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An Innovative Modelling Approach to Assess Stormwater Pollutant Loads from the Port of Brisbane, Australia

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Keywords

Stormwater quality; Mike URBAN; port water quality

Abstract

Port land uses are subjected to unique anthropogenic activities compared to typical urban land uses. This uniqueness results in distinctive stormwater quality characteristics. Such distinction in stormwater quality has made conventional approaches used for pollutant load estimations inaccurate. This is also the case for the Port of Brisbane (PoB).

The study discussed in the paper was conducted to estimate the pollutant contributions from Port specific land uses at PoB. For estimation, software modules embedded in Mike URBAN were used. An innovative approach was adopted in modelling where the conventional model calibration step was not needed to be performed to generate suitable site specific parameters. Instead, equations and site specific parameters that replicate pollutant build-up and wash-off were generated from an extensive field investigation. Models were simulated incorporating site specific parameters from six different Port specific land uses and rainfall events from three representative years. Outcomes of the modelling exercise were used to identify the distinct pollutant contributions from different Port land uses.

INTRODUCTION

Ports commonly attract significant scrutiny due to the nature of their operations and the environmental sensitivity of their locations. In this context, the quality of stormwater runoff from port premises merits particular attention as it can be an important source for a variety of pollutants to the marine environment. This is also the case for the Port of Brisbane (PoB). The Port of Brisbane is located at the mouth of the Brisbane River, adjacent to the Moreton Bay Marine Park, which is an area of high ecological and conservation value (see Figure 1a).

Port land uses are unique in terms of the anthropogenic activities occurring on them (Goonetilleke et al. 2009). This uniqueness results in distinctive stormwater quality characteristics different to other conventional urban land uses. However, commonly in stormwater management and treatment

design, all the different Port land uses are combined and considered as equivalent to industrial land use, which is a typical urban land use. Such an approach can result significant errors in pollutant load estimations resulting in inadequate stormwater treatment.

Port land uses generate appreciable loads of stormwater pollutants and hence, mitigation of the impacts created by these pollutant loads is important. Based on the geographical and unique drainage characteristics of the Ports, targeted mitigation is more viable rather than lumped and end-of-pipe treatment measures. A strategy for targeted mitigation can only be developed with the appropriate assessment of potential pollutant contributions from different Port land uses.

