



## Evaluation of pollutant build-up and wash-off from selected land uses at the Port of Brisbane, Australia

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### ABSTRACT

The quality of stormwater runoff from seaports can be an important source of pollution to the marine environment. Currently, little knowledge exists with regards to the pollutant generation capacity specific to seaports as they do not necessarily compare well with conventional urban land use. The research project focussed on the assessment of pollutant build-up and wash-off. The study was undertaken using rainfall simulation and small impervious plots for different port land uses with the results obtained compared to typical urban land uses.

The study outcomes confirmed that the Port land uses exhibit comparatively lower pollutant concentrations. However, the pollutant characteristics varied across different land uses. Hence, the provision of stereotypical water quality improvement measures could be of limited value. Particle size <150 µm was predominant in suspended solids. Therefore, if suspended solids are targeted as the surrogate parameter for water quality improvement, this particle size range needs to be removed.

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### 1. Introduction

Stormwater quality modelling relies on predetermined values based on land use type to assess pollutant loads. Pollutant export relationships and storm and base flow concentrations are generally available for various common land uses such as residential, commercial and industrial areas (for example BCC, 2005). However, seaports present a very different land use.

Currently, little knowledge exists with regards to the pollutant generation capacity specific to land uses in a seaport. The unique nature of activities in a port and the different land uses such as cargo handling, container loading and storage and vehicle marshalling do not necessarily compare well with conventional urban industrial or commercial areas. Secondly, traffic related factors have been shown to be among the most important sources of stormwater pollution (Bannerman et al., 1993; Sartor and Boyd, 1972). The traffic characteristics in a port area are different to a conventional urban area. This relates to the vehicle mix such as the far greater prevalence of heavy trucks, diesel combustion vehicles and vehicle speeds when compared to the predominance of petrol combustion vehicles in an urban area. Consequently, the types of pollutants and event mean concentrations (EMCs) used as data inputs based on an industrial and commercial land use mix for modelling purposes is questionable.

Published work in relation to seaports primarily tends to focus on the water quality or environmental values in the receiving waters such as the downstream bay or estuary (for example Connell et al., 1998; He and Morrison, 2001; Jones et al., 2005). Though the receiving waters can be of environmental importance, the lack of characterisation of water quality from an important stormwater generation source is a significant limitation. This would make the source identification of pollutants in the receiving waters difficult. Also, without this detailed understanding, the efficacy of the stormwater quality mitigation measures implemented cannot be determined with certainty. The research project discussed in this paper focussed on the assessment of pollutant build-up and wash-off from the current Port of Brisbane facilities and comparison with typical urban land uses of residential, commercial and industrial.

### 2. Materials and methods

#### 2.1. Study approach

Using a specially designed rainfall simulator and small impervious surface plots, the project entailed the development of a comprehensive database on pollutant build-up and wash-off for a range of different land uses without the dependency on natural rainfall. This approach was adopted in order to overcome significant challenges. Pollutant wash-off is a complex process varying with a range of catchment and climatic characteristics. Investigation of such complex processes using naturally occurring rainfall

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events faces innate difficulties due to the high variability of rainfall intensity, non-uniformity of rainfall associated with the use of large heterogeneous areas and lack of control of physical factors. In this context, the use of rainfall simulation for pollutant wash-off investigations has merit as it can significantly enhance the transferability of the research due to the reduction of physical variables.

Another significant constraint in understanding pollutant build-up and wash-off arises from data collection at the catchment scale. Due to the heterogeneity of built-up areas, catchment scale studies are not particularly suitable for the derivation of baseline parameters. Therefore the use of small test plots to ensure homogeneity can help to reduce the large number of variables and lessen the location specific nature of the outcomes (Herngren et al., 2005). The research project was formulated on the above fundamental concepts.

## 2.2. Study area

Seaports are being subjected to increasing environmental scrutiny due to the nature of their operations as they can be an important source of pollution to the marine environment. This is a significant issue for the Port of Brisbane. As shown in Fig. 1, the Port is located at the mouth of the Brisbane River (latitude:  $-27.382^\circ$ , longitude:  $153.168^\circ$ ) adjacent to the Moreton Bay Marine Park, which is an area of high ecological and conservation value. Due to the growing emergence of the Port as a major regional economic hub, there is ongoing expansion of its footprint. This in turn results in increased impervious area and greater potential for stormwater

runoff into Moreton Bay Marine Park. Therefore, it is imperative to develop an in-depth understanding of stormwater runoff quality and to ensure that appropriate strategies are in place for quality improvement.

## 2.3. Rainfall simulator

The primary objective of rainfall simulation is to replicate natural rainfall events as closely as possible. Design details of the rainfall simulator can be found in Herngren et al. (2005). It consists of an A-frame structure with three Veejet 80100 nozzles spaced one metre apart on a swinging nozzle boom such that the nozzle spray height is 2.4 m as illustrated in Fig. 2. This height is adequate for creating terminal velocities similar to natural rainfall for all drop sizes (Duncan, 1972). The runoff plot area of  $1.5 \times 2$  m was chosen so that optimum rainfall uniformity was achieved (Christiansen, 1942). The nozzle boom is connected to a small motor in order to swing in either direction. The speed of the swing and delay time is controlled which enables the simulator to be calibrated for different rainfall intensities. The water pressure at the nozzle boom can be adjusted so that the simulator creates the required rain drop size distribution.

