0.9082|
| RR NH$_4^+$-N = -0.0444 + 0.026 * T | 30 | 0.6712| <0.0001   | 0.0894| 0.9382|
| RR Turbidity = 0.4775-0.0087 * T | 30 | 0.4399| <0.0001   | 0.0879| 0.8494|
| RR COD$_{Mn}$ = 0.0892–0.0016 * T | 30 | 0.2056| 0.0118    | 0.0291| 0.7111|
| RR Fe = 0.4991–0.0075 * T | 30 | 0.5511| <0.0001   | 0.0609| 0.8110|
| RR Mn = 0.113 + 0.0047 * T | 30 | 0.3234| 0.0010    | 0.0606| 0.8646|

RR: removal rate; T: temperature (degree Celsius); n: sample size; RMSE: root mean square error; GRG: grey relational grade based on 795 data lines; DO: dissolved oxygen. For DO, the removal rate is actually the increase rate.
Further analyses indicated that the removal rates (increase rate for DO) for major water quality indexes showed significantly different seasonal modes (Fig. 3). The increase rate of DO was highest in summer and lowest in winter. The RR for NH₄⁺-N was highest in summer and lowest in winter. The RR for total Mn was highest in summer and lowest in autumn. The RRs for total Fe and turbidity were highest in spring and lowest in summer. The RR for COD₅₇ was highest in winter and lowest in spring. Jiaxing City has a long summer, lasting for 143 days, accounting for 39.2% of the year, which is favorable for the increase of DO and removal of NH₄⁺-N and total Mn; while the second-longest season, winter, with duration of 100 days (27.4%), favors COD₅₇ removal. This is in contradiction with the common opinion that the wetland

![Fig. 3 – Seasonal mode of removal rate of water quality index.](image)
will release more COD$_{mn}$ to the water in winter due to the plant release or litter decomposition. The regular harvesting of aquatic plants at the time when autumn turns into winter might partly explain this point.

Hydraulic residence time was a key factor governing differences in wetland treatment effects. While wetlands with short hydraulic residence times are generally effective in retention of particulate matter contaminants and pathogens, wetlands with longer hydraulic residence times are required to optimize nutrient removal (Díaz et al., 2009). The incorporation of the West Region (wetland functioning zones: 15.3 hm$^2$) into SJY-CW (total area of wetland functioning zones: ca. 60 hm$^2$) actually improved the whole purification level of SJY-CW, whose hydraulic loading rate changed from 39.2 cm/d to 29.2 cm/day and hydraulic residence time from 3.43 to 4.13 days. This can be seen from the treatment weight of the West Region in Table 4, the increase rate of DO saturation and removal rates of NH$_4$$^+$-N as well as UIA in Table 2, and the corresponding continuous variations in Fig. 4. Starting in July 2009, the increase rates of DO reached a new
level. The average level (157.38%) of DO increase rates after July 2009 was 3.7 times of that (42.48%) before July 2009. However due to the varying operation modes in the West Region (natural flow under water head without pumping) and Great East Region (heading-up with pumps and gates), the purification mechanisms were a little different in these regions. Furthermore, the submerged pipe jacking in Beijiao River connecting the West Region and Great East Region was suspected to spoil the purified outlet water from West Region, and the likely mixing of input from the Beijiao River into the pipe jacking also placed a load on the inflow water in Great East Region. These might be the reasons that the increase of purification level was not proportional to the difference between hydraulic loading rates, especially for turbidity, COD\textsubscript{Mn}, total Fe, total Mn, and TN (Table 2, Fig. 2). The returning peaks of some indexes in Fig. 2 were the representation of the consequences. The direct support for this supposition is still under study. In any case, as far as the robust and resistant weighted comprehensive index of water quality is concerned, the purification degree was basically the same during the two operation stages (Table 1), although the water quality index of the inlet significantly decreased at the second stage.

From Fig. 4, we could detect more complex and variable fluctuating trends for major water quality indexes as compared with temperature. This strongly suggested that other factors such as inlet flow rates and concentrations and several features of the annual biogeochemical cycle could also contribute to the observed patterns of nutrient and pollutant removals; atmospheric influences, including rain, evapo-transpiration and water reaeration, also followed seasonal patterns (Kadlec and Reddy, 2001; Pedescoll et al., 2011). Some of the factors will be described and discussed in Sections 2.5 and 2.6.

