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Frequency analysis of urban runoff quality in an urbanizing catchment of Shenzhen, China

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SUMMARY

This paper investigates the frequency distribution of urban runoff quality indicators using a long-term continuous simulation approach and evaluates the impacts of proposed runoff control schemes on runoff quality in an urbanizing catchment in Shenzhen, China. Four different indicators are considered to provide a comprehensive assessment of the potential impacts: total runoff depth, event pollutant load, Event Mean Concentration, and peak concentration during a rainfall event. The results obtained indicate that urban runoff quantity and quality in the catchment have significant variations in rainfall events and a very high rate of non-compliance with surface water quality regulations. Three runoff control schemes with the capacity to intercept an initial runoff depth of 5 mm, 10 mm, and 15 mm are evaluated, respectively, and diminishing marginal benefits are found with increasing interception levels in terms of water quality improvement. The effects of seasonal variation in rainfall events are investigated to provide a better understanding of the performance of the runoff control schemes. The pre-flood season has higher risk of poor water quality than other seasons after runoff control. This study demonstrates that frequency analysis of urban runoff quantity and quality provides a probabilistic evaluation of pollution control measures, and thus helps frame a risk-based decision making for urban runoff quality management in an urbanizing catchment.

1. Introduction

Urban runoff is a major source of surface water pollution in urban areas (Akan, 1988; Andres-Domenech et al., 2010a,b; Behera et al., 2006; Fu et al., 2009, 2010). It has been well documented that runoff quality is closely related to rainfall characteristics such as rainfall intensity, rainfall duration, storm frequency, and Antecedent Dry Period (ADP) (e.g., Chow and Yusop, 2008; Kim et al., 2007; Lee and Bang, 2000). Thus runoff quality can vary considerably in different rainfall events. For example, Huang et al. (2007) showed that the Event Mean Concentration (EMC) for Chemical Oxygen Demand (COD) ranges from 41 to 464 mg/l based on the study of five rainfall events in a small catchment in Macau. Qin et al. (2010) found that the maximum EMC for COD is over five times higher than the minimum value in a typical urbanizing area in China.

In order to consider the variability in runoff quality, it is suggested that the frequency distributions of runoff quality and pollutant loads be used as indicators to evaluate the impact of pollution in receiving water bodies (Andres-Domenech et al., 2010b). This helps to determine the global water quality conditions of the receiving waters, gain an insight into the duration and frequency of events that do not satisfy water quality standards, and thus support the decision maker to select the most appropriate and sustainable solution for water quality management and planning problems in a risk-based decision making framework (McIntyre, 2004).

The challenge in characterizing water quality with a frequency distribution often arises from the scarcity of water quality data and the expensive cost in obtaining new data (e.g. Akan, 1988). Thus, in many situations, it is normally impossible to construct an accurate frequency distribution with observed data. However, water quality models have been used to provide estimates of urban runoff quality (Obropta and Kardos, 2007; Zoppou, 2001). And the frequency distribution of urban runoff quality can be analyzed by the simulation-based methods. In general, there are two methods: analytical probability method and long term continuous simulation.

In an analytical probability method, the rainfall event characteristics (e.g., rainfall depth, duration, intensity, and inter-event time) in an urban drainage system are typically considered as random variables with specified probability distribution functions (PDFs). The PDFs are then mathematically transformed by rainfall

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runoff and quality models into the PDFs of system performance variables (such as runoff volume, Event Mean Concentration of pollutants, and pollutant load to receiving waters) (Akan, 1988; Andres-Domenech et al., 2010a; Chen and Adams, 2007; Li and Adams, 2000). However, a major limitation of these approaches lies in the representation of storm events. That is, the rainfall variables are often assumed to be independent, and can be represented by the same type of PDFs (e.g., normal distributions) such that their joint PDF may be expressed as the product of their marginal PDFs. Moreover, the rainfall runoff and quality model has to be simplified, otherwise, the analytical probability distribution of model outputs cannot be derived (Akan, 1988). And thus this approach is normally recommended for the preliminary planning and design stage because of its computational efficiency (Behera et al., 2006).

Continuous simulation is based on water quality simulations over a long term period (e.g., several years) and statistical analysis of the simulation results. This approach can take most random rainfall characteristics into account and evaluate the long-term performance of urban drainage systems (Andres-Domenech et al., 2010b; Demuynck et al., 1997). Prior studies have focused on the overall performance of the systems, represented by an integrated indicator, e.g. cumulative water volume and pollutant mass, efficiency of pollutant removal, rate of non-compliance with the water quality standards in the entire simulation period. For example, Calabro and Viviani (2006) evaluated the performance of storm tanks with different storage volumes, devices and operational rules for a continuous simulation period of five years in the case of Parco d'Orle'ans catchment and for a period of one year in the case of Fossolo catchment in Italy. Mannina and Viviani (2009) compared the pollution loads discharged to receiving bodies by separate and combined sewer systems during both dry and wet weather. Freni et al. (2010) assessed the effects of different distributed and centralized urban storm-water management techniques on reducing accumulated overflow volumes and total suspended solids loads over a period of 6 years. Although numerous efforts have been made to investigate the overall performance of urban drainage systems based on a long term continuous simulation, there are very few studies reporting frequency distributions of event-based runoff quality and pollutant loads. These distributions are essential to analyze the risks in a drainage system. In addition, rainfall characteristics and their seasonal variations have significant effects on the runoff quality and pollutant loads. However, to the best of our knowledge, these effects have not been documented in the previous studies.