The rainfall simulator was calibrated for the rainfall intensities selected for the study and verified for kinetic energy and drop size distribution, which along with rainfall intensity are the primary parameters essential for characterising rainfall events (Herngren et al., 2005; Hudson, 1963; Loch, 1982). The procedure adopted has been explained in detail in Herngren et al. (2005). In order to re-produce natural rainfall quality characteristics in the area as closely as possible, the average chemical quality of rainfall in the Brisbane region was investigated by testing natural rainfall samples for pH, electrical conductivity (EC) and dissolved organic carbon (DOC). These parameters were chosen due to their ability to alter the physico-chemical characteristics of pollutants in runoff. The pH of rainfall influences the bio-availability of heavy metals whilst, organic carbon influences the concentration of PAHs present in the dissolved phase (Tai, 1991; Wang et al., 2001). EC is important due to its ability to enhance the adsorption affinity of

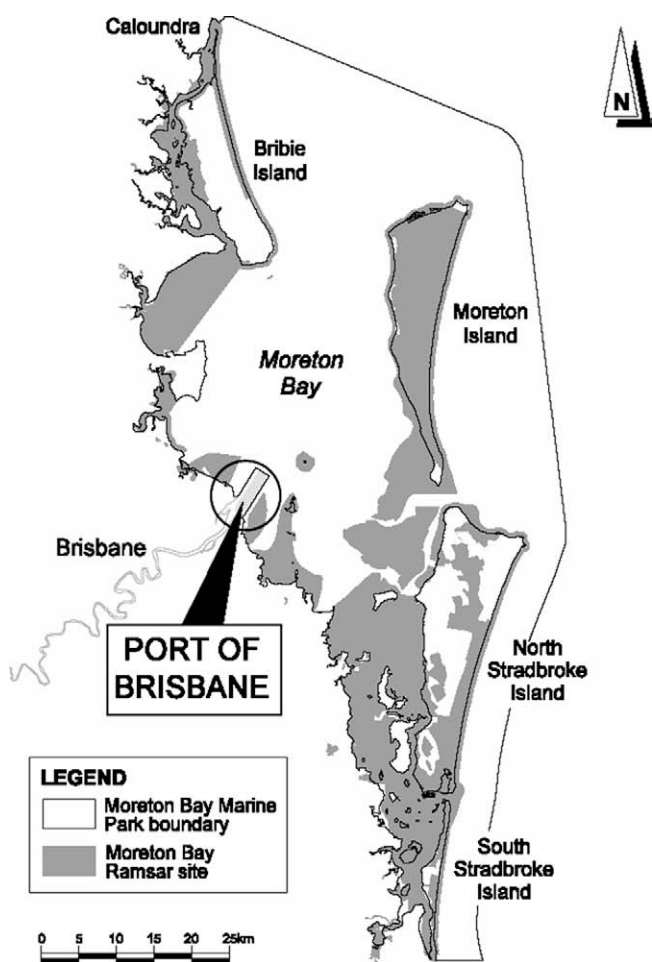


Fig. 1. Study site location: Port of Brisbane, Australia.

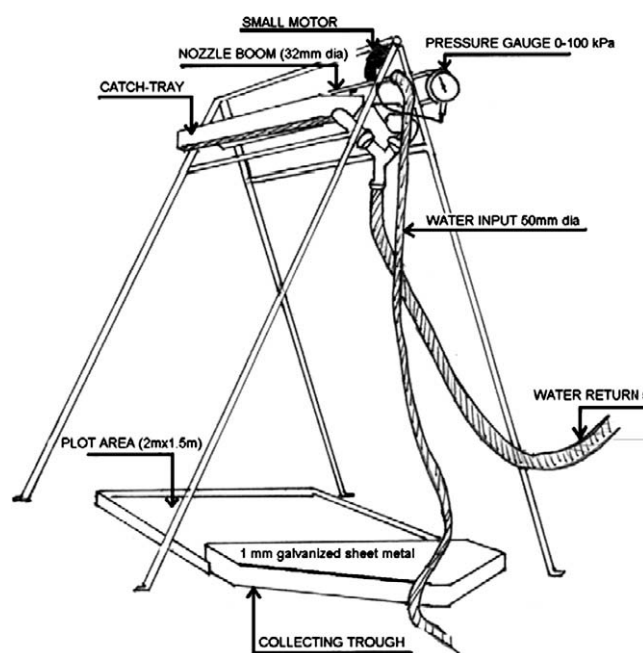


Fig. 2. Schematic of the rainfall simulator used for the study. Source: Herngren et al. (2005).

solid particles (Pechacek, 1994). De-ionised water was spiked to obtain the required natural rainwater quality profile.

#### 2.4. Pollutant build-up data collection

Techniques commonly used for pollutant build-up sample collection from impervious surfaces which include brushing/sweeping and/or vacuuming have inherent advantages and disadvantages. Researchers have often used combinations of both in order to enhance the collection efficiency (Deletic and Orr, 2005; Robertson et al., 2003). Brushing or sweeping of road surfaces are generally efficient in collecting relatively larger particles. Bris et al. (1999) noted that vacuuming is preferable for collecting finer particles. A commercially available domestic vacuum system modified to enhance the sample collection and retention efficiency was used for build-up sampling. The sampling efficiency of the vacuum system when tested under laboratory conditions was found to be 97%. A detailed description of the vacuum system and the testing undertaken is given in Egodawatta (2007). A minimum of seven days of fine weather was ensured prior to collecting any samples to allow for sufficient pollutant build-up. Research has shown that the total build-up asymptote to an almost constant value as the antecedent days increase and that after about seven days it remains virtually constant (Egodawatta and Goonetilleke, 2006).

#### 2.5. Pollutant wash-off data collection

The four rainfall intensities simulated were selected to cover the range commonly experienced in the Brisbane region and accounted for the rainfall characteristics commonly used in the design of water quality treatment facilities. The durations were selected to match with as many design storm events for the region as possible. Consequently, based on four rainfall intensities and three different durations, 12 different design rainfall events were replicated ranging from 1 year to 10 year average recurrence interval and 65–133 mm/h rainfall intensity.

