A Holistic Assessment of Stormwater Quality from Urban Catchments

M.N. Chong*, J.P.S. Sidhu*, R.K. Aryal**, J.Y.T. Tang***,
W. Gernjak**, B.I. Escher***, S. Toze*

** CSIRO Land and Water, Ecosciences Precinct, Boggo Rd, Dutton Park, Queensland, 4102, Australia (E-mail: meng.chong@csiro.au; jatinder.sidhu@csiro.au; simon.toze@csiro.au)*
*** AWMC, The University of Queensland, St Lucia, Queensland, 4072, Australia (E-mail: r.aryal@awmc.uq.edu.au; w.gernjak@awmc.uq.edu.au)*
**** ENTOX, The University of Queensland, Kessels Rd, Cooper Plains, Queensland, 4108, Australia (E-mail: y.tang@uq.edu.au; b.escher@uq.edu.au)*

ABSTRACT
Stormwater is one of the last major untapped urban water resources that could be exploited as an alternative water source in Australia. The information in the current Australian Guidelines for Water Recycling relating to stormwater harvesting and use only emphasize a limited number of stormwater quality parameters. In order to supply stormwater as a source for higher value end-uses, a more comprehensive assessment on the potential public health risks has to be undertaken. Owing to the stochastic variations in rainfall and catchment hydrology and the types of non-point pollution sources that can provide contaminants relating to different anthropogenic activities and catchment land uses, the characterisation of public health risks in stormwater is complex, tedious and not always possible to assess through conventional detection and analytical methods. In this study, a holistic approach was undertaken to assess potential public health risks in urban stormwater samples from a medium-density residential catchment. A combined chemical-toxicological assessment was used to characterise the possible health risks from chemical pollutants, while a combination of culture methods quantitative polymerase chain reaction (qPCR) detection methods were used for detection and quantification of faecal indicator bacteria (FIB) and pathogens in urban stormwater. Preliminary results showed that the concentration of chemical pollutants and the associated toxicity was relatively low. However, the concentrations of heavy metals particularly Cadmium (Cd) and Lead (Pb) have exceeded the Australian guideline values, indicating potential public health risks. Also, high numbers of FIB were detected in stormwater samples obtained from wet weather events. In addition, qPCR detection of human-related pathogens suggested frequent sewage ingression into the urban stormwater runoff during wet weather events. Further stormwater quality monitoring study will be conducted at different contrasting urban catchments, in order to undertake a more comprehensive public health risk assessment.

KEYWORDS
Alternative water source; public health risks; water conservation; stormwater quality monitoring; WSUD.

INTRODUCTION
In Australia, the push towards achieving sustainable water environment through Water Sensitive Urban Design (WSUD) has promoted the use of various alternative water sources to augment the traditional mains water from the grid. Among the various alternative water sources, stormwater appears to be an attractive water source that can be harvested on a large-scale basis to meet the volumetric demand from the ever intensifying urbanisation across all major cities in Australia. At present, the stormwater harvesting and use schemes are mostly restricted to irrigation of lawns, golf courses and public open spaces. The potential presence of a range of pollutants in urban stormwater due to the stochastic variations in rainfall and catchment hydrology, as well as source contributions from different anthropogenic activities has prompted the necessity to understand the associated public health risks prior to utilising the source water for higher value end-uses (i.e. potable

augmentation of dams, indirect potable reuse, hot water systems, filling up toilet cisterns and washing machine cold tap and others) (Chong *et al*., 2011). A good understanding of untreated urban stormwater is essential, as it allows for the development of a risk management framework to ensure decreases in water quality from approved standards are avoided, as well as in making informed decisions on required "*fit-for-purpose*" water treatment processes.

Previously, a number of studies have found diverse pollutants in stormwater, which include suspended solids, nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), pesticides, herbicides, faecal indicator bacteria (FIB), pathogens and others (Duncan, 2002; Erikkson *et al*., 2007; Vezzaro & Mikkelsen, 2011). The existing stormwater guidelines within the Australian Guidelines for Water Recycling only encompass a limited set of stormwater quality parameters (NRMMC, EPHC & NHMRC, 2009), thus additional stormwater quality parameters are required to enable a comprehensive risk assessment if stormwater is to be utilised for higher value end-uses (i.e. potential human contact, ingestion and cross-connection of stormwater pipeline). The use of, extensive monitoring campaigns on urban stormwater quality however are usually constrained by technical problems (i.e. collection of representative samples), resource availability (i.e. analytical equipment and budgets availability) and stochastic variations in rainfall and catchment hydrology. These issues can impede an accurate a full suite of stormwater quality analysis for subsequent risk detection and quantification. Previous studies have reported on analysing stormwater qualities based on event mean concentration (EMC) to estimate the average pollutant concentrations and loads from rainfall events (Kim *et al*., 2004; Khan *et al*., 2006). To date, however, not a single study has provided a sound methodological and comprehensive risk assessment approach to comprehensively assess the potential public health risks in stormwater for a better risk management framework, water treatment and reuse scheme.