2.5. Inlet concentration effect

The removal rates of water quality indexes in SJY-CW varied sensitively with inlet concentrations and pollution load. Constructed wetland removals are a function of inlet concentrations and hydraulic loading rates (Knight et al., 2000). Combining GRA (Table 5) with scatter plots and regression analyses (drawings and results not shown), the removal rates of most water quality indexes in SJY-CW increased significantly (n = 795, p < 0.0001) with inlet concentrations, especially for turbidity (R\textsuperscript{2} = 0.3355), COD\textsubscript{Mn} (R\textsuperscript{2} = 0.1225) and total Fe (R\textsuperscript{2} = 0.2306) and relatively slight for NO\textsubscript{2}−N (R\textsuperscript{2} = 0.0347) and total Mn (R\textsuperscript{2} = 0.0562). However the increase rates of DO are negatively related to inlet concentrations (n = 795, R\textsuperscript{2} = 0.3671, p < 0.0001). The DO increase rates at the outlet decreased with DO concentrations at the inlet following a hyperbolic curve (Fig. 5, Eq. (6)). The inlet DO concentrations were lower, and the DO increase rates in SJY-CW were higher. According to Eq. (6), when the inlet DO level was more than 9.90 mg/L, the DO increase rates would be lower than zero. Nonetheless, the outlet DO absolute levels increased with the inlet DO concentration increase as usual (data and figures not shown). However, a single inlet DO concentration cannot predict the outlet DO concentration well according to the regression analysis model, with a (C\textsubscript{p}) value of 25.9931. When temperature entered the model, (C\textsubscript{p}) became 3.0000 and the regression model was statistically effective (Eq. (7)). This reflected the coupling effect of inlet concentration and temperature on the outlet DO absolute levels and increase rates. The removal rates of NH\textsubscript{4}−N are almost not related to inlet concentrations (n = 795, R\textsuperscript{2} = 0.0030, p = 0.1213). When inlet NH\textsubscript{4}−N concentrations were less than 0.5 mg/L, the average NH\textsubscript{4}−N removal rate of SJY-CW was 26.6% ± 101.6% (mean ± S.D.) with coefficient of variation of 382.6%. However, when inlet NH\textsubscript{4}−N concentrations were greater than or equal to 0.5 mg/L, the average NH\textsubscript{4}−N removal rate was 44.7% ± 30.6% (mean ± S.D.) with coefficient of variation of 68.4%. Therefore at low inlet NH\textsubscript{4}−N concentrations, SJY-CW had highly variable removal rates for NH\textsubscript{4}−N, even negative values; at high inlet NH\textsubscript{4}−N concentrations, SJY-CW showed quite stable removal rates for NH\textsubscript{4}−N. Similar to DO, outlet NH\textsubscript{4}−N concentrations could not be reliably predicted without the explanatory contribution of temperature (Eq. (8)). The prediction model (C\textsubscript{p}) value changed sharply from 430.1593, when considering only the inlet concentration effect, to 3.0000 considering both inlet concentration and temperature effect.

\[
RR(\text{DO}) = -0.2942 + \frac{2.9124}{\text{DO}}
\]

where: RR(\text{DO}): DO increase rates at outlet; DO: DO concentrations at inlet; (C\textsubscript{p}) = 3.0000; RMSE (root mean square error): 0.6789.

\[
\text{outDO} = 3.9861 + 0.5845 \cdot \text{inDO} - 0.03440 \cdot T
\]

where: outDO: DO concentrations at outlet; T: temperature; inDO: DO concentrations at inlet; n = 795; R\textsuperscript{2} = 0.4336; inDO partial R\textsuperscript{2} = 0.4157; T partial R\textsuperscript{2} = 0.0179; (C\textsubscript{p}) = 3.0000; p < 0.0001.

\[
\text{outNH}_4 = 0.5363 + 0.5998 \cdot \text{inNH}_4 - 0.5327 \cdot T
\]

where: out\text{NH}_4: NH\textsubscript{4}−N concentrations at outlet; T: temperature; in\text{NH}_4: NH\textsubscript{4}−N concentrations at inlet; n = 795; R\textsuperscript{2} = 0.7623; in\text{NH}_4 partial R\textsuperscript{2} = 0.6335; T partial R\textsuperscript{2} = 0.1288; (C\textsubscript{p}) = 3.0000; p < 0.0001.