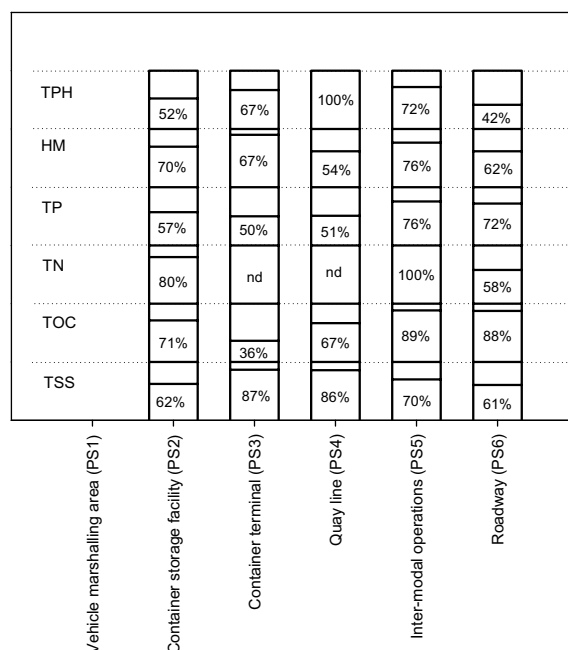
For pollutant wash-off collection, a frame with rubber flaps was used as the plot border and attached securely to the paved surface to prevent water from entering or escaping. A specially designed collection trough was attached to the frame to collect the runoff samples (Herngren et al., 2005). Impervious surface test plots which were in typical condition were chosen at each of the study sites. In the case of roads, the plots were located in the centre between the kerb and the median strip. The amount of street-

**Table 2**  
Details of the test methods used

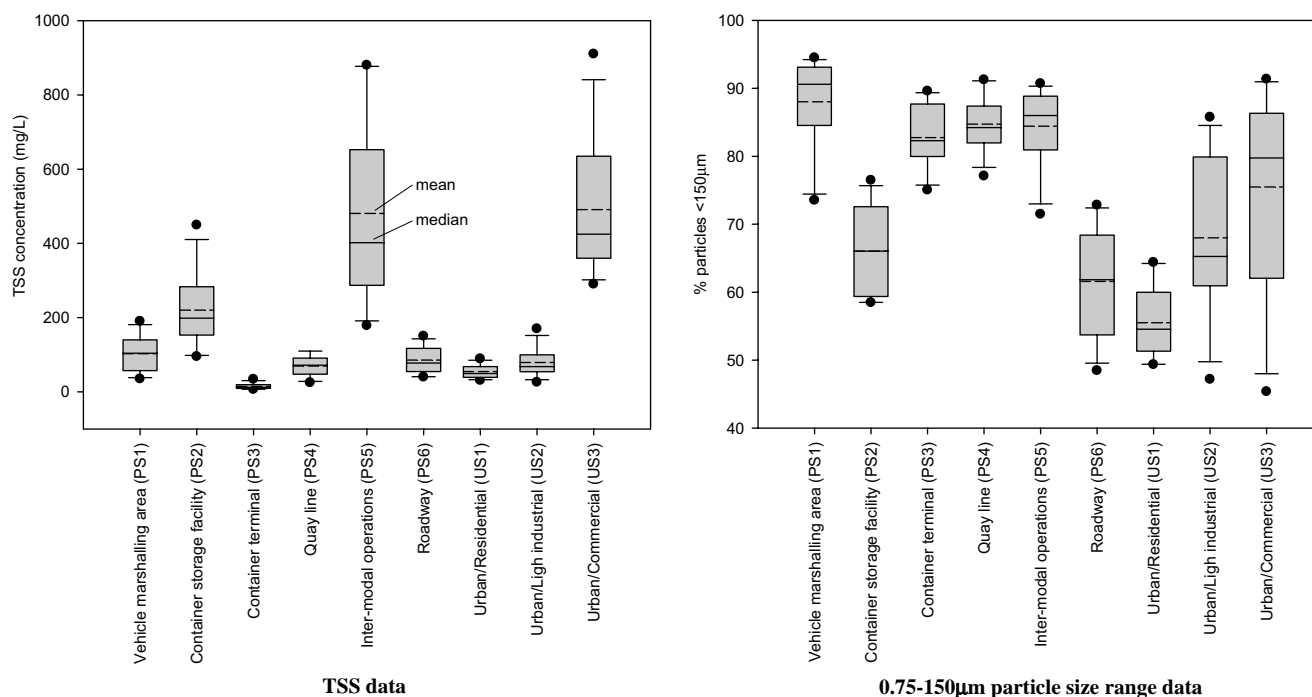
Parameter	Test method no.	Comments
pH	4500H (APHA, 1999)	Combined pH/EC-meter was used
Electrical conductivity (EC)	2520B (APHA, 1999)	Combined pH/EC-meter was used
Total suspended solids (TSS)	2540D and 2540C (APHA, 1999)	Samples filtered using a 0.75 µm glass fibre filter.
Total organic carbon (TOC)	5310C (APHA, 1999)	Filtrate used to measure total dissolved solids (TDS) and dissolved organic carbon (DOC)
Particle size distribution		Used a Malvern Mastersizer S instrument
Nitrite-N and Nitrate-N	4500F (APHA, 1999)	Dissolved and total components were determined
Total kjeldahl nitrogen (TN)	4500B (APHA, 1999)	By calculation
Total phosphorus (TP)	US EPA Methods 200.7 (US EPA, 2001)	Using inductively coupled plasma optical emission spectrometry dissolved and total components were determined
Heavy metals including Al, Pb, Cd, Cr, Cu, As, Ni, Zn	and 6010B (US EPA, 1996c)	
Hg	US EPA Method 7470A (US EPA, 1994), APHA (1999) Method 3112B	Using cold vapour atomic absorption spectrometry dissolved and total components were determined
BTEX (Benzene, toluene, ethylene, <i>m</i> + xylene, <i>o</i> -xylene and total BTEX)	US EPA Method 8260 (US EPA, 1996e)	Using purge and trap gas chromatograph mass spectrometer dissolved and total components were determined
Total petroleum hydrocarbons (TPH) C6–C9		
Total petroleum hydrocarbons (TPH) C10–14, C15–C28, C29–C36	US EPA Methods 3510C (US EPA, 1996b) and 8015B (US EPA, 1996d)	Using gas chromatography/flame ionization detector dissolved and total components were determined
PAHs – naphthalene, acenaphthalene, acenaphthene, fluorene, phenanthrene, anthracene, flouranthene, chrysene benzo [a] anthracene, benzo [a] pyrene, Dibenz [a,h] anthracene, pyrene, 2-methylnaphthalene, total PAH	US EPA Method 8270C (US EPA, 1996f) and 3500B (US EPA, 1996a)	Using purge and trap gas chromatograph mass spectrometer dissolved and total components were determined

