Stormwater reuse treatment requirements and screening-level risk assessment at two urban spatial scales

Ian M. Brodie

ABSTRACT

Monitoring was conducted at two urban spatial scales (lot-scale road surface and residential subdivision) to assess treatment requirements for non-potable stormwater reuse by irrigation. A screening-level risk assessment was also made focusing on metals, nutrients, cations and pesticides. Composite stormwater samples were taken at two locations in Toowoomba, Australia. Road runoff had higher treatment requirements for suspended solids but less for disinfection. No organic load or salinity reduction is generally needed, and pH adjustment is an occasional requirement for road runoff only. For both stormwaters, hardness was rated at very soft, which may potentially increase corrosion of irrigation equipment. Sodium adsorption ratios were also low indicating a limited risk of soil degradation under irrigation. Nutrient and metal concentrations also pose a low risk. High turbidity and low alkalinity of road runoff makes it easier to treat with coagulants compared to the subdivision runoff. Pesticide analysis of 121 compounds found road runoff concentrations below levels of detection, except for Simazine and Hexazinone. Although detectable, these pesticide concentrations were within Australian drinking water guidelines.

Key words | non-potable reuse, risk assessment, stormwater harvesting, urban runoff, water quality monitoring

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INTRODUCTION

Stormwater reuse in Australia and elsewhere is becoming acceptable practice to supplement urban water supplies, especially for non-potable uses. The design and performance of a reuse system, involving the capture, storage, treatment and reticulation of stormwater, is expected to be closely linked to the scale at which the proposed system will operate.

Figure 1 illustrates three spatial scales common within the urban landscape, ranging from 'lot-scale' small individual surfaces (order <1 ha) to 'subdivision-scale' of moderately sized development (order 1 to >100 ha) with homogeneous landuse to 'catchment-scale' urban areas (order >>100 ha). The three scales represent a continuum within the urban stormwater system; the lot-scale surfaces form the components of a subdivision and, in turn, the various subdivisions form an urban catchment.

From a water quality perspective, stormwater treatment requirements will vary amongst other factors, with the spatial scale. A small reuse system treating road runoff would have a treatment technology specific to the polluted characteristics of this type of surface runoff. For a larger system servicing a residential subdivision, the stormwater quality is expected to differ due to runoff contributions from surfaces other than roads. The variation in runoff quality between different surfaces can be significant. Brodie & Dunn (2009), for example, found from stormwater sampling that average suspended solids concentration in road runoff can be up to 22-fold and five-fold the respective concentrations of roof and carpark runoff. As scale increases to a catchment with a mix of landuses, the stormwater quality may again differ because of, for example, the increased presence of wet weather sewer overflows and creek erosion caused by urban runoff. Soil disturbance during

doi: 10.2166/wrd.2012.072

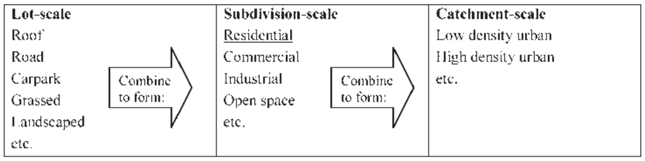

Figure 1 | Spatial scales within the urban stormwater system. Underlined elements are evaluated in this paper.

construction activity can also lead to poor stormwater quality, leading to increases in suspended solids loads by a factor of 100 or more (Pisano 1976).

The above discussion highlights the low likelihood that a 'one size fits all' approach will apply to the treatment requirements of harvested urban stormwater. This paper investigates these treatment requirements and also provides an initial risk assessment through stormwater monitoring conducted at two scales; a lot-scale road surface and a low-density residential subdivision. Data collection was undertaken at Toowoomba which is a regional city located in South East Queensland, Australia (see Figure 2).

