



On the risks from sediment and overlying water by replenishing urban landscape ponds with reclaimed wastewater[☆]

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ABSTRACT

The extensive use of reclaimed wastewater (RW) as a source of urban landscape pond replenishment, stimulated by the lack of surface water (SW) resources, has raised public concern. Greater attention should be paid to pond sediments, which act as 'sinks' and 'sources' of contaminants to the overlying pond water. Three ponds replenished with RW (RW ponds) in three Chinese cities were chosen to investigate 22 indices of sediment quality in four categories: eutrophication, heavy metal, ecotoxicity and pathogens risk. RW ponds were compared with other ponds of similar characteristics in the same cities that were replenished with SW (SW ponds). Our results show a strong impact of RW to the eutrophication and pathogenic risks, which are represented by organic matter, water content, total nitrogen, total phosphorus and phosphorus fractions, and pathogens. In particular, total phosphorus concentrations in the RW pond sediments were, on average, 50% higher than those of SW ponds. Moreover, the content of phosphorus, extracted by bicarbonate/dithionite (normally represented by BD-P) and NaOH (NaOH-P), were 2.0- and 2.83-times higher in RW ponds, respectively. For pathogens, the concentrations of norovirus and rotavirus in RW pond sediments were, on average, 0.52 and 0.30- log times those of SW ponds. The duration of RW replenishment was proved to have a marked impact on the eutrophication and pathogens risks from sediments. The continued use of RW for replenishment increases the eutrophication risk, and the pathogens risk, especially by viral pathogens, becomes greater.

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1. Introduction

With the increase in human population and the development of urbanization, extensive use of water resources leads to a lack of surface water (SW) to replenish the landscape ponds within the urban area that are used for aesthetic and recreational purposes. Most landscape ponds are shallow with high levels of evaporation. Therefore, the landscape effects of these water bodies are often barely satisfactory because of inadequate water supply. This is a

common problem in cities with water shortages (Englert et al., 2013; Yi et al., 2011). Because of its consistent availability and controllability, the effluent from wastewater treatment plants (WWTPs) is already widely used to supply landscape water bodies in many countries and areas, such as the Beijing Olympics Lake in China (Li et al., 2015), Shihwa Lake in Korea (Oh et al., 2010) and Elsinore Lake in America (Marks, 2006).

The differences in quality of SW and reclaimed wastewater (RW) have raised concerns about the safety of landscape ponds replenished with RW (RW ponds). Currently, because visual effects are the most obvious indicators of urban landscape ponds and because of the relatively high concentration of nutrients contained in RW, eutrophication of these water bodies has attracted the most concern (Dakos et al., 2009; Winder and Cloern, 2010). In particular, the phosphorus in WWTP effluents is readily absorbed by algae (Muhid et al., 2013) and utilized in the production of biomass, often manifested in algal blooms. However, urban landscape ponds also

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offer recreational use. Therefore, their ecological and health effects should be of concern. Furthermore, RW may contain other contaminants that are not present or appear in smaller concentrations in SW. These emerging contaminants include pharmaceuticals, illicit drugs, personal care products (Maier et al., 2015; Onesios et al., 2009; Petrie et al., 2015), bacterial and viral pathogens from faeces (Zhou et al., 2015) and heavy metals (Liu et al., 2005). In addition, new contaminants are produced during the treatment process, such as microbial products with recalcitrant properties (Englert et al., 2013; Michael-Kordatou et al., 2015), and disinfection by-products (DBPs) (Abusallout and Hua, 2016). Problems have arisen from the use of RW that have indicated the presence of these harmful substances in RW directly or indirectly. For example, the deleterious effects of heavy metals on yields have been observed in soils irrigated with RW (Liu et al., 2005). Furthermore, health risks to irrigation workers and the public are posed by exposure to microorganisms in RW used for landscape irrigation (Weber et al., 2006). Moreover, health problems caused by pathogens in RW is drawing wide attention (Teklehaimanot et al., 2015; Toze, 2006). These include bacillary dysentery caused by *Shigella* (Zhou et al., 2015), poliomyelitis and neonatal multi-organ failure caused by enterovirus (EV) (Muehlenbachs et al., 2015), and forceful vomiting and watery diarrhoea caused by norovirus (NV) (Teunis et al., 2008). Therefore, the necessity to analyze the potential impacts of replenishing urban landscape ponds with RW more comprehensively cannot be overemphasized.

