Inadequacy of land use and impervious area fraction for determining urban stormwater quality

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Abstract: Urban stormwater quality is multifaceted and the use of a limited number of factors to represent catchment characteristics may not be adequate to explain the complexity of water quality response to a rainfall event or site-to-site differences in stormwater quality modelling. This paper presents the outcomes of a research study which investigated the adequacy of using land use and impervious area fraction only, to represent catchment characteristics in urban stormwater quality modelling. The research outcomes confirmed the inadequacy of the use of these two parameters alone to represent urban catchment characteristics in stormwater quality prediction. Urban form also needs to be taken into consideration as it was found have an important impact on stormwater quality by influencing pollutant generation, build-up and wash-off. Urban form refers to characteristics related to an urban development such as road layout, spatial distribution of urban areas and urban design features.

Keywords: *Land use; Impervious fraction; Stormwater quality; Urban form; Water quality modelling*

1. Introduction

Stormwater runoff has been recognised as the major non-point source of pollution to urban receiving waters (Kostarelos et al. 2011). Consequently, strategies to mitigate stormwater pollution have received significant attention in recent years. In this context, stormwater quality modelling plays a key role in prediction and for providing insights to decision makers, which are essential for the formulation of appropriate mitigation strategies. Suitable parameters for accurately representing catchment characteristics are essential in stormwater quality modelling. Currently, land use and impervious area fraction are taken into consideration in modelling (Brabec 2009; Gaddis and Voinov 2010; Cheng et al. 2010). However, as stormwater quality is multifaceted, a limited number of factors may not adequately explain the complexity of water quality response to a rainfall event or site-to-site differences in stormwater quality (Novotny and Olem 1994). This suggests that current modelling approaches based solely on land use and impervious area fraction can be questionable and could lead to inaccuracies in stormwater quality estimations. This paper presents the outcomes of an in-depth research study which investigated the adequacy of using land use and impervious area fraction only, to represent catchment characteristics for modelling and prediction of urban stormwater quality.

2. Materials and methods

2.1 Study catchments

The study areas consisted of four urban catchments with similar geology and predominant soil type located in the Gold Coast, Queensland State, Australia. The three smaller catchments, namely, Alextown, Gumbeel and Birdlife Park are in effect subcatchments of the larger Highland Park catchment (Fig. 1). The three smaller catchments have solely residential land use whilst Highland Park is predominantly residential with small areas of commercial and industrial land uses. Fig.1 provides a summary of the relevant characteristics of each catchment. It is noteworthy that Alextowm and Gumbeel have the same impervious area fraction.

Insert Fig. 1 Study catchments and catchment characteristics

2.2 Data collection and sample testing

Continuous monitoring of each catchment has been undertaken since 2002 using automatic monitoring stations established at the outlets to collect stormwater runoff samples and to measure runoff quantity during rainfall events. Additionally, an automatic rain gauge has been established in close proximity to the catchments (refer to Fig.1).

The samples collected were proportionately mixed to form composite event samples and tested for total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS) and total organic carbon (TOC). Outcomes were in the form of event mean concentrations (EMC, mg/L). Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA 2005). Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS 1998).

A total of 40 rainfall events were used for the analysis after careful assessment of available rainfall and pollutant EMC data. All of the selected rainfall events were less than or equal to 1 year Average Recurrence Interval (ARI). This ARI was considered acceptable as most stormwater treatment systems are commonly designed based on rainfall events less than 1 year ARI (Guo and Urbonas 1996). The rainfall events were divided into high-intensity events (average intensity > 20 mm/h) and low-intensity (average intensity < 20 mm/h). The rainfall event data is given in Table 1. However, pollutant EMC data was not available for all of the catchments for all the 40 rainfall events investigated. For example, Birdlife Park had 16 events where both rainfall and stormwater quality data were available. Each applicable rainfall event per catchment was considered as a separate event and some events were common for a number of catchments. Accordingly, this resulted in 13 high-intensity and 56 low-intensity events.