Stormwater harvesting is in its infancy in Australia with relevant national guidelines being released in 2009 (NWQMS 2009). Standardised practices to minimise health and environmental risks are identified for small-to-medium reuse schemes involving open space irrigation. These practices were developed based on untreated stormwater quality data compiled from the literature. There is a lack of Australian data for some parameters, including boron and herbicides, and the risk assessment was also based on monitoring data from different catchment types (e.g. road, industrial) pooled together into a single urban category (NWQMS 2009). Additional catchment monitoring, such as the Toowoomba study, is of value to further refine the assessment of stormwater reuse risks.

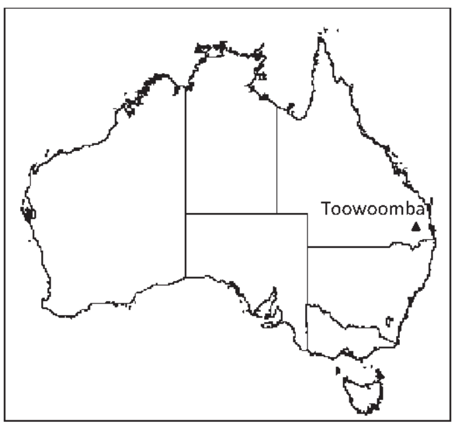

Figure 2 | Toowoomba location map.

METHODS

Selected water quality parameters

The selected water quality parameters (Table 1) were divided into two groupings: parameters used to characterise potential stormwater treatment processes and pollutants of concern that are important from a risk management perspective. Treatment characterisation parameters include bacterial and physiochemical measures.

Stormwater from urban areas contains an extensive array of contaminants. Ledin *et al.* (2002) identified 63 metals, 640 xenobiotic organic compounds and 33 microbiological pathogens that could be found in stormwater. It is impractical to measure all stormwater contaminants, so various attempts have been made to identify priority pollutants

Table 1 | Selected water quality parameters

Treatment characterisation parameters

Bacteria – Faecal coliforms

Physiochemical[a] – BOD_5, TSS, turbidity, VSS, TOC, TDS, conductivity, pH, oils and grease, hardness, alkalinity

Pollutants of concern

Metals[b] – Aluminium Al, Antimony Sb, Arsenic As, Barium Ba, Beryllium Be, Boron B, Cadmium Cd, Chromium Cr, Cobalt Co, Copper Cu, Iron Fe, Lead Pb, Lithium Li, Manganese Mn, Mercury Hg, Molybdenum Mo, Nickel Ni, Selenium Se, Silver Ag, Strontium Sr, Tin Sn, Titanium Ti, Vanadium V, Zinc Zn

Nutrients – Total Nitrogen (N-Ammonia, N-Oxidised, N-kjeldahl), Total Phosphorus (Ortho-phosphorus)

Cations – Sodium Na, Calcium Ca and Magnesium Mg

Chemicals[c] – Pesticides (suite of 37 organophosphate pesticides, 32 organochlorine pesticides including Aldrine, Chlordane, DDE, DDT and Lindane, 22 herbicides including Simazine, 13 synthetic pyrethroids and 17 unclassified pesticides).

[a] BOD_5: biological oxygen demand; TSS: total suspended solids; VSS: volatile suspended solids; TOC: total organic carbon; TDS: total dissolved solids.
[b] These metals are a standard suite of analysis and not all are of major concern. Underlined parameters were included in the NWQMS screening-level risk assessment.
[c] Chemical testing was restricted to road stormwater.

(e.g. Cabezas & McConnell 1999; Ruby *et al.* 2002; Eriksson *et al.* 2007), predominately focusing on the release of chemical compounds into the environment.

Based on a review of Australian (Vanderzalm *et al.* 2004; Waugh & Padovan 2004; Kemp & Kumar 2005; Hatt *et al.* 2006) and international studies (Makepeace *et al.* 1995; Lee 1998; Burton & Pitt 2001), the selected pollutants of concern in Table 1 were classed in the following groups: metals, nutrients and chemicals (specifically pesticides). Cations were also included as the application of irrigation water with a high sodium adsorption ratio (SAR) and low salinity can lead to poor soil structure and sodicity (Rengasamy & Olsson 1991). Other parameters that warrant consideration are pathogens, hydrocarbons, phenolics and anionic surfactants but were outside the scope and budget of an initial screening-level assessment.

