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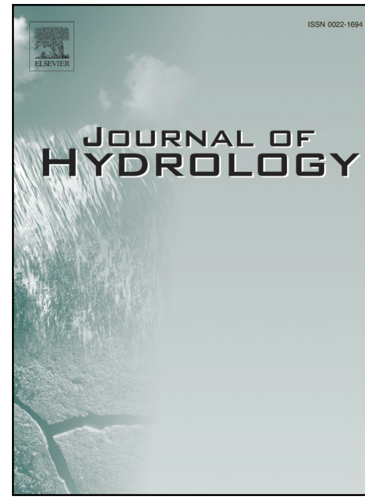

Frequency analysis of urban runoff quality in an urbanizing catchment of Shenzhen, China

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Essential title page information

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Abstract

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 5mm, 10mm, and 15mm 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.

Keywords: urban runoff; water quality; continuous simulation; frequency analysis; urbanization; runoff control

1 Introduction

Urban runoff is a major source of surface water pollution in urban areas (Akan, 1988; Andres-Domenech et al., 2010a, 2010b; 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 Band, 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 interevent 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 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 six 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 Material 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) (Table1).

Fig.1 Map of the Shiyan River catchment

Table 1 Observed rainfall data for model calibration and validation

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 one hour 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 definition of IETD, the statistical characteristics of some important variables, such as rainfall amount and ADP, can be extracted from the historical rainfall record. 1688 rainfall events with rainfall amount more than 5 mm were identified based on IETD = 3 hours since there is no runoff generated when rainfall depth is less than 5 mm in the catchment.

The frequency distribution characteristics of rainfall events in the catchment are shown in Fig. 2. The averaged event rainfall amount is 27 mm, but 50% of event rainfall amounts are less than 16 mm. And the events with a rainfall amount between 5-15mm, 15-25mm and more than 25mm account for around 48.5%, 18.2% and 33.3%, respectively. The averaged ADP is 4.2 days. And the events with ADP less than 1 day, between 1-10 days and more than 10 days account for around 37.9%, 50.9% and 11.2%, respectively.

Fig. 2 Frequency distributions of rainfall amount and ADP

2.3 Rainfall runoff and quality model

The IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) model was used to simulate the rainfall runoff processes in the case study catchment (Croke et al., 2005).The IHACRES model consists of nonlinear and linear modules. The nonlinear module converts rainfall to effective rainfall. The linear module uses the unit hydrograph approach to transform effective rainfall to streamflow. In the statistical loss module the effective rainfall is expressed as:

$$u_t = \left[c_1(\phi_t - I)\right]^p r_t \quad (1)$$

where t is time (min), r_t and u_t are rainfall and effective rainfall (mm), respectively, c_1, I and p are parameters for mass balance, soil moisture index threshold and non-linear response terms, respectively, and Φ_t is a soil moisture index (mm) given by:

$$\phi_t = r_t + (1 - 1/\tau)\phi_{t-1} \quad (2)$$

The parameter τ is the time constant or, inversely, the rate at which the catchment wetness declines in the absence of rainfall. The initial soil wetness index (Φ_0) is related to the soil wetness at the end of the previous rainfall event (Φ_r) and antecedent dry period (*ADP,* day), and is calculated as

$$\phi_0 = \phi_r (1 - 1/\tau)^{ADP/\Delta t} \quad (3)$$

where Δt is simulation time step (day).

In the linear module, the instantaneous unit hydrograph (IUH) is formulated as the two-parameter gamma distribution (Singh, 2004):

$$IUH(t) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} t^{\alpha-1} e^{-t/\beta}, \alpha \geq 1, \beta > 0 \tag{4}$$

where α is the shape parameter, β is the scale parameter, and Γ is the gamma function.

Pollutant wash-off during storm events is commonly modelled as an exponential decay function of the available surface pollutant load (Rossman et al., 2008):

$$dP_t / dt = -c_2 q_t^{c_3} P_t \tag{5}$$

where P_t is pollutant buildup in the catchment at time t (kg), c_2 is wash-off coefficient, c_3 is wash-off exponent, and q_t is runoff rate (mm/hour). By solving the differential equation (5), the following equation can be obtained:

$$C_t = \frac{c_2 P_0 q_t^{c_3 - 1}}{A} \exp\left(-c_2 \int_0^t q_t^{c_3} dt\right) \tag{6}$$

where C_t is pollutant concentration in runoff at time t (mg/l), P_0 is initial pollutant buildup in the catchment at the beginning of the rainfall (kg) and A is catchment area (km^2). P_0 can be evaluated by an exponential equation proposed by Alley and Smith (1981):

$$P_0 = \left(\frac{Accu}{Disp}\right) A \cdot Peim\left(1 - e^{-Disp \cdot ADP}\right) + P_r e^{-Disp \cdot ADP} \tag{7}$$

where $Accu$ is the buildup rate (kg/(km^2 d)), $Disp$ is the decay rate (d^{-1}), P_r is the residual pollutant after last rainfall event (kg), and $Peim$ is the percentage of impervious area.

Runoff during storm events comprises of dry weather (no-rain day) flow and storm runoff. The dry weather flow and pollutant loads were determined by measurement before each storm event, thus storm runoff could be estimated by subtracting those values from wet weather flow. Therefore, the six-parameter IHACRES model (c_1, I, p, τ, α and β) and four-parameter pollutant buildup and washoff model (c_2, c_3, *Accu* and *Disp*) are used to describe the rainfall runoff pollution processes. Since COD is one of the main pollutants in the Shiyan River catchment, it is taken as the representative water quality indicator in this study.