Insert Table 1 Rainfall characteristics

3. Results and discussion

3.1 Comparison of data

A comparison of pollutant EMCs for the four study catchments was initially undertaken as shown in Fig. 2. Significant differences in pollutant EMCs among the four catchments can be noted. This is despite the fact that Alextown, Birdlife Park and Gumbeel have the same land use (residential), whilst Highland Park also contains a significant fraction of residential area (see Fig.1). Also, Gumbeel and Alextown have the same impervious area fraction (70%). Gumbeel has the highest TOC EMC (19.11 mg/L) and TN EMC (10.30 mg/L) for high-intensity events while Alextown has much lower EMC values for the same type of rainfall events. Birdlife Park has the highest TP EMCs (2.62mg/L) while Highland Park has the highest TSS EMC (426.82 mg/L) for high-intensity events although Birdlife Park and Highland Park catchments have lower impervious area fractions (see Fig.1). Additionally, as the number of high-intensity events is limited in each catchment (see Table 1), the pollutant EMCs generated from a rainfall event (on 13/11/2002 - 021113) which was recorded for all the four catchments were also compared. It was found that there are still significant differences in pollutant EMCs although all catchments experienced the same event. These observations confirm that land use and impervious area fraction alone have limited ability to define stormwater quality and that additional catchment characteristics need to be taken into consideration. Furthermore, these outcomes also highlight the fact that stormwater quality can be significantly different within the same catchment due to the influence of rainfall characteristics.

Insert Fig. 2 Comparison of pollutant EMCs

3.2 Multivariate data analysis

As the primary objective of the research study was to assess the adequacy of using land use and impervious area fraction only to represent catchment characteristics for modelling and prediction of urban stormwater quality, the analysis was undertaken separately for the two types of rainfall events (high-intensity and low-intensity) in order to minimise the influence of rainfall characteristics. The GAIA method (Graphical Analysis For Interactive Aid) which provides a two dimensional graphical representation of a multicriteria problem via the display of a principal component biplot was applied to identify relationships between the catchments and stormwater quality due to its strength in analysing correlations between criteria and actions. Detailed descriptions of GAIA can be found elsewhere (Keller et al. 1991). DecisionLab software (DecisionLab 2000) was used for the analysis. TN, TP, TOC and TSS EMCs were considered as criteria while rainfall events in the four catchments were considered as actions in GAIA. Accordingly, this resulted in two matrices of 13×4 for high-intensity events and 56×4 for low-intensity events (rainfall events × pollutant EMCs). Fig. 3 shows the two GAIA biplots obtained.

Insert Fig. 3 GAIA biplot for two rainfall types

High-intensity events: According to Fig.3a, most rainfall events for Highland Park and Gumbeel catchments (falling within the circle in Fig.3a) point in the same direction as the four pollutant EMC vectors whilst rainfall events in Alextown and Birdlife Park catchments are positioned opposite to the four pollutant EMC vectors. Additionally, the decision axis Pi points in the direction of Highland Park and Gumbeel rainfall events. This confirms that Highland Park and Gumbeel generated relatively higher pollutant EMC values than Alextown and Birdlife Park catchments.

Low-intensity events: According to Fig.3b, it can be noted that rainfall events in Birdlife Park and Highland Park catchments display greater scatter than Alextown and Gumbeel. Additionally, Birdlife Park and Highland Park rainfall events are primarily spread along the negative PC2 axis, to which TSS and TOC vectors are also projected. This means that the rainfall events in Birdlife Park and Highland Park generate higher variations in stormwater runoff quality, particularly in relation to TSS and TOC. Alextown rainfall events are clustered around the origin whilst all of Gumbeel rainfall events are spread along the PC1 axis and projected on the positive PC2 axis, to which TN and TP are also projected. These observations confirm that the rainfall events in Alextown generate relatively low variations in stormwater quality compared to the other catchments, whilst rainfall events in Gumbeel produce high variations in TN and TP EMC values.

Outcomes from GAIA analysis: Alextown and Gumbeel have the same impervious area fraction (70%) and land use (residential). However, the stormwater quality characteristics of the two catchments are significantly different. This is attributed to two primary reasons. Firstly, the spatial distribution of impervious areas in the two catchments is significantly different. Compared with Alextown, the impervious area in Gumbeel is spatially clustered as the access road is the major drainage path. The Gumbeel catchment is located in a ridge area with the access road in the middle with houses and gardens on either side at a lower elevation than the road surface (see Fig.1). The layout of Gumbeel catchment results in relatively shorter travel distance leading to higher runoff flow velocity, shorter time of response to rainfall and faster transport of pollutants to receiving waters than in the case of Alextown which has dispersed impervious surfaces. These factors would result in differences in pollutant wash-off characteristics. Additionally, the differences in the spatial layout of impervious areas in the different catchments would also result in differences in pollutant build-up, thus directly influencing the wash-off load (Lee et al. 2009). Therefore, though the processes may remain the same, there would be differences in the pollutant build-up and wash-off characteristics in the different catchments. This would mean that not only impervious area fraction but also their spatial distribution plays an influential role in urban stormwater quality. Secondly, Alextown is maintained by a caretaker. However, in the case of Gumbeel, the residences have a varying degree of management and care. This is attributed to the relatively higher variation in pollutant EMC values in Gumbeel when compared to Alextown.

