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Selecting rainfall events for effective Water Sensitive Urban Design: A case study in Gold Coast City, Australia

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ABSTRACT

The current approach for protecting the receiving water environment from urban stormwater pollution is the adoption of structural measures commonly referred to as Water Sensitive Urban Design (WSUD). The treatment efficiency of WSUD measures closely depends on the design of the specific treatment units. As stormwater quality is influenced by rainfall characteristics, the selection of appropriate rainfall events for treatment design is essential to ensure the effectiveness of WSUD systems. Based on extensive field investigations in four urban residential catchments based at Gold Coast, Australia, and computer modelling, this paper details a technically robust approach for the selection of rainfall events for stormwater treatment design using a three-component model. The modelling results confirmed that high intensity-short duration events produce 58.0% of TS load while they only generated 29.1% of total runoff volume. Additionally, rainfall events smaller than 6-month average recurrence interval (ARI) generates a greater cumulative runoff volume (68.4% of the total annual runoff volume) and TS load (68.6% of the TS load exported) than the rainfall events larger than 6-month ARI. The results suggest that for the study catchments, stormwater treatment design could be based on the rainfall which had a mean value of 31 mm/h average intensity and 0.4 h duration. These outcomes also confirmed that selecting smaller ARI rainfall events with high intensity-short duration as the threshold for treatment system design is the most feasible approach since these events cumulatively generate a major portion of the annual pollutant load compared to the other types of events, despite producing a relatively smaller runoff volume. This implies that designs based on small and more frequent rainfall events rather than larger rainfall events would be appropriate in the context of efficiency in treatment performance, cost-effectiveness and possible savings in land area needed.

1. Introduction

Treatment efficiency of Water Sensitive Urban Design (WSUD) structural elements are closely dependent on the design specifications (Hatt et al., 2007). Additionally, effective treatment design not only entails efficient treatment performance, but is also related to cost-effectiveness such as device size and land area required (Hatt et al., 2006). Treatment system design should take into account the influential factors in relation to stormwater quality, with rainfall characteristics playing a significant role (Dechesne et al., 2004; Kleinman et al., 2006; Smullen et al., 1999; Liu et al., 2012; Brodie and Rosewell, 2007; Alias et al., 2014). For example, Brodie and Rosewell (2007) noted the influence of rainfall intensity on stormwater quality and used the square of the rainfall intensity to measure the kinetic energy available in rainfall for the wash-off process. Alias et al. (2014) reported that rainfall depth and rainfall intensity are two key rainfall characteristics which influence the wash-off process compared to the antecedent dry period. Therefore, the selection of appropriate rainfall events for design is critical to ensure the effectiveness of the treatment system.

In treatment design, the conventional approach is to consider stormwater quality as a stochastic variable, irrespective of the nature of the rainfall event (Wong and Somes, 1995; Wong et al., 2002). Such an approach can diminish the overall performance of the treatment system since stormwater quality can be influenced

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by a range of rainfall types such as high intensity-short duration and low intensity-long duration events (Liu et al., 2012). Other than stormwater quality, quantity characteristics need to be considered in treatment design. The design volume being too small can lead to a large number of rainfall events exceeding the capacity of the treatment device. Alternately, there will be increased cost for limited gain in efficiency if the design volume is too large (Guo and Urbonas, 1996). These facts highlight the need for the prudent selection of design rainfall events for stormwater treatment design based on stormwater quality and the appropriate runoff volume.

The current research study was underpinned by the knowledge created in previous research undertaken by Liu et al. (2012) in order to provide a technically robust approach for the selection of rainfall events for stormwater treatment design. In the research conducted by Liu et al. (2012), three rainfall types were defined based on monitored rainfall events and the resulting stormwater runoff quality as given by pollutant event mean concentration (EMC). The three rainfall types were, high intensity-short duration (Type 1), high intensity-long duration (Type 2) and low intensity-long duration (Type 3). It was found that Type 1 and Type 2 tend to generate relatively higher EMC values in stormwater runoff while the Type 3 tends to produce relatively lower EMCs. Additionally, Liu et al. (2012) have pointed out the correlationship between stormwater quality and rainfall characteristics such as average rainfall intensity, rainfall duration and antecedent dry days. Average intensity plays a more important role in relation to stormwater quality compared to antecedent dry days, while long rainfall durations have a dilution effect and can lead to relatively low EMCs.

