Spatial and temporal variations of water quality in an artificial urban river receiving WWTP effluent in South China
Di Zhang, Yi Tao, Xiaoning Liu, Kuiyu Zhou, Zhenghao Yuan, Qianyuan Wu and Xihui Zhang

ABSTRACT

Urban wastewater treatment plant (WWTP) effluent as reclaimed water provides an alternative water resource for urban rivers and effluent will pose a significant influence on the water quality of rivers. The objective of this study was to investigate the spatial and temporal variations of water quality in XZ River, an artificial urban river in Shenzhen city, Guangdong Province, China, after receiving reclaimed water from WWTP effluent. The water samples were collected monthly at different sites of XZ River from April 2013 to September 2014. Multivariate statistical techniques and a box-plot were used to assess the variations of water quality and to identify the main pollution factor. The results showed the input of WWTP effluent could effectively increase dissolved oxygen, decrease turbidity, phosphorus load and organic pollution load of XZ River. However, total nitrogen and nitrate pollution loads were found to remain at higher levels after receiving reclaimed water, which might aggravate eutrophication status of XZ River. Organic pollution load exhibited the lowest value on the 750 m downstream of XZ River, while turbidity and nutrient load showed the lowest values on the 2,300 m downstream. There was a higher load of nitrogen and phosphorus pollution in the dry season and at the beginning of wet season.

Key words | dissolved oxygen, nitrogen and phosphorus, reclaimed water, spatial and temporal variation, WWTP effluent

INTRODUCTION

The effluent of wastewater treatment plants (WWTPs) provides an alternative source for a wide variety of purposes, including toilet flushing in building, road cleaning, and restoration of streams as reclaimed water (van Roon 2007; Chen et al. 2013; Bai et al. 2014). Among them, the usage amount for recreational/environmental enhancement accounted for the largest part, about 34% of the total reclaimed wastewater (Yi et al. 2011). Reclaimed water is not only an environmentally beneficial solution to reduce nutrient loading to alleviate future water supply needs, but can address the increasing qualities of treated wastewater (Okun 2000; Levine & Asano 2004). Furthermore, reclaimed wastewater provides stable water quantity for recharging the surface waters for landscape and recreational use in urban centres of the cities suffering water shortage, especially during the dry season. Reclamation facilities and reuse sites are not necessarily located near one another, so reclaimed water must be transported by pipes. However, transmission lines and facilities are often an expensive cost. Therefore, supply of reclaimed water to an urban river nearby can be regarded as a more reasonable and effective choice for the administrators to accomplish the sustainable management of water sources (Campbell & Scott 2011; Van de Meene et al. 2011).

Management of the artificial waters in terms of meeting both quantity and quality requirements is a challenge (Levine & Asano 2004). Although reclaimed water has been treated to remove the majority of organic matter, nutrients and other wastes, it still inevitably contains a certain amount of pollutants (Crook & Surampalli 1996). Wang et al. (2015) analyzed the occurrence of 36 pharmaceutical and personal care products (PPCPs) in urban river water.
samples collected from Beijing, Changzhou and Shenzhen in China, and found effluent from WWTPs were the predominant pathways through which PPCPs were entering into aquatic environment in all investigated areas. Vitali et al. (1997) found that there is a direct relation of phthalate esters levels with the input of urban or industrial treated wastewaters near the sampling point in rivers and lakes of the Rieti District (central Italy). Mercury (Hg) concentrations were found to exceed the Italian quality standard for fresh-water in four major rivers in Calabria (southern Italy) (Protano et al. 2014). Thus, reclaimed water will offset the water volume of urban rivers during the dry season, but effluent with higher level pollutants fail to meet landscaping water standards, and would cause a decline in the water quality of rivers, aggravate eutrophication in artificial waters and stimulate growth of phytoplankton species (Tselentis & Alexopoulou 1996; Yi et al. 2011; Jin et al. 2014).

Municipal wastewater reclamation is playing an important role to alleviate the pressure from water shortage in many cities of China (Zhang et al. 2013). Actually, more urban centres in northern China are facing a serious water shortage crisis (Cheng et al. 2009) and, thus, WWTP effluent has been adopted to recharge artificial waters. Several projects for wastewater treatment, reclamation and reuse for landscaping water have been successfully operated for years, such as Beijing Olympic Park (Ernst et al. 2007; Qiao et al. 2011). However, successful application of these projects was based on advanced treatment processes (membrane bioreactors and specific phosphorus adsorption columns) to meet high requirements for landscaping water use (Mujeriego & Asano 1999; Oller et al. 2011). It is not practical or reasonable for other cities in China to adopt similar advanced treatment processes.

