Replenishment of landscape water with reclaimed water: Optimization of supply scheme using transparency as an indicator

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Abstract

With shortages of urban water resources, reclaimed water (RW) has become increasingly important as an alternative water source, especially for replenishing landscape waters. To meet the requirements of landscape quality control when RW is used for partial replacement of the surface water (SW) source to a channel-type urban water in a city in northwest China, scenario analyses were carried out by mathematical modelling. Water transparency (measured by SD) is used as an intuitive indicator to reflect the comprehensive influence of suspended solids (SS) and algae growth on the water’s aesthetic quality. Findings indicate that although the significantly higher nutrient concentrations of RW might bring about higher algae growth potential, in comparison with SW, its much lower SS concentration could offset the adverse effects on SD, to a large extent. By embedding the water quality model, calibrated and validated based on a two-year measurement data into MIKE 3 software for both SD and algae growth calculation, computer simulations were carried out to assist a series of scenario analyses of RW utilization and optimization of the water supply scheme. As a result, to meet the requirement of SD > 80 cm at the control section of the landscape water, the total water inflow required was not increased but decreased with the optimal application of RW. The advantages of lower SS in RW to reduce the demand inflow of total water was more evident with the higher requirement of SD. Replenishment of the channel-type urban water by RW was thus, proven feasible from the viewpoint of landscape quality control.

1. Introduction

Due to rapid urbanization, natural lakes and rivers cannot meet the increasing demand for scenic environment water in urban areas. Therefore, artificial urban landscape waters have rapidly emerged, such as Lake Elsinore in California (Marks, 2006), Shihwa Lake in South Korea (Oh et al., 2010), and Olympic Lake in China (Li et al., 2014) as the complement to these natural waters. However, with the growing imbalance between urban water supply and demand, the available sources of surface water (SW) and municipal water for the supplementation of urban water bodies have gradually declined (Yi et al., 2011; Zaibel et al., 2016; Zhao et al., 2015). Consequently, the functions of these artificial landscapes have deteriorated because of insufficient water for replenishment (Zeng et al., 2013). Therefore, alternative water resources are becoming increasingly important for meeting these water needs. Because of its stability and controllability, reclaimed water (RW) from wastewater treatment plants (WWTPs) effluents have been widely used to supply urban waters in many countries and regions. For example, in California, USA, about 25% of the effluent from WWTPs is used to replenish lakes (Marks, 2006). Similarly, in Osaka, Japan, about 50% of the effluent from WWTPs is used to improve water features in nearby recreational leisure venues (Marks, 2006). In China, the state has made great effort to conserve and augment the limited water resources available to meet growing water demands. Accordingly, an increasing number of cities utilize RW for landscape water replenishment, such as the ornamental ponds and lakes in public parks (Yi et al., 2011).

The functions of urban landscape water include controlling flooding and improving the urban climate, but perhaps their most important function is maintaining the condition of urban water bodies to provide better living environments for local residents (Li et al., 2014; Stoianov et al., 2000). Visual indicators of landscape water quality include turbidity, colour, and transparency (Liu et al., 2013; Swift et al., 2006). Water transparency is distinct from diffuse light attenuation.
(Preisendorfer, 1986), and due to its relation to the concentrations of inorganic suspended solids, phytoplankton, and dissolved organic matter in the water, it could reflect the integrated effects of multiple factors, such as turbidity, colour, and the abundance of algae (Håkanson and Boulon, 2003; Liu et al., 2012; Losada, 2001; Preisendorfer, 1986; Tilzer, 1988). It also plays a critical role in the structure of phytoplankton communities (Håkanson and Boulon, 2003; Reynolds, 1998) such as cyanobacteria may outcompete other phytoplankton species and proliferate at low levels of water transparency (Håkanson and Boulon, 2003). Moreover, water transparency directly affects the survival of benthic animals and plants (Håkanson and Boulon, 2003; Tyler, 1968), and thus, reflects the stability of aquatic ecosystems. Some researchers have used water transparency as a target indicator to analyse its temporo-spatial distribution and the factors that influence it (Sommaruga and Augustin, 2006; Swan et al., 2007; Wang et al., 2014). It has also been used as a monitoring index to measure the water quality of urban lakes (Wang and Zhang, 2006). Overall, water transparency is an important, comprehensive indicator of the water quality and visual landscape effects of urban waters.

