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Multivariate Analysis for Stormwater Quality Characteristics Identification from Different Urban Surface Types in Macau

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Abstract Statistical analysis of stormwater runoff data enables general identification of runoff characteristics. Six catchments with different urban surface type including roofs, roadway, park, and residential/commercial in Macau were selected for sampling and study during the period from June 2005 to September 2006. Based on univariate statistical analysis of data sampled, major pollutants discharged from different urban surface type were identified. As for iron roof runoff, Zn is the most significant pollutant. The major pollutants from urban roadway runoff are TSS and COD. Stormwater runoff from commercial/residential and Park catchments show high level of COD, TN, and TP concentration. Principal component analysis was further done for identification of linkages between stormwater quality and urban surface types. Two potential pollution sources were identified for study catchments with different urban surface types. The first one is referred as nutrients losses, soil losses and organic pollutants discharges, the second is related to heavy metals losses. PCA was proved to be a viable tool to explain the type of pollution sources and its mechanism for different urban surface type catchments.

Keywords Stormwater quality · Principal component analysis · Urban catchments · Macau

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Non-point pollution resulting from urban stormwater runoff is recognized as one of the major causes of quality deterioration in the receiving water bodies in urban areas (Tsihrintzis and Hamid 1997). Before any practical steps are taken to control the quality of urban runoff, it is necessary to first specify the characteristics of urban stormwater runoff (Taebi and Droste 2004). It is possible to relate stormwater runoff characteristics to different types of urban surfaces by knowing specific drainage catchments with different predominate land cover (Rimer et al. 1978; Chebbo and Gromaire 2004; Gnecco et al. 2005; Goonetilleke et al. 2005).

Multivariate technique including principal component analysis (PCA) proved to be a viable tool to make water quality analysis (Wunderlin et al. 2001; Hamers et al. 2003; Vazquez et al. 2003). However, few studies on urban stormwater quality analysis by multivariate technique have been reported (Yamada et al. 1993; Goonetilleke et al. 2005). Characteristics of urban stormwater quality in Macau still remain poorly understood (Huang et al. 2007).

The main objectives of this study are to (1) clarify the major pollutants of stormwater from different urban surface types based on the univariate statistical analysis of in situ data; (2) identify the linkages between stormwater quality and urban surface types through PCA method.

Materials and Methods

Six catchments with different characteristics in urban areas of Macau were selected. A brief summary of site characteristics is given in Table 1.

Two roofs materials were chosen, e.g. iron and concrete roof. Iron roof is a popular choice in Macau, which occupies more than 60% of all roof materials. Because it tends to be rusted in coastal areas, two iron roofs were further chosen by the extent of being suffered from rust. Among these, iron roof A and B has been equipped for about 10 and 5 years, respectively.

SunYiXian (SYX) roadway catchment, with area of 3,875 m^2, in which average daily traffic counts are 30,000 vehicles, and the pavement is asphalt. The land-use around SYX roadway is mostly commercial and undeveloped.

YaLianFang (YLF) catchment is intensively developed as residential/commercial catchments, and the percentages of impervious area are 60 with 20,000 vehicles per day. There are 27,000 habitants in this catchment. ErLongHou (ELH) Park catchment is just upstream of the YLF catchment. It comprised more than 70% of lawn, garden and woods, 30% of road surface, tennis court, etc. Fig. 1 shows the location of study catchments.

Automatic monitoring stations were established at the outlet of each study catchments except the roof catchments. Each station was equipped with an automatic event sampler (ISCO 6712) and rain gauge to grab samples and obtain rainfall 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. The rainwater from roofs catchments was manually collected through constructing a rainwater collection system to collect 1 L of run-off rainwater from the roof runoff. Sampling in the study catchments was carried out during the period from June 2005 to September 2006. At the time of all sampling, the runoff flow rate was also measured. Number of rainfall events sampled was listed in Table 1.

The samples were collected and analyzed according to APHA standard methods (APHA et al. 1992). Water quality parameters included pH, total suspended solid (TSS), COD_{Cr}, TOC, total nitrogen (TN), total phosphorus (TP), and heavy metals including Zn, Pb, and Cu.