The degree of treatment depends on what purpose the water will serve. When the reclaimed water fails to meet the requirement of supplementing the urban river, upgrading the wastewater treatment process might be required to escape the deterioration of water quality of the urban river after receiving reclaimed water. Thus, reclaimed water facilities are constantly monitored to ensure that only high quality reclaimed water is distributed (Tanaka et al. 1998). Meanwhile, investigation on the influence of receiving reclaimed water on the water quality of urban rivers is also required to analyze the potential of WWTP effluent as reclaimed water (Mladenov et al. 2005; Dickenson et al. 2011). Few studies were conducted regarding the impacts of WWTP effluent on the receiving artificial waters in South China. This paper focused on the spatial and temporal variations of water quality in XZ River from April 2013 to September 2014, and demonstrated the feasibility of water reuse on a large scale and its role in sustainable management.

MATERIALS AND METHODS

Sample collection

The XZ River is located in an urban centre of Shenzhen city and runs for over 5,000 m from the reservoir spillway upstream to the Shenzhen bay downstream. The upstream (XZ1) is severely polluted by untreated domestic wastewater discharge, especially in the dry season (from October to March), while pollutants on the river bank and land will also be brought into the river due to stormwater in the wet season. The WWTP effluent is discharged upstream (XZ2) and 10 m downstream from XZ1. The volume of supplemented water is approximately 50,000 m³/d, and much higher than the river flow at XZ1 original river, which is mainly composed of untreated domestic wastewater from residents nearby.

Water samples were collected monthly from the river at nine sampling sites along the river (XZ1, XZ3–10) as well as from the WWTP effluent point (XZ2) from April 2013 to September 2014. As shown in Figure 1, sampling site XZ1 lay 10 m upstream of the replenishment point, XZ2 is the water replenishment point, while XZ3 to XZ10 are the sampling sites at 50 m, 200 m, 350 m, 750 m, 2,300 m, 2,900 m, 3,600 m and 5,000 m downstream from the discharging point (XZ2), respectively (Table 1).

Water quality analysis

Multi-parameter water quality monitoring instrument (YSI, EXO, USA) was used to measure in situ dissolved oxygen

Figure 1 | Location of XZ River in Shenzhen, Guangdong Province, China.
(DO) and turbidity. Water quality parameters, including total phosphorus (TP), ortho-phosphate (PO₄³⁻/P), total nitrogen (TN), ammonium-nitrogen (NH₄⁺-N), nitrate nitrogen (NO₃⁻-N), dissolved organic carbon (DOC) and chemical oxygen demand (CODCr), were also analyzed according to Chinese National Standards (State Environmental Protection Administration of China 2002).

Multivariate statistical techniques and data treatment

To define the relationship between the various pollutants and their influence on their temporal and spatial distribution characteristics, the analysis of parameters variation in single-dimension time or space were applied in this study (Bu et al. 2010). The factor analysis method was used to assess the effects of these parameters on water quality. The KMO and Bartlett methods were used to test the ambit of the factor analysis results. SPSS18.0 was used in the analysis process.

RESULTS AND DISCUSSION

The corresponding change in water quality along the XZ river

Sensory index

The DO of the supplementary water was higher than that of XZ River (Figure 2(a)), and the DO of the river exhibited an increasing trend until 750 m downstream with the supplementation of reclaimed water. The largest DO value (7.0 mg/L) occurred on the 750 m downstream. The increase in DO along the river was attributed to the fast flowing of river, resulting in strong disturbance and higher capacity of air to increase the DO level.

The DO began to decrease rapidly until 2,300 m downstream. The average DO value fell to 2.0 mg/L on the 3,600 m downstream, and was less than 2.0 mg/L on the 5,000 m downstream, which is less than the Level V Environmental Quality Standard for surface water in China (2 mg/L, GB3838-2002). Many substances that consumed oxygen existed on the downstream, such as ammonium and organic matter. The slowing water flow means that those substances had enough time to react with the DO, thus ensuring its rapid degradation. The results also showed that the supplementary water could increase the DO of the receiving water to 7.0 mg/L, resulting in higher self-purification performance. The effective distance (defined as the distance from the discharging point to the inflexion point) for DO of the river was nearly 750 m. If a DO of 2.0 mg/L was set as an ecological security level, the effective distance could be regarded nearly 2,300 m.