Sediment acts as both 'sinks' and 'sources' for contaminants in the overlying water and poses a great impact on the stability of landscape ponds ecosystems. As a 'sink' for pollutants in the overlying pond water, the sediment can adsorb nitrogen, phosphorus, heavy metals, and micro-organic contaminants, accumulate dead algae and so on. Therefore, contaminants concentrations in sediment could be 2–5 orders of magnitude greater than those in the overlying water (Avila-Perez et al., 1999; Dachs et al., 1999; Fytianos and Kotzakioti, 2005; Zahra et al., 2014). Moreover, sediment could be a gathering place for pathogens because of the lack of ultraviolet (UV) exposure and the effects of zooplankton (Bradshaw et al., 2016; McGuigan et al., 2012; Staggemeier et al., 2015). The high organic matter (OM) content would allow pathogens to survive and become active in the sediment, causing the concentrations to increase 1–4 orders of magnitude (3–4783) higher than those in the overlying water (Boone and Gerba, 2007; Garzio-Hadzick et al., 2010; John et al., 2009). On the one hand, the function of sediment as a habitat and nutrients source for benthic organisms would affect its 'sink' properties. Consequently, pollutants such as heavy metals and micro-organic contaminants may be enriched in the benthic animals and plants and enter the food chain (Huang et al., 2013; Kalantzi et al., 2014), thus, threatening the water resources used for recreational purposes. On the other hand, high concentrations of pollutants in sediment would also pose greater risks to the aquatic life and ecosystems in the overlying water. Furthermore, because landscape ponds are generally shallow, the sediment could act as a contaminant 'source' to the overlying water when disturbed by natural or human recreational activity, which may result in polluting materials being released back into the overlying water column (Flora et al., 1975; Goyal et al., 1977; Huang et al., 2013). This would pose risks to the aquatic life and ecosystems in the overlying water. Nutrients released from sediment have been shown to be the main reason for increased algal booming in summer (Mayer et al., 1999). The heavy metals and micro-organic contaminants released from sediment could also be absorbed by animals and plants in the overlying water, thereby affecting their growth and reproduction (Huang et al., 2013; Kalantzi et al., 2014). Although tourists do not touch landscape pond sediments directly, risks to human health can be

caused by skin contact and ingestion of the overlying water during recreational activities (Dorevitch et al., 2011; Toze, 2006; Vergara et al., 2016). It reported that the most probable cause of human health risks from water bodies is the resuspension of pathogens from underlying sediment (Brookes et al., 2004; Xagorarakis et al., 2014). Overall, the ecological and health risk could be significantly affected by the quality of sediment in landscape ponds. Hence, it is significant and important to analyze these effects of sediments in RW ponds.

To the best of our knowledge, this is the first study to gain insight into the effects of sediments from RW ponds by comparing them with SW ponds and to reveal the differences related to ecological and health risks. Overall, the effects on four categories (represented by 22 indices) of sediment quality in landscape ponds replenished by RW were analyzed: eutrophication risk (9 indices), heavy metals (6 indices), ecotoxicity (1 index) and pathogens (6 indices). We compared RW ponds with nearby SW ponds in three Chinese cities. We have identified the critical effects of the sediment quality from RW replenished ponds, which will contribute to a better understanding of RW as a source for replenishing urban landscape ponds, and thus improve the management of RW reuse and promote the appropriate utilization of RW.

2. Materials and methods

2.1. Selected ponds and water sources for pond replenishment

The landscape ponds of Cuihu in Kunming city (designated R1), Fengqing in Xi'an city (R2) and Lingang in Tianjin city (R3) in China, which are solely replenished by RW, were chosen for sampling and analysis. SW ponds matching the key characteristics of the three RW ponds were selected for comparison, which were located in Yueya in Kunming city (S1), Lianhua in Xi'an city (S2) and Changhong in Tianjin city (S3), respectively.

The basic characteristics of all ponds are listed in Table 1. The six ponds were reconstructed from pre-existing natural ponds and lined with geotextile. Before the study in 2015, the ponds R1, S1, R2, S2, R3 and S3 had been operated for about 9, 10, 5, 5, 3 and 6 years, respectively, after the reconstruction. The six ponds were not vegetated and mainly used for aesthetic and recreational purposes. All six ponds have similar hydraulic and morphologic features, with hydraulic retention time (HRT) ranging from 28 to 40 days. The average depths range from 1.5 to 2.2 m, and the surface areas range from 5×10^4 to 12×10^4 m². In addition, the replenishment frequency of the six ponds was once per day and did not receive input from stormwater runoff. Before 2015, the RW ponds in Cuihu, Fengqing and Lingang had received RW for circa 9, 5, and 3 years, respectively. Water quality characteristics of RW and SW as source water to the ponds are presented in Table 1. All the RW supplies are transported from related WWTPs to the RW ponds by pipelines. The SW used for SW ponds replenishment comes from natural urban rivers. Pond S2 receives its water through an artificial underground tunnel, while ponds S1 and S3 are naturally connected with rivers. In addition, average concentration of chlorophyll-a (Chl-a) recorded in R1, S1, R2, S2, R3 and S3 were 138, 40, 110, 55, 70 and 30 mg/m³, respectively.

2.2. Sample collection and preparation

Field investigations were conducted from January to December 2015. Samples were collected once a month. Rainy days were excluded from sampling, and in the event of rainfall, there was no sampling for at least five days. Four sites for sediment sampling were chosen uniformly for each pond. The samples were collected using a Ponar grab (HAD-XDB0201D, Beijing, China) from the

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