The aim of this study was to concurrently investigate the potential chemical, toxicological and microbiological qualities of untreated stormwater from an urban catchment. This study constitutes one of the first in Australia to comprehensively assess the potential public health risk in urban stormwater. A medium density residential stormwater supply catchment at Fitzgibbon in northern Brisbane was used as a case study. A flow-proportional sampling method was used to capture the peak flows in the hydrograph before compositing the samples (i.e. over the entire hydrograph) into a final sample for EMC analysis. The composite EMC samples were analysed using various advanced analytical methods such as (1) heavy metals analysis, UV and fluorescence spectroscopic methods for organic pollutants, (2) bioassays for different toxicological end-points and (3) standard membrane filtration technique and quantitative PCR for detection and quantification of faecal indicator bacteria (FIB) and pathogens. With this study, it is anticipated that a greater insight into pollutants in urban stormwater can be gained so that appropriate management practices can be devised to minimise associated public health risks where possible.

METHODS

Sampling location. Fitzgibbon, the case study catchment, is located in the northern suburbs of Brisbane, Australia. It is a medium density residential stormwater supply catchment, which covers a total area of 290 ha. The impervious surface coefficient was estimated using image classification and cadastral filtering of high-resolution visible aerial photography method and was determined to be 0.25-0.30. This stormwater catchment area is situated in a growing residential hub of northern Brisbane and consists of mixed residential dwellings, commercial centres and buildings, education facilities and semi-rural areas. At present, the Urban Land Development Authority (ULDA) is considering the harvesting of stormwater runoff from this supply catchment to serve as an alternative water source for non-potable uses (i.e. toilet cisterns, cold water laundry tap and general external uses such as car washing, garden watering and public open space irrigation). Figure 1 shows the case study catchment as well as the current urban stormwater sampling location.

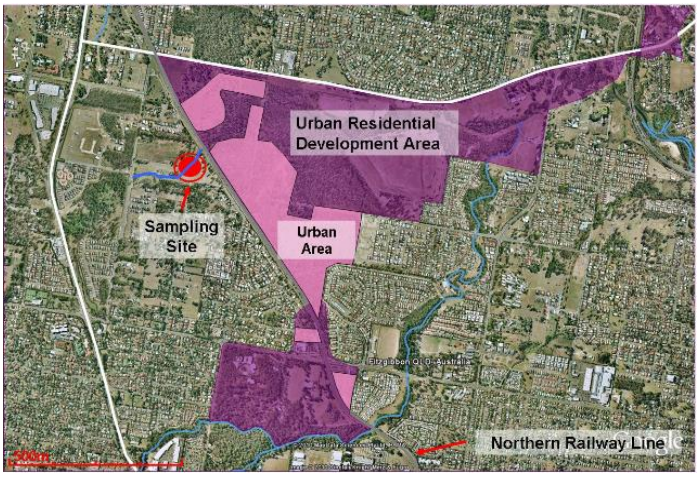


Figure 1: Case study catchment and the current urban stormwater sampling location.

Figure 2: Automatic sampler (a.k.a. Octopus sampler) setup with 24 x 20 L HDPE bottles in a tailor-made shed.

Sampling strategy. Figure 2 shows the three automatic samplers (ISCO 6700 series) that were used in parallel for urban stormwater samples collection in this study. These samplers were programmed to fill up to 24 x 20 L high-density polyethylene containers (HDPE) during a storm event. In this instance, three automatic samplers were used to capture the dynamics of stormwater flow (i.e. peak flows) where the samplers were simultaneously triggered to give a sample volume of 20L for each preset flow threshold. This large sample volume was required for subsequent concentration and analysis of viral and protozoan pathogens. A submersible Argonaut Flow Doppler (Thermo Fisher Sci) was installed to measure the in-stream stormwater flow during the wet weather events, so as to trigger the automatic samplers for sample collection. The Argonaut Flow Doppler is capable of accurate measurement of depth and velocity, following a series of manual flow gauging and calibration procedures. A remote telemetry system was used to notify research staff via 'SMS alert' once the first 20L of samples was collected at the site. This system removes the need for sample refrigeration, as the research team can attend to the site for (almost) immediate sample collection and transfer back to the laboratory for subsequent analysis. To avoid cross-contamination in the HDPE bottles, they were cleaned using sodium hypochlorite solution (10%) and rinsed with ultra-pure water (MilliQ system, Millipore) in the laboratory before the used HDPE bottles were replaced at the field site.