Furthermore, Birdlife Park and Highland Park generated relatively higher pollutant EMC values for TP and TSS compared to Alextown and Gumbeel (see Fig.2), even though these two catchments have lower impervious area fractions (see Fig.1). This confirms that the impervious area fraction alone cannot explain the stormwater quality characteristics. Additionally, Birdlife Park and Highland Park also produced higher variations in stormwater quality than Alextown and Gumbeel for low-intensity events (see Fig.3b). This can be attributed to the nature of the urban development in the catchment. Compared to Alextown (townhouses) and Gumbeel (duplex housing around a cul-de-sac), Birdlife Park and Highland Park have relatively dispersed urban development including a network of through-roads. Lee et al. (2009) have noted that urban catchments with mixed land use presents the worst case scenario in terms of stormwater quality since interspersed land uses lead to a complexity of drainage connections and more extended road systems to connect different land parcels. Goonetilleke et al. (2005) have noted that characteristics related to an urban development such as road layout, spatial distribution of urban areas and urban design features can be referred to as urban form. Based on the above discussion, it can be concluded that for modelling and prediction, urban form also needs to be taken into consideration in addition to land use and impervious area fraction. This in turn confirms the inadequacy of using land use and impervious area fraction only to represent catchment characteristics for modelling and prediction of urban stormwater quality.

4. Conclusions

The research outcomes confirmed that conventional catchment characteristics, namely land use and impervious fraction alone are inadequate for providing a comprehensive understanding of stormwater quality characteristics. Therefore, modelling approaches based solely on these two parameters can lead to inaccurate predictions and thereby compromise the efficiency of stormwater quality treatment designs. It was found that urban form also plays an important role in stormwater quality by influencing pollutant generation, build-up and wash-off. This highlights the need to take urban form into account in stormwater quality modelling and prediction.

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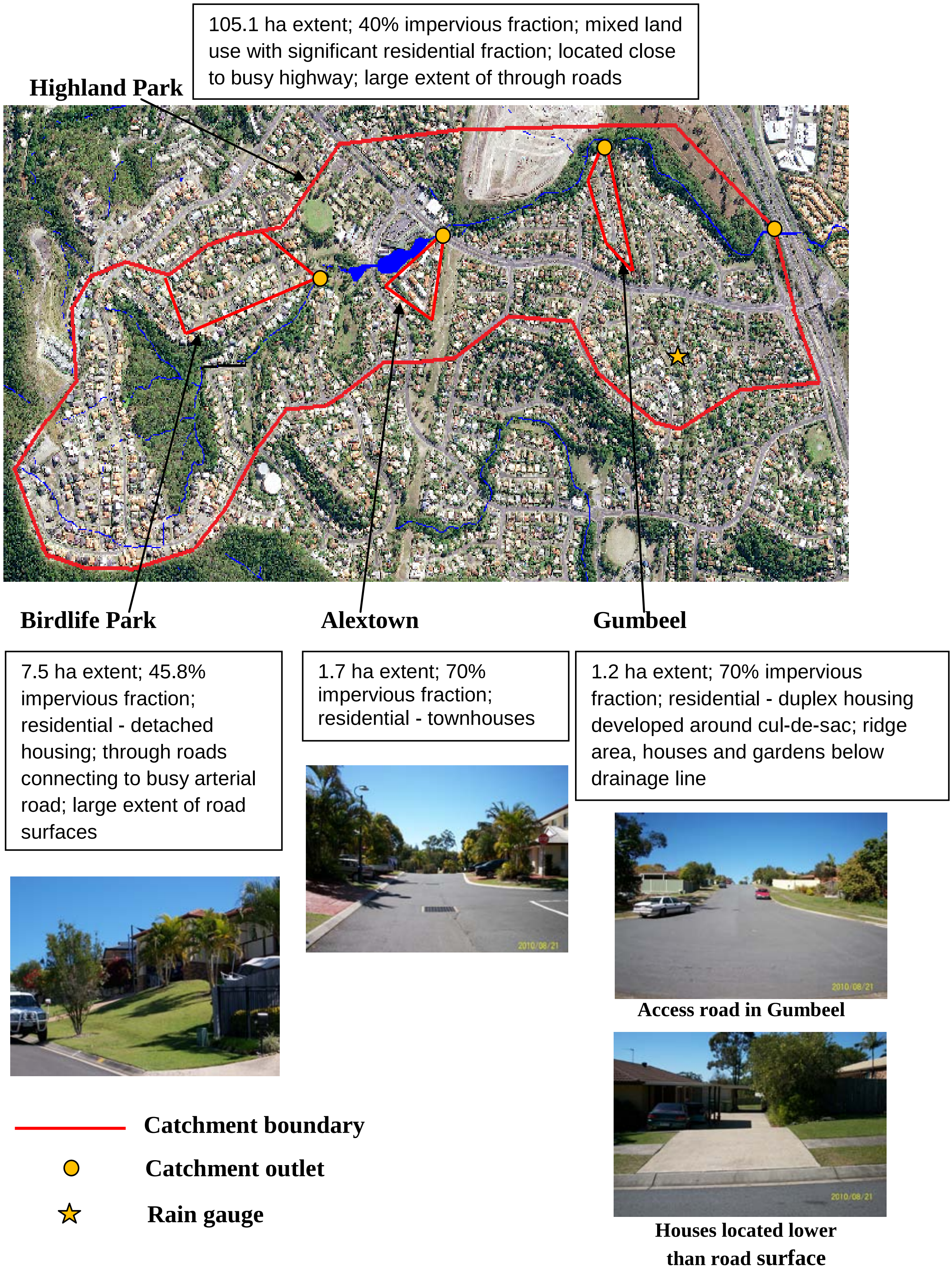