Stormwater sampling

Details of the two sampling sites are presented in Table 2. The sewered residential subdivision is established with no disturbance by construction activity. A composite flow sampler (Brodie & Porter 2004) was used at the road site to obtain flow-weighted samples. An automatic sampler was installed at the stormwater pipe outlet of the residential subdivision and triggered by a flow depth sensor to collect a composite sample. A threshold 1 cm pipe flow depth was selected to initiate the sampling. Storms exceeding 1 mm rainfall, duration longer than 15 min and having an antecedent dry period longer than 20 h were targeted for data collection and analysis. Further details of sampling methods can be found in Khan (2009). Sample handling and processing was performed based on QEPA (1999).

The monitored storms had rainfalls that ranged from a few millimetres up to 35 mm. This covers the majority of rainfall events experienced in Toowoomba; based on long-term historical records (Bureau of Meteorology Station 041103, 1869–2007, www.bom.gov.au) 92% of raindays have totals less than 25 mm. Water balance analysis by Brodie (2011) also suggests that capture equivalent to impervious-surface runoff of 15 mm is a reasonable basis for stormwater harvesting in the Toowoomba region. The monitored storms are thus considered representative of those events that would be utilised for stormwater reuse.

Table 2 | Toowoomba stormwater sampling site characteristics

Feature	Road	Residential subdivision
Location	Clifford Street, inner city area	Robindale Drive, near university
Catchment area	450 m^2	12.2 ha
Land use	Secondary road (3,500 vehicles/day)	Low density residential (600 m^2 lots)
Drainage	Concrete curb, no pipe	Concrete curb to pipe system
Surfaces	100% roadway	11.5% roadway, 2.5% pavement, 30% roof, 46% grass/lawns, 10% open space/park
Sample events	Feb 2008 to Dec 2008, 8 storms	Jan 2009 to May 2009, 6 storms
Event rainfall	Rainfall 7.0–30.5 mm, duration 0.38–14.9 h, peak intensity 4.3–56.6 mm/h	Rainfall 2.4–35.4 mm, duration 0.17–20 h, peak intensity 1.2–153 mm/h

RESULTS AND DISCUSSION

Treatment characterisation

Results of sample analyses for treatment characteristics are compiled in Table 3 as log-normalised median values and the measured range. Several parameters can be compared with a stringent post-treatment quality target, in this case based on Class A recycled water suitable for irrigating public open space (QEPA 2005).

Salient points based on the measured data, with reference to expected untreated stormwater concentrations (from NWQMS 2009) are:

- Median road stormwater concentrations were higher than subdivision values with the exception of faecal coliforms, hardness and alkalinity.
- Faecal coliforms in road and subdivision stormwater were measured at relatively low concentrations and hence require disinfection rates of 0.6–2.2 log-reductions, respectively. Ultraviolet light is the most common disinfection treatment in Australia to treat stormwater (Hatt

Table 3 | Treatment characterisation for road and residential subdivision stormwater. Results are reported as median, minimum–maximum

Parameter[a]	Road	Residential subdivision	Class A target
Faecal coliforms (CFU/100 mL)	44, 1–250	1,650, 54–>5,000	Median <10 CFU/100 mL
BOD_5 (mg/L)	6, 2–29	2, 2–6	Median <20 mg/L
Turbidity (NTU)	82, 50–222	4.0, 1.9–26	Max <5 NTU
TSS (mg/L)	173, 71–460	6.5, 2–297	Median <5 mg/L
TDS (mg/L)	61, 2–150	3,1–48	Median <1,000 mg/L
pH	6.6, 5.7–6.8	6.85, 6.4–7.1	Range 6–8.5
VSS (mg/L)	76, 35–87	5.5, 2–73	–
TOC (mg/L)	10, 7–17	3.8, 2.5–12	–
Oils and grease (mg/L)	<10, <10–47	<10,<10–13	–
Hardness (mg/L)	13.5, 4–31	19, 12–103	–
Alkalinity (mg/L)	<20, <20–50	49, 30–116	–

[a]CFU: colony forming units; BOD_5: biological oxygen demand; TSS: total suspended solids; TDS: total dissolved solids; VSS: volatile suspended solids; TOC: total organic carbon.

et al. 2006) and is capable of readily achieving these reductions.

