Increased use of reclaimed water could be one of the solutions to Beijing’s growing water shortage, particularly for non-potable (e.g. landscaping) purposes. The dragon-shaped river, a large artificial waterscape built on the site of the 2008 Beijing Olympic games, offers a useful case study of the issues and challenges attendant on wastewater reclamation and reuse. Of particular interest is the use of phytoremediation techniques for bioremediation of nutrient loads. This article presents the results of ongoing monitoring which indicate that phytoremediation is succeeding in preventing eutrophication, though some challenges, notably management of aquatic biomass, remain.

Introduction

With increasing population, urbanization and climate change, water shortages are now appearing all over the world, including in China’s capital city, Beijing. In an average year, Beijing has 2680 million m$^3$ of available water from existing sources, or about 123.8 m$^3$ per capita, making Beijing a water-stressed city by international standards (National Bureau of Statistics of China, 2016; Staddon, 2010). Water experts are therefore developing multiple alternative water resources to help address this imbalance. Currently there are four main water resources for water supply into Beijing: surface water, groundwater, the South-North Water Transfer Scheme and reclaimed water, accounting for 13%, 55%, 10% and 22% of total available resources, respectively (Jensen & Yu, 2016). The 22% of water supply provided through wastewater reclamation in 2013 amounted to around 860 million m$^3$ and is expected to rise to 1200 million m$^3$ by 2020 as new schemes are completed. Wastewater reuse is clearly a key part of Beijing’s future water balance.

Reclaimed water reuse is receiving more and more attention from water specialists, with well-known and successful systems in place in locations as diverse as Windhoek, Namibia, and Singapore (Bixio et al., 2006; Jensen & Yu, 2016; Staddon, 2010). These are systems for direct potable reuse of treated wastewater, however, and there are many,
many more examples of non-potable wastewater reuse. Non-potable wastewater reuses can include irrigation, industrial cooling water, car washing, landscape irrigation, and ecological/environmental supplementation during periods of low base flow. Reclaimed water quality can be an issue, however. Physical and chemical contaminants such as pH, chemical oxygen demand (COD), total phosphorus (TP) and total nitrogen (TN), as well as microbial contamination, need to be reduced to below regulatory norms before even non-potable use is possible (Bixio et al., 2006; Huertas et al., 2008; Salgot, Huertas, Weber, Dott, & Hollender, 2006). In 2000, quality standards for reclaimed water for non-potable use were published by the Chinese government, and these standards have been revised several times since (Yi, Jiao, Chen, & Chen, 2011). Current standards stipulate that $\text{BOD}_5$ (biological oxygen demand calculated by the five-day method) should be below 6 mg/L, TN should be below 15 mg/L, and TP should not exceed 0.5 mg/L. Even within these standards, however, there remains a risk of eutrophication in certain circumstances (Soyupak, Mukhallalati, Yemi, Bayar, & Yurteri, 1997). Moreover, the complex structure of water quality regulation (with multiple departments exercising control over different sources of wastewater and different potential end uses) makes regulatory compliance challenging (Jensen & Yu, 2016). Therefore, reclaimed water reuse faces both technical and regulatory challenges (Liu & Persson, 2013).

As host of the 29th Olympic Summer Games in summer 2008, China strongly promoted the concept of a high-tech and environmentally sustainable games, and the games venues themselves were designed to showcase Chinese developments in sustainable urbanization, including reclaimed water use and rainwater harvesting (Jensen & Yu, 2016). In particular, the main Olympic site master plan included a specially built wastewater treatment plant, linked to a series of slow-flow water bodies which together form a semi-natural ecosystem – the dragon-shaped river – which terminates in the Dragon Lake, now considered a beauty and biodiversity hotspot. In this study, we focus on the use of phytoremediation to address eutrophication pressures in the dragon-shaped river.

**An overview of the water quality situation of the dragon-shaped river at the Beijing Olympic Park**

The Beijing Olympic Park was the main location for the games, and many of its structures (such as the Bird’s Nest and the Water Cube) have become iconic buildings. Of particular interest to water managers and scholars is the artificial river/lake complex, shaped like a dancing dragon, which was designed to provide a semi-natural structure integrating the Olympic site along a north-south axis. As shown in Figure 1, the head of the dragon forms the central water feature of the Olympic Forest Park at the northern end of the site; the body runs down the eastern side of the park; and the tail coils around the National Stadium (the Bird’s Nest) at the southern extremity. The watershed in the Olympic Park is the world’s largest artificial landscape using reclaimed water as the sole water source, with a total water surface area of 84.2 hm$^2$, and a total water storage capacity of 1.3 million m$^3$.