Temporary monitoring sites were installed at the outlet of the catchment to measure streamflow and associated water quality. Field experiments were conducted for 10 no-rain days and 4 storm events between April 2009 and September 2010. The streamflow was measured by Sontek/YSI Argonaut-SW (1ASW-33000 model) at 10 min intervals; and the COD was measured by Horbi UV-COD online monitor (OPSA-150) at 30 min intervals. Rainfall data was recorded by an automated gauge (1-min interval) at Shiyan reservoir rainfall monitoring station operated by Shenzhen Meteorology Bureau.

The parameter values for the rainfall runoff and quality model of the Shiyan River catchment were calibrated against measured data in April 2009 (Table 1). The genetic algorithm (GA) was used to search the optimal values of the 10 model parameters with the objective to maximize the combined Nash-Sutcliffe (NS) coefficients of runoff and water quality:

$$NS = 1 - \frac{\sum \left(v_{sim} - v_{obs,t}\right)^2}{\sum \left(v_{obs,t} - \overline{v_{obs}}\right)^2} \quad (8)$$

where v is runoff Q (m^3/s) or COD (mg/L); the subscript *sim* and *obs* denote the simulated and observed values, respectively. Assuming that runoff and water quality have an equal importance in model calibration, the two NS coefficients are combined into a single objective using the weighted sum method. The ranges of the model parameters used in the search are shown in Table 2. In the optimization process of the GA, we set the values of the genetic parameters to 100 for population size, 90% for crossover and 1% for mutation probability. We continued the search process for 200 generations. The optimized values of model parameters are shown in Table2, and the corresponding *NS* of runoff and COD is

0.774 and 0.824, respectively. The model was further validated against measured data in Sept 2010 (Table 1), and *NS* of runoff and COD is 0.826 and 0.844, respectively. Fig. 3 shows a comparison between the simulated and measured data. The results indicate that the simulated data fit well with the trends of time series measured and can be used to assess the performance of pollutant control measures.

Table 2 Optimized values of model parameters

Fig. 3 Comparison between measured and calculated data

2.4 Indicators of rainfall runoff quality

To have a more comprehensive evaluation of runoff quality, four indicators are used to describe the runoff pollution characteristics in the catchment: total runoff depth, Event Pollutant Loads per unit area (EPL), EMC, and peak concentration during a rainfall event. A brief introduction is given to EPL and EMC below.

EPL, mass of pollutant washed off per unit area per rainfall event (t/km^2), describes the area-averaged intensity of runoff pollutant loads. It can be expressed as:

$$EPL = \frac{M}{A} = \frac{\int_0 C_t Q_t dt}{A} \cong \frac{\sum C_t Q_t \Delta t}{A} \quad (9)$$

where C_t is constituent at time t and Q_t is storm water discharge at time t; M is pollutant mass and A is catchment area (km^2); Δt is discrete time interval. EPL can be used for total pollutant mass control in a catchment.

Event Mean Concentration (EMC), mean pollutant concentration in runoff per rainfall event (mg/L), reflects water quality of runoff (or runoff pollution degree/level) in a catchment. It can be expressed as (Bertrand-Krajewski et al., 1998):

$$EMC = \frac{M}{V} = \frac{\int_0^t C_t Q_t dt}{\int_0^t Q_t dt} \cong \frac{\sum C_t Q_t \Delta t}{\sum Q_t \Delta t} \quad (10)$$

where V is runoff volume during the storm event. EMC can be used in water quality management and concentration control for a catchment. EMC is regarded as a good measure to represent rainfall runoff quality (Kim et al., 2007; Lee and Bang, 2000).

3 Results and discussion

3.1 Rainfall runoff quantity and quality

Each point in Fig.4 represents a rainfall event. The x-coordinate is event rainfall amount and y-coordinate is one of runoff indicators (total runoff depth, EPL, EMC or peak concentration of COD) of a rainfall event.

Fig. 4 Rainfall amount vs. runoff quantity and quality

A close relationship between rainfall amount and runoff depth is shown in Fig.4a. The maximum total runoff depth during rainfall events is 132mm, which is equivalent to a runoff volume of 3.3 million m^3 in the catchment. With increasing event rainfall amount, the total runoff depth nonlinearly increases, resulting in a nonlinear increase in runoff coefficient (defined as the ratio of rainfall amount to runoff depth). For example, the events with a rainfall amount of 50mm, 100mm and 200 mm have an average runoff coefficient of 0.34, 0.39 and 0.49, respectively.

EPL has a tendency to initially increase with event rainfall amount (Fig.4b). It is because the surface runoff in a heavier rainfall event has capacity to flush off more pollutant buildup in the catchment. However, when the rainfall amount is more than 115mm, the upper envelope curve of EPL reaches an equilibrium value of 25t/km^2 (equivalent to a COD loading of 265t from the catchment during a rainfall event). It implies that the possible maximum COD accumulated in the catchment is 25t/km^2, which can be totally flushed off by the surface runoff when the rainfall amount is more than 115mm. In addition, the EPL of events with the same rainfall amount can be substantially different due to the other rainfall factors such as ADP. Generally, a rainfall event with longer ADP has more pollutant buildup at the beginning of the rainfall, and thus more pollutant loading can be potentially flushed off during rainfall event.

