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Characterization of surface runoff from a subtropics urban catchment

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Abstract

Characteristics of surface runoff from a 0.14-km^2 urban catchment with separated sewer in Macau was investigated. Water quality measurements of surface runoff were carried out on five rainfall events during the period of August to November, 2005. Water quality parameters such as pH, turbidity, TSS, COD, TN, Zn, Pb, and Cu were analyzed. The results show that TN and COD are the major pollutants from surface runoff with mean concentration of 8.5 and 201.4 mg/L, both over 4-fold higher compared to the Class V surface water quality standard developed by China SEPA. Event mean concentration (EMC) for major pollutants showed considerable variations between rainfall events. The largest rainfall event with the longest length of antecedent dry weather period (ADWP) produced the highest EMC of TN, TSS and COD. From the pollutographs analysis, the peak concentration of TN precedes the peak runoff flow rate for all three rainfall events. The tendency of the concentration of TSS, turbidity and COD changing with runoff flow varies between rainfall events. The relationship between TSS and other parameters were analyzed to evaluate the efficiency of the physical treatment process to control the surface runoff in the urban catchment. Based on the correlation of parameters with TSS, high treatment efficiency of TSS, TN and COD was expected. The most significant event in term of first flush is the one with the strongest rainfall intensity and longest length of ADWP. TN always showed first flush phenomenon in all three rainfall events, which suggested that the surface runoff in the early stage of surface runoff should be dealt with for controlling TN losses during rainfall events.

Key words: surface runoff; event mean concentration (EMC); first flush; Macau

Introduction

Researchers have found that the load and concentration of suspended solid, nutrients, heavy metals and organic pollutants discharge from urban surface runoff are higher than that in untreated polluted and rural areas (Sartor and Boyd, 1972; Field and Pitt, 1990). These contaminants will detrimentally impact aquatic organisms and alter the characteristics of the ecosystem, which may lead to deterioration of water quality and degradation of stream habitats in urban areas.

Since the 1960s, international society has come to realize the urban surface runoff is the major pollution problem in urban areas. Developed countries such as USA and European Union paid more attentions to investigate the characterization of urban surface runoff before developing surface runoff management planning (Zabel *et al*., 2001). In fact, before any planning is done or any practical steps are taken to control the quality of urban runoff, it is necessary to first specify the characteristics of urban surface runoff (Taebi and Droste, 2004). Many researches have been carried out to characterize the surface runoff pollutants discharged from small catchments of differing urban surface type, including roofs, highway, and different land-use catchments (Yaziz *et al*., 1989; Chang *et al*., 2004; Choe *et al*., 2002; Gnecco *et al*., 2005; Chebbo and Gromaire, 2004; Yusop *et al*., 2005; Deletic, 1998; Goonetilleke *et al*., 2005). In recent years, the study on characterization of highway runoff (Zhao *et al*., 2001) and roof runoff (Che *et al*., 2001; Wang *et al*., 2005) have been reported in China. But till now, there are few reports about the characterization of surface runoff in an urban catchment environment in China including Macau.

The objective of this study was to investigate the characteristic of surface runoff from an urban catchment with separated sewer system in Macau, based on the analysis of the major pollutants from surface runoff, pollutographs analysis, correlation analysis between TSS and other parameters, and first flush phenomenon analysis so as to develop strategy for urban surface runoff management in Macau.

1 Methods

1.1 Description of study catchment

The YLF catchment is located in the centre of Macau

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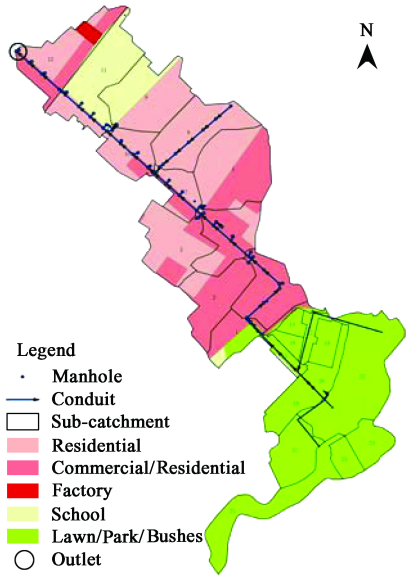

Fig. 1 Map of the YLF (Yalianfang) urban catchment.