Of this total surface area, the main dragon-shaped river and lake structures occupy 48.5 hm$^2$ and have a total water storage capacity of 0.75 million metres$^3$. The river itself is 2.7 km in length and 20–125 m wide, and its depth varies from about 0.6–1.2 m. The
river is divided into nine individual sections by eight road bridges, with each section connected by an underground culvert. Water flows northwards from the first section (the tail of the dragon, W1 in Figure 1) to the last section (the neck of the dragon, W9). The water gradually deepens from the edges inward to the centre, but only to a maximum depth of 1.24 m at its deepest point in section W8.

The amount and frequency of reclaimed water inflow varies considerably, for example between 2400 and 3500 m$^3$/d. Despite this variability, key nutrients (TN, TP, NH$_3$-N) in the reclaimed water usually meet the wastewater quality standards for ‘scenic water’ in China (Table 1). During normal operation, no untreated wastewater is discharged into the river. Non-point contamination does arrive in surface water

Table 1. Main chemical parameters of reclaimed water at the W1 inlet (see Figure 1 for location).

| Sampling date       | NH$_3$-N (mg/L) | Total nitrogen (mg/L) | Total phosphorus (mg/L) | Chemical oxygen demand (mg/L) | Turbidity (NTU) |
|---------------------|-----------------|-----------------------|------------------------|-------------------------------|----------------|
| 20 September 2010   | 0.35            | 11.0                  | 0.04                   | 3.96 (Cr)                     | 18.0           |
| 21 October 2010     | 0.21            | 2.28                  | 0.04                   | 4.3 (Cr)                      | 4.79           |
| 21 June 2011        | 1.6             | 11.0                  | 0.2                    | 7.96 (Cr)                     | 21.0           |

Note: Cr = chromium. COD-Cr is a standard measurement method for COD value which uses K$_2$Cr$_2$O$_7$ as oxidant to determine COD value.
runoff, but this contributes only 4.04% of the TN, 15.2% of the TP, 8.17% of the COD and 14.47% of the NH$_3$-N loading. The issues related to non-point source contamination are not specifically discussed in this article.

By 2010, signs of eutrophication were appearing: floating (organic) material was reported in the river, and there were growing numbers of complaints about the smell from the water. The most likely explanation for this was relatively high levels of nitrogen and phosphate, combined with the shallow water level, the low velocity of water flow from W1 to W9, and sufficient sunshine reaching the bottom of the shallow sections to create perfect conditions for algal and microbial overgrowth, along with the foul smell – in other words, eutrophication was occurring.

To improve the situation, aquatic plants were placed in all nine sections to promote phytoremediation of nutrients and thereby reduce eutrophication. The process had three steps: cleaning the river channel of algal biomass; planting submerged plants according to a carefully planned scheme; and the operation, monitoring and management of the resulting enhanced water system. In the first step, the river channel was cleared of weeds and microorganisms were added to re-activate bottom sediments and form a benthic microbial degradation system. In the second step, submerged plants were selected and planted in the nine sections in carefully calculated ratios and densities. The selection of the plants was based on the measured contamination levels and a review of the secondary literature on phytoremediation. This literature (e.g. Gross, Erhard, & Iványi, 2003; Hilt & Gross, 2008) suggests that plants such as Ceratophyllum demersum L. (hornwort) and Najas marina L. (spiny water nymph) release allelochemicals that inhibit anaerobic decomposition, a primary cause of foul smells and turbidity. These plants, and also plants from the Elodea (waterweed) and Potamogetonaceae (pondweed) families, can be assembled into clumps or complexes that work together in the river, with different allelochemicals released by different plants, so that most kinds of harmful algae are inhibited (Körner & Nicklisch, 2002). Such constructed plant communities can also inhibit the production of harmful types of cyanobacteria. In the final step, a monitoring programme was put in place to assess the contribution of each basin to phytoremediation of target pollutants (TN, TP, COD).

The ecological engineering was completed by the end of 2010. The monitoring began two years later, and from April 2013 to July 2014, samples were taken twice per month in each of the nine segments (Figure 1, W1 to W9), at about 0.1 m below the surface, except during winter, when the surface freezes. The water quality parameters measured include COD, TN, ammonia (NH$_3$-N) and TP, and sample analyses were conducted in accordance with the methods described in the state publication, ‘Water and Wastewater Monitoring and Analysis Method’ (State Environmental Protection Administration of the People’s Republic of China, 2002).