As the event rainfall amount increases, the EMC at the upper envelope curve initially rapidly rises, reaches a peak value of 990 mg/l (corresponding to a rainfall amount of 50mm), and then declines in an approximately exponential fashion (Fig.4c). Generally, more rainfall amount has capacity to flush off more pollutant buildup in the catchment and results in higher EMC. However, when the capacity of pollutant wash-off is more than the pollutant buildup in the catchment, more rainfall amount causes lower EMC. Similar to EPL, the events with the same rainfall amount can have a rather different EMC because of different ADPs.

EMC and peak concentration during a rainfall event have a strong correlation with a correlative coefficient of 0.948. However, the two indices have different trend as the event rainfall amount increases. As the event rainfall amount increases, the peak concentration of COD at the upper envelope curve initially rises, reaches a peak value of 1420 mg/l (corresponding to rainfall amount of 58mm), and then slowly declines (Fig.4d). When the rainfall amount is more than 50mm, the increase in rainfall amount has less effect on the peak concentration than that on EMC.

This is because the COD concentration reaches the peak value in the initial stage of rainfall event, in which the rainfall amount is usually no more than 50 mm in the Shiyan River catchment. Similarly, the events with the same rainfall amount have different peak concentrations because they have different ADPs.

3.2 Frequency distribution of runoff quantity and quality

The cumulative frequency distributions of runoff quantity and quality indicators are shown in Fig. 5 and represented by the solid lines without makers, denoted as 'interception 0mm' as they represent the current runoff characteristics without any additional control measures. Generally, the dispersion of the probability/frequency distribution of a variable can be quantitatively evaluated by the coefficient of variation (C_v), which is defined as the ratio of the standard deviation to the mean. A zero value of C_v indicates that there is no variation in the variable and all values are the same. And the higher C_v, the greater the level of dispersion around the mean. In addition, the asymmetry of the probability/frequency distribution of a variable can be evaluated by the skewness (C_s). A zero value of C_s indicates that the values are relatively evenly distributed on both sides of the mean. Positively skewed data (skewness, $C_s>0$) have concave downward cumulative frequency distributions, which imply that the bulk of the data is less than the mean, or the variable has relatively few high values. Conversely, a negative C_s represents a concave upward cumulative distribution, which implies most of the data are greater than the mean, or the variable has relatively few low values.

Fig.5 Effects of different levels of initial runoff control

The cumulative frequency distribution of total runoff depth is a predominantly positive, concave downward curve with a C_s of 5.8 (Fig.5a), which implies that most rainfall events have a runoff depth less than the averaged value of 7.5mm. And the events with runoff depth less than 5mm, 10mm and 15mm account for 66.3%, 80.6% and 87.7%, respectively. In addition, the curve has a Coefficient of variation (C_v) of 2.16, which means rainfall events in the catchment have a widely different runoff depth.

The cumulative frequency distribution of EPL (COD) presents a concave downward curve with a C_s of 2.28 (Fig.5b). The averaged EPL (COD) is 3t/km^2, and 50% of rainfall events have EPL less than 0.6 t/km^2. The rainfall events with EPL more than 1t/km^2, 5t/km^2 and 10t/km^2, account for 43.0%, 19.5% and 10.1%, respectively. In addition, rainfall events in the catchment have a different EPL (COD) with a C_v of 1.67.

As seen in Fig.5c, the cumulative frequency distribution of EMC presents a slightly concave downward curve with a C_s of 0.64. A 40 mg/l threshold is chosen for COD concentrations in the case study according to the V class of Environmental Quality Standards for Surface Water in China (State Environmental Protection Administration of China, 2002). The rainfall events with EMC greater than 40 mg/l account for 88.3%. In addition, the averaged EMC is 300 mg/l and C_v of EMC is 0.76 in the catchment.

Similar to EMC, the cumulative frequency distribution of peak concentration of COD presents a slightly concave downward curve with a C_s of 0.62 (Fig.5d). The rainfall events with peak concentration greater than 40 mg/l account for 91.9%. In addition, the averaged value is 450 mg/L and C_v of peak concentration is 0.75 in the catchment.

The results indicate that the runoff quality in the catchment has a high risk of non-compliance with the surface water quality regulations.

3.3 Effect of initial runoff control

The local government proposed to compare three initial runoff control schemes (Scheme1, 2 and 3) with the intent of reducing the risk of poor water quality in the catchment. The three schemes have capacity to intercept initial runoff depth of 5mm, 10mm and 15mm, respectively. The runoff control level can be compared to a commonly used indicator, catchment storage ratio, defined as the total storage volume in a catchment divided by its impervious area. Recall that the catchment has an area of 25 km^2 with 32 % of impervious landuse, Schemes 1, 2 and 3 represent a catchment storage ratio of 143, 286 and 429 m^3/ha, respectively. The ratio of scheme 1 is close to the recommend values; however the ratios of schemes 2 and 3 are in the upper ranges reported in the literature (Andres-Domenech et al., 2010b). In the study, frequency distributions of rainfall runoff pollution derived from continuous simulation were used to support the water quality risk analysis for these interception schemes. Without loss of generality, the four indicators (total runoff depth, EPL, EMC and peak concentration) of a rainfall event under a scheme were assumed to 0 when the total runoff of the event is less than the corresponding interception level of the scheme.