**Table 1**  
Description of port land use sites used for the rainfall simulation trials

Site ID	Land use	Surface	Description
PS1	Vehicle marshalling area	Asphalt	Parking area for heavy transport vehicles
PS2	Container storage	Asphalt	Used to store empty and full 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	Inter-lock pavers	Operates as a road-rail inter-change site using mobile plant
PS6	Roadway	Asphalt	Typical of a major traffic arterial entering a port
US1	Residential	Asphalt	Typical single family dwellings
US2	Light industrial	Asphalt	Contains a range of small to medium enterprises such as auto repair shops and metal fabricators
US3	Commercial	Asphalt	Shopping centre car park



**Fig. 3.** Schematic of the particle size distribution of build-up pollutants. Percentages provided for the fraction <150 µm; nd – not detected; HM (heavy metals) and TPH values have been averaged for the different species detected.



**Fig. 4.** Comparison of TSS and 0.75–150 µm particle size range data in wash-off for all simulated rainfall events. The box plots given shows the lower quartile (25th percentile), upper quartile (75th median), and the mean and median.

deposited pollutants was assumed to be the same for the individual wash-off plots at each site.

### 2.6. Selection of experimental sites

A total of nine different land uses were investigated. This included six sites within the Port of Brisbane and three conventional urban land use sites in the close proximity including residential, light industrial and commercial land uses. The data from the latter three sites were used for comparison purposes. Details of the study sites are given in Table 1.

### 2.7. Sample handling and testing

The preservation and handling of samples was undertaken as specified in AS/NZS 5667.1:1998. The wash-off samples collected for each event was considered to be the event mean concentration (EMC) for that particular storm event. The build-up and wash-off samples were assessed for a range of pollutants typically associated with urban land uses. Samples were filtered and the residue and filtrate were analysed separately. The parameters tested and the test methods used are given in Table 2.

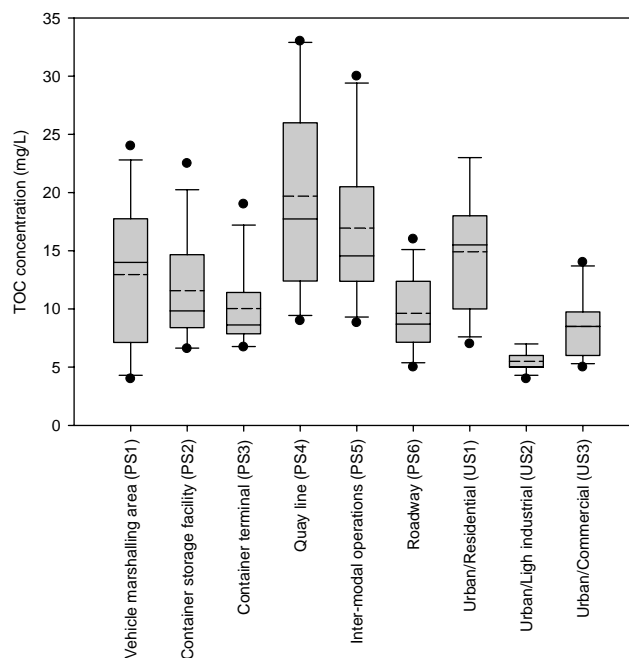
**Table 3**  
Particle size distribution of TSS in pollutant wash-off and percentage DOC fraction in TOC (combined data for all events)

Site	Particle size distribution of suspended solids (%)		Percentage DOC/TOC
	<150 µm	>150 µm	
PS1	91	9	75
PS2	68	32	87
PS3	85	15	73
PS4	87	13	89
PS5	88	12	89
PS6	63	37	93
US1	57	43	90
US2	70	30	89
US3	74	26	87

## 3. Results and discussion

### 3.1. Pollutant build-up

The results obtained from the particle size distribution of the build-up samples are summarised in Fig. 3. It is evident that a significant fraction of the particles are below the 150 µm range. This is quite strongly evident in the case of heavy metals (over 60% in PS2, PS3, PS5, PS6) and TPH (over 70% in PS3, PS4, PS5). Therefore,



**Fig. 5.** Comparison of TOC data in wash-off for all simulated rainfall events. The box plots given shows the lower quartile (25th percentile), upper quartile (75th median), and the mean and median same as in Fig. 4.

any stormwater quality improvement strategies adopted should be capable of trapping this particle size range.