Joining Table 5 with Table 3, the removal rates of major water quality indexes always had higher GRGs (mean increase by 0.1014) with temperature than those with inlet concentrations. This certainly suggested that the temperature effect

| Table 5 – Grey relational grade between removal rate of water quality index and inlet concentration. |
|---|---|---|---|---|---|---|---|
| n = 795 | Removal Rate | Turbidity | DO | NH\textsubscript{4}−N | NO\textsubscript{2}−N | COD\textsubscript{Mn} | Fe | Mn |
| Inlet | 0.7551 | 0.7698 | 0.8125 | 0.8211 | 0.6580 | 0.7409 | 0.7380 |
was more determining than the inlet concentration effect concerning the pollutant removal processes (Kadlec and Reddy, 2001; Knight et al., 2000; Kadlec and Wallace, 2009). To summarize, the outlet concentrations and removal rates of major water quality indexes were affected by the inlet concentrations, which were the original force providing the pollution load and materials base. However, the temperature and seasonal conditions in SJY-CW dramatically affected the wetland purification efficiency and played an indispensable role. For most water quality indexes, relatively high temperature was favorable to their removal and transformation due to the enhanced biogeochemical wetland cycle and microbial processes (Kadlec and Reddy, 2001).

2.6. Rainfall and external river water level effect

Jiaxing City is located in the subtropical monsoon climate zone with abundant and significant rainfall, which evidently determines the river water level (grey relational grade: 0.9291, \(n = 10,872\)). In plain stream networks, the river water level responds quickly to rainfall due to the crisscrossed connecting watercourses and increasing amounts of impervious pavements. The relationship between the rainfall and the flood water level indicates that negative hydrological effects of human activities and the change of the earth surface due to the urbanization process have an increasingly significant impact on the flood risk besides the rainfall, which makes the relationship between rainfall and flood water level more complicated (Ye et al., 2011). The multi-year average rainfall distribution at one year scale is typical of the “two peaks” type with plum rain flood season (May to July) and typhoon rain flood season (August to September). The mean and median of rainfall are 9.95 mm and 5.00 mm respectively. According to the fitted Gamma distribution (Appendix A Fig. S14), 90% of rainfall belongs to small to moderate type with rainfall of less than 25 mm; the remaining 10% belongs to large to storm type with rainfall between 25 mm and 100 mm, while this minor part plays a key role in determining the flood events and external river water quality. The mean and median water levels in Jiaxing City are 1.18 m and 1.15 m above sea level respectively. According to the fitted Gamma distribution (Appendix A Fig. S15), 65% of water levels fall between 0.99 m and 1.50 m. Data showed that the source water quality in SJY-CW was significantly affected by the regional rainfall and external river water level (Table 6). The GRG (0.8847) between the weighted comprehensive index of water quality (\(I_j\)) of inlet water in SJY-CW and regional rainfall was considerably higher than that (0.7584) between \(I_j\) and external river water level. In rainy season, the Spearman correlation coefficient (0.1651) between \(I_j\) and rainfall was also slightly higher than that (0.1398) between \(I_j\) and water level. Since rainfall had a significantly direct impact on the river water level (Ye et al., 2011), we inferred that the rainfall was the prime driver that drove the source water quality variation of SJY-CW. In fact, the runoff pollution with street dusts containing a large and concentrated amount of heavy metals and polycyclic aromatic hydrocarbons in the upper watershed of Xincheng River has substantial impacts on the stream network quality (Zhao et al., 2008, 2009a, 2009b).