As shown in Fig.5a, when Schemes 1, 2 and 3 are taken, only 33.7%, 19.4% and 12.3% of rainfall events, respectively, have surface runoff discharged into the downstream river. The statistical calculation shows that Schemes 1, 2 and 3 can intercept 35.5%, 52.2% and 62.1% of all the runoff volume in the catchment for a long term period, respectively. And the C_s of runoff depth under scheme 1, 2 and 3, decreases from 5.8 in the case of no interception to 4.01, 3.36 and 2.94, respectively. This is because the percentage of the rainfall events with relatively small total runoff depth (compared to the mean) is significantly reduced after interception.

Initial runoff control schemes can significantly reduce pollutant loading (Fig.5b). For example, the percentage of rainfall events with EPL>1t/km^2 under scheme1, 2 and 3 decreases from 43.0% in the case of no interception to 22.7%, 13.5% and 9.4%, respectively. And Scheme 1, 2 and 3 have the capacity to intercept 45.67%, 69.92% and 82.19% of all the pollutant loading (COD) in the catchment for a long term period, respectively. Furthermore, the C_s of EPL under scheme1, 2 and 3 decreases from 2.28 in the case of no interception to 1.31, 1.06 and 0.96, respectively. This is because the percentage of the rainfall events with relatively low EPL (compared to the mean) is significantly reduced after interception.

Initial runoff control schemes can significantly improve runoff quality (Fig.5c). For example, the percentage of rainfall event with EMC >40mm/L under scheme 1, 2 and 3 decreases from 88.3% in the case of no interception to 32.6%, 18.6%, 11.8%, respectively. Meanwhile, the maximum EMC is significantly reduced under the three schemes and the reduction levels roughly reflect the corresponding interception levels. This observation is also true for EPL. And C_s of EMC under scheme 1, 2 and 3 is 0.04, 0.003 and 0.04, respectively, which indicates EMCs have an even distribution of frequency after interception.

The peak concentration of COD decreases after interception (Fig.5d). For example, the percentage of rainfall event with peak concentration>40mm/L is 33.35%, 19.19% and 12.26% under scheme 1, 2 and 3, respectively. However, compared to the maximum EMC, the maximum peak concentration has little change after interception. The reason is that the maximum peak concentration usually occurs when the total runoff depth is greater than 20mm before interception, which approximately corresponds to the rainfall amount of 58mm (Fig. 3a and c). The schemes with an interception level of 15mm have little effect on the maximum peak concentration. In addition, the cumulative frequency distribution of peak concentration presents a concave upward curve, and the C_s of peak concentration under scheme 1, 2 and 3 is -0.35, -0.49, and -0.39, respectively, which implies that most rainfall events have a peak concentration more than the mean after interception.

Fig. 6 summarizes the impacts of the three interception schemes on runoff quality in terms of the specified thresholds of the four indicators.

It is obvious that increasing interception level further reduces the pollutant loading, EMC, and peak concentration but also increases the intercepted runoff at the same time, which results in less runoff available downstream, potentially affecting aquatic life. It should be noted that the first 5 mm interception has more significant effects, reflected by the steeper gradients in the left part of the curves. The gradients are reduced as the curves tend to flat out to the right. This reflects the effects of the first flush phenomenon in the catchment. This figure can be used by decision makers to balance the effects on water quality and quantity and determine the most appropriate scheme that satisfies their preference.

Fig.6 Runoff quantity and quality after interception

3.4 Effect of seasonal rainfall variation

Rainfall in the Shiyan River catchment has significant temporal variation. According to rainfall records, the wet season in the catchment can be divided into three periods: pre-flood season (March to May), flood season (June to August) and post-flood season (Sept to October). In this study, the effects of seasonal variation in rainfall events have been investigated to provide a better understanding of the performance of initial runoff control measure. We chose Scheme 2 (interception 10mm) and two indicators (EMC and peak concentration) for the analysis.

As seen in Fig.7a, the cumulative frequency distributions of EMC in pre-flood, flood and post-flood seasons present similar concave downward curves with C_s of 0.49, 0.70 and 0.66, respectively. The percentage of rainfall events with EMC>40mg/L in different seasons is around 89%. However, EMCs in pre-flood season is slightly higher than those in other seasons when the cumulative frequency is less than 45%.

Fig.7 Effect of initial runoff control in different seasons

With interception under Scheme 2, the cumulative frequency distribution of EMC in pre-flood, flood and post-flood seasons change to approximately linear or slightly concave upward curves with C_s of -0.18, 0.08 and 0.05, respectively (Fig.7b). This is because the percentage of the rainfall events with relatively low EMC (compared to the mean) significantly decreases after interception. Furthermore, pre-flood season has significantly higher EMC than other seasons. For example, the rainfall events with EMC>40mg/l in pre-flood, flood and post-flood seasons in Scheme 2 account for 22.67%, 17.43% and 16.99%, respectively. The reasons are related to the characteristics of rainfall events in different seasons. Since the rainfall events with total runoff depth<10mm have no surface runoff discharged into the downstream river in Scheme 2, we only considered the rainfall events with total runoff depth>10mm. As shown in Fig.8, the pre-flood season has lower percentage of events with rainfall amount > 50mm and higher percentage of rainfall events with ADP>10 days than other seasons. As explained in section 3.1, less rainfall amount may result in higher EMC for the events with rainfall amount> 50mm (Fig. 4c), and longer ADP results in higher EMC. Therefore, the pre-flood season has higher frequency of rainfall events with higher EMC than other seasons after initial runoff control.