Because of the distinct qualities of RW and SW, the effects on the quality and transparency of landscape water replenished with RW is different from that of SW. Water transparency is reported to be affected mainly by the concentration of suspended particles (Liu et al., 2012; Wang et al., 2014) and the abundance of phytoplankton (Håkanson and Boulon, 2003; Sommaruga and Augustin, 2006). Compared with SW, the concentrations of nutrients, such as nitrogen and phosphorous, are greater in RW, which, although, do not directly affect water transparency, could promote the growth of algae in the water, and thereby indirectly decrease water transparency (Li et al., 2014). In contrast, because RW undergoes a treatment process that involves sedimentation or even membrane filtration in WWTPs, the concentration of suspended matter is lower than that in SW (Gücker et al., 2006; Li et al., 2013), which promotes increased transparency in the receiving water bodies. Therefore, the overall effects of urban waters replenishment with RW on the water transparency remain unclear and merit further study. However, little research has been published on this topic to date (Sommaruga and Augustin, 2006; Swan et al., 2007; Wang et al., 2014).

Nonetheless, because the water quality of actual water bodies is easily disturbed by the external environment (Blersch et al., 2013; Li et al., 2014; Zhang et al., 2017), it is difficult to study the effects of RW application on urban waters through experimental methods. However, numerical models are suitable for analysing these practical problems and may elucidate the physical and chemical relationships between transport and transformation of pollutants in water bodies. Computation techniques have developed considerably in recent decades and have successfully been applied as scientific tools for studying flow and pollutant transport in water bodies, and for assessing water quality changes in response to variable inputs, including the quality and quantity of the replenishment water source (Paliwal and Patra, 2011; Stoianov et al., 2000; Zhu et al., 2008). Therefore, the effects of urban landscape water replenishment with RW on water quality can be simulated with such models. Among the available numerical models, the MIKE model, which was developed by the Danish Hydraulic Institute (DHI), has been widely used, such as for the analyses of the Hooghly estuary in India (Paliwal and Patra, 2011), the Han River in China (Zhu et al., 2008), and Everglades National Park in the USA (Stoianov et al., 2000).

The objective of this research was to elucidate the effects of RW replenishment on the quality and transparency of an urban landscape water and to assess the feasibility of using RW from the viewpoint of landscape quality control. This was done by establishing a water transparency calculation model in the MIKE 3 software based on an existing detailed, physically based water quality model. Scenario analysis was carried out using an urban channel-type landscape water in northwest China, which was within the constraints of a lack of natural water source for replenishment and a proposed use of RW for replenishment. Based on this simulation, a water supply scheme of RW replenishment for the water body is proposed with water transparency as the control indicator. The results provide a theoretical basis for protecting the visual landscape effects of water and may help alleviate the problem of urban water resources deficiency.

2. Materials and methods

2.1. Case description and data collection

2.1.1. Channel-type landscape water

The channel-type landscape water evaluated in this study is located in a large city in northwestern China. It was reconstructed from a pre-existing paleochannel and has a total length of 6.3 km, a width of 60–120 m and an average depth of 5.2 m. There is a scenic area at 3.3 km downstream of the inflow point. It is an isolated water body with no obvious natural inflows. Its water flow rate of about 0.66 m3/s is maintained by SW transported via artificial channels. However, due to difficulties associated with continued use of the original water source, only half of its flow volume (0.33 m3/s) could be maintained. Therefore, it was necessary to find an alternative water source for replenishment. RW from a nearby WWTP was proposed as a substitute for the water replenishment. The WWTP mainly receives domestic sewage, and the effluent water quality meets the discharge standard of pollutants for municipal WWTPs (SEPA and AQSIQ, 2002).

2.1.2. Sampling and water quality analysis

Sample points were set at nine locations along the water (Fig. 1) to determine the water quality (including at the inlet, that is, the quality of the source water. Monthly water samples were collected between 10:00 and 11:00 a.m. from October 2013 to September 2015, whereby the first ten days of each month and all rainy days were excluded from sampling. Three-litre samples of water were collected from 0.5 m below the surface at each sampling site, which were then transported to the laboratory for immediate testing. Water temperature (T), dissolved oxygen, pH, and water transparency were measured in situ. Total nitrogen (TN), ammonia–nitrogen (NH4+-N), nitrate–nitrogen (NO3--N), total phosphorus (TP), inorganic phosphorus (IP), chlorophyll a (Chl-a)
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