### 3.2. Pollutant wash-off

#### 3.2.1. Total suspended solids (TSS)

Fig. 4 provides box plots for the comparison of TSS data for the different study sites. Other than for PS5, the data for the other Port

study sites compare well with the data for typical urban land use sites, with PS1, PS3, PS4 and PS6 being comparable to residential and light industrial land uses. The higher TSS concentrations found in PS5 most likely reflects the pavement surface rather than the land use characteristics. This is due to material build-up in the jointing sand of the inter-locking pavers at this site. The relatively higher concentration observed at PS2 is attributed to the site usage. It is hypothesised that the storage of containers results

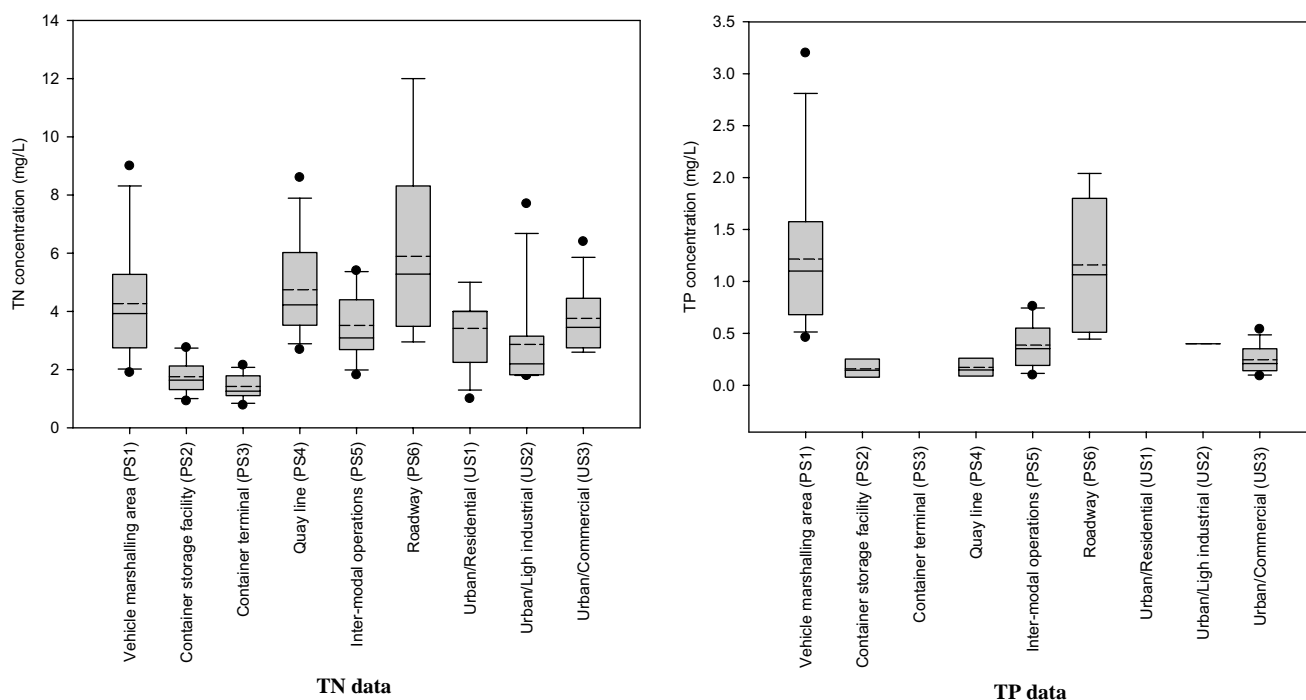


Fig. 6. Comparison of nutrient data in wash-off for all simulated rainfall events. The box plots given shows the lower quartile (25th percentile), upper quartile (75th median), and the mean and median same as in Fig. 4.

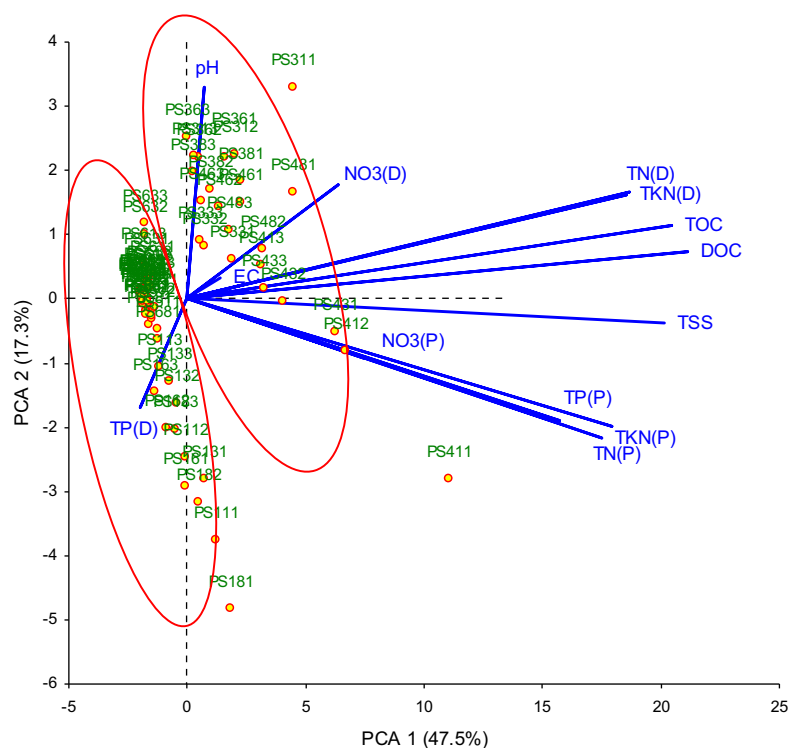


Fig. 7. PCA biplot for nutrients (concentration as mg/L per mg of build-up). (D) – dissolved; (P) – particulate; NO – nitrate; TKN – total kjeldahl nitrogen.



in conditions conducive to the prevention of removal of solids by wind and rain.

### 3.2.2. Particle size distribution

Table 3 compares the particle size distribution data for the different sites averaged for all the simulated events. Considering the Port data alone, it is evident that the greater percentage of suspended solids is in the 0.75–150  $\mu\text{m}$  range. This confirms the results obtained from the pollutant build-up study discussed above and further strengthens the argument that stormwater quality improvement strategies should target this size range for removal.