Fig. 8 Rainfall amount and ADP in different seasons

Similarly to EMC, the cumulative frequency distributions of peak concentration in pre-flood, flood and post-flood seasons present similar concave downward curves with C_s of 0.53, 0.68 and 0.55, respectively (Fig.7c). The percentage of rainfall event with peak concentration>40mg/L in different seasons is around 92%. In Scheme2, the cumulative frequency distribution of peak concentration in pre-flood, flood and post-flood seasons change to concave upward curves with C_s of -0.51, -0.52 and -0.07, respectively (Fig.7d). The rainfall events with peak concentration>40mg/L in pre-flood, flood and post-flood seasons in Scheme 2 account for 23.14%, 18.33% and 17.70%, respectively. Due to the same seasons for EMC, the pre-flood season has higher frequency of rainfall events with higher peak concentration than other seasons after initial runoff control.

4 Conclusions

This paper uses the long-term simulation approach to derive the frequency distribution of urban runoff quality in an urbanizing catchment and evaluate the impacts of proposed runoff control schemes on the distribution. Further, the effects of seasonal variation in storm events are investigated to provide a better understanding of the performance of control measures. The results obtained are summarized below:

(1) Urban runoff quantity and quality in the rapidly urbanizing catchment have significant variations between rainfall events, and different indicators have rather different characteristics. With increasing event rainfall amount, the total runoff depth and runoff coefficient nonlinearly increase. The upper envelope curve of EPL initially increases and then levels off after the rainfall amount reaches 115mm. The upper envelope curve of EMC initially rapidly rises, after reaching a peak value, and then declines in an approximately exponential fashion. Peak concentration behaves similarly to EMC but declines slowly after the peak. Due to the effects of ADP, the events with the same rainfall amount have very different EPL, EMC and peak concentration of COD.

(2) Urban runoff quality in the rapidly urbanizing catchment has a high percentage of non-compliance with the surface water quality regulations. 43.0% of rainfall events have an EPL (COD) more than 1t/km^2; 88.3% of rainfall events have an EMC (COD) greater than 40 mg/L; and 91.9% of rainfall events have a peak concentration (COD) greater than 40 mg/L. The cumulative frequency distributions of total runoff depth, EPL, EMC and peak concentration of COD present a concave downward curve, which implies that most of the rainfall events have a relatively low runoff pollution level compared to the mean.

(3) Runoff control schemes can significantly improve the runoff quality in the catchment. In a long term period, the schemes with capacity to intercept initial runoff depth of 5mm, 10mm and 15mm can intercept 35.5%, 52.2% and 62.1% of all the runoff volume, and 45.67%, 69.92% and 82.19% of all the pollutant loading (COD) from the catchment, respectively. And the three schemes decrease the percentage of rainfall events with EMC >40mm/L from 88.3% to 32.6%,

18.6%, 11.8%, and the percentage of rainfall events with peak concentration>40mm/L from 91.9% to 33.35%, 19.19% and 12.26%, respectively. The diminishing marginal benefits are found with increasing interception levels in terms of water quality improvement. Furthermore, the cumulative frequency distributions of EMC and peak concentration change to a convex curve, which implies that most of the rainfall events have a relatively high concentration compared to the mean after interception.

(4) Runoff control schemes have different effects at different seasons due to seasonal variation in rainfall events. In the study, the pre-flood season has higher risk of non-compliance with the surface water quality standards than other seasons after initial runoff control.

The urban runoff quantity and quality have considerable variations in different rainfall events in an urbanizing catchment, thus, characterizing frequency distributions of runoff quantity and quality can provide a probabilistic evaluation of pollution control measures, and will help frame a risk-based decision making for urban runoff quality management in an urbanizing catchment.

It should be noted that the paper is limited to the analysis of rainfall runoff pollution of the catchment at the current urbanization level. The model needs to be calibrated against newly observed data at a different urbanization level if the study catchment undergoes further urbanization in the future.

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Figure captions

Fig. 1 Map of the Shiyan River catchment

Fig. 2 Frequency distributions of rainfall amount and ADP

Fig. 3 Comparison between measured and calculated data

Fig. 4 Rainfall amount vs. runoff quantity and quality

Fig. 5 Effects of different levels of initial runoff control

Fig. 6 Runoff quantity and quality after interception

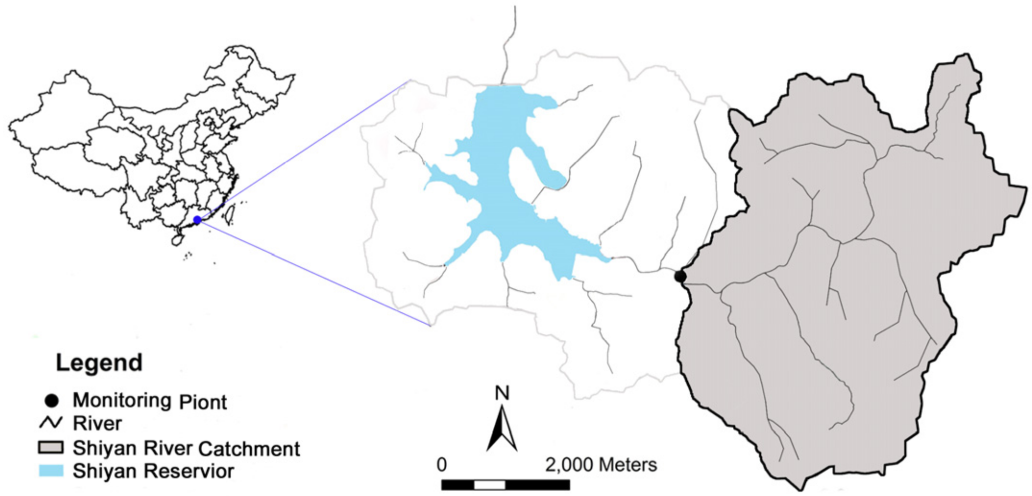
Fig.7 Effect of initial runoff control in different seasons