Organic Carbon Structure using UV spectroscopic analysis. UV spectroscopic analysis method is a well-known qualitative tool to identify the nature and quantity of organic substances, their functionality, and sometimes their molecular weight (Korshin *et al*., 1997). In this study, the UV analysis was performed using a UV spectrometer (Varian 50 Bio). The spectrophotometer was

operated at bandwidth 1 nm, with a quartz cell of 10 mm path length, wavelength of 190 to 400 nm and at a scanning speed of 190 nm/min (slow). In this instance, the photometric accuracy was 0.004 Abs at 1.0 Abs.

Heavy metals analysis. Stormwater samples were filtered through 1.2 µm and analysed in ICP/MS (Hewlett-Packard). Quantitative measurement was done after calibration with standard samples.

Fluorescence spectroscopic analysis. Three-dimensional fluorescence excitation-emission matrix (EEM) spectra were used to identify the nature of organic substances by changing excitation wavelength and emission wavelength simultaneously without destroying the samples. The EEM spectra provide important information on both the physical and chemical properties of the organics of various origins in stormwater. In this study, the EEM spectra were obtained using a spectrofluorometer (Perkin Elmer LS 55) with a wavelength range of 200 nm to 500 nm (for excitation); and 280 nm to 500 nm (for emission). The spectra were taken at an incremental wavelength of 5 nm in excitation; and 2 nm in emission. The EEM value of blank (Milli-Q water) data was subtracted from the analysed samples for blank correction. The data obtained from EEM was analysed using Microsoft Excel®.

Baseline toxicity – Bioluminescence inhibition in Vibrio fischeri. The non-specific toxicity assay is widely recognised in the field of eco-toxicology as the standard assay to measure acute cytotoxicity (Macova *et al*., 2011). A 30-min bioluminescence inhibition test with the marine bacterium *Vibrio fischeri* was performed according to the protocol of the International Standard Organization (ISO 11348–3) (ISO, 1998). This test is also often known as the Microtox test. Freeze-dried bacteria were reconstituted in saline buffer containing 4 mM KCl, 10 mM $MgCl_2$, 10 mM MOPS β-[*N*-morpholino] pro-panesulfonic acid), and 346 mM NaCl with the pH adjusted to 7.0 ± 0.2 with HCl/NaOH. Precisely 500 µl of diluted bacterial suspension were mixed with 500 µl of sample in the saline buffer (plus a maximum 2.5% [v/v] of ethanol at the highest-exposure concentration) and incubated for 30 min at 288 ± 1 K. The luminescence output was then read with a LUMIStox 300 luminometer. Data evaluation was performed according to the ISO 11348–3 protocol.

Quantification of FIB. Quantification of FIB (*E. coli* and *Enterococcus* spp.) was performed by the standard membrane filtration technique. Briefly, 1 and 10mL samples were filtered through 47mm 0.45µm nitrocellulose (Millipore) filters and placed on respective selective agar plates in triplicate. *E. coli* was enumerated on Chromocult™ coliform agar (Merck) and *Enterococci* on Chromocult™ enterococci agar (Merck). Plates were incubated at 37°C overnight and then typical colonies were counted to determine the average number of colony forming units (cfu $100mL^{-1}$). The remaining water sample was the concentrated using hollow fiber ultra-filtration using disposable hemoflow cartridges to less than 100 mL.