The knowledge created by Liu et al. (2012) can provide guidance in relation to stormwater treatment design in the context of water quality. However, the impact of runoff volume generated by rainfall events was not investigated in their research study. As noted above, design of a stormwater treatment system should also take into account the runoff volume captured. In this context, modelling is an appropriate approach since it can generate the required stormwater quality and quantity data. Accordingly, the research study was based on extensive hydrologic and stormwater quality modelling and underpinned by field data collected from four urban residential catchments. The research outcomes provide guidance for efficient and cost-effective stormwater treatment design.

2. Materials and methods

2.1. Study areas

Four urban residential catchments were selected for the modelling study. They were, Alextown, Gumbeel, Birdlife Park and Highland Park, which are located at Gold Coast, Australia. Gold Coast is situated to the south of Brisbane, the state capital and is the sixth largest city in Australia. Gold Coast has a subtropical climate. The average summer temperature ranges from 19 °C to 29 °C and winter from 16 °C to 21 °C. The mean of annual rainfall depth is around 1300 mm. Alextown, Gumbeel and Birdlife Park are in effect subcatchments of the larger Highland Park catchment. The study catchments are characterised by the similar geology based on the Neranleigh-Fernvale metasediments and have similar predominant soil type (mainly Kurosols) and topography. This ensured that these factors would not differently influence the stormwater runoff quality characteristics. A small tributary of the Nerang River, Bunyip Brook is the study catchment's primary stormwater drainage, which starts from the westward hilly region and flows towards the Nerang River. The integrated pipe and channel network connecting various parts of the catchment to the tributary further facilitates stormwater drainage. The four study catchments have been continuously monitored for water quantity, quality and rainfall using automatic monitoring stations established at catchment outlets for runoff flow measurement and collection of samples for laboratory analyses for water quality parameters (see Figs. S1 and S2 in the Supplementary information) (Goonetilleke et al., 2005). The four catchments are shown in Fig. 1 while the data monitoring program is provided in the Supplementary information.

2.2. Model description

Commercially available stormwater quality models are typically not adequately sensitive to effectively simulate all of the important rainfall characteristics such as, antecedent dry days and rainfall intensity. This leads to difficulties in investigating relationships between different rainfall characteristics and stormwater quality. In order to overcome this constraint, the three-component model illustrated in Fig. 2, which incorporates the relevant hydrologic processes (quantity) and pollutant processes (quality) in relation to build-up and wash-off was adopted for this research study.

The simulation of stormwater quantity was undertaken using MIKE URBAN (2008). This model was selected after a rigorous review of commonly used models in Australia. Detailed information on the stormwater quantity estimation can be found in Liu (2011), while information regarding model setup and the calibration procedure adopted (see Figs. S3–S5 and Tables S3–S4) is provided in the Supplementary information.

Pollutant build-up and wash-off analysis were undertaken using the mathematical equations developed by Egodawatta and Goonetilleke (2006) and Egodawatta et al. (2007), respectively, as shown in Eqs. (1) and (2) below. Detailed information on the derivation of coefficients can be found in Tables S1 and S2 in the Supplementary information.

$$B = aD^b \quad (1)$$

where B—build-up load (g/m^2), D—antecedent dry days (days), a—multiplication build-up coefficient (dimensionless), b—power build-up coefficient (dimensionless).

$$Fw = W/W_0 = C_F\left(1 - e^{-kIt}\right) \quad (2)$$

where Fw—wash-off fraction (%), W—weight of the material washed-off after time t (g/m^2), W_0—initial weight of the material on the catchment surface (g/m^2), C_F—capacity factor (dimensionless), I—rainfall intensity (mm/h), k—wash-off coefficient (dimensionless).

The simulated pollutant loads, runoff volumes and pollutant EMCs for each rainfall event were used in the subsequent analysis. Total solids (TS) was adopted as the indicator pollutant. This is due to the importance of solids which act as a mobile substrate in the transport of other pollutants (Nelson and Booth, 2002; Vaze and Chiew, 2002; Rossi et al., 2005).

2.3. Data analysis

Data analysis was undertaken as follows:

1) Runoff volume, pollutant build-up and wash-off were simulated using the three-component model discussed above for the same 41 rainfall events investigated by Liu et al. (2012) to derive pollutant EMC values.
2) The three-component model was validated for its sensitivity to important rainfall characteristics such as antecedent dry days, average rainfall intensity and rainfall duration to assess its ability and accuracy for developing the approach for rainfall event selection. This was undertaken by comparing the relationship between simulated pollutant EMC (obtained from Step 1) and