Furthermore, from the data it is evident that the particle size distribution at PS2 and PS6 are different to the other four sites with a comparatively low percentage <150  $\mu\text{m}$ . It is hypothesised that in the case of PS6, this would be due to relatively high traffic flow of heavy vehicles creating wind turbulence to remove some of the finer fraction. It is hypothesised that in the case of PS2, the presence of stacked containers results in conditions conducive to the trapping of larger particles and the prevention of their removal through meteorological conditions such as wind and rain rather than the smaller particles. The box plots for the 0.75–150  $\mu\text{m}$  size

range given in Fig. 4 above, further confirms the above observations. Other than for PS2 and PS6, there is reasonable consistency among the other sites. Furthermore, it shows that the port sites have a much higher fraction of finer particles when compared to the urban sites. Consequently, the important issue that is highlighted is the fact that the particle size distribution can vary due to a number of quite different reasons. Hence the strategy and design of structural measures to remove suspended solids needs to be carefully formulated to suit site characteristics. A 'one size fits all' approach may not be adequate.

### 3.2.3. Organic carbon

In terms of water quality, organic carbon is an important pollutant due to its ability to influence the presence of other pollutants. Binding to solid particles by hydrocarbons and heavy metals is enhanced by the presence of organic carbon (Herngren et al., 2006). In sediment, particulate organic carbon is important for sorption. However, DOC is specifically responsible for the distribution of hydrocarbons between aqueous and sediment bound phases. These impacts are termed as 'solubility enhancement' and 'solids concentration effect'. Solubility enhancement is the reduction of the solid-solution partition coefficient that increases

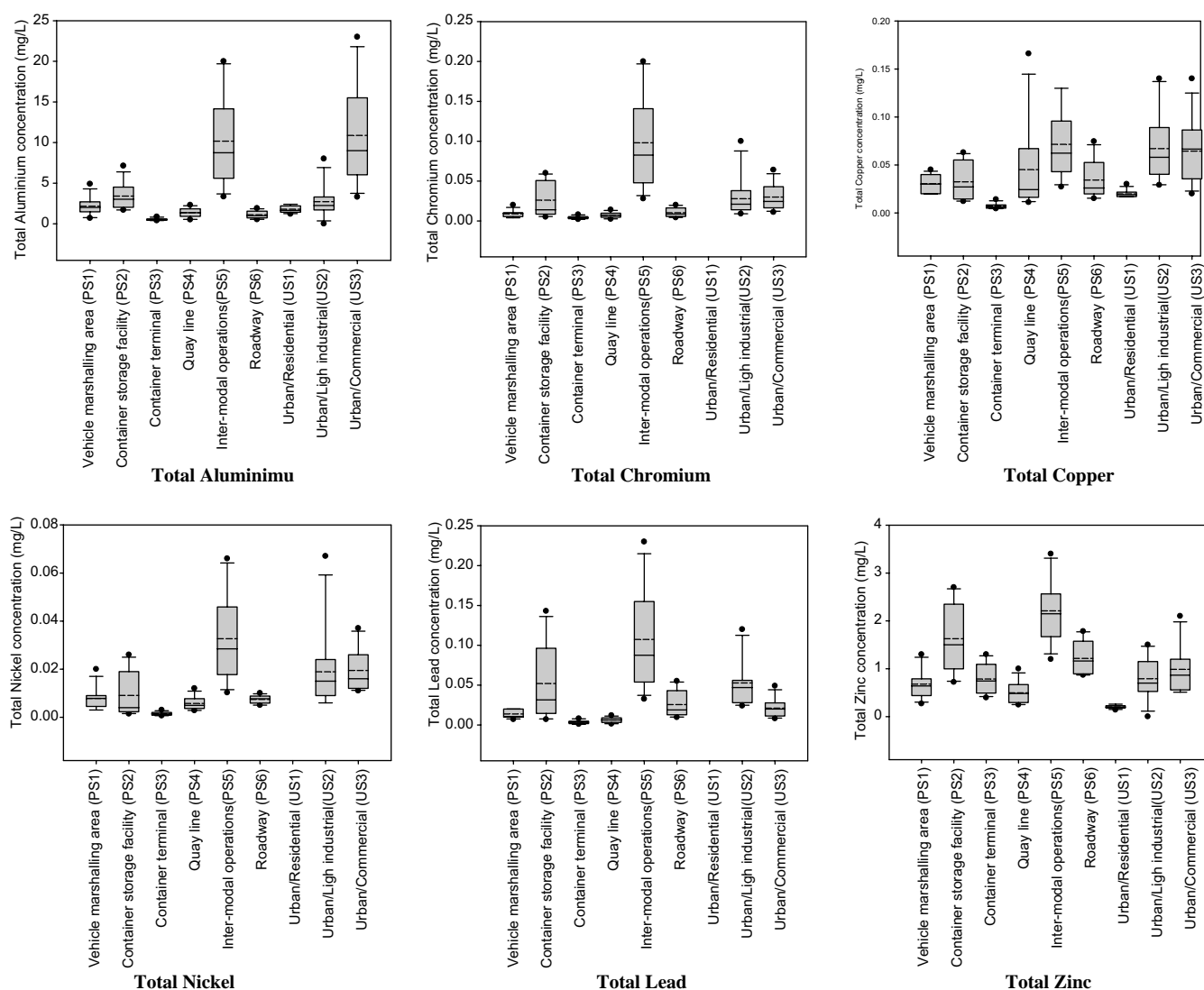


Fig. 8. Comparison of heavy metals data in wash-off for all simulated rainfall events. The box plots given shows the lower quartile (25th percentile), upper quartile (75th median), and the mean and median same as in Fig. 4.

the soluble fraction. The solids concentration effect is where the organic matter in the sediment dissolves into solution and brings about the solubility enhancement effect described above (Warren et al., 2003). As Table 3 above illustrates, a very significant fraction of TOC is present as DOC. Unfortunately, typical structural measures for water quality mitigation cannot remove DOC.