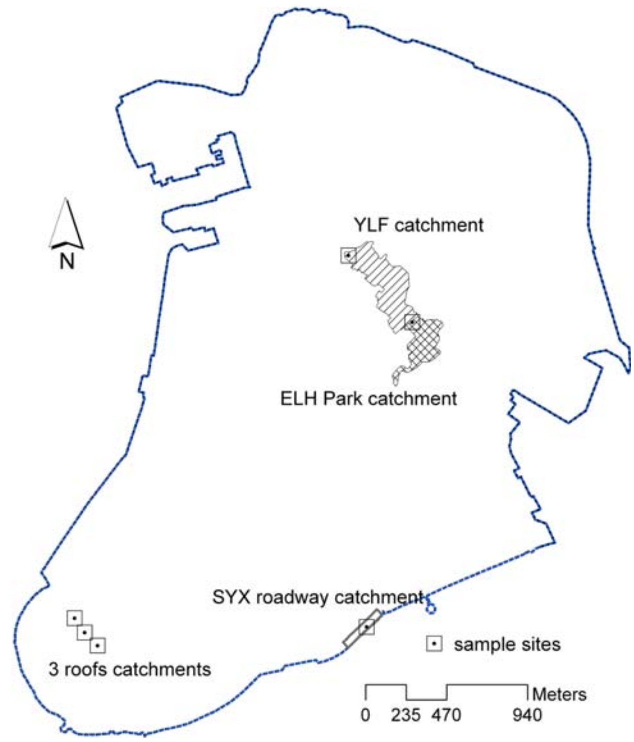

Fig. 1 Location of study catchments

Results and Discussions

Analysis of the stormwater runoff data obtained at the automatic sampling stations permits generalized comparisons of runoff characteristics from different urban surface type. Univariate statistical analysis was undertaken based on the data from June 2005 to September 2006. Table 2 gives the mean concentration and standard deviation (SD) of quality parameters for the study catchments.

According to the Class V surface water standard developed by China SEPA, water quality parameters of urban stormwater runoff whose mean concentration value

Table 1 Description of study catchments

Experiment catchments	Area (hm^2)	Landuse	Percent impervious (%)	Slope (%)	Number of rainfall events sampled
YaLianFang (YLF)	13.650	Commercial and residential	60	7.8	13
ErLongHou (ELH) Park	4.670	Lawn, garden and woods	30	13.7	8
SunYiXian (SYX) roadway	3.870	Asphalt road	90	0	5
Iron A roof	0.045	Iron roof	100	15.0	3
Iron B roof	0.020	Iron roof	100	0	3
Concrete roof	0.006	Concrete roof	100	0	2

Table 2 Summary of water quality data in study catchments

Catchments (sample number)	Parameters (mg/L with exception of pH)								
	pH	Zn	Pb	Cu	TSS	TN	TP	TOC	COD
Iron A roof (23)									
Mean	6.9	7.95	0.020	0.004	–	2.72	–	13.4	48.5
SD	0.2	5.02	0.017	0.003	–	1.36	–	7.7	29.7
Iron B roof (23)									
Mean	6.8	4.94	0.008	0.005	–	2.93	–	10.5	31.3
SD	0.1	2.67	0.007	0.003	–	1.42	–	4.5	28.9
Concrete roof (15)									
Mean	8.1	0.03	0.005	0.005	–	2.08	–	6.5	12.3
SD	0.4	0.02	0.004	0.003	–	0.65	–	1.7	6.9
YLF (148)									
Mean	7.3	0.17	0.042	0.008	181.3	7.46	0.86	16.6	132.9
SD	0.3	0.22	0.064	0.011	419.1	7.99	0.79	25.4	197.3
ELH (87)									
Mean	7.3	0.14	0.091	0.022	82.8	5.58	0.56	17.2	105.8
SD	0.3	0.19	0.057	0.012	194.7	3.06	0.69	18.7	129.5
SYX (48)									
Mean	7.5	0.24	0.056	0.041	417.2	3.58	0.24	17.8	117.8
SD	1.2	0.20	0.074	0.032	597.4	3.17	0.20	9.8	96.5
Standard[a]	6–9	≤2	≤0.1	≤1	–	≤2	≤0.4	–	≤40

[a] Class V surface water standard developed by China SEPA

exceeded the standard were identified as the major pollutants (see Table 2). As for iron roof runoff, Zn is the most significant pollutant. The mean concentration of Zn from the iron roof runoff is 1–2 magnitude higher than that from all the other urban surface types including concrete roof. Chang et al. (2004) and Gnecco et al. (2005) had similar observations. Obviously, the mean concentration of Zn from iron A roof runoff is higher than that from iron B roof, which implies that usage of roof materials with iron will badly influence the quality of receiving water as iron roof tends to be rusted with time. Some measures should be put forward to stop the further utility of the iron roofs in Macau. A sensible choice of roofing materials should enable a reduction in the micro-pollutant load in stormwater runoff water to be achieved (Chebbo and Gromaire 2004).

The mean value of pH from concrete roof runoff is 8.1. This effect may be due to the existence of alkaline material in concrete roof. Thomas and Greene (1993) also found such phenomenon in their research.