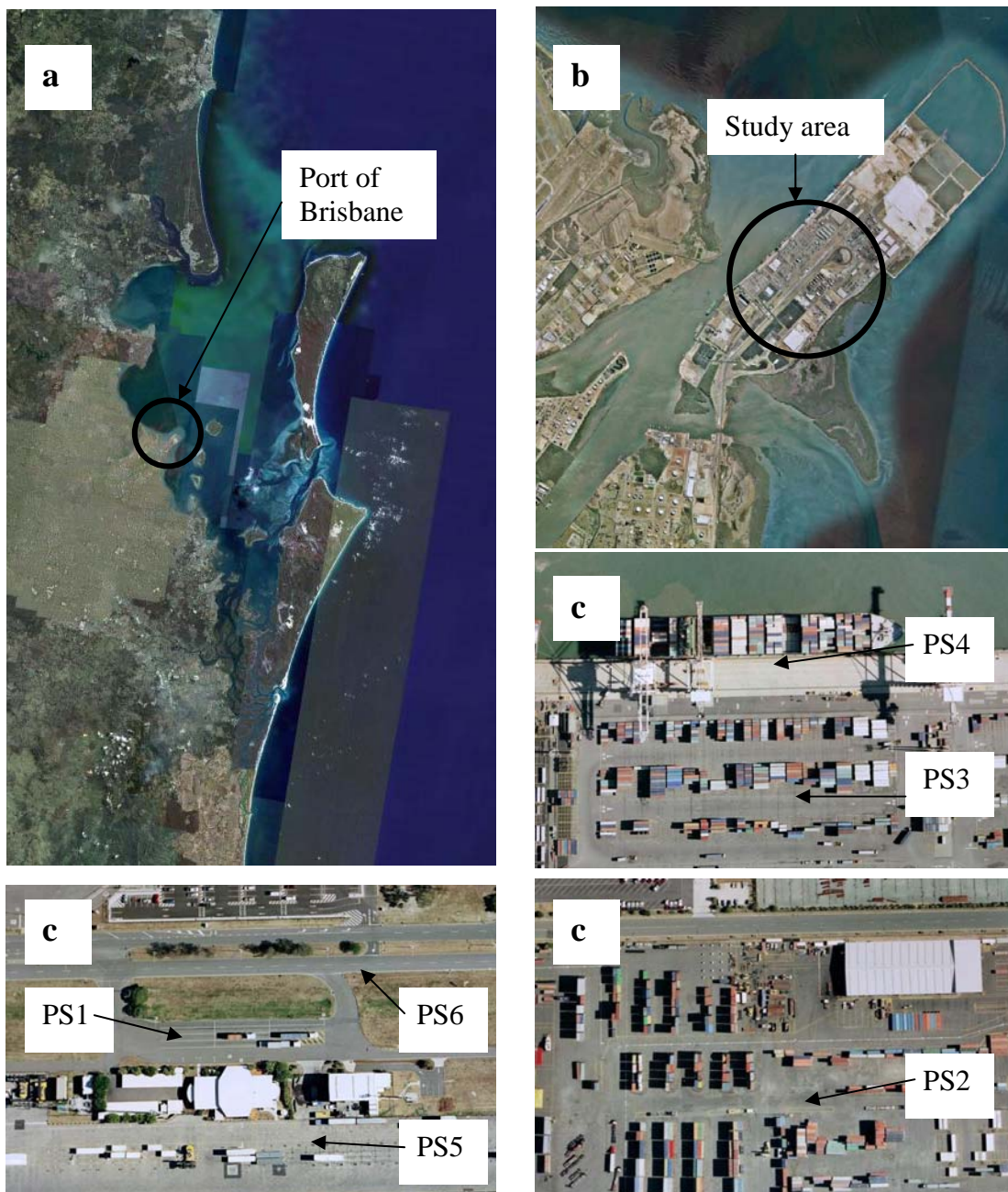


Figure 1: Study area and study sites; (a) Morton Bay, (b) Port of Brisbane and (c) Port specific land uses.

Typically, pollutant loads contributed by different land uses are assessed by analysing the water quality at catchment outlets. This requires in-depth monitoring of runoff and water quality data. Due to the complex nature of Port drainage networks, monitoring to obtain a comprehensive set of data is difficult and resource intensive (Grayson et al. 1997). Difficulty in obtaining data also undermines the use of conventional modelling approaches. In conventional modelling, a significant amount of measured data is essential for calibration and verification. Even after calibration, the real ability of a model to simulate each and every aspect of a storm event is questionable (Bertrand-Krajewski, 2007).

Therefore, a methodology which does not depend on event monitoring is desirable to evaluate the pollutant generation from Port land uses. In this regard, a methodology to extrapolate small-plot pollutant processes to catchment scale was considered to be the most appropriate (Egodawatta, 2007). In this methodology, mathematical equations to replicate plot scale pollutant build-up and wash-off processes were developed for the different Port land uses. Data required for developing build-up and wash-off process equations were generated by in-depth field investigations conducted at different Port land uses. The pollutant process equations were then applied to generate knowledge on water quality at the catchment outlets. For this purpose, software modules embedded in Mike URBAN were used. This approach is not only scientifically valid but also free from potential errors that can result in event monitoring arising from the heterogeneity of catchment surfaces.

MATERIAL AND METHOD

Study area and study sites

Field investigations were conducted at six different land uses at the Port of Brisbane (PoB) to generate data relating to pollutant build-up and wash-off. The descriptions of the sites are given in Table 1 and Figure 1(b & c).

Table 1: Descriptions of the six Port land uses

ID	Land-use	Surface cover	Description
PS1	Vehicle marshalling area	Asphalt	Parking area for heavy transport vehicles
PS2	Container storage	Asphalt	Used to store full and empty containers ready for trans-shipment by road
PS3	Container terminal	Asphalt	Typically used for short term storage of containers brought across the quay line
PS4	Quay line	Concrete	The interface between vessel unloading and land based movements
PS5	Inter-modal operations	Interlock pavers	Operates as a road-rail interchange site using mobile plant
PS6	Roadway	Asphalt	Typical of a major traffic arterial entering a port

The study sites were selected so that they cover a range of port specific land uses and impervious surface types. The plot surfaces were representative in terms of surface characteristics and anthropogenic activities.