(Fig.1). It covers 0.14 km^2 and has a impermeability of 60%. The study catchment is a densely populated residential/commercial area with 24000 inhabitants. The catchment mainly consists of residential/commercial (55.2%) and lawn/park (34.8%) (Fig.1 and Table 1). The sewer network is separated.

Table 1 Description of study catchment

Characterization	Value
Area (km^2)	0.14
Land-use (%)	
Factory	0.52
School	9.45
Residential and commercial	24.54
Residential	30.66
Lawn/park	34.83
Sewer type	Separated sewer
Slope (%)	7.75
Percent impervious (%)	60
Stream lengths (m)	868
Vehicle (d-1)	20000
Population (person)	24000

1.2 Sample collection and testing

Automatic monitoring station was established at the outlet of study catchment. An automatic event sampler (ISCO 6712) and rain gauge was equipped to grab samples and obtain rainfall depth during storms. Sampling was done at 5–10 min intervals in the first 60 min of storm events and then 30 min intervals for receding flow stage. Sampling in the study catchment was carried out during the period from August to November in 2005. At the time of all samplings, the runoff flow rate was also measured using ISCO 750 area velocity module excepting for two rainfall events on 9 August, and on 16 August. Unfortunately, the flow meter did not work appropriately during these two rainfall events.

The samples were collected and analyzed according to APHA standard methods (APHA, 1992). Water quality parameters included pH, turbidity, Total suspended solid (TSS), COD, total nitrogen (TN), and heavy metals including Zn, Pb, and Cu.

1.3 Characteristic of rainfall events monitored

Five rainfall events were sampled during the period from August to November, 2005 (Table 2).

Table 2 Characteristic of rainfall events and antecede dry weather period condition in YLF (Yalianfang) catchment

Rainfall date	Depth (mm)	Duration (min)	Average intensity (mm/h)	ADWP (h)
2005/08/09	7.2	58	7.4	85.4
2005/08/16	15.2	81	11.3	16.4
2005/08/21	3.4	122	1.7	9.2
2005/08/24	2.4	80	1.8	56.7
2005/11/14	11.4	121	5.7	1072.5

ADWP: antecede dry weather period.

1.4 Calculation of event mean concentration (EMC)

Typically, the concentration of pollutant in surface runoff is represented as event mean concentration (EMC) due to the large fluctuation during the rainfall. An EMC of a pollutant in a specific catchment is obtained from the division of the total pollutant mass by the total runoff volume in that event and catchment (Eq. (1)).

$$EMC = \frac{\sum_{i=1}^{N} \bar{C}_i \bar{Q}_i \Delta t_i}{\sum_{i=1}^{N} \bar{Q}_i \Delta t_i} = \frac{\sum_{i=1}^{N} \Delta M_i}{\sum_{i=1}^{N} \Delta V_i} \quad (1)$$

In which N, $\bar{Q}_i$, $\overline{C_i}$, ΔM_i, ΔV_i and Δt_i, are number of samples, average runoff flow rate, average runoff pollutant concentration, runoff pollutant mass, and runoff volume in the time interval, respectively.

2 Results and discussion

2.1 Urban surface runoff quality

A statistical summary of urban surface runoff quality for the catchment study is given in Table 3.

Based on the data in Table 3, the following can be discerned.

Water quality parameters whose arithmetic mean concentration exceeded the Class V surface water standard developed by China SEPA were identified as the major pollutants. Arithmetic mean concentration of TN and COD is 8.5 mg/L and 201.4 mg/L, respectively, all exceed the Class V surface quality standard by more than 4 factors. The maximum concentration of TN and COD from surface runoff is 52.0 mg/L and 1274.0 mg/L whereas their minimum concentration is 0.9 mg/L and 7.3 mg/L, respectively, which indicates that serious nitrogen and organic pollutant losses may happen during rainfall events in YLF catchment. However, the concentration of heavy metals i.e. Cu, Zn, Pb presents at a low level.