Fig. 5 gives the comparison of TOC data. With the exception of PS4 and PS5, the TOC data obtained compares well with all three urban land uses. It is hypothesised that the inter-lock pavers used at PS5 provide opportunity for mosses, lichen and algae to colonise these spaces due to the residue moisture within the jointing sand.

PS4 has a concrete paving and whilst it has been shown to generate a much lower TSS concentration, the TOC concentration was the highest when compared to the other sites tested. It is hypothesised that organic build-up from wind blown agriculture product loading in nearby areas may have resulted in organic residue build-up on the surface.

### 3.2.4. Nutrients

Fig. 6 provides comparisons of TN and TP data. Taking into consideration the vertical scale of Fig. 6 and possible sampling and testing errors, it is evident that the Port land uses compare well with the urban land uses.

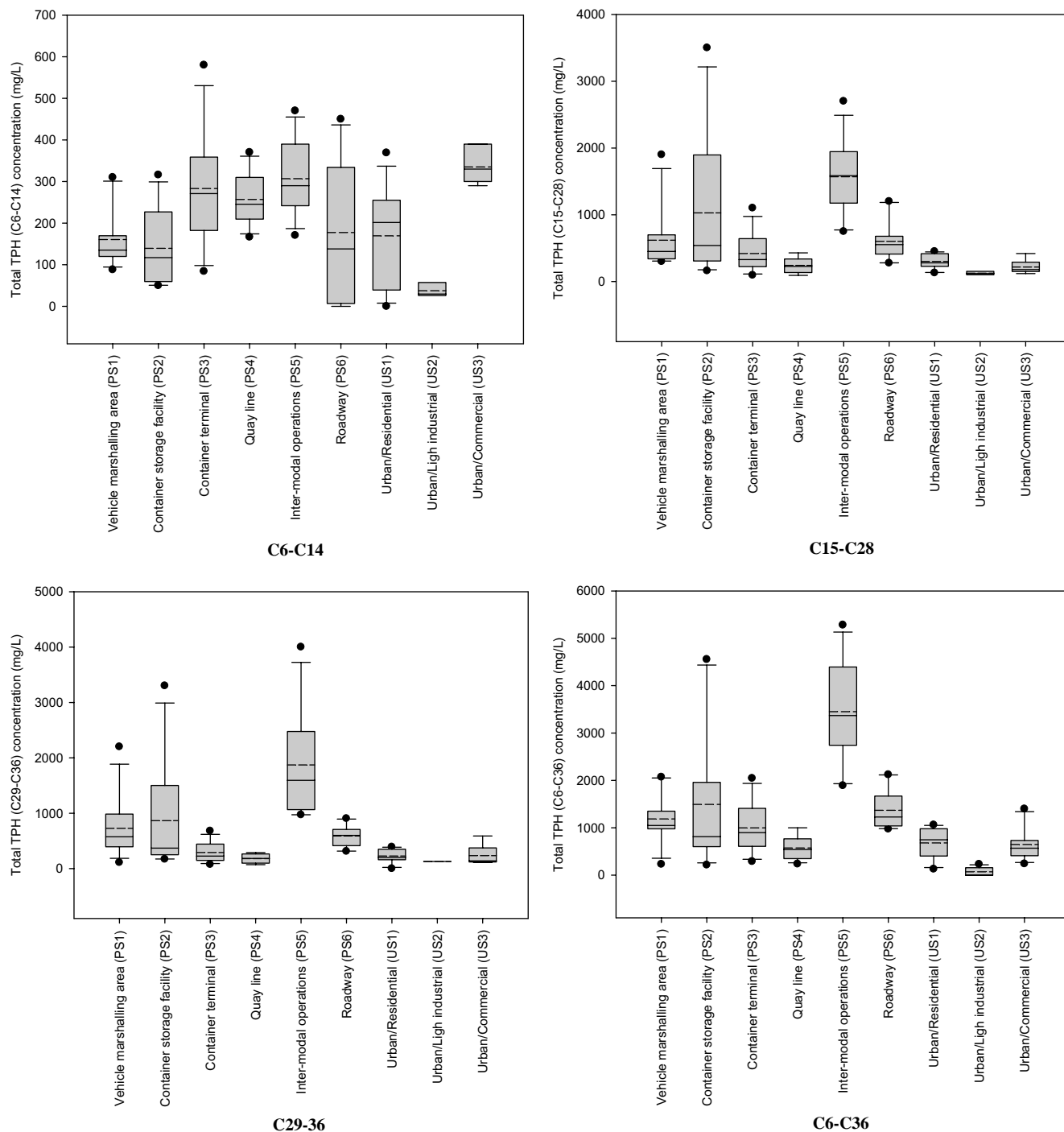


Fig. 9. Comparison of total petroleum hydrocarbons data in wash-off for all simulated rainfall events. The box plots given shows the lower quartile (25th percentile), upper quartile (75th percentile), and the mean and median same as in Fig. 4.

The TP concentrations were below detection in the case of PS3, US1 and US2. Though a box plot is shown in the case of PS2, only three data points, which is the minimum was present. Data collected indicates that all but two sites have TP concentrations below that detected in a commercial setting. PS1 and PS6 represent heavy vehicle traffic ways.