Study tools

Build-up and wash-off samples were collected from confined 3m² plot surfaces at each site. Build-up pollutant samples were collected using a vacuum system. The vacuum system consisted of a small circular foot with a coarse brush attached to the end to enhance collection efficiency. As described by Bris et al. (1999) use of a brush helps to dislodge particles from impervious surfaces and the small foot concentrates vacuum power to a small area. The vacuum system consisted of a water filtration system capable of retaining a majority of finer particles within the water column. Performance of the vacuum system was tested prior to the field sample collection. The system was found to be 97% efficient in collecting and retaining particulate pollutants under laboratory conditions.

Pollutant wash-off samples were collected from artificially simulated rainfall events. For this purpose, a specially designed rainfall simulator as shown in Figure 2 was used. The simulator was designed to re-produce natural rainfall events as closely as possible (Herngren et al. 2005). The rainfall simulator consisted of three Veejet 80100 nozzles connected to a nozzle boom and stands at 2.4m above the ground level. The height was selected so that simulated raindrops reach terminal velocity at 41kPa nozzle boom pressure. It was verified that the flow from the nozzles disintegrated into droplets with drop size distribution equivalent to regional rainfall events at the specified pressure (Herngren et al. 2005). The nozzle boom was designed to swing in either direction with controlled speed and delay to simulate the range of rainfall intensities that are required to simulate for the study. De-mineralised water was spiked to replicate typical rainfall quality in terms of electrical conductivity, pH and organic carbon content. These parameters were selected due to their influence in altering the physico-chemical characteristics of stormwater pollutants (Warren et al. 2003).

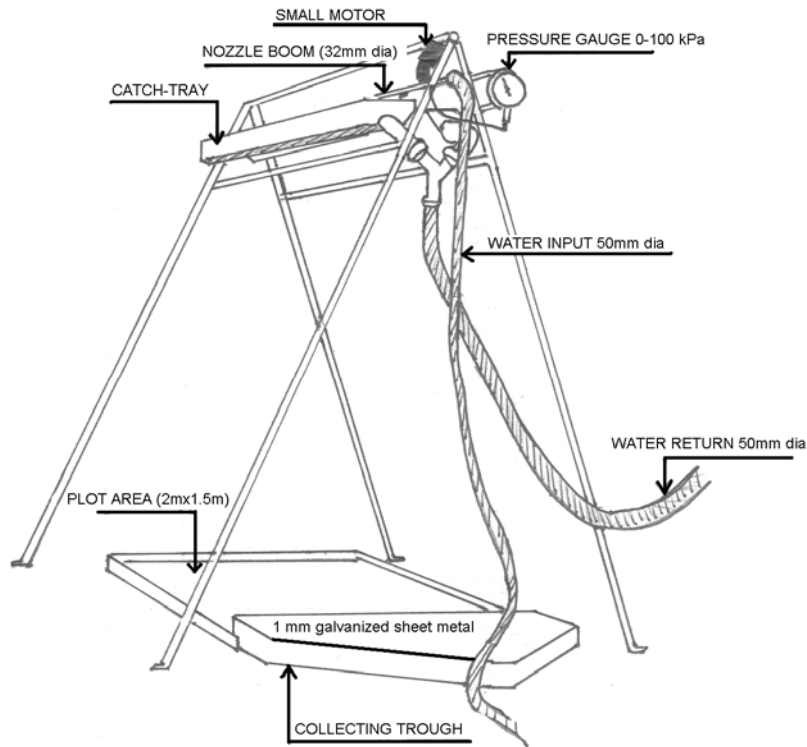


Figure 2: Sketch of rainfall simulator: adopted from Hengren et al. (2005).

Rainfall simulations were conducted on impervious surfaces with mild slope so that the runoff generated within the plot area flows into the collecting trough. Runoff collected was then transferred to plastic containers. The plot boundary was fixed and sealed to the impervious surface to prevent the escape of the runoff created within the plot area. Details of the design and operation of rainfall simulator can be found in Hengren et al. (2005).

Sample collection and testing

Build-up samples were collected at different time periods. However, the number of antecedent dry days considered was always more than seven days for each sample collection. This was to ensure that appreciable amounts of pollutants were present on the impervious study surfaces. As noted by Egodawatta and Goonetilleke (2006), pollutant accumulation on an impervious surface reaches a near constant level within 21 days and 75% of this amount accumulates within the first seven days.