By comparison with the surface water standards for

Table 3 Summary statistics of surface quality of YLF catchment in Macau

Parameters	pH	Zn (mg/L)	Pb (mg/L)	Cu (mg/L)	TSS (mg/L)	TN (mg/L)	COD (mg/L)
Maximum	7.6	0.185	0.0153	0.0248	2600.0	52.0	1274.0
Minimum	6.7	0.008	0.0011	0.0014	10.0	0.9	7.3
Arithmetic mean	7.2	0.055	0.0032	0.0049	318.6	8.5	201.4
Standard deviation	0.2	0.039	0.0030	0.0040	525.3	10.5	292.2
CEPA standard	6–9	⩽2	⩽0.1	⩽1	-	⩽2	⩽40

Sample numbers for pH, TSS, TN, Cu, Zn, Pb, and COD are 57, 45, 48, 44, 43, 40 and 47, respectively.

China, results showed that surface runoff is badly polluted especially for TSS, COD, and TN. Yusop *et al*. (2005) had similar observation during their research in a tropical urban catchment with a land-use compose of about 27% agriculture, 37% residential and commercial and 28% lawn/parks/bushes. TN mainly sourced from soil loss of lawn and garden chemical such as fertilizer (Whipple *et al*., 1983). There is a park at the upstream of the YLF catchment (Fig.1). When strong intensity rainfall event occurred, with soil losses and nitrogen losses happened, it may make the surface runoff quality high concentration level of TSS and TN.

EMC for various parameters showed considerable variations between events (Table 4). The rainfall event on 14 November registered the highest EMC value for major pollutants. The next highest is for event 24 August and the lowest for the rainfall event on 21 August. EMC of TN and COD for event on 14 November is 15.14 mg/L and 464.5 mg/L, are over 7–11 times higher than that of event on 21 August.

EMC from urban surface runoff depends largely on both build-up and wash-up processes (Butcher, 2003). In this study, EMCs for TN, TSS and COD have a close relation with the length of ADWP and the rainfall intensity. The largest rainfall event on 14 November with the longest length of ADWP produced the highest TN, TSS and COD concentration (Table 4). The other investigator also observed that the number of dry days preceding a rainfall event significantly affects the quality of runoff water from the catchment systems (Yaziz *et al*., 1989).

Table 4 Event mean concentration of 3 rainfall events in YLF catchment

Parameter	Event mean concentration (EMC)		
	2005/8/21	2005/8/24	2005/11/14
Turbidity (NTU)	17.7	54.52	60.14
TSS (mg/L)	22.34	/	788.34
TN (mg/L)	2.22	1.96	15.14
COD (mg/L)	41.14	169.17	464.50

2.2 Pollutographs analysis of surface runoff

Combining runoff quality and flow data at YLF catchments produces pollutographs. The pollutographs of major pollutants from three rainfall events are showed in Fig.2.

The peak concentration of TN precedes the peak runoff flow rate in all three rainfall events. TN concentration shows higher level at the early stage of surface runoff. The peak concentration of TN appears at the third, first and fourth sample for three rainfall events, respectively. It tends