The “hidden” (or called cryptic) diffuse pollution might be of great significance to the river source water quality. One

| Situation       | Item          | \(I_j\)       | Note                           |
|-----------------|---------------|---------------|--------------------------------|
| All seasons     | Rainfall      | GRG = 0.8847  | \(n = 638\)                    |
| All seasons     | Water level   | GRG = 0.7584  | \(n = 638\)                    |
| Dry season      | Water level   | \(r = 0.1045\)| \(n = 393; p = 0.0384; Pearson\) |
| Rainy season    | Rainfall      | \(r = 0.1651\)| \(n = 245; p = 0.0096; Spearman\) |
| Rainy season    | Water level   | \(r = 0.1398\)| \(n = 245; p = 0.0287; Spearman\) |

Fig. 5 – Variation of DO increase rate with inlet DO concentration. The red stars denote the data points. The blue straight line is the linear regression equation. The green lines describe the 95% confidence limits for the linear regression equation. DO: dissolved oxygen.
cannot see it, but that does not mean it is not there. Jiaxing City is located in the typical plain stream networks of the Yangtze River delta in East China (Fig. 1a). The hydraulic conditions become vulnerable, complex and variable because of the upstream foreign water and self-pollution in Jiaxing City. The relationships between the weighted comprehensive index of water quality of inlet water in SJYC-W and regional rainfall and external river water level (Table 5) indirectly corroborate the “hidden” diffuse pollution. The rainfall is the primary mover for flushing and mobilizing a huge amount of diffuse pollution hidden in the multi-tiduous stream branches as well as their catchments. Therefore, when the rainfall events took place, the river source water quality was dramatically impaired (Table 5). The complicated quantitative coupling mechanisms between the rainfall and river water quality need further detailed research. Undoubtedly, with the regional point source pollution gradually controlled, the diffuse pollution sources, especially the “hidden” ones, are bound to be the controlling focus in the future.

2.7. Treatment weight of pond and wetland systems

SJYC-W is composed of various ponds and plant-bed/ditch wetlands with series connection (Fig. 1b and c). Pond–wetland combinations have been widely adopted in treatment wetlands (Kadlec and Wallace, 2009). Distinctively, SJYC-W applied unique landscape mosaics, with pretreatment pond and plant-bed/ditch systems as well as a post-treatment pond. The relative performance levels strongly suggest that optimal combinations of ponds and wetlands can provide the best treatment (Kadlec, 2005). The calculation results based on the weighted comprehensive index of water quality (f) indicated whether the ponds with unequal sizes or the wetlands with plant-bed/ditch systems were both functioning well (Table 4). The South Region and North Region, with a fairly concentrated quantity of plant-bed/ditch systems (36.29%), possessed the highest treatment weight (0.461). It is necessary to point out that the East Region with two consecutive large, deep purifying ponds (32.88%) had a considerable treatment weight (0.318). This is different from the view that the placement of a pond as the final element in a wetland treatment system is generally not desirable from the standpoint of TSS reduction (Kadlec, 2005; Kadlec and Wallace, 2009). During the 1st operation stage without the West Region, the treatment weight for the South Region and North Region, and that for the East Region was 0.556 and 0.444 respectively. It was roughly estimated that the treatment weight ratio of plant-bed/ditch systems to ponds per unit area is 0.855–1.171:1. The average ratio is 1.005:1 (±1). Though the treatment weight per unit area of plant-bed/ditch systems and ponds was approximately equal, they treated different pollutants at relatively high removal rates. During the 1st operation stage, the plant-bed/ditch systems were more efficient in removing NH₄⁻N (weight: 0.620) and raising the DO level (weight: 0.775); the ponds were relatively efficient in removing COD₅₅ (weight: 0.782), total Fe (weight: 0.752), and total Mn (weight: 0.531). During the 2nd operation stage, the plant-bed/ditch systems were more efficient in removing NH₄⁻N (weight: 0.696 for West Region, 0.664 for South Region and North Region), COD₅₅ (weight: 0.731 for West Region, 0.637 for South Region and North Region), and raising the DO level (weight: 0.576 for West Region, 0.774 for South Region and North Region); the ponds were relatively efficient in removing total Fe (weight: 0.913) and total Mn (weight: 0.749). The purifying functions of SJYC-W were the coupled effects of area and functioning zones.