Rainfall simulations were undertaken for four different average rainfall intensities. Each intensity was simulated in three duration compartments. Rainfall intensities and durations were selected so that they are representative in 1, 2, 5 and 10 year average recurrence interval (ARI) rainfall events. Rainfall intensities and durations simulated are given in Table 2.

Table 2: Simulated rainfall events

Event	Intensity (mm/hr)	Approx. Duration (min)
1 year ARI	65	20
1 year ARI	86	10
1 year ARI	115	5
2 year ARI	65	35
2 year ARI	86	20
2 year ARI	115	10
2 year ARI	133	7
5 year ARI	133	13
10 year ARI	65	65
10 year ARI	86	40
10 year ARI	115	25
10 year ARI	133	17

Samples collected from build-up and wash-off investigations were tested for total suspended solids (TSS). TSS was assumed as the indicator pollutant. TSS was tested based on the method specified in 2540D and 2540C (APHA 1999). Specified protocols and procedures were followed during sample collection, handling and transport. Further details of sample collection and testing are available in Goonetilleke et al. (2009).

Water quality modelling software

Water quality modelling software was selected so that it supports the methodology described by Egodawatta (2007) for extrapolating plot-scale pollutant process information to catchment scale. For this purpose, the selected water quality modelling software needed to be physically based and with site specific parameters are being obtainable from the field investigations. Based on these requirements, SWMM module embedded in Mike URBAN software was selected. Mike URBAN is a user-friendly software platform which supports a range of hydrologic, hydraulic and water quality modelling tools (Mike URBAN 2009).

SWMM is a dynamic simulation model, capable of simulating both quality and quantity of runoff. The model primarily consists of an atmospheric component which replicates rainfall and atmospheric deposition of pollutants and a land surface component which receives rainfall from the atmospheric component and estimates the resulting surface runoff and pollutant loading. Outcomes of the land surface component then feed into the transport component. The transport component contains network conveyance elements such as channels, pipes and regulators and storage/treatment devices that transport water to the catchment outlet (Rossman, 2004).

The SWMM land surface component is primarily based on the nonlinear storage reservoir routing method. Capacity of the storage reservoir is considered equivalent to total depression storages on the surface and the other losses are accounted by simulating physically based equations such as Horton's infiltration equation (Rossman, 2004). Therefore, most parameters used have physical meaning and can be obtained from data generated from field investigations.

SWMM water quality modules simulate pollutant build-up and wash-off processes on impervious surfaces (Rossman, 2004). Equations used in SWMM to replicate build-up and wash-off are in agreement with the common understanding developed by Ball et al., (1998); Egodawatta and Goonetilleke (2006) and Egodawatta et al. (2007). This enabled the development of site specific parameters relating to build-up and wash-off using the data obtained from field investigations. Methodology adopted for the development of site specific parameters is discussed in detail below.

MODEL SETUP AND SIMULATION

Modelling approach

A primary task of the modelling was to extrapolate information relating to plot-scale pollutant processes to catchment scale. For this purpose, the Container Storage (PS2) area was selected as the representative catchment. During the first stage of modelling, site specific parameters relating to pollutant build-up and wash-off for the Container Storage area was used. These parameters were changed accordingly to replicate other specific land uses in model simulations.

The drainage network in the Container Storage area included a limited pipe network with significantly large impervious catchment surface (see Figure 2). Information relating to the drainage network and other relevant parameters such as catchment area, impervious surface percentage were obtained from maps and aerial photographs.

It was important to setup the land surface component of SWMM accurately in order to obtain high accuracies in water quality simulations. This highlights the importance of using reliable parameters such as impervious surface depression storage for model setup. In SWMM, depression storage is considered as the storage volume of the model's conceptual storage reservoir (Rossman, 2004). The depression storage was calculated using the data generated during rainfall simulations. In this regard, the difference between simulated rainfall depth and runoff depth during the initial portion of simulations was considered as the depression storage. The depression storages obtained for different land uses are given in Table 3.