The major pollutants from urban roadway runoff are TSS and COD. Stormwater runoff from commercial/residential and Park catchments show high level of COD, TN, and TP concentration. Due to higher percentages of impervious area, runoff from the YLF catchment exhibits higher concentration values of TSS, COD, TN and TP than that from ELH Park catchment, which suggests that the polluted nature of urban stormwater runoff changes as urbanisation increases.

Interestingly, mean concentration of heavy metals (including Pb, Zn, Cu) of stormwater runoff from different urban surface types in Macau except Zn from iron roof runoff all is in a very low level.

The standard deviation (SD) for TSS, COD, TN, and TP from YLF, ELH Park, and SXY roadway catchments, and Zn from the iron roofs runoff are great, which reflects great uncertainties of stormwater quality. This makes urban stormwater quality control more difficult.

Principal component analysis (PCA) was further done for pattern recognition. As a multivariate statistical data analysis technique, PCA reduces a set of raw data into a number of principal components, which retain the most variance with the original data. Detail descriptions of PCA can be found in the literature (Zhang and Yang 2002).

Principal component analysis (PCA) was performed by mean of the statistical packages SPSS12.0 in YLF, ELH Park and SYX catchments. Three roof catchments did not undertake PCA for their relative scarcity of sampled data. The distribution of principal loading Bitplots for the individual study catchments were presented in Figs. 2, 3 and 4. It is worth to note that principal component analysis resulted in most of the data variance being contained in the first two components, namely, PC1 and PC2 in Figs. 2, 3 and 4. Moreover, in the Bitplots, loading situated closely together represent variables that are highly correlated. According to these rules, PCA was used for pattern recognition and identification of correlation between various pollutant parameters and different urban surface type catchments in Macau.

Just as shown in Fig. 2, PC1 was concerned with the heavy metals including Pb, Zn and Cu in SYX roadway catchment. As some researchers found that Pb, Zn, Cu and other heavy metals mainly sourced from vehicle's exhaust (Sansalone and Buchberger 1997).Vehicles activities constitute the major sources of stormwater runoff, which sounds reasonable for an urban roadway with 30,000 vehicles per day in Macau. TSS, TN, TP and TOC closely correlated in Fig. 2, which suggests that TN, TP and TOC must be in sediment detached form. In other words, nutrients leaching and organic pollutants losses accompanied with constituents washoff from urban roadway runoff. Nitrogen might not source from wet deposition for its particulate form. Few nitrogenous fertilizer used in the lawns planted in middle of the roadway is surmised to be its source. As an asphalt road, TOC in particulate form greatly depends on the vehicles activities (Sansalone and Buchberger 1997). Just as illustrated in Table 2, mean concentration of TP from SYX roadway runoff shows a low level and this might have occurred from soil losses.

COD shows a slight correlation with PC2, but a medium correlation with PC1 (see Fig. 2). It is understandable that the source of COD tends to be from vehicles activities. There is slight correlation between TSS and Cu, Zn and Pb. It is postulated that the heavy metals must be primarily in dissolved form. Moreover, Cu, Zn and Pb correlated closely with each other.

As shown in Fig. 3, PC1 is connected with TSS, TN, COD and TP. Meanwhile, PC2 is related to heavy metals including Cu, Zn, and Pb in YLF catchment. The information of such two factors underlied is similar as mentioned in SYX roadway catchment. The differences – soil losses, nutrient and organic pollutants losses – became the major pollution source instead of vehicles' exhaust for YLF catchment. This difference is due to the fact that there is a Park, ELH Park, just at the upstream of the YLF catchment (see Fig. 1). It is postulated that there would be high usage of fertilizer for the lawns of the Park. Soil losses and nutrients losses might happen when storms occurred, which would make the stormwater quality have high concentration level of TSS and nutrients (Huang et al. 2007). Whipple et al. (1983) also found that TN and TP mainly sourced from soil losses and leaching of lawn and garden chemicals such as fertilizer. COD might mainly source from fertilizer leaching with soil losses. As for the YLF catchment, 20,000 vehicles per day might become the major source of heavy metals including Cu, Pb and Zn.