2.8. Overall load reduction of SJYC-W

The Xincheng River wetland treatment project moderately suppresses the pollution load and mitigates the health risk in the micro-polluted source water with regard to drinking waterworks (Yin et al., 2010). The Xincheng River adjacent to the drinking water plant has an average surface width of 35.2 m and a mean depth of 2.98 m. The general water flow velocity is taken as 0.2 m/sec. It is calculated that the daily water volume at the discharge cross-section of Xincheng River is about 1.82 million tonnes. SJYC-W as a huge off-line (relative to instream) treatment facility continually treated and supplied about 0.18 (maximum 0.25) million tonnes water to the drinking water plant every day during its initial two year operation period. So the daily offline treated source water amount accounted for about 10% of the discharge across the Xincheng River. During the operation period with duration of 847 days, SJYC-W supplied in total 146 million tonnes purified raw water to the drinking water plant. The load reductions for NH₄⁻N, COD₅₅, total Fe, and total Mn were 66.2 tonnes (38.86%), 49.7 tonnes (5.97%), 56.2 tonnes (35.64%), and 8.49 tonnes (22.14%) respectively (Table 7). The increased absolute amount of DO was 303 tonnes (73.63%). The pollution load reduction has significantly improved the source water quality and reduced the treatment cost in the drinking water plant.

The Xincheng River wetland treatment project (Shijiuyang CW) provides a successful paradigm for a drinking water source processor. Driven by the prototype of Shijiuyang CW, two other updated larger drinking water source treatment wetlands (Guanjinggang CW, Changshuitang CW) are now already in operation and one same-scale wetland (Taishangang CW) is still in construction in the stream networks of the Yangtze River Delta, and more people will be benefited. Since the urban land resource is limited and highly valuable, the wetland has to serve multiple functions for society. Most important, people

| Item                     | Value       | LR percentage |
|--------------------------|-------------|---------------|
| Operation days (day)     | 847         |               |
| Water supply for SJY-DWP (tonnes) | 146023645 |               |
| Input DO (kg)            | 411924.28   |               |
| LR DO (kg)               | 303293.21   | 73.63%        |
| Input NH₄⁻N (kg)         | 170321.57   |               |
| LR NH₄⁻N (kg)           | 66194.91    | 38.86%        |
| Input COD₅₅ (kg)         | 832971.99   |               |
| LR COD₅₅ (kg)            | 49705.14    | 5.97%         |
| Input Fe (kg)            | 157770.52   |               |
| LR Fe (kg)               | 56228.47    | 35.64%        |
| Input Mn (kg)            | 38371.94    |               |
| LR Mn (kg)               | 8494.25     | 22.14%        |

LR: load reduction; LR DO: increased amount of DO; DO: dissolved oxygen.
love to see how the dirty water becomes clear and flows into the drinking water plant that serves their families.

3. Conclusions

Shijiu Yang Constructed Wetland (SJY-CW) adopted a semi-subsurface flow system with pond-wetland complexes as a processor of the drinking water source, in which the wetland part simulated the natural reed-bed/ditch systems in lacustrine ecotones and applied an innovative constructed root channel technology. Studying wetlands at field scale presents numerous challenges associated with the wide variability in wetland environmental conditions, and more explicit studies are required to explore the trends and relationships. This study is based on altogether 28 months of daily continual monitoring results in SJY-CW and provides valuable information about the comprehensive performance assessment of pond and plant-bed/ditch combinations that can guide future design and management considerations for the construction and restoration of drinking water treatment wetlands. The following findings stand out: (1) Pond-wetland complexes could improve the micropolluted drinking source water quality by one grade (from IV to III) according to GB 3838-2002 under hydraulic loading rate 39.2–29.2 cm/day and hydraulic residence time 3.43–4.13 days. (2) Plant-bed/ditch wetland and pond had an approximately equal (0.855–1.171:1) treatment weight but focused on separate preferential pollutants when about 35% of total inflow water amount passed through the root channels within plant beds in the present operation mode. (3) The treatment performance of major water quality indexes increased with the total area of functioning zones, temperature, and inlet concentrations. Pond and plant-bed/ditch combinations exhibited stable treatment efficiency and further upgrading treatment potential for the micro-polluted river source water. (4) Regional rainfall significantly determined the external river water levels and adversely affected the inlet water quality. It was suggested that the “hidden” diffuse pollution in the multitudinous stream branches as well as their catchments should be the controlling emphases for river source water protection in the future. (5) Shijiu Yang constructed-wetland provides a successful paradigm of a drinking water source processor. Driven by the prototype of SJY-CW, two other updated larger drinking water source treatment wetlands are now in operation and one same-scale wetland is still under construction in the Yangtze River Delta, and more people will be benefited.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jes.2015.11.006.

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