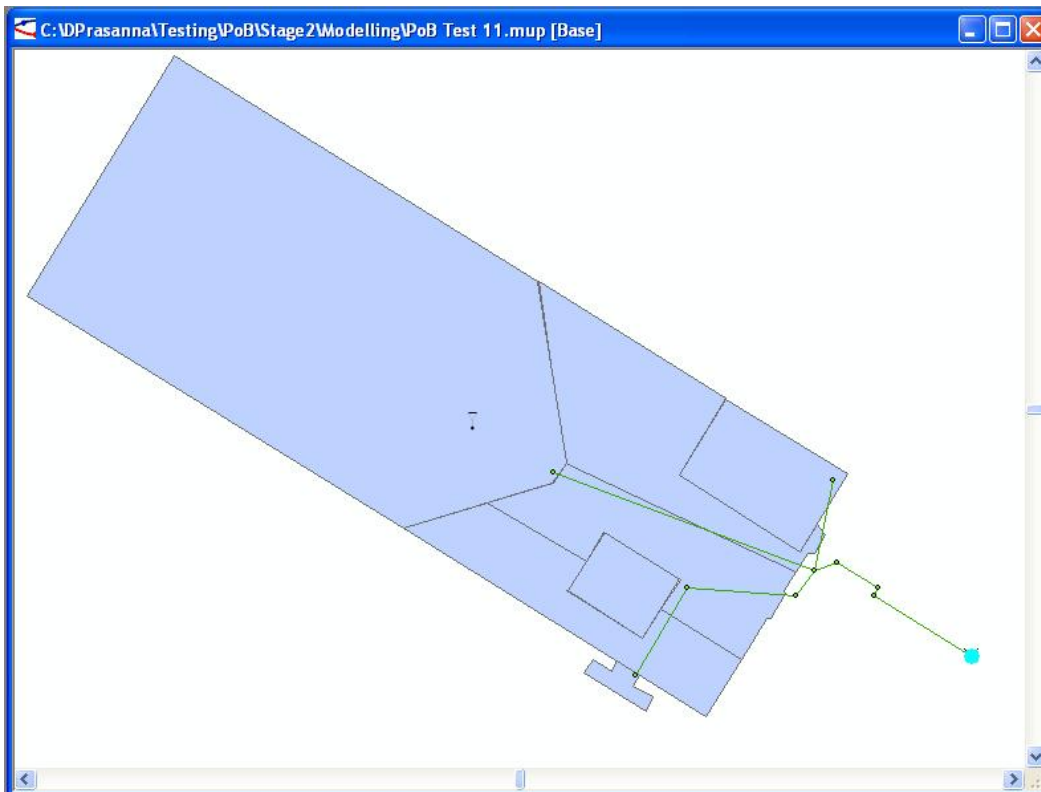


Figure 2: Catchment model for Container Storage area

Table 3: SWMM Initial loss, Build-up Coefficients and Wash-off Coefficients

Site ID	Depression Storage (mm)	Build-up coefficients			Wash-off coefficients	
		C1	C2	C3	C4	C5
PS1	5	29.4	16.5	0.16	0.25	0.76
PS2	5	53	32	0.16	0.25	0.76
PS3	6	4.3	2.5	0.16	0.25	0.76
PS4	3	7.3	4.4	0.16	0.5	0.76
PS5	7	117	70.2	0.16	0.15	0.76
PS6	6	104	62.7	0.16	0.25	0.76

As evident in Table 3, the depression storages obtained for Port land uses are significantly high compared to values recommended for typical urban impervious surfaces. For example, Boyd and Milevski (1996) recommend 0 to 2mm initial depression storage losses for urban impervious surfaces. High depression storages in Port land uses could be attributed to the high permeability of the underlying sandy sub layer in the Port area, infiltration through pavement cracks and the rough surface texture created by heavy usage and land settlement. Furthermore, the flat terrain of the impervious surfaces can also be a factor which can lead to the temporary stagnation of rainwater.

The lowest recorded depression storage is for the Quay line (PS4), which is a concrete surface. The highest initial loss is for the Inter-modal Operations area (PS5) where interlocking pavers can infiltrate a significant portion of runoff into the sub layer through the gaps between pavers. Presence of gaps may lead to continuing losses for the PS5 surface. Unfortunately, the

model formulation does not allow continuing losses for impervious surfaces. Initial losses for other sites (Asphalt) are moderate.

Water quality input parameters

Accurate simulation of water quality requires appropriate representation of the wash-off process. As commonly understood, pollutant wash-off load is a function of pollutant load available on the surface prior to a rain event. The amount of pollutant available on the surface is typically calculated by replicating the pollutant build-up process.