Fig. 8 Rainfall amount and ADP in different seasons

Table captions

Table 1 Observed rainfall data for model calibration and validation

Table 2 Optimized values of model parameters


Legend
Monitoring Piont
River
Shiyan River Catchment
Shiyan Reservior
N
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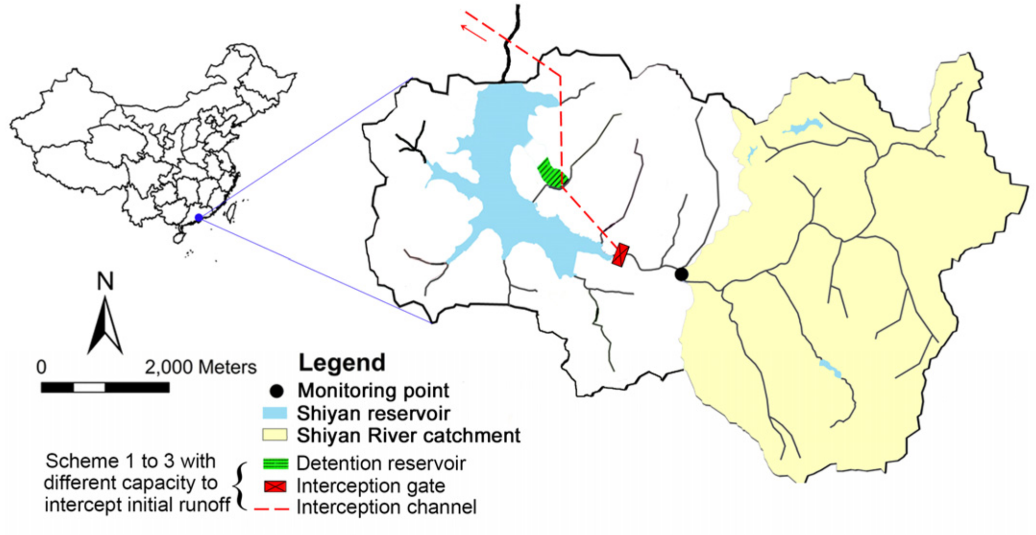
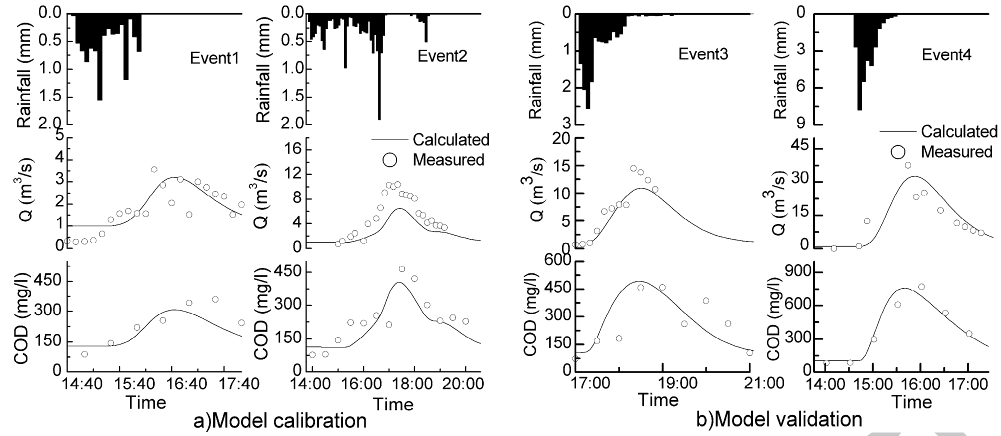
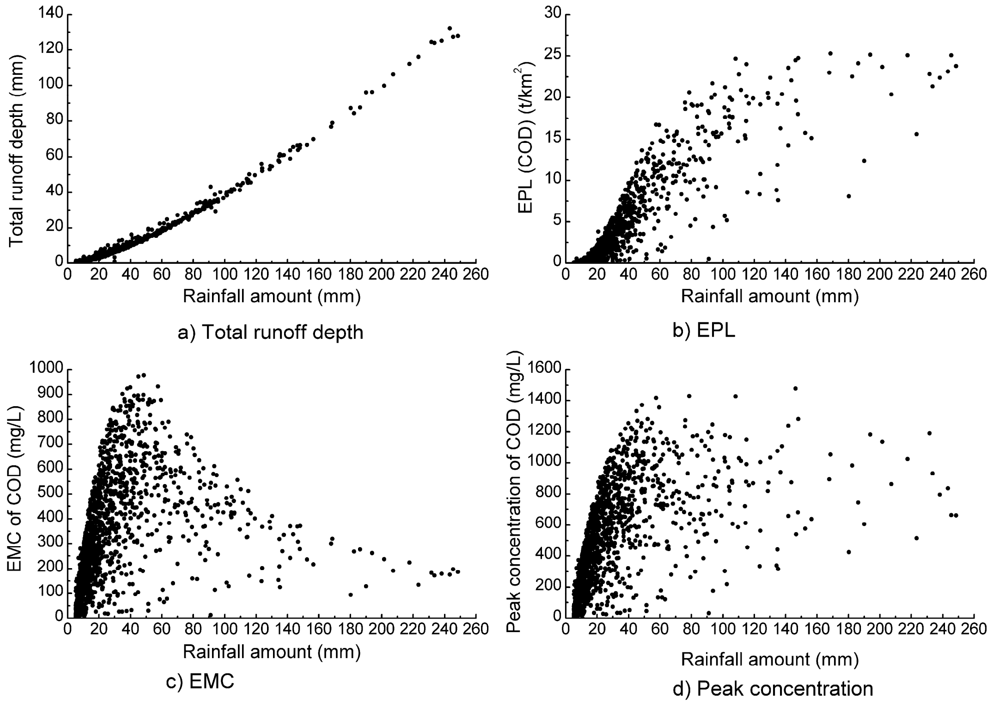
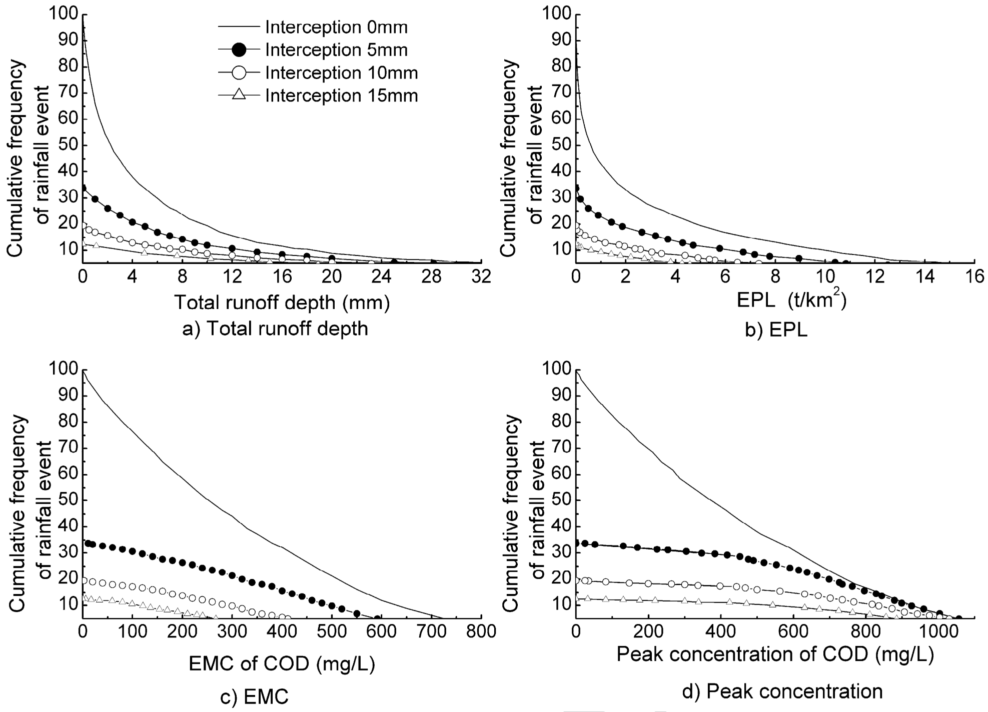
2,000 Meters