**Measured impact of phytoremediation**

**Landscape effects before and after planting**

The landscape’s scenic value improved considerably after the introduction of the submerged plants. Before, the water had looked green, with grey suspended solids and poor transparency, as well as the much-commented-upon foul smells.
Afterwards, the water was clear enough to see directly to the bottom, and both surface scum and foul smells largely disappeared. Since the implementation of the submerged plant communities, no return of eutrophic conditions was observed, even in hot weather. The submerged plants seem to have reduced turbulence in the water bodies, supported sedimentation and prevented sediment resuspension, thus increasing transparency (Horppila & Nurminen, 2003). They also improved circulation of energy and gases (particularly oxygen) between water, sediments and plants, thus forming a healthier and more integrated system with higher phyto and bio remediative abilities.

**Main contaminants in the dragon-shaped river**

After 12 months of monitoring the water quality in the nine sections, the results were as follows. Both TN and TP decreased progressively from section W1 to section W9, though the results for TN were the most impressive. This gradient of TN and TP concentrations was in accordance with expectations – reclaimed water fed in at the beginning of section W1 flows along from W2 to W9, with nutrient levels decreasing in each successive section (Figure 2). For TP concentration, as it was initially low (less than 0.4 mg/L) in the reclaimed water in W1, measured reductions were smaller. The average TP concentrations in the sections from W1 to W9 were normally below 0.1 mg/L, which meets the requirement of third-class surface water quality in China (the standard for third-class water is $\text{TP} \leq 0.2 \, \text{mg/L}$), indicating that the main contaminant in the dragon-shaped river is nitrogen.

A closer look at TN concentration change from W1 and W9 was undertaken. The TN values obtained during the 12-month monitoring period fluctuated considerably. One reason may be non-point pollution from rainfall and resultant surface water runoff, especially from nutrient application by horticulturalists and landscape

![Figure 2. Total nitrogen (TN) and total phosphorus (TP) change from section W1 to section W9 (see Figure 1 for locations).](image-url)
managers. Seasonal effects related to the submerged plant system could also explain some of this variation. Beijing’s climate is characterized by a typical north temperate semi-humid continental monsoon climate, with hot and rainy summers and cold and dry winters. Both spring and autumn are relatively short. The TN concentration was relatively low in warmer summer temperatures. It appears that the sunshine and high temperatures of summer are good for plant growth, and therefore for nutrient absorption and transformation. TN levels were usually higher at other times of the year.

Overall, we conclude that the installation of engineered plant communities has been successful in reducing eutrophication pressures in the dragon-shaped river. There is however a consequence of considerable importance for the sustainability of the new system. Harvesting of aquatic plant biomass is very important in maintaining macrophytic plant communities’ purification potency. Thus, regular management of submerged plants is essential, or decomposing submerged macrophytes will release nitrogen back into the water, reducing nitrogen removal efficiency (Feng et al., 2008; Vymazal, 2002; Vymazal & Kröpfelová, 2009) and increasing COD and BOD$_5$. Timely harvest in summer could also contribute to better nutrient removal by promoting additional fresh growth, and therefore bioremediation.

To determine the bioavailability of different forms of nitrogen, ammonia levels were also monitored at each sampling point. Ammonia concentrations were very low compared with TN concentrations in all sections. Ammonia concentrations in all the samples were under, and usually well under, 1 mg/L, which meets the requirement of third-class water according to the regulatory surface water standard used in China. It is already recognized that submerged macrophytes have a better nitrogen removal capacity compared to emergent macrophytes, because they can absorb nitrogen from both sediment and water through root and body (Kadlec, 2006; Taguchi & Nakata, 2009). In the dragon-shaped river, substances like nitrogen (TN and NH$_3$-N) and phosphorus in reclaimed water can survive as necessary nutrients for submerged plants to grow and develop, some (such as ammonia) can be absorbed by plants directly, and some can be utilized metabolically, reducing residual contaminant volumes.

The oxygen concentration decreased with depth; thus the availability of dissolved oxygen at the bottom is limited. With the submerged plants in the water system, oxygen can be transferred by plant root, forming an aerobic-anoxic-anaerobic environment in the root zones, which provides conditions for the formation of nitrite and nitrate from nitrogen. Therefore we conclude that initially TN concentrations (in W1, W2 and W3) are partly transformed by high nitrite and nitrate production, with ammonia concentrations remaining low.

