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Spatial variations of storm runoff pollution and their correlation with land-use in a rapidly urbanizing catchment in China

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ABSTRACT

The composition of land use for a rapidly urbanizing catchment is usually heterogeneous, and this may result in significant spatial variations of storm runoff pollution and increase the difficulties of water quality management. The Shiyan Reservoir catchment, a typical rapidly urbanizing area in China, is chosen as a study area, and temporary monitoring sites were set at the downstream of its 6 sub-catchments to synchronously measure rainfall, runoff and water quality during 4 storm events in 2007 and 2009. Due to relatively low frequency monitoring, the IHACRES and exponential pollutant wash-off simulation models are used to interpolate the measured data to compensate for data insufficiency. Three indicators, event pollutant loads per unit area (EPL), event mean concentration (EMC) and pollutant loads transported by the first 50% of runoff volume (FF50), were used to describe the runoff pollution for different pollutants in each sub-catchment during the storm events, and the correlations between runoff pollution spatial variations and land-use patterns were tested by Spearman's rank correlation analysis. The results indicated that similar spatial variation trends were found for different pollutants (EPL or EMC) in light storm events, which strongly correlate with the proportion of residential land use; however, they have different trends in heavy storm events, which correlate with not only the residential land use, but also agricultural and bare land use. And some pairs of pollutants (such as COD/BOD, NH_3-N/TN) might have the similar source because they have strong or moderate positive spatial correlation. Moreover, the first flush intensity (FF50) varies with impervious land areas and different interception ratio of initial storm runoff volume should be adopted in different sub-catchments.

1. Introduction

Many catchments in developing countries are undergoing fast urbanization which is usually characterized by population increase, economic growth as well as drastic changes of land use from natural/rural to urban area (Mallin, 2009; Yusop et al., 2005). During the urbanization process, some catchments experience water quality deterioration due to rapid increase of pollution loads. Nonpoint source pollution resulting from storm water runoff has been recognized as one of the major causes of pollutants in many cities. For example, it has been observed that the mean event chemical oxygen demand (COD) load from urban runoff in Beijing (China) accounted for at least two-thirds of the daily load in sewage treatment plants (Liu et al., 2005). In the study on storm water pollution in Isfahan (Iran), Taebi and Droste (Taebi and Droste, 2004) found that the mean concentrations of organic matter in storm water are much higher than that in raw sanitary wastewater. These high values of storm runoff pollutant loads underline the fact that both point and nonpoint sources cannot be neglected in water quality management (Candela et al., 2009; Freni et al., 2010).

Because storm runoff pollutants are generated and transported in a diffuse manner and their sources are related to the physiographic factors of individual catchments, storm runoff pollution usually presents significant spatial variations, with land use being one of the most important factors (Tong and Chen, 2002; Yusop et al., 2005). Many studies have been carried out to relate land-use types to storm runoff pollution characteristics in a catchment, and they can be classified into three categories according to the complexity of the land-use structure:

(1) Single homogeneous land-use types: these studies tend to relate water quality of runoff according to a single land-use type. For example, surface runoff pollutants may be discharged from different types of homogeneous land use, e.g. residential, commercial and

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industrial areas (Ackerman and Schiff, 2003), highway (Kim et al., 2005), parking lot and bridge (Kim et al., 2007b) as well as special surface runoff in city zoo (Zhao et al., 2007).

(2) Predominant land-use types: these studies tend to associate the water quality of runoff to a predominant land-use type in the catchment. The studies were carried out in sub-catchment scale and a single land-use type is chosen to represent nature of the relevant catchment (Lee et al., 2002). For example, (Graves et al., 2004) conducted a study to characterize storm water quality from predominant land-use types (citrus, pasture, dairy and golf courses, etc.) along coast of Florida. (McLeod et al., 2006) observed that runoff from commercial land use have considerably higher unit loads than two residential catchments in Saskatoon, Canada.

(3) Diverse/mixed land-use types: these research were carried out for catchments with diversified and no prevailing land-use types. For example, in the study of runoff pollution from four watersheds with different proportions of forestry and agricultural land use in the Geum River Basin, Korea, Kim et al. (2007a) found that the agricultural land use has greater impacts on EMC compared to forestry according to the correlation analysis between EMC data and the ratio of agricultural land use to the total area. In the catchment with sufficient data, simulation model can be developed to evaluate runoff pollution under different land-use types. (Tong and Chen, 2002) adopted a water quality assessment tool—the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) to model the plausible effects of land use on water quality in the East Fork Little Miami River Basin. The simulation results indicate that the order for nitrogen output in different land-use types during storms was: agriculture/impervious urban/forest/pervious/urban/barren land.