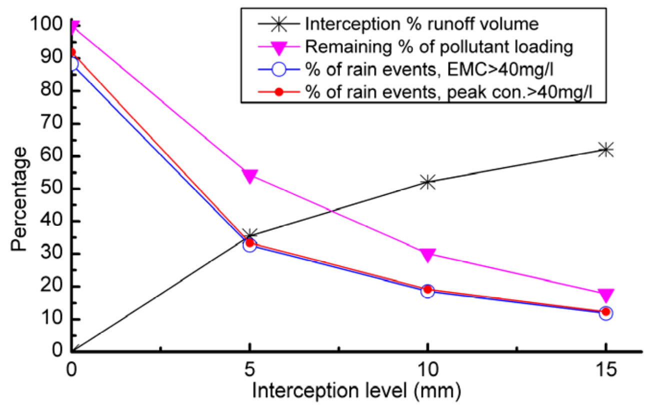
579

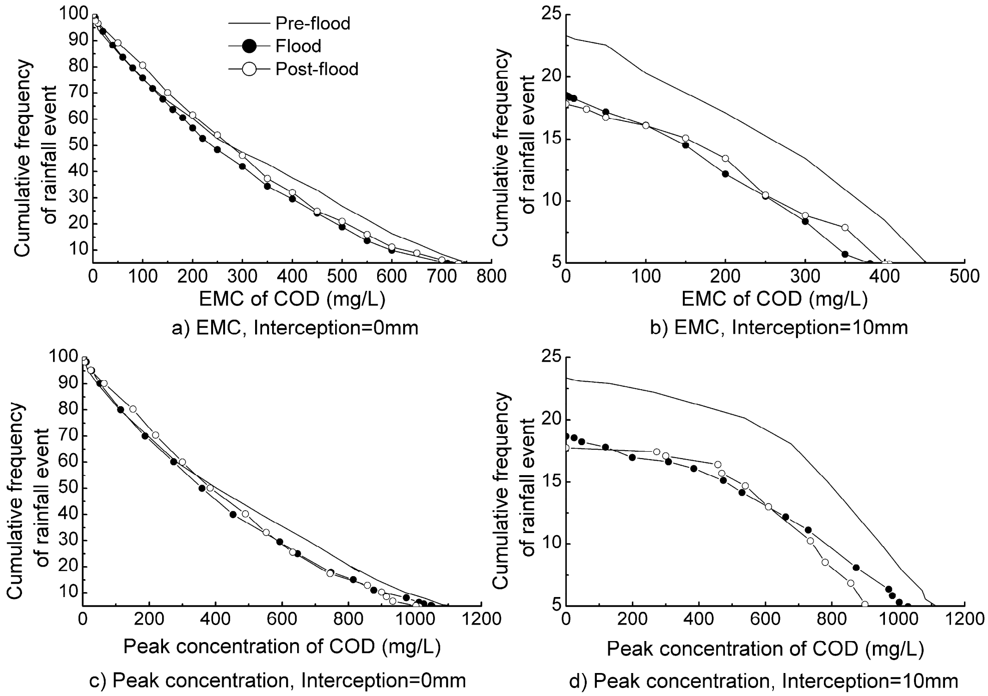
580 
N
0
2,000 Meters
Legend
Monitoring point
Shiyan reservoir
Shiyan River catchment
Scheme 1 to 3 with different capacity to intercept initial runoff
Detention reservoir
Interception gate
Interception channel