Detection of Pathogens. Nucleic acid was extracted from 200 µL of the concentrated samples using the MoBio PowerSoil DNA isolation kit (MoBio Laboratories, Inc., Carlsbad, CA). Duplex PCR was used to improve detection of pathogens from the concentrated water samples. Analysis for the enteric pathogens adenovirus, polyomavirus, *Salmonella enterica, Campylobacter* spp, *Giardia lamblia* cysts and *Cryptosporidium parvum* oocysts was undertaken using published primer and probe sets. The human faecal contamination marker, *E. faecium* esp gene was detected by using previously published primer sets. PCR was carried out after extraction of DNA from the enriched sample (500 µL). The human specific *Bacteriodes* HF183 gene was detected in the DNA extracted from concentrated water samples with published primer sets. Fresh primer and probe sets for real time PCR using Primer3 software were designed for *C. jejuni* and *C. coli* targeting mapA and ceuE genes, respectively (GenBank numbers X80135 and X88849). Standards for PCR amplification

were prepared from the genomic DNA of standard cultures of *C. jejuni*, *C. coli*, *Salmonella enterica* serovar *typhimurium*, human adenovirus type 41, and human polyomavirus (JC). The concentration of the genomic DNA was measured by using a NanoDrop ND-1000 spectrophotometer. After calculation of genomic copy numbers, a serial 10-fold dilution (10^6 to 10^0 copies per µl of DNA) was prepared from the genomic DNA. To determine the potential presence of PCR inhibitory substances in the DNA extracted from water samples, a sample of cachou-pH extract was spiked with 10^3 gene copies of adenovirus. The cycle threshold (C_T) values obtained for stormwater samples spiked with adenovirus were compared to those of the control MilliQ water spiked with adenovirus DNA to determine the extent, if any, of PCR inhibition. Quantitative PCR reactions were performed on Bio-Rad iQ5 (Bio-Rad Laboratories, California, USA), using iQ supermix (Bio-Rad) or So Fast™ EvaGreen® Supermix (Bio-Rad). Bovine serum albumin (BSA) was added to each reaction mixture to a final concentration of 0.2 µg μL^{-1} to relieve PCR inhibition. For each PCR run, a corresponding positive (i.e., target DNA) and negative (sterile water) control was included.

RESULTS AND DISCUSSION

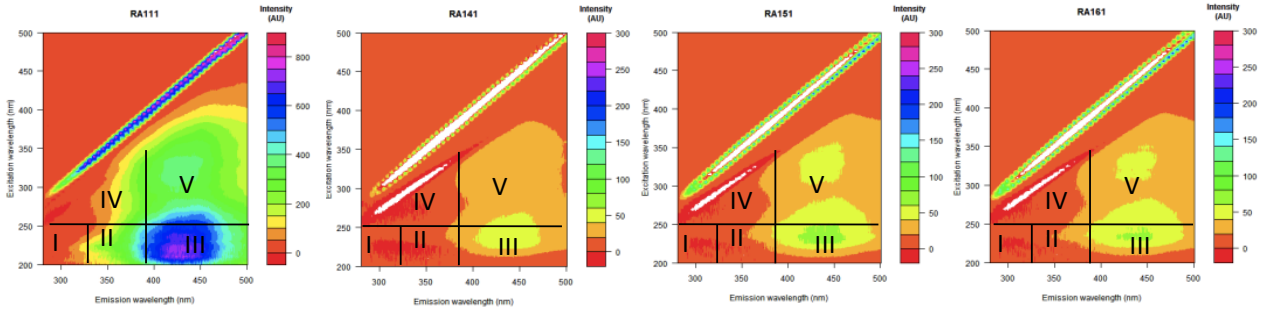
Heavy metals and spectroscopic analysis

Table 1 shows the heavy metals detected in the urban stormwater samples from the Fitzgibbon catchment. Results showed that there is a large variation in the concentration range over the four wet weather events sampled to-date. Some of the heavy metals such as Cd, and Pb were found to exceed the Australian stormwater harvesting and use guideline values, which indicate the presence of potential health risk.

Table 1: Heavy metals concentration (µg/L) in stormwater samples.

Metals	Max	Min	Av	St Dev	Guideline
Cd	31.10	4.10	18.49	15.94	2.00
Cr	18.50	2.70	8.79	3.82	50.00
Cu	20.69	3.55	8.79	4.52	2000.00
Pb	13.24	0.10	6.73	4.18	10.00
Zn	68.56	0.56	16.01	18.81	3000.00

Fluorescent spectroscopic analysis was carried out to provide a rapid assessment on the organic composition in the collected stormwater samples and for information on a further suite of chemical analysis required (Chen *et al.*, 2003). Figure 3 illustrates the EEM spectra of stormwater collected from the four sampled weather events (i.e. one dry weather and three wet weather events). According to Chen *et al*. (2003), Region I represents the aromatic protein I; region II on aromatic protein II; region III on soluble microbial by-product-like; region IV on fulvic acid-like and region V on humic acid-like. The EEM spectra indicated that the dry weather event contained a much higher concentration of fulvic and humic compounds than the wet weather events. This might be owing to the potential decomposition of organic matter in the urban canal during low flow (stagnant) condition. As for the wet weathered EEM spectra, it was found that these samples had very similar organic constituents from the analysed urban stormwater samples. This indicates that the presence of organics in stormwater is quite specific to the catchment site and might be dominated by land use characteristics, which determines potential diffuse sources contribution to stormwater runoffs.