- Biological oxygen demand (BOD_5) and total dissolved solids (TDS) concentrations for both road and subdivision stormwater are low and no organic load or salinity reduction is required. No pH adjustment is generally required, except for a single road sample recording of 5.7. This outcome suggests that road runoff is slightly acidic, as documented by Duncan (1999), and pH adjustment may be occasionally required.
- Treatment to achieve water clarity is necessary, although less so for the subdivision stormwater. Requirements based on maximum turbidity are 98 and 80% for road and subdivision, respectively.
- The median volatile suspended solids/total suspended solids (VSS/TSS) ratio is 50% for subdivision stormwater, significantly higher than the median 25% determined for road runoff. A large proportion of suspended particles consisting of organic matter of low specific weight (typically 1.1, from Lawrence & Breen 1998) has design implications for treatment systems based on particle settling.
- Total organic carbon (TOC) is generally low, but any chlorine treatment design should allow for the possibility of disinfection byproducts, such as trihalomethanes, known to be carcinogenic.
- Oils and grease have a mode of treatment different to other pollutants. The low measured concentrations are unlikely to require specific unit processes or inhibit other treatment mechanisms.
- Hardness, expressed as $CaCO_3$ equivalent, was low and both stormwaters can be classed as ‘very soft’. No scaling problems associated with calcium build up are anticipated, but the low hardness may increase the corrosion potential to treatment and irrigation equipment. This may occur if hardness is less than 60 mg/L (NWQMS 2000), as is the case for measured hardness in the majority of runoff samples.
- Alkalinity is a measure of capacity to neutralise acids and represents the bicarbonate-carbonate character of the water. Because of its buffering effects, alkalinity is important in particle coagulation. Based on a classification system proposed by Pitt *et al.* (2002), which uses turbidity and alkalinity, the subdivision samples fall into a Class IV category. This is a ‘low’ turbidity (<10 NTU), ‘low’ alkalinity (<50 mg/L) water which is the most difficult water to coagulate. Addition of alkalinity or turbidity is expected if alum or ferric chloride is used. In comparison, the road samples are a Class II category of ‘high’ turbidity (>100 NTU), ‘low’ alkalinity (<50 mg/L) water which is relatively easy to coagulate. Cationic polymers are very effective, while anionic and non-ionic polymers may also be effective. Alkalinity may need to be added for alum or ferric chloride coagulation, if pH falls during treatment (<5 for alum, <6 for ferric chloride).

Pollutants of concern

The results of metal analyses are presented as a comparison plot (Figure 3) of measured stormwater ranges with the typical urban stormwater concentrations given in NWQMS (2009). A total of 12 metals were included by NWQMS in their screening of potential environmental risks of using untreated urban stormwater for irrigation. If the monitored stormwater quality is 'similar to or better than' the typical concentrations, then standardised treatment and risk management actions can be applied.

To be similar, it was assumed the mean ± one standard deviation of the measured concentrations would need to be approximately equal to or less than that of the NWQMS concentrations. This was the case for aluminium, cadmium, copper, chromium, lead and zinc for road stormwater. For subdivision runoff, all metals met the similarity test except for arsenic and mercury. Road stormwater concentrations of arsenic, barium, iron, manganese, mercury and nickel fail the similarity test and warrant closer evaluation:

- The limit of detection (LOD) for arsenic in the road runoff samples was 0.04 mg/L and all measured samples were below this LOD. The long-term trigger value (LTV) in irrigation water is 0.1 mg/L. The measured arsenic concentration in road runoff is below the LTV and thus