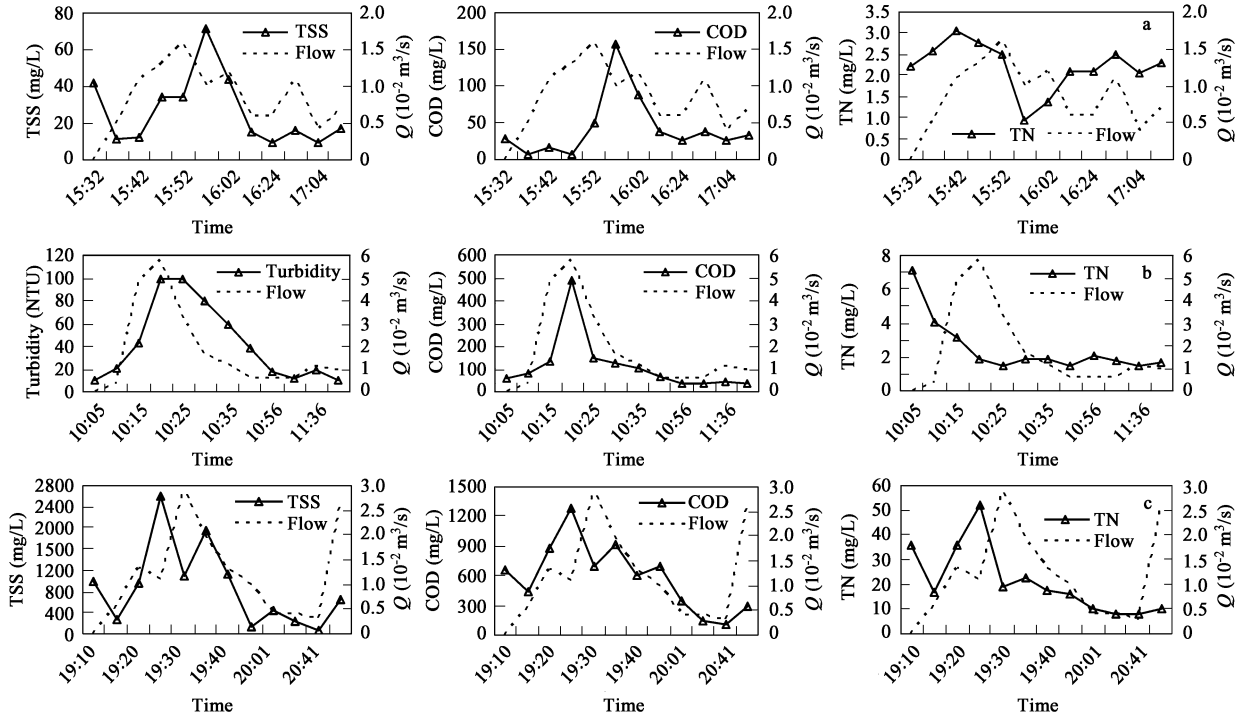

Fig. 2 Pollutographs for 2005/8/21 (a), 2005/8/24 (b) and 2005/11/14 (c) rainfall event in YLF catchment.

to decrease with the runoff flow, no matter whether another flow peak exits or not. Especially for the rainfall event on 24 August, the highest concentration of TN appears at the first sample and then gradually decreases, showing strong flushing effects (Fig.2b). This suggests that TN source might be exhausted and subjected to dilution at the initial phase of surface runoff.

The tendency of the concentration of TSS, Turbidity and COD changing with runoff flow varies between rainfall events. For the rainfall events on 21 August and 24 August, the peak runoff flow rate precedes the peak concentrations of TSS, Turbidity and COD (Figs.2a and 2b). On the contrary, the peak runoff flow rate followed by the peak concentrations of TSS, Turbidity and COD for the event on 14 November (Fig.2c).

The rainfall characteristic, ADWP condition and land cover in the study catchment influences the profile of pollutographs. Lower rainfall intensity (rainfall events on 21 August and on 24 August) made rainfall slowly infiltrate, generate the surface runoff, and wash off the pollutants on the surface of the catchment. As mentioned before, a park located in the upstream of YLF urban catchment may cause longer time processes. Comparably, the rainfall event on 14 November with more depth (11.4 mm) and rainfall intensity (5.7 mm/h) enabled the buildup mass on the surface to wash off quickly. In additional, it has the longest length of ADWP, which provided a more buildup mass in the same street-sweeping condition.

2.3 Relationship between TSS and other parameters

The relationship between TSS and other parameters were analyzed to evaluate the efficiency of the physical treatment process and summarized in Table 5. The degree of correlation was in the following order: COD>TN>Zn>Pb>Cu. TSS had high correlation with COD and TN with a high value (>0.85) of the coefficient of determination R^2, which indicates that a close relationship between soil losses and nitrogen discharge from urban surface runoff. It could be surmised that most of COD and TN exist in the form absorbed by soil particles (Goonetilleke *et al*., 2005). From a management perspective, structural surface improvement measures such as detention basins or sediment traps would be effective in removing most of the nutrient pollutants and organic pollutants in the urban surface runoff discharge from the YLF catchments.