Although numerous efforts have been made to investigate spatial variations of storm runoff pollution in urban or agricultural predominant catchments, there are very few studies reporting storm runoff characterization in rapid urbanization catchment in developing countries with high population density (e.g. China) (Li et al., 2007), even though the spatial variation of runoff pollution is significant in such catchments. One reason is that a rapid urbanization catchment usually has heterogeneous land use with a mixed land-use types. And it is difficult to identify one predominant type of land use to "represent" the nature of the relevant catchment or sub-catchment. Another reason may be the huge amount of anthropology activities in the catchment. Many anthropogenic activities in a rapid urbanization catchment, such as massive construction or building, insufficient or lag development of sewage treatment infrastructure, poor waste management (or non-environmentally friendly behaviors) as well as agricultural activities in "urban" area (or vice versa) are potential sources of runoff pollution (Pegram et al., 1999). Moreover, due to a lack of gauging stations with long-term hydrological and water quality monitoring in the developing area, runoff pollution investigation and management often suffer from insufficient data (Li et al., 2007; Yusop et al., 2005). Hence there is a need to characterize and examine the spatial variations of runoff pollution for water quality monitoring and management in urbanization catchment.

The paper focuses on analyzing the spatial variations of storm runoff pollution in a rapidly urbanizing Shiyan reservoir catchment, China, which has 6 sub-catchments with different proportions of land use. The aims are (1) to characterize spatial variation trend of storm runoff pollution, (2) to identify effects of land-use patterns on spatial variations and (3) to relate the findings to runoff pollution monitoring and management schemes (e.g. pollutant loads control, water quality control and drainage system design) in rapid urbanization catchments.

2. Study area

The Shiyan reservoir catchment is located in Shenzhen city, southeast China, with total drainage area of 44.77 km^2. The main tributaries are Shiyan (SY), Shenken (SK), Baikeng (BK), Mabu (MB), Yunniu (YN) and Wangjia (WJ) rivers/streams forming 6 sub-catchments (Fig. 1). The catchment has a mild, subtropical maritime climate with a mean annual temperature of 22.4 °C and the mean annual precipitation of 1,933 mm, 85%–90% of which falls from April to September.

The catchment has undergone rapid urbanization in the last 20 years. Its population has increased from 26,000 in 1990 to 269,000 in 2007. Around 63% of catchment area is impervious land use. However, the urbanization levels and land-use patterns of each sub-catchments are different. SY is the largest sub-catchments with 32% of impervious land use and characterizes by a mix of residential (10%), industrial (16%), agricultural (29%) and sparse forest (37%) land use; WJ sub-catchment has the highest percentage of industrial (60%) and residential (16%) land use, and the impervious land use has reached to 85%. Although SK and BK have similar percentage of impervious land use (around 48%), SK has more percentage of residential (7%) and bare land (12%); MB and YN are predominantly agricultural, but MB has 2.4% and 2.9% of residential and road land use, respectively, and YN only has 5.9% of residential land use. Table 1 shows a summary of these characteristics.

Shiyan reservoir has become increasingly important during the development of Shenzhen City. The reservoir was built in 1960s for flooding prevention and agricultural irrigation. However, to meet the increasing water demand for rapid population increase and economic growth, the reservoir begun to store and supply water for municipal use in 1990. Moreover, the reservoir's

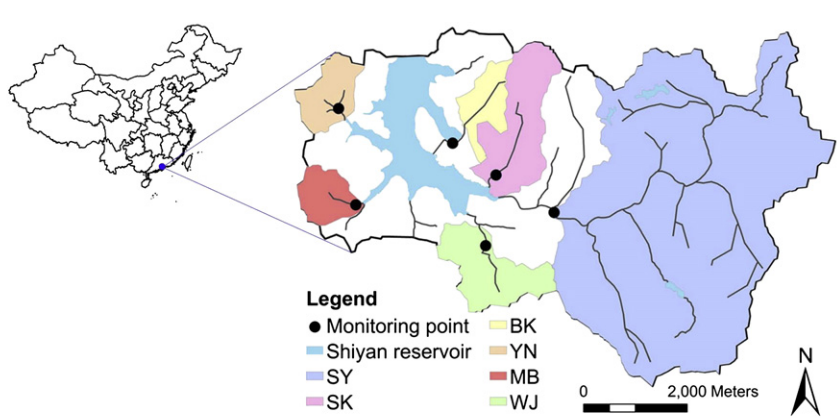

Fig. 1. Map of Shiyan Reservoir catchment.