As commonly accepted, pollutant build-up on an impervious surface is a function of the antecedent dry days. As noted by numerous researchers (for example Ball et al., 1998; Sartor and Boyd, 1972), build-up is a decreasing rate increasing function. This function can be replicated using a range of mathematical forms. However, a power function is considered as the most suitable to replicate pollutant build-up on impervious surfaces, under Australian conditions (Ball et al., 1998; Egodawatta and Goonetilleke 2006). SWMM is capable of simulating pollutant build-up in the form of a power function. The function used in SWMM is as follows:

$$B = C1, C2 D^{C3} \quad \text{Equation 1}$$

Where:

B – Build-up load after D days (g)

D – Antecedent dry days

C1 – Maximum possible build-up

C2 & C3 – Build-up coefficients
(SWMM, 2009)

As explained by Egodawatta (2007), build-up exponent (C3) represents the rate at which the pollutants accumulate on impervious surfaces during the initial period of build-up. C3 varies with the nature and extent of anthropogenic activities on the surfaces and the pollutant re-distribution capacity. Egodawatta (2007) has noted that the parameter C3 is sensitive only to significant variations in build-up rates and recommended the use of a constant value. Since the build-up loads observed on Port land uses are in same order as the values observed by Egodawatta (2007), a value of 0.16 was adopted for this study.

The build-up coefficient C2 relates to the maximum build-up on a given surface. This is primarily related to the pollutant holding capacity of a particular surface which is influenced by surface texture. Since the surface texture is a variable for the selected six land uses and also not consistent with the sites described by Egodawatta (2007), values for C2 were estimated. Values for C2 were estimated by adjusting Equation 1 to result in the measured amount of build-up load matching the appropriate antecedent dry days.

As indicated in SWMM (2009), C1 is the upper cut-off range for pollutant build-up. This was assumed to be the value equivalent to build-up resulting from a 21 day dry period (Egodawatta, 2007). Calculated build-up coefficients for different land uses were in metric units. These coefficients

were required to be converted to the specific unit structure adopted in SWMM. The build-up coefficients that were derived based on field measurements and converted to SWMM unit structure are given in Table 3.

Wash-off is commonly regarded as an exponential decay equation. As noted by Egodawatta et al. (2007), the exponential equation for wash-off varies primarily with rainfall duration and varies stepwise with rainfall intensity. However, the exponential equation used in SWMM does not take into account the variation in rainfall intensity and duration separately. It uses runoff rate (R) as the primary rainfall-runoff variable. The exponential equation used in SWMM is as follows:

$$W = B \times C4 R^{C5} \quad \text{Equation 2}$$

Where:

W – Wash-off load

B – Build-up load

R – Runoff rate

C4 & C5 – Wash-off coefficients
(SWMM, 2009)

In this study, coefficients C4 and C5 were derived so that the exponential wash-off function results in best-fit with the observed wash-off behaviour. In this regard, coefficient C5 was assumed to be a constant irrespective of the land use or impervious surface type and C4 varies with the impervious surface type. The optimum values obtained as wash-off coefficients are given in Table 3.

Boundary conditions and simulations

The primary boundary condition that a stormwater quality model requires is rainfall records. However, rainfall records should be selected in accordance with the nature of the study and the capabilities of the model. SWMM is capable of simulating rainfall events in fine times-steps. In terms of intended outcomes, a long-term estimate of pollutant export is the most important in describing the potential pollutant contribution from a land use. This required simulation of rain events from a number of years.

In order to limit the number of simulations, rainfall data from representative three years was selected. Rainfall records for these three years were obtained in 6 minute time steps. From the rainfall records, significant events where the event rainfall depth is greater than the depression storages were selected for simulations. In this regard, a total of 59, 44, and 43 rainfall events were selected for 1999, 2004 and 2005 respectively, for the initial simulations. The three representative years, 1999, 2004 and 2005 were selected so that they are above average, average and below average in terms of annual rainfall depth.

The 146 events selected for simulations belonged to a spectrum of rainfall events ranging from 5 to 102mm rainfall depth. Considering the repetitive nature of this task and the generation of overlapping data, it was decided to select a set of ten representative storm events to be used for the simulation of the other land uses. The selection of the representative ten events was done by analysing the water quality responses for the simulated events at

the Container Storage area. Simulated events and selected representative events are shown in Figure 3.