Fig. 1 Study catchments and catchment characteristics

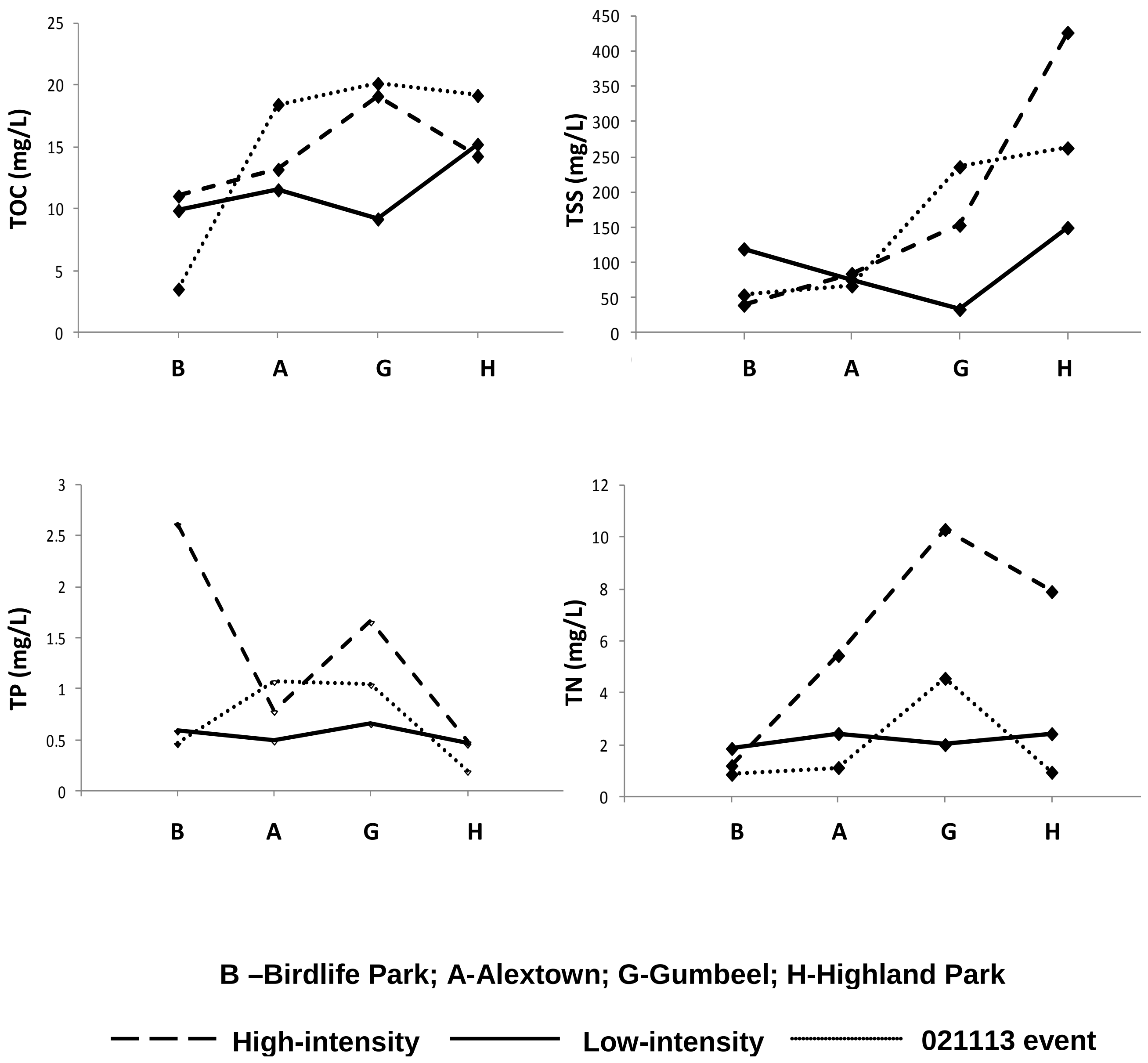
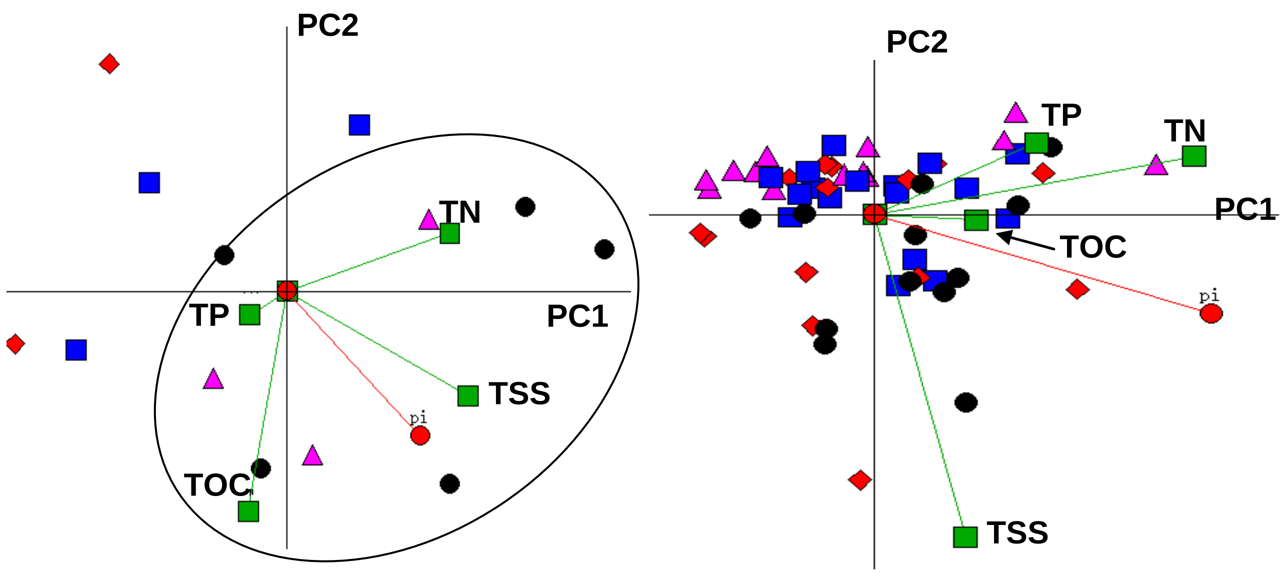