(a) **(b)** **(c)** **(d)**

Figure 3: EEM spectra of stormwater collected during (a) dry and (b-d) wet weather events.

Bioassays analysis

Results of the baseline toxicity were shown to be very similar across the four sampling events (Figure 4). In comparison to a study sampling across seven barriers in an indirect potable water recycling scheme (Macova *et al*., 2011), the measured baseline toxicity in this study was shown to be 10 times lower than that of raw sewage. In comparison, the measured toxicity in stormwater samples from wet weather events has shown similar levels of chemical mixture burden to the secondary treated sewage effluent. This suggests that urban stormwater might require fewer polishing treatment stages for the removal of chemical contaminants to achieve a Class A^+ water source status for non-potable uses.

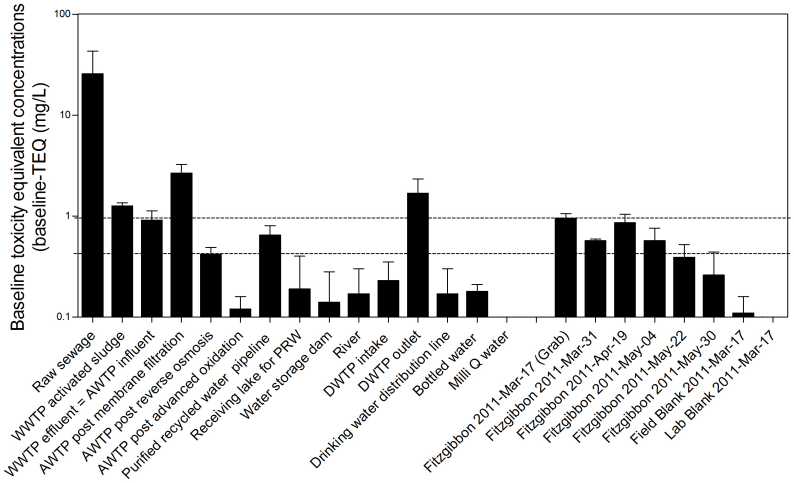


Figure 4: Baseline toxicity comparison of stormwater events with an indirect potable recycling scheme in SEQ, Australia.

Quantification and Detection of FIB and Pathogens

Table 2 shows the FIB numbers for stormwater samples collected from the four sampled weather events at the Fitzgibbon site. Results show that the *E. coli* and *Enterococcus* spp. numbers during the wet weather flow events were higher than the dry weather event. No significant difference was observed between *E. coli and Enterococcus* spp. numbers during the dry or wet weather flow events.

Table 2: Quantification of FIB in collected stormwater under dry and wet weather events in Fitzgibbon site.

Fitzgibbon Site (Event)	***E. coli* (CFU/100mL)**	***Enterococcus* (CFU/100mL)**
Dry weather event	3.60×10^2	5.10×10^2
Wet weather event 1	1.33×10^2	1.27×10^2
Wet weather event 2	8.93×10^3	2.23×10^4
Wet weather event 3	1.07×10^4	3.11×10^4

Table 3: PCR detection of pathogens in collected stormwater under dry and wet weather events in Fitzgibbon site.

Fitzgibbon Site (Event)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Dry weather event	+	+	-	-	NT	NT	-	+
Wet weather event 1	+	+	-	-	NT	NT	-	-
Wet weather event 2	+	-	+	-	+	-	-	+
Wet weather event 3	+	-	+	+	+	+	+	+

Note: 1: *Campylobacter spp*, 2: *C.jejuni*, 3: *C.coli*, 4: *Salmonella*, 5: *Adenovirus*, 6: *Polyomavirus*, 7: *Esp genes*, 8: *Bacteriodes HF183*, *NT: Not Tested.*

Table 3 shows the summary of PCR detection of pathogens in stormwater samples collected from the Fitzgibbon catchment. All samples were tested positive with the *Campylobacter* species primer set, which primarily detects *C. jejuni*, *C. coli* and *C. lari*. After speciation primers analysis, the occurrences of *C.jejuni* and *C.coli* were only detected at certain events. Human specific adenovirus and polyomavirus were also detected in the collected water samples after storm events. The human-specific Bacteriodes HF183 marker was widely found in the stormwater samples tested, suggesting that there was contamination from human sewage during both the dry and wet flow events. In comparison, the *E. faecium esp* gene was found in one wet weather event only. Unlike HF183, the *esp* gene was absent in the water samples containing even higher FIB counts (Table 3) after storm events, suggesting its low prevalence in stormwater.