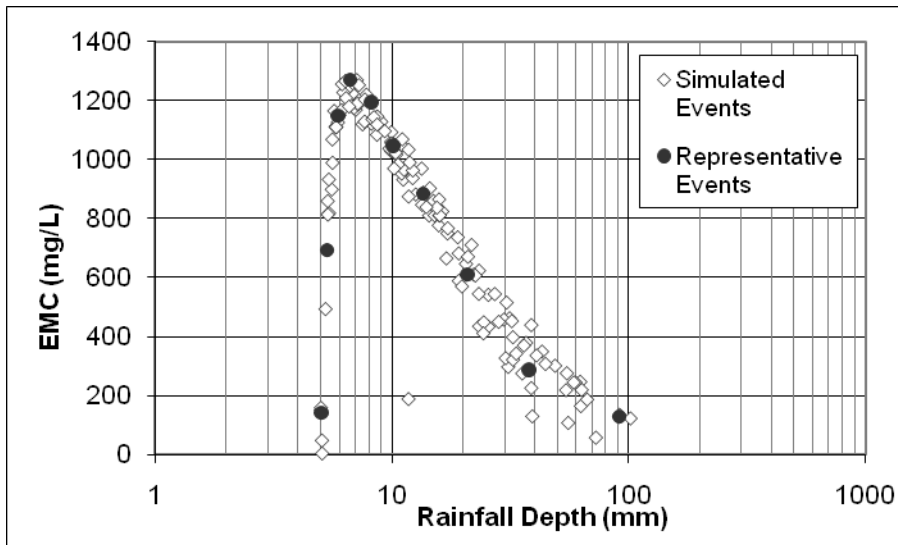


Figure 3: Simulated events for Container Storage area and selected representative events.

The computer model was simulated for the selected set of ten rainfall events by varying the site specific parameters corresponding to different land uses as given in Table 2. Outcomes from the representative event simulations were used to develop predictive equations for each land use. These equations were then used to predict water quality for all the (146) rainfall events.

RESULTS AND DISCUSSION

Analysis of annual pollutant export loads

The predicted water quality for the 146 rainfall events from each land use was used for the analysis of long term pollutant contributions. The outcomes of the analysis were presented in the form of annual pollutant contributions and statistical parameters of EMC data.

Table 4 gives the pollutant contributions in kg/ha/year for each land use for the three years investigated. The pollutant contribution from each site for the three years shows significant variation. Average of these three years would be the most appropriate estimate. However, it is possible to use the pollutant contribution data estimated for any of these three years depending on the annual rainfall depth.

As evident in Table 4, PS3 (Container Terminal) and PS4 (Quay Line) show significantly low annual pollutant contributions compared to the other land uses. This is primarily due to the low pollutant build-up recorded at these sites. Low pollutant build-up can be attributed to the use of automated cargo handling and specially designed vehicles for short range cargo transfer at these land uses. In contrast, PS5 (Inter-model Operations) and PS6 (Roadway) recorded high annual pollutant contributions compared to the other land uses. Though interlocking pavers in PS5 produce less

frequent runoff due to high infiltration, it indicates that the resulting runoff contained a high pollutant load. This could be due to the ready availability of pollutants trapped between the pavement crevices. The Roadway on the other hand is subjected to a high volume of traffic which primarily consists of heavy vehicles. This could lead to the generation and deposition of high pollutant loads on the road surface.

Table 4: Annual TSS export from Port land uses

Site ID	Land use	Pollutant load (kg/ha/year)			
		1999	2004	2005	Average
PS1	Vehicle marshalling area	983.7	682.6	657.8	774.7
PS2	Container storage facility	1856.3	1286.1	1239.9	1460.7
PS3	Container terminal	135.5	90.7	86.4	104.2
PS4	Quay line	247.1	183.0	194.1	208.1
PS5	Inter-modal operations	3389.1	2153.2	1959.6	2500.6
PS6	Roadway	3427.1	2290.2	2183.6	2633.6

Analysis of EMC

Pollutant contributions from land uses are also assessed based on average and standard deviation of event mean concentrations (EMC). In fact, simple design and management tools such as MUSIC uses average EMC and standard deviation of EMC as primary input parameters for water quality estimations (MUSIC, 2005). It is commonly considered that the EMC records for a particular catchment are in a normal distribution (Duncan 1999). However, frequency distribution of EMC for PS2 site as shown in Figure 4 shows that the distribution is not normal. This was the case for most of the land uses assessed in this study. It was assumed that this is possibly due to the fact that only one specific location was considered, namely the Port of Brisbane unlike in the case of Duncan (1999) who investigated a range of different geographic and climatic conditions.