Figure 2(b) shows that the turbidity of WWTP effluent ranged from 15 to 24 nephelometric turbidity units (NTU) (average 16.7 NTU), much lower than that of the upstream river (from 37 to 116 NTU, average 69.2 NTU). The average turbidity gradually decreased from 48.4 to 24.9 NTU along the river until 2,300 m downstream from the discharging site. Therefore, the turbidity of the receiving water was significantly decreased after receiving WWTP effluent. Upstream is shallow and, thus, is prone to sediment deposition in a manner akin to that in a horizontal flow grit chamber. However, the pollutants in the downstream with greater depth were released from the sediment to the water, resulting in resuspension of particulate matter.

Organic pollutant indices

The DOC and CODCr concentrations of WWTP effluent were much lower than those upstream (Figure 2(c) and 2(d)). Thus, organic pollutants in the downstream decreased after receiving WWTP effluent. The decreasing trend of DOC and CODCr before 750 m downstream might be attributed to the dilution effect and biodegradation because of higher DO level. However, they began to show an increasing trend after that, and remained at the same level as the original discharging point on the 2,300 m downstream. The reason might be the release of organic matter and biological decomposition.

Phosphorus-containing compounds

Figure 2(e) shows that the TP concentration of WWTP effluent (0.4 mg/L) was much lower than that of upstream in the
Figure 2 | Variation of water parameters along the XZ River.
river (2.2 mg/L). The TP concentration quickly decreased to 1.3 mg/L at 50 m from the discharge point and decreased to 0.66 mg/L on the 2,300 m downstream. Therefore, the TP arising from WWTP effluent discharge can be effectively removed and may not aggravate water eutrophication. The reason was that the TP concentration of WWTP was much lower and the granular phosphorus adsorbing any particulate matter became deposited as sediment, the dissolved phosphorus changed only a little from 350 to 2,300 m downstream. The change of the concentration of dissolved phosphorus was the same as that of TP at sampling points upstream from the discharge.

However, from 2,300 m downstream, both TP and \( \text{PO}_4^3-\text{P} \) concentrations increased gradually (Figure 2(e) and 2(f)). This might be correlated with the release of phosphate and the increased turbidity. This study showed that supplementary water can effectively decrease the TP and \( \text{PO}_4^3-\text{P} \) concentrations over an effective distance of nearly 2,300 m.

Nitrogen-containing compounds

Figure 2(g), 2(h) and 2(i) show the variations of TN, \( \text{NO}_3^-\text{N} \) and \( \text{NH}_4^+\text{-N} \) in XZ River after receiving WWTP effluent, respectively. The TN concentration of WWTP effluent (average 19.6 mg/L) was higher than that of upstream (average 17.5 mg/L). The TN concentration increased to 18.8 mg/L at 50 m downstream from the discharge point. The TN concentration remained at around 19.0 mg/L from 50 to 2,300 m downstream, and then decreased to 17 mg/L from 2,300 to 5,000 m downstream. The TN concentrations surpassed the worst Level V Standard for surface water (2 mg/L, GB 3838-2002). The \( \text{NH}_4^+\text{-N} \) concentration in the WWTP effluent (average 7.4 mg/L) was much lower than that upstream (average 11.5 mg/L), and gradually decreased from 11.5 to 9.8 mg/L at 50 m downstream from the discharging point XZ2. It decreased to 7.1 mg/L from 50 to 2,300 m downstream, and then gradually increased to 8.5 mg/L from 2,300 to 5,000 m downstream. The \( \text{NO}_3^-\text{N} \) concentration of WWTP effluent (average 9.5 mg/L) was much higher than that upstream (average 2.7 mg/L). The \( \text{NO}_3^-\text{N} \) concentration increased to 6.3 mg/L at 50 m downstream from the discharging point. The reason might be that \( \text{NH}_4^+\text{-N} \) was converted into \( \text{NO}_3^-\text{N} \) with the nitrification of nitrifying bacteria and other aerobic bacteria. The \( \text{NO}_3^-\text{N} \) concentration was stable at around 8.1 mg/L from 50 to 2,300 m downstream, and then decreased to 4.9 mg/L from 2,300 to 5,000 m downstream. The results indicated that WWTP effluent was prone to cause eutrophication by enhancing the loads of TN and \( \text{NO}_3^-\text{N} \).