Fig. 2 Comparison of pollutant EMCs

(Note: For each pollutant EMC in “High-intensity” and “Low-intensity”, the mean values were obtained on the basis of different catchments and rainfall event types while the pollutant EMCs for the 021113 event is given as an example to illustrate the difference in pollutant EMCs in different catchments experiencing a same rainfall event. TN=total nitrogen; TP=total phosphorus; TSS=total suspended solids, TOC=total organic carbon and 021113 event= event occurring on 13/11/2002)

Graphics program for creating this figure was Excel 2007



a: High-intensity events (matrix 13×4, Δ=77.33%) **b: Low-intensity events (matrix 56×4, Δ=64.82%)**

● Highland Park ■ Alextown ◆ Birdlife Park ▲ Gumbeel

Fig. 3 GAIA biplot for two rainfall types

(Δ=the variance of original data matrix explained by GAIA biplot)

Graphics program for creating this figure was DecisionLab

Table 1 Rainfall characteristics

Rainfall characteristics	**High-intensity**	**Low-intensity**
Average intensity (mm/h)	26.95-52.73	5.3-16.8
Duration (h)	0.25-1.67	0.08-8.4
ARI	≤ 1	≤ 1
Data availability per catchment		
Birdlife Park (16)[1]	2	14
Alextown (20)	3	17
Gumbeel (16)	3	13
Highland Park (17)	5	12

[1] Total number of applicable rainfall events