CONCLUSIONS

In conclusion, the preliminary results from the four sampled events suggest that the occurrence and concentration of chemical pollutants in urban stormwater runoff and the associated baseline toxicity is relatively low when compared to other alternative water sources such as wastewater. However, the concentrations of heavy metals particularly for cadmium (Cd) and lead (Pb) have exceeded the Australian guideline values, indicating potential public health risks. The microbiological quality of urban stormwater may not be as good as commonly perceived, with high numbers of FIB found during wet weather flow events. In addition, it was also found that there was potential human sewage contamination present during wet weather events, suggesting possible sewer overflow events. Further stormwater quality monitoring is required to increase confidence in its utilisation as an alternative water source for higher value end-uses or to determine the level of treatment prior to use. The outcomes of this preliminary monitoring study suggests that further stormwater treatment is required and more particularly, a disinfection treatment to reduce the microbiological pollutants in stormwater. The on-going and detailed monitoring data obtained from this study and other urban catchments throughout Australia will enable a more comprehensive and accurate health risk assessment to be undertaken. This will enable a determination on how urban stormwater can be used for a wider range of end-uses (i.e. potable and non-potable) than currently permitted, as well as the necessary water treatment processes required to mitigate the associated public health risks in urban stormwater.

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REFERENCES

Chen, W., Westerhoff, P., Leenheer, J. and Booksh, K. (2003). Fluorescence excitation-emission matrix regional integration to quantify spectra for dissolved organic matter. *Environmental Science and Technology*, **37**, 5701-5710.

Chong, M.N., Aryal, R.K., Sidhu, J.P.S., Tang, J.Y.T., Toze, S. and Gardner, T. (2011). Urban stormwater quality monitoring: From sampling to water quality analysis. *Symposium on Environmental Monitoring, The 7th International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2011), Adelaide, Australia, 6-9 December 2011.*

Duncan, H.P. (2003) *Stormwater quality*, In: T.H.F. Wong (Ed.), *Australian Runoff Quality*, Sydney Australia: Institution of Engineers, Australia (available from http://www.arq.org.au).

Erikkson, E., Baun, A., Scholes, L., Ledin, A., Ahlman, S., Revitt, M., Noutsopoulos, C. and Mikkelsen, P.S. (2007). Selected stormwater priority pollutants – a European perspective. *Science of the Total Environment*, **383**, 41-51.

ISO International Organization of Standardization (1998). *Water quality – Determination of the inhibitory effect of water samples on the light emission of Vibrio fisheri (Luminescent bacteria test) – Part 3: Method using freeze-dried bacteria*, Geneva Switzerland.

Khan, S., Lau, S.L., Kayhanian, M. and Stenstrom, M.K. (2006). Oil and grease measurement in highway runoff – sampling time and event mean concentrations. *Journal of Environmental Engineering ASCE*, **132**, 415-422.

Kim, L.H., Kayhanian, M., and Stenstrom, M.K. (2004). Event mean concentration and loading of litter from highways during storms. *Science of the Total Environment*, **330**, 101-113.

Korshin, G.V., Li, C.W., Benjamin, M.M. (1997). Monitoring the properties of natural organic matter through UV spectroscopy: a consistent theory. *Water Research*, **31**, 1787-1795.

Macova, M., Toze, S., Hodgers, L., Mueller, J.F., Bartkow, M. and Escher, B.I. (2011). Bioanalytical tools for the evaluation of organic micropollutants during sewage treatment, water recycling and drinking water generation. *Water Research*, **45**, 4238-4247.

NRMMC, EPHC & NHMRC. (2009). Australian guidelines for water recycling: Managing health and environmental risks (Phase 2) – *Stormwater harvesting and reuse*, Canberra, Australia.

Vezzaro, L. and Mikkelsen, P.S. (2011). Application of global sensitivity analysis and uncertainty quantification in dynamic modelling of micropollutants in stormwater runoff. *Environmental Modelling and Software*, In Press: doi:10.1016/j.envsoft.2011.09.012.