Compared to previous studies based on continuous simulation, this paper aims to provide a more comprehensive assessment of the potential impacts of proposed runoff control schemes on urban runoff quality and quantity. Runoff quality is represented by Chemical Oxygen Demand (COD) because it is one of the main pollutants in the study catchment. The impact assessment conducted in this study has the following aspects: (1) using four different event-based indicators, i.e., total runoff depth, event pollutant load (EPL), Event Mean Concentration (EMC), and peak concentration that are calculated from a long term continuous simulation; (2) examining the effects of the rainfall amount on these indicators; (3) investigating the cumulative frequency distributions of these indicators; and (4) discussing the seasonal changes of these frequency distributions. This method is demonstrated with a series of 41-year rainfall data in an urbanizing catchment in Shenzhen, China. The results obtained reveal that urban runoff quality in the catchment has a high risk of non-compliance with the surface water quality regulations. The proposed runoff control schemes significantly reduce the water quality risk of runoff pollution, and have different effects in different seasons due to seasonal variation in rainfall events. This method is able to provide a probabilistic evaluation of pollution control measures that helps move towards a risk-based decision making framework for water quality management.

2. Materials and methods

2.1. Study area

The Shiyan River catchment is located in Shenzhen city, southeast China (Fig. 1). It is the longest tributary of Shiyan Reservoir. The Shiyan River catchment has undergone rapid urbanization in the last 20 years, and its population increased from 21,000 in 1990 to 213,000 in 2007. It has an area of 25 km^2 with 32% of impervious land use in 2007, characterized by a mix of residential (10%), industrial (16%), agricultural (29%) and sparse forest (37%) land uses. Currently, the water quality of the river has a high rate of non-compliance with the water quality regulations. Due to high population density, lack of environmental consciousness, and inadequate litter management in the rapidly urbanizing area, nonpoint source pollution resulting from urban runoff becomes one of the major sources of pollutants (Qin et al., 2010). For example, the peak concentration of COD during four rainfall events measured in 2009–2010 is as high as 360–770 mg/L, and is 18–38 times higher than the maximum permitted COD concentration in the river (20 mg/L) (Table 1).

Two types of drainage systems co-exist in the Shiyan River catchment: combined sewer systems in the early developed areas and separate sewer systems in the newly developed areas. However, due to inadequate sewer networks coverage, mis-connection between wastewater and storm water pipelines, unregulated sewage flows are frequently discharged into the Shiyan River and subsequently entering the reservoir. To improve the water quality of the reservoir, the local government has proposed a plan to construct a runoff control system at the downstream of Shiyan River catchment (Fig. 1). The system comprises of an interception gate, an interception channel and a detention reservoir. It aims to intercept the initial rainwater with high pollution load in the catchment. Thus its capacity is closely linked to the level of interception that needs to be decided by the local government. This paper will provide a probabilistic evaluation of different levels of interception by characterizing frequency distributions of urban runoff quantity and quality and will help frame a risk-based decision making for planning and management of storm water quality in the future.

2.2. Historical rainfall data

The Shiyan River catchment has a mild, subtropical maritime climate with a mean annual temperature of 22.4 °C and mean annual precipitation of 1933 mm, 85–90% of which falls from April to September. A rainfall monitoring station was set in the Shiyan River catchment since 1961, as shown in Fig. 1. A series of 41-year rainfall data at a time step of 1 h was used to conduct the long-term continuous simulation of the catchment model. Augmented Dickey–Fuller (ADF) (Dickey and Fuller, 1979) tests were performed (with intercept but without trend) to detect the stationarity of annual total rainfall and annual maximum hourly rainfall (1961–2002). The test indicated that both the annual total rainfall and annual maximum hourly rainfall time series are stationary, with a Mackinnon approximate $P < 0.01$. To analyze statistics of runoff water quality, the long term rainfall record was divided into separate rainfall events in terms of the inter-event time definition (IETD), which is defined as the minimum inter-event time period between two consecutive pulses of rainfall (Li and Adams, 2000). Rainfall pulses that are separated by a time interval greater than the IETD are considered to be separate events. Based on the