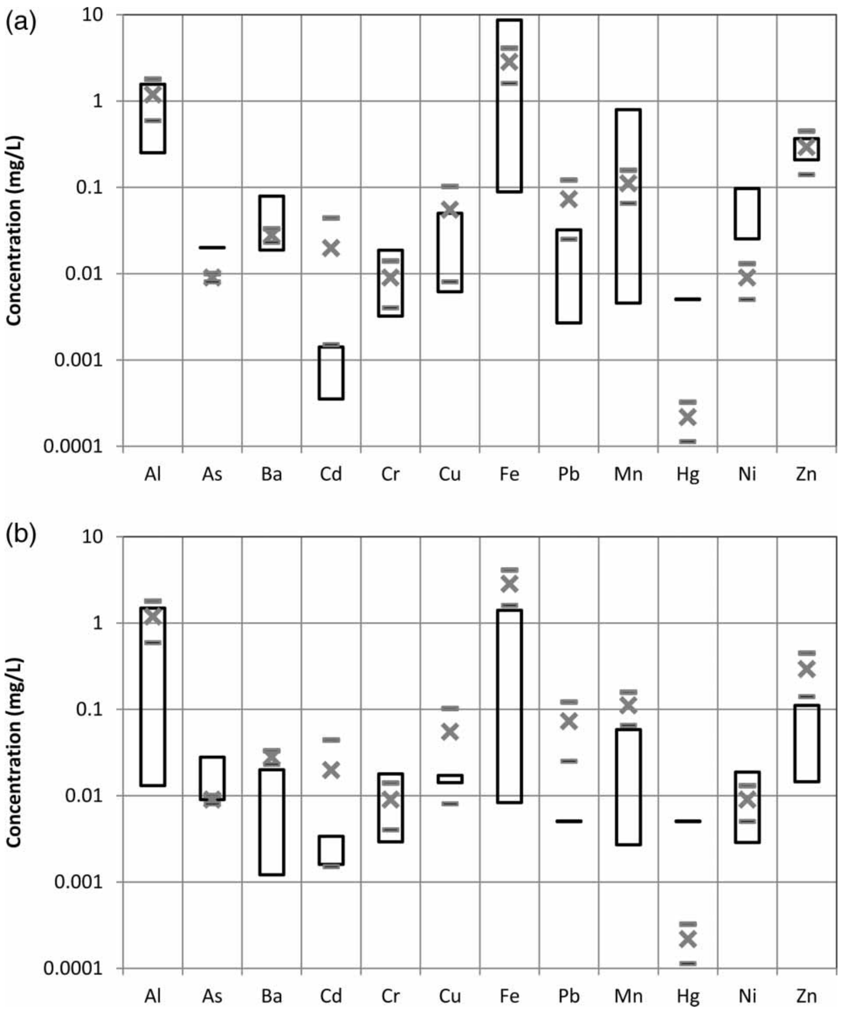

Figure 3 | Comparison of NWQMS nutrient screening levels (X = mean, — = ± 1 standard deviation) with measured ranges of (a) road and (b) residential stormwater concentrations (shown as boxes).

is considered to be within acceptable limits. (This was also the case for subdivision runoff.)

- Barium is not included on the list of metals in NWQMS (2000) having a LTV in irrigation water, so is assumed to be of no significant concern.
- Iron was identified by the NWQMS screening-level assessment as a potential key environmental hazard of irrigating with stormwater. The measured iron concentrations measured in the road runoff fell in a wide range from 0.05 to 7.8 mg/L. The upper end of the measured iron concentrations exceed the LTV for irrigation water (0.2 mg/L), but is lower than the short-term trigger value (STV, 10 mg/L). This means that there is a medium risk of iron clogging irrigation systems in the medium term (i.e. when the system is operated for longer than 20 years).
- Manganese can also precipitate out to clog irrigation equipment and can cause the formation of black bacterial slime which also reduces the efficiency of water application. The measured road runoff quality for manganese ranged from <0.0025 to 0.35 mg/L. The irrigation water targets are the same as iron (LTV= 0.2 mg/L, STV= 10 mg/L). As the manganese concentrations in the raw stormwater are comparatively low, the risk of clogging by bacterial slime build up is considered to be small.
- The LOD for mercury was 0.01 mg/L and all samples exhibited concentrations below this limit. Due to this accuracy limitation, it cannot be stated definitively that the measured concentrations were above the typical concentrations reported in NWQMS (2009).
- Measured nickel concentrations in road runoff are consistently higher than the adopted NWQMS values. However, the maximum measured nickel concentration (0.1 mg/L) is below the LTV in irrigation water (0.2 mg/L) and is thus considered to be within acceptable limits.