Additionally, multivariate analysis in the form of principal component analysis (PCA) was undertaken for the normalised values based on pollutant build-up. This was in order to eliminate any bias due to the possible influence of the antecedent dry period on build-up. Hence, the definition of concentration refers to mg/L per mg of build-up. PCA is a pattern recognition technique employed to understand the correlations among different variables and clusters among objects. The PCA technique is used to transform the original variables to a new orthogonal set of principal components (PCs) such that the first PC contains most of the data variance and the second PC contains the second largest variance and so on. The orthogonality of PCs enables the user to interpret the data variance associated with each PC independently. Though PCA produces the same amount of PCs as the original variables, as the first few contain most of the variance, they are often selected for interpretation. This in turn reduces the number of variables without losing useful information contained in the original data set. PCA is useful where large volumes of data can be processed in order to explore and understand relationships between variables. Detailed descriptions of PCA can be found elsewhere (Adams, 1995; Massart et al., 1988). The resulting PCA biplot is given in Fig. 7.

The following conclusions can be derived from Fig. 7:

- There are two data clusters, with PS1, PS2, PS5 and PS6 in Cluster 1 and PS3 and PS4 in Cluster 2. The separation into clusters is primarily due to differences in concentration of dissolved and particulate nutrients and TOC and DOC. This would mean that there are differences in nutrient wash-off processes for these two clusters.
- There is strong correlation between TOC and DOC which would mean that most organic carbon is in the form of DOC.
- Nutrients in particulate form correlate with TSS. This suggests that any mathematical relationship for describing TSS wash-off is also valid for the particulate nutrients.
- Dissolved components of nutrients show poor correlation with TSS. This would mean that the wash-off process for dissolved nutrients is different to that of TSS and particulate nutrients.
- All dissolved fractions other than TP(D) show correlation with TOC and DOC. TP(D) show little variation, suggesting that only a limited fraction is in dissolved form.

### 3.2.5. Heavy metals

Arsenic (As), Cadmium (Cd) and Mercury (Hg) concentrations were consistently very low or below detection limits for the wash-off samples. As such only the results for Aluminium (Al), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb) and Zinc (Zn) were analysed. The results from the sample testing confirmed that all the heavy metal species are primarily in particulate form, with the dissolved (filtered) fraction being low or below detection limits. Box plots for these heavy metals in terms of total concentrations are given in Fig. 8.

The heavy metals in the wash-off from Port land uses compare well with the urban land uses other than in the case of PS5 for most metal species, PS2 primarily for lead and PS6 for Zinc. It is also important to take into consideration possible sampling and testing errors as the concentrations fall within a relatively small range. PS6 being a roadway, it is possible that the relatively high concentration of Zinc is due to the wear and abrasion of tyres and other vehicle components, lubricants and combustion of fuel. The elevated

heavy metal concentrations at PS5 are attributed to the specific land use at this site. Being an inter-modal operations area, metallic fines resulting from the deposition of combustion by-products and tyre and vehicle wear from vehicle movements is possible. Similar reasons could be attributed to the high heavy metal concentrations and in particular the presence of lead at PS2.

### 3.2.6. BTEXs and PAHs

The concentrations BTEXs and polycyclic aromatic hydrocarbons (PAH) in the wash-off were below detection limits and hence is not discussed any further.

### 3.2.7. Total petroleum hydrocarbons (TPH)

The box plots for TPH are given in Fig. 9. TPH in the environment originate from lubricants and the partial combustion of fossil fuels. The C6–C14 range belongs to gasoline, C15–C28 range belongs to diesel and the C29–C36 range belongs to lubricants.

Considering the figure given above, it is evident that there is no consistency in terms of which site is the worst polluted for the different fractions of TPH tested. Considering only TPH fraction <C14 which is the gasoline range, a number of sites from PS3 to PS5 appear to be equally polluted. For the range C15–C28, which is the diesel range and for the range C29–C36, which is the lubricants range PS5 site is the most polluted even when compared to the urban land uses. Also for the entire TPH range (C6–C36), once again PS5 is the most polluted. It is hypothesised that this is due to the nature of activities taking place at this site and the resulting slow vehicle speeds. However, most importantly it underlines the fact that there is significant variability between the different sites when TPH pollution is considered.

## 4. Conclusions

The results derived from the extensive study into pollutant wash-off from different port land uses and the comparison with typical urban land uses highlights a number of important issues:

- The detailed comparison with pollutant build-up and wash-off characteristics as illustrated in Figs. 4–6 and Figs. 8 and 9 confirmed that a seaport environment is unique in terms of pollutant characteristics and is not comparable to typical urban land uses. Therefore, the use of pollutant loading factors commonly adopted for urban water quality modelling is not feasible for calibrating a water quality model for a seaport. For most pollutant types, the port land uses exhibited lower pollutant concentrations when compared to typical urban land uses.
- It was evident that the pollutant characteristics varied across the different land uses. Furthermore these differences in pollutant characteristics were not consistent in terms of the land use thus precluding the development of simple mathematical relationships. The ranking of sites in terms of the severity of pollution generation is also not consistent and changes for different pollutant types. Hence, the implementation of stereotypical structural water quality improvement devices could be of limited value.
- The predominance of the <150µm particle size range in suspended solids in pollutant build-up as well as wash-off is highly significant. This would mean that the common approach of targeting of suspended solids as the surrogate parameter for water quality improvement would only be effective if this specific particle size range is removed.
- The particle size distribution can vary due to a number of quite different reasons. Hence the strategy and design of structural measures to remove suspended solids needs to be carefully formulated to suit site characteristics. A 'one size fits all' approach may not prove to be adequate.



- The land cover or surface paving was found to influence pollutant build-up and wash-off. For example, the inter-modal operating area (PS5) with inter-locking pavers was found to be the most polluted in terms of suspended solids build-up. This is attributed to the entrapment of sediments within the inter-locking pavers. Also, this site was consistently ranked quite highly in relation to most pollutant types. This could be due to the combination of surface paving and land use.

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