Table 5 Regression coefficients between TSS and other parameters

Parameters	COD	TN	Zn	Pb	Cu
Regression coefficients	0.899	0.870	0.217	0.132	0.006
Sample no.	35	36	31	31	32

2.4 First flush phenomenon analysis

The phenomenon known as "the first flush of storm runoff" usually assumed that the first part of runoff is most polluted (Deletic, 1998). To assess the first flush, researchers usually use curves of the cumulative fraction of total pollutant mass vs. the fraction of total cumulative runoff volume for the event. Geiger (1987) used the point of maximum divergence from the 45 slopes to quantify the first flush (Deletic, 1998). In this study, the first flush phenomenon was identified by Geiger's definition.

The curves of major pollutants from YLF catchment were reproduced for three rainfall events (Fig.3). Insufficient data makes any statistical analysis scarcely significant, although some interesting information can be obtained by looking at the characteristics of the monitored rainfall events and the related curves (Gnecco *et al*., 2005). The most significant event in term of first flush is the one of November 14, 2005. Compared to the other rainfall events, this rainfall event owns the longest length of ADWP and the strongest rainfall intensity, and both buildup and wash off processes also are the strongest, which maybe lead to the significant first-flush effects.

Additionally, TN always showed first flush phenomenon in all three rainfall events, which suggested that the runoff in the early stage of surface runoff should be dealt with for controlling TN losses during rainfall events.

3 Conclusions

TN and COD are the major pollutants from surface runoff with mean concentration of 8.5 and 201.4 mg/L, both over 4-fold higher compared to the Class V surface water quality standard developed by China SEPA.

Event mean concentration (EMC) for major parameters showed considerable variations between rainfall events. The largest rainfall event with the longest length of ADWP produced the highest TN, TSS and COD concentration.

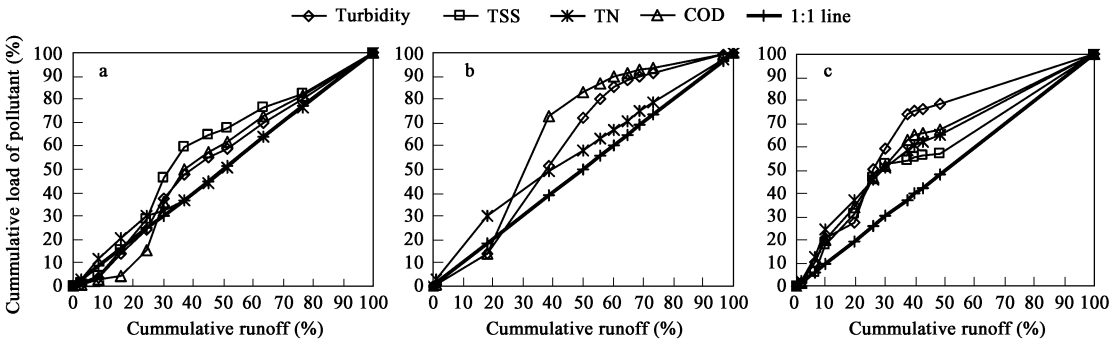

Fig. 3 Cumulative curves of Turbidity, TSS, TN, COD in three rainfall events. (a) 2005/8/21; (b) 2005/8/24; (c) 2005/11/14.

TN concentration shows higher level at the early stage of runoff. The peak concentration of TN precedes the peak runoff flow rate for all three rainfall events. While the tendency of the concentration TSS, turbidity and COD changing with runoff flow varies between rainfall events. The rainfall characteristic, ADWP condition and land cover affects the profile of the pollutographs.

The relationship between TSS and other parameters were analyzed to evaluate the efficiency of the physical treatment process to control the surface runoff in the urban catchment. The degree of correlation was in the following order: COD>TN>Zn>Pb>Cu. Based on the correlation of parameters with TSS, high treatment efficiency of TSS, TN and COD was expected.

The most significant event in term of first flush is the one with the strongest rainfall intensity and longest length of ADWP. TN always showed first flush phenomenon in all three rainfall events, which suggested that the runoff in the early stage of surface runoff should be dealt with for controlling TN losses during rainfall events.

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