A similar comparison can be performed for the nutrients included in the NWQMS screening analysis. Selected nutrient concentrations for the measured stormwater and adopted NWQMS statistics are presented in Figure 4. Based on the similarity test, the measured road and subdivision runoff were 'similar to or better than' the adopted NWQMS raw stormwater concentrations and thus the nutrient load is generally considered to be a low irrigation hazard. Median nutrient concentrations in road stormwater were above the subdivision values.

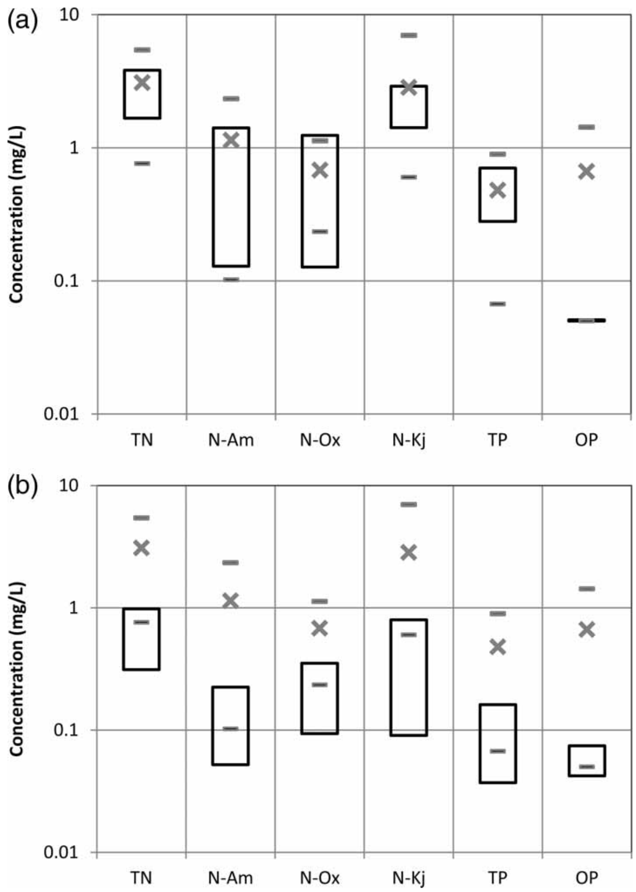

Figure 4 | Comparison of NWQMS metal screening levels (X = mean, – = ± 1 standard deviation) with measured ranges of (a) road and (b) residential stormwater concentrations (shown as boxes).

Some metals were not included in the NWQMS screening evaluation but were included in the analytical suite. In this case, the measured metal statistics of the stormwater samples were compared with their respective LTV in irrigation water (Figure 5). For the prescribed metals having LTVs, the measured runoff concentrations are below these LTVs and hence are within acceptable limits. No LTV values are assigned for antimony, silver, strontium, tin and titanium, so it is assumed that these metals are not of significant concern. With the exceptions of beryllium, strontium and cadmium, the median metal concentrations in road stormwater samples were above the subdivision concentrations.