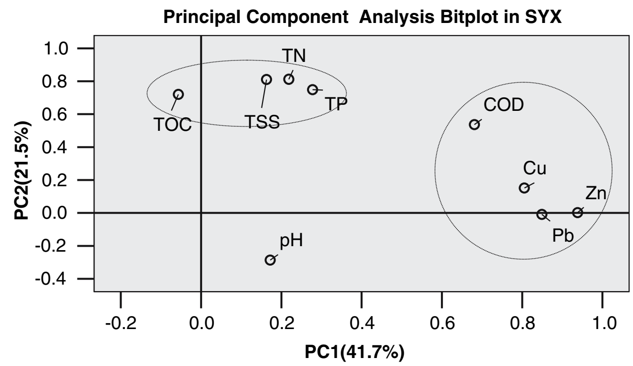

Fig. 2 Bitplot for SYX roadway catchment

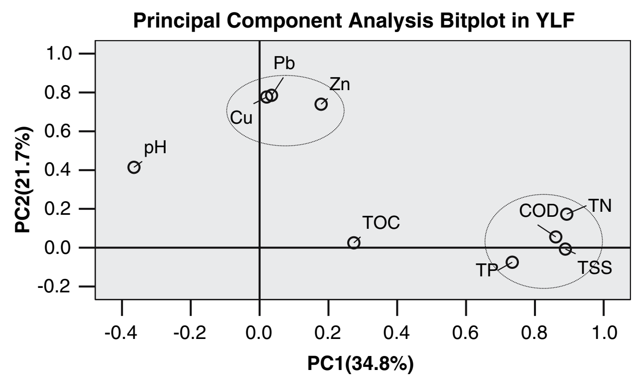

Fig. 3 Bitplot for YLF catchment

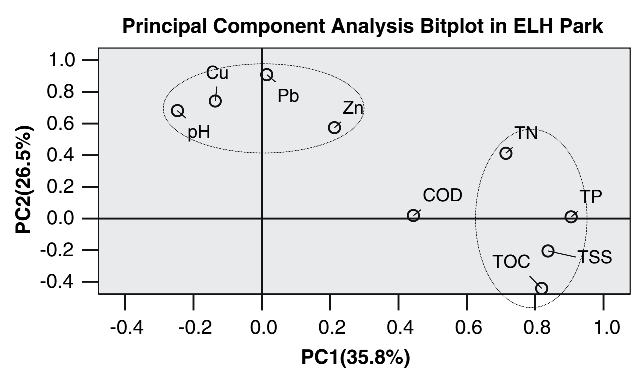

Fig. 4 Bitplot for ELH Park catchment

From Fig. 3 it is clear that TSS has a significant correlation with TN, COD and TP but no heavy metals including Cu, Zn and Pb. It is surmised that COD, TN, TP might be in particulate form and Cu, Zn and Pb in dissolved form. Cu, Zn and Pb correlated closely with each other. TOC has a weak correlation with PC1 and no correlation with PC2. Most TOC would be primarily in the dissolved form. Its source might relate not with vehicles activities but with land cover of the Park located at the upstream of YLF catchment.

To a great extent, the pattern in ELH Park is similar as that of YLF catchment (see Fig. 4). Just as mentioned above, both the effects of usage of chemical fertilizers on the lawn and garden and soil losses during storms make TN, TSS, TP concentration high level from ELH Park stormwater runoff. The little difference is that for PC1 in ELH Park related closely not to COD but to TOC. In ELH Park, there are more 70% lawn, garden and woods. Extensive tree canopy and leaf litter can result in high level of TOC in particulate form. Goonetilleke et al. (2005) had such an explanation about this phenomenon.

Fig. 4 show that TSS has a strong correlation with TN, TP, and TOC. Most TN, TP and TOC may be in particulate form. PC1 underlied the information that nutrients, organic pollutants leaching accompanied with soil losses. TSS did not correlate with Cu, Zn and Pb. Heavy metals including Cu, Zn and Pb might be primarily in dissolved form. PC2 connected with Cu, Pb, Zn, and pH. Heavy metals losses might not relate to soil losses, road surface in the Park may be the important influencing factor. As for COD, there is medium correlation with PC1 but no relation with PC2. The mechanism of COD tends to relate with the information that PC1 contained.

According to the results by PCA in all three catchments, from a perspective of pollution source of stormwater runoff, two potential pollution sources were identified. The first one concerned with TSS and TN, TP, TOC or COD, referred as nutrients losses, soil losses and organic pollutants discharge, the second was related to heavy metals including Zn, Pb and Cu, referred as heavy metals losses. Furthermore, each pollutant source underlined the important information regarding strong correlation of the quality parameters with each other, namely, TSS had close correlation between TN, TP, TOC or COD for the first pollution source. Zn, Cu and Pb correlated closely with each other for the second pollution source.

For the first pollution source, structural stormwater improvement measures such as detention basins or sediment traps would be effective in removing most of nutrients and oxygen demanding material. For the second pollution source, just as mentioned before, it can be concluded that heavy metals (including Pb, Cu, Zn) losses is not a major problem for urban stormwater runoff except Zn from iron roof runoff in Macau.

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