Compared with nitrogen and phosphorus, COD levels in the water system were not similarly reduced from section W1 to section W9. COD concentrations from W1 to W9 were similar, and even showed some increase as surface runoff entered the system. The highest COD concentration was in W6 (106 mg/L), but observed values were mainly in a range of 20–40 mg/L. COD removal is mainly dependent on the activity of microorganisms by the processes of aerobic or anaerobic degradation (Sani, Scholz, & Bouillon, 2013; Vymazal, 2002), but there are not enough filters in the submerged plant ecosystem for the formation of the necessary biofilm, so little or no COD is removed. Based on the current ecosystem, we suggest that a constructed wetland could
be built along the river basin to improve COD levels and reduce environmental risk (Vymazal & Kröpfelová, 2009; Zhang et al., 2014).

From the basic water parameter analysis in the dragon-shaped river, it can be concluded that the water quality was improved by the implementation of engineered aquatic plant communities, but it is still hard to meet the surface water standard, and there is still a risk of eutrophication related to surface runoff along the system. Nevertheless, with these aquatic plants in place the reclaimed water can safely be used to augment flows through the dragon-shaped river and into Dragon Lake. Therefore, the submerged plants played a key dual role in the dragon-shaped river: removing nutrients, as well as inhibiting the growth of harmful algae.

**Issues and challenges in reclaimed water reused for landscape values**

The dragon-shaped river is a good example of reclaimed water implementation in China, and its experience can be compared with similar projects elsewhere in China and around the world. However, our study shows that there are still persistent challenges, particularly relating to sustained nutrient removal across the broader spectrum (nitrates, nitrites, etc.) and the sustainable management of resulting plant biomass. As can be seen from the water quality analysis of the whole dragon-shaped river, little or no COD was removed through planting, so there is certainly a need for further re-engineering of the system with a view to reducing COD levels. Moreover, harvesting of submerged plants is an effective way to physically remove bio-accumulated nutrients (and other contaminants, e.g. metals) from the river. Indeed, regular removal of biomass is necessary, otherwise submerged macrophytes will eventually release nitrogen back into the water during decomposition. Final disposal options for this submerged plant biomass (up to 10 tonnes during the summer season) are still under development (Feng et al., 2008). The freshly harvested plants are rich in water, with moisture content of more than 90%, and could be used as feedstock for anaerobic digestion-based methane recovery. Another option might be co-composting with other wastes, not least because the harvested materials are rich in compost-friendly nutrients (N, P, K). Without careful attention these system wastes could create potentially damaging leachate runoff and a perfect breeding ground for mosquitoes and flies. Study of the optimal management of harvested biomass from the dragon-shaped river is currently being undertaken by the authors of this article.

Another problem follows from the under-recognized challenge of integrating wastewater reuse schemes into existing ‘conventional’ treatment systems or treated water discharge management systems. With respect to linking alternative water supply systems to conventional systems, one development path could be to disaggregate distribution of potable and non-potable supplies by creating a complete ‘dual’ reticulation system. This is of course enormously expensive and disruptive. Another development path could be to upgrade treatment of wastewater to the point where it meets Chinese government standards for drinking water, but this is as yet a long way off. It is also not certain that increasing production of non-potable standard treated wastewater will necessarily compensate for increased abstractions and pollutant discharges and reduced natural inflows in the natural environment.
Conclusions

From this case study of Beijing’s dragon-shaped river system, it can be seen that without phytoremediation water quality struggles to meet the national environmental quality standards for surface water and actually tends towards eutrophic conditions. As more and more artificial lakes and rivers start to receive reclaimed water as a supplement to natural inflows, phytoremediation may be a useful option for avoiding eutrophication and attendant aesthetic problems. It is environmentally friendly and cost-effective to employ an engineered plant-based treatment system, and the management of the dragon-shaped river has been a success. Currently, however, there are no specific standards or regulations for such approaches to water quality management. There is also a need for design and engineering guidance appropriate to Chinese urban conditions. Thus, there is an urgent need for evidence-based guidelines for reclaimed water and sustainable landscape management, including water quality control and landscape impact evaluation, as well as life cycle–focused management of macrophytes in the ecological system. There is also an emerging debate about how such ‘decentralized’ solutions can integrate with ‘centralized’ solutions to best achieve water quality outcomes (Jensen & Yu, 2016) – the experience of the dragon-shaped river could be quite instructive.

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