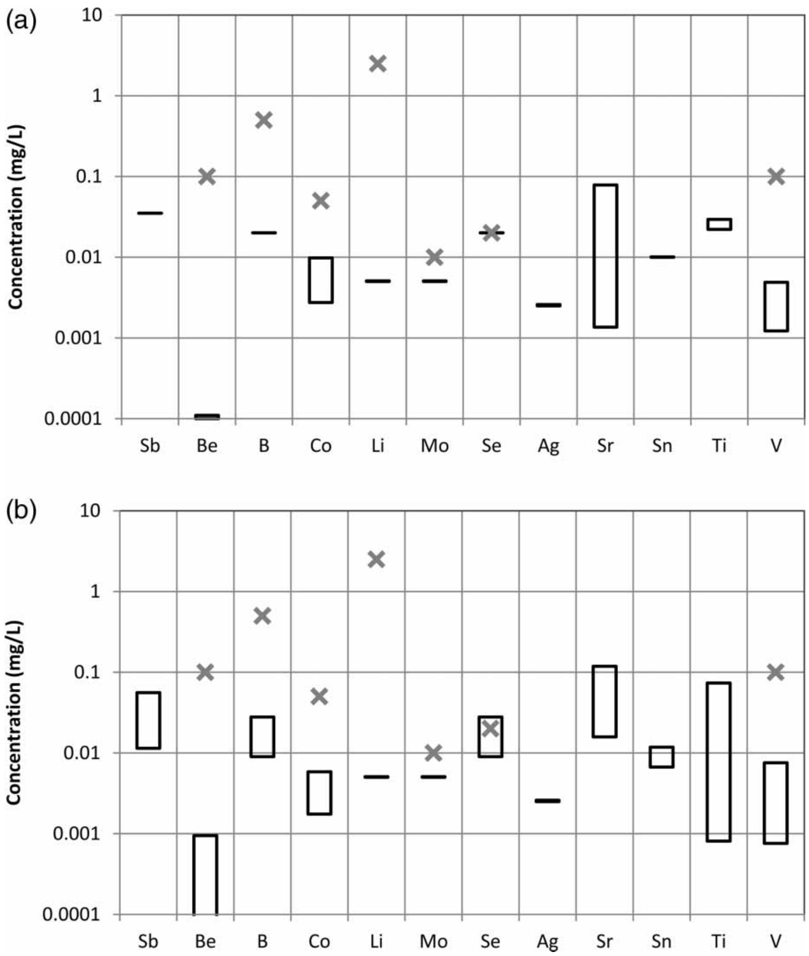

Figure 5 | Comparison of non-NWQMS screening metals based on long-term trigger value for irrigation water (shown as **x**) with measured ranges of (a) road and (b) residential stormwater concentrations (shown as boxes).

The cations sodium, calcium and magnesium are also included as pollutants of concern (Table 1) due to their potential for soil degradation. The relative concentration of sodium to calcium and magnesium incorporated as the SAR is an indicator of this risk. This ratio, ranging from 0.2 to 0.45 and 0.2 to 0.85 for road and subdivision runoff, respectively is within acceptable limits (QDERM 2011).

Due to cost constraints, pesticide analysis was conducted of road samples for three storms only (26/02/2008, 18/03/2008 and 27/03/2008). All of the 121 pesticide compounds tested were at concentrations less than their LOD (typically 0.0001 mg/L) except for Simazine (0.0001–0.002 mg/L) and Hexazinone (0.0001–0.0011 mg/L). Simazine is a triazine herbicide used to control broad-leaved weeds and remains active in the soil for up to 7 months after application. It is linked to cancers and human endocrine disorders and is banned in the European Union. Hexazinone is also a triazine herbicide used for the control of some grasses, broadleaf weeds and some woody species, by inhibiting photosynthesis. It is relatively persistent in soils with a mean half-life of 90 days, but is water-soluble and can contaminate groundwater and surface waters (Tu *et al.* 2001).

In the absence of specific trigger values for stormwater harvesting, the more stringent Australian drinking water guidelines (NHMRC and NRMMC 2004) were used to evaluate the pesticide contamination in the collected samples. Guideline limits for pesticides are based on the analytical LOD, which for Simazine and Hexazinone has been set at 0.0005 and 0.002 mg/L, respectively. The measured concentrations in the road runoff samples