The effect of WWTP effluent discharge on improvement of river self-purification capacity

The corresponding transformation among TN, \( \text{NO}_3^-\text{N} \) and \( \text{NH}_4^+\text{-N} \) in the XZ River, along with changes in DO content, were investigated to evaluate the improvement of river self-purification ability on nitrogen pollutants due to WWTP effluent discharge, as shown in Figure 3(a). At 600 m downstream from the discharge point, the DO concentration increased to 7.0 mg/L and remained steady until 750 m downstream. The dominant nitrifying bacteria and other aerobic microorganisms were in ascendance due to the aerobic condition of water bodies. In this section, the \( \text{NH}_4^+\text{-N} \) concentration decreased from 9.8 to 7.1 mg/L, while the \( \text{NO}_3^-\text{N} \) concentration increased from 6.3 to 8.6 mg/L. The reason might be that the ammonium was transformed to nitrate due to the nitrification process. In theory, 1 mg of ammonium nitrogen oxide consumes...
4.5 mg of DO. In this study, keeping a high DO level was an important factor in guaranteeing the stability of this nitrification process. Supplementary water can improve the concentration of DO, suppress the sediment release process, and create an advantage for nitrifying bacteria and other aerobic organisms. However, the DO concentration decreased rapidly after 2,300 m downstream. It had fallen to approximately 2 mg/L by 3,600 m downstream, while it further decreased to below 2 mg/L by 5,000 m. The water was hypoxic and in an anaerobic state and, thus, anaerobic microorganisms such as denitrifying bacteria were in ascendance. In this section, the NH$_4^+$-N concentration increased from 7.1 to 8.6 mg/L, and the NO$_3^-$-N concentration decreased from 8.6 to 4.9 mg/L. Therefore, the effect of the DO had been completely subsumed, and the river had lost its self-purification ability in this anaerobic environment. The results showed that supplementary water was helpful in improving the DO level in the water, thus increasing the river’s self-purification ability with respect to NH$_4^+$-N pollution in the water body: such purification occurred within an effective distance of 2,300 m.

Correlation analysis of particulate matter (turbidity) and TP was undertaken to evaluate the improvement of river self-purification ability after the addition of the supplementary water. As shown in Figure 3(b), TP and turbidity were linearly correlated. The results showed that the turbidity gradually decreased and particulate pollutants, such as TP and COD, then also gradually decreased. The river’s improvement of river self-purification ability lay within an effective distance of 750 m downstream from the effluent discharge point.

Table 2 | Water quality parameters: load matrix after VARIMAX rotation

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<th>Water quality parameter</th>
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<th>3</th>
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<td>0.724</td>
<td>-0.312</td>
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<tr>
<td>TP</td>
<td>0.092</td>
<td>0.869</td>
<td>-0.098</td>
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<tr>
<td>TN</td>
<td>0.96</td>
<td>-0.051</td>
<td>-0.009</td>
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<tr>
<td>NTU</td>
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<tr>
<td>DO</td>
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<tr>
<td>NH$_4$-N</td>
<td>0.783</td>
<td>0.279</td>
<td>0.16</td>
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<tr>
<td>NO$_3$-N</td>
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<td>-0.072</td>
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<td>TOC</td>
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<td>-0.85</td>
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<tr>
<td>DN</td>
<td>0.957</td>
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<tr>
<td>DP</td>
<td>0.109</td>
<td>0.783</td>
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Table 3 | Eigenvalues and cumulative variance during principal component extraction

<table>
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<tr>
<th>Initial eigenvalue</th>
<th>Total Variance %</th>
<th>Cumulative%</th>
<th>Extraction of sum of squares loaded</th>
<th>Total Variance %</th>
<th>Cumulative%</th>
<th>Rotate the sum of squares loaded</th>
<th>Total Variance %</th>
<th>Cumulative%</th>
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<td>23.842</td>
<td>52.968</td>
<td>2.623</td>
<td>23.842</td>
<td>2.739</td>
<td>24.904</td>
<td>51.368</td>
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<tr>
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<tr>
<td>5</td>
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<td>89.95</td>
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which each part whose characteristic value exceeded unity was extracted, and rotated through the maximum variance method: three components of load matrix are shown in Table 2. In addition, Table 3 shows that the extraction of three kinds of main component contributed 69.127% of overall cumulative variance and, thus, it basically met the needs of the analysis.

Principal component 1 contributed 29.125% of overall cumulative variance, and showed a strong correlation with TN, NH$_4^+$-N, NO$_3^-$-N and DN. It showed that principal component 1 represented the nitrogen pollution. Principal component 2 contributed 23.842% of overall cumulative variance, and showed a strong correlation with PO$_4$-P, TP, DP and NTU. It meant that principal component 2 represented the phosphorus pollution. In addition, high correlations between phosphorus and turbidity verified that the particulate phosphorus was the predominant form. Principal component 3 contributed 16.159% of overall cumulative variance and showed a strong correlation with temperature. It showed that principal component 3 represented the influence of water temperature on water quality. According to the analysis of each principal component score, it is feasible to understand the temporal and spatial distributions prevailing in XZ River with respect to the characteristics of nitrogen and phosphorus pollution. A higher score means more significant influence of that component.