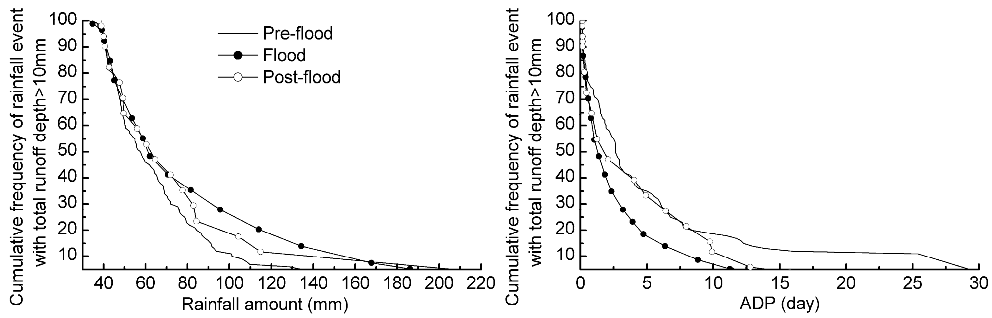
581 
Event1
Event2
Event3
Event4
Rainfall (mm)
Q (m³/s)
COD (mg/l)
Calculated
Measured
Time
a)Model calibration
b)Model validation


Total runoff depth (mm)
Rainfall amount (mm)
a) Total runoff depth
EPL (COD) (t/km²)
Rainfall amount (mm)
b) EPL
EMC of COD (mg/L)
Rainfall amount (mm)
c) EMC
Peak concentration of COD (mg/L)
Rainfall amount (mm)
d) Peak concentration

583 
Interception 0mm
Interception 5mm
Interception 10mm
Interception 15mm
Cumulative frequency of rainfall event
Total runoff depth (mm)
a) Total runoff depth
EPL (t/km2)
b) EPL
EMC of COD (mg/L)
c) EMC
Peak concentration of COD (mg/L)
d) Peak concentration

584 
Interception % runoff volume
Remaining % of pollutant loading
% of rain events, EMC>40mg/l
% of rain events, peak con.>40mg/l
Percentage
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
Interception level (mm)


Pre-flood
Flood
Post-flood
Cumulative frequency of rainfall event
EMC of COD (mg/L)
a) EMC, Interception=0mm
b) EMC, Interception=10mm
Peak concentration of COD (mg/L)
c) Peak concentration, Interception=0mm
d) Peak concentration, Interception=10mm

586 

a) Rainfall amout in different seasons

b) ADP in different seasons

Table 1 Observed rainfall data for model calibration and validation

Event	Date	Rainfall amount (mm)	ADP (day)	Discharge (m3/s)	COD (mg/l)
1	April 13,2009	8.9	15	0.32-3.56	88-360
2	April 18,2009	13.3	2.6	0.72-10.36	78-464
3	September 2,2010	13.9	1.4	0.71-14.53	73-460
4	September 7,2010	29.5	5.8	0.23-37.62	81-772

Table 2 Optimized values of model parameters

Symbols	Meanings	Units	Search ranges	Optimized values
c_1	mass balance parameter in effective rainfall function	mm^{-1}	[1e-3,3e-3]	2e-3
I	soil moisture index threshold in effective rainfall function	mm	[4,10]	5
p	non-linear response parameter in effective rainfall function	dimensionless	[0.3,0.5]	0.36
τ	time constant of wetness declines	dimensionless	[8e+2,1e+3]	916
α	shape parameter of gamma distribution	dimensionless	[3,5]	3.9
β	scale parameter of gamma distribution	dimensionless	[15,20]	19.2
c_2,	pollutant wash-off coefficient	dimensionless	[1e-2,2e-2]	1.2e-2
c_3,	pollutant wash-off exponent	dimensionless	[1,1.5]	1.45
Accu	pollutant buildup rate	$kg/(km^2\ d)$	[1e+6,1.5e+6]	1.2e+6
Disp	pollutant buildup decay rate	d^{-1}	[0.1,0.4]	0.19

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

>Distributions of four runoff quality indicators are derived from continuous simulation

>Impacts of runoff control schemes are analyzed from the distributions

>Marginal benefits of improving water quality diminish as runoff control level increases

>Pre-flood season has higher water quality risk than other seasons after runoff control

>Our approach helps frame a risk-based decision making for urban runoff management