Figure 4 indicates that the EMCs fall into two ranges, one from 100 to 500 mg/L range and the other from 800 to 1200 mg/L range. Most of the events that produce EMC in the range of 100 to 500 mg/L are those that produce relatively high runoff volumes. EMCs of these events are low particularly due to the limited amount of pollutants available on impervious surfaces. On the other hand, most of the events that produce EMCs in the range of 800 to 1200 mg/L belong to relatively low runoff events which result from high intensity short durational rain events. Such events result in high pollutant concentrations.

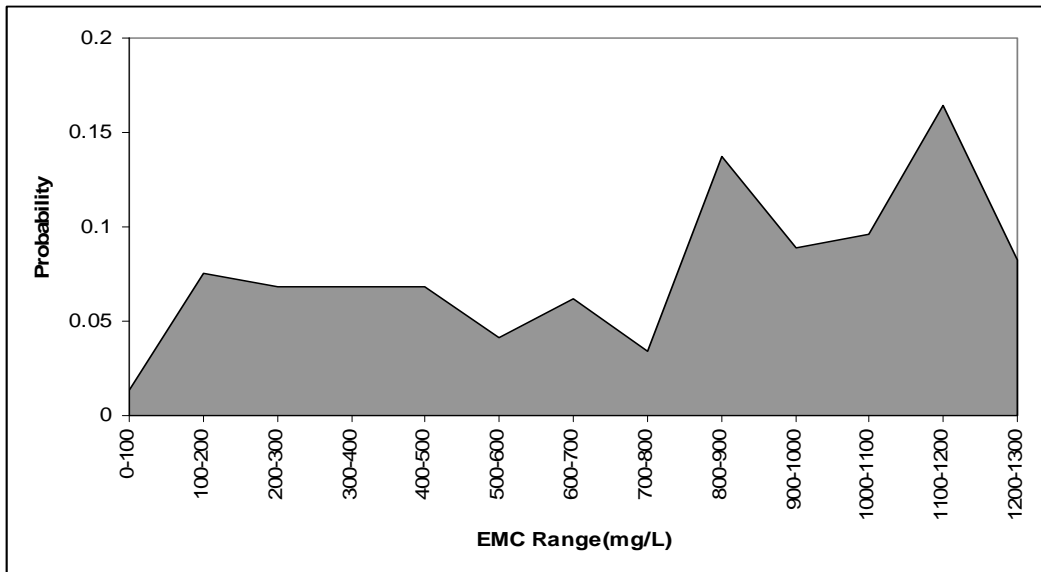


Figure 4: Frequency distribution of TSS EMC for PS2

Table 5 gives the EMC's and respective standard deviations derived for Port land uses. As evident in Table 5, standard deviations for all the land uses are relatively high. This is primarily due to the significant deviation of the probability distribution of EMC values from a normal distribution.

Table 5: Mean and Standard deviations of TSS EMC for Port land uses

Site ID	Land use	Mean EMC (mg/L)	Standard deviation
PS1	Vehicle marshalling area	288.2	219.8
PS2	Container storage facility	541.0	409.3
PS3	Container terminal	42.5	34.9
PS4	Quay line	70.1	60.8
PS5	Inter-modal operations	892.4	619.6
PS6	Roadway	1060.1	852.2

CONCLUSIONS

Analysis of pollutant contributions from Port specific land uses leads to the following conclusions:

- The pollutant contributions from each site for the three years showed significant variation. This is due to the variation in annual rainfall depths and the number of rain events in each year.
- Land uses such as Container Terminal and Quay Line showed significantly low annual pollutant contributions compared to the other land uses. This is attributed to the use of automated cargo handling and specially designed vehicles for short range cargo transfer.
- Land uses such as Inter-modal Operations and Roadway recorded high annual pollutant contributions compared to the other land uses. This is due to the ready availability of pollutants trapped between the

pavement crevices in Inter-model Operations area and high traffic related pollutant generation in Roadway.

- Frequency distribution of EMCs could not be related to a normal distribution. Frequency distribution of EMCs observed in this research study showed significant influence exerted by the regional rainfall characteristics, rather than catchment and land use characteristics.

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