**Spatial characteristics.** In all monitoring cycles (Figure 4(c)), the principal component 1 (nitrogen pollution) score upstream from the discharge point was lower than that at S1, was highest at S2 (effluent discharge point), and decreased slowly to S4 (250 m downstream), increased slightly at S5 (350 m) and S6 (750 m), then gradually reduced thereafter. This revealed that the supplementary water’s nitrogen pollution load was higher and, thus, the reclaimed water’s nitrogen pollutant contribution was greater. For principal component 2 (phosphorus pollution), maximum and minimum scores were found at S1 and S2. The scores showed a decreasing trend from S3 to S7, but an increasing trend from S8 to S10. This showed that the upstream original water and downstream sediment pollution were the main source of phosphorus pollution, while the supplementary water’s phosphorus pollution load was low, and it means a dilution effect of reclaimed water in the channel.

The study showed that the key area of nitrogen pollution lay within the first 2,300 m downstream of the effluent discharge point, and the supplementary water exerted a greater influence on the nitrogen pollution in the river. Phosphorus pollution mainly occurred in the original water and between 3,600 and 5,000 m downstream. Supplementary water decreased the P level and, thus, improved the phosphorus pollution status.

**Temporal characteristics.** Data from throughout the monitoring period are shown in Figure 5. Considering the
The differences between these points, they were further divided into upstream (XZ1), discharge point (XZ2), 250 to 750 m (XZ3 to XZ6), 2,300 to 2,900 m (XZ7 and XZ8) and 3,600 to 5,000 m (XZ9 and XZ10).

The original water is shown in Figure 5(a). Principal component 1 (nitrogen pollution) reached a maximum score in December, higher scores in October, November, and January, lower (but nevertheless still positive) scores from February to May, and a negative score at other months. Principal component 2 (phosphorus pollution) reached a maximum score in March, with the second highest score found in October, higher scores in January, February, April, May, August, and November, and low (but nevertheless still positive) scores in June and July. The results showed that the phosphorus pollution was serious in addition to the peak value of the original water in December, and it was also more serious during the dry season. The situation of the supplementary water is shown in Figure 5(b): principal component 1 (nitrogen pollution) reached its maximum score in December, and had a negative score in March, May, and October. The values of October, December, January, February, and April were greater than 1.0. Principal component 2 (phosphorus pollution) only returned a positive score in May. The results showed that nitrogen was the main pollutant at the effluent discharge point. The pollution load was higher in the dry season than in the wet season. Between 250 and 750 m downstream (Figure 5(c)), principal component 1 (nitrogen pollution) showed that a score distribution and absolute score was similar to that at the effluent discharge point. Principal component 2 (phosphorus pollution) showed a score distribution similar to that of the original water, but the score itself was significantly reduced. Between 2,300 to 2,900 m downstream (Figure 5(d)) and 3,600 to 5,000 m (Figure 5(e)), principal component 1 (nitrogen pollution) and principal component 2 (phosphorus pollution) had score distributions which were similar to those upstream, but their scores themselves decreased further.

This study showed that the phosphorus pollution in the original water upstream from the effluent discharge was serious in addition to that in December. Supplementary discharge points should be paid more attention with regard to nitrogen pollution. Nitrogen pollution was more serious in the dry season than at other times. In brief, the water pollution load was higher in the dry season than in the wet season. Regarding the phosphorus pollution, the pollution was relatively serious during the dry season. The middle part of river kept only a low level of phosphorus pollution. The phosphorus pollution levels downstream increased significantly during the dry season and at the beginning of the wet season.
CONCLUSIONS

This research studied the temporal and spatial variations of pollutants in XZ River after receiving reclaimed water from WWTP effluent. The results show that the DO concentration can be obviously increased with the addition of reclaimed water as a supplement source. The improvement of the water’s DO level would help to control the release of sediment-load-based pollutants and to promote the self-purification ability with regard to ammonium nitrogen pollution. Supplementary water can effectively reduce overall turbidity. Low turbidity of reclaimed water could effectively continue for a distance of 2,300 m downstream. The combined organic pollution load (COD, DOC) can be reduced in the effective distance of 750 m.

The key area for phosphorus pollution lay upstream in the original river and between 3,600 m and 5,000 m downstream. Supplementary water could effectively reduce the concentration of phosphorus 2,300 m downstream, but the TP concentration remained higher than 0.6 mg/L (at Level V on the Chinese surface water rating). Nitrogen pollution was more serious in the dry season and at the beginning of the wet season. Although the supplementary water deteriorated the river quality due to increased TN and NO3-N pollution loads, it facilitated the reduction of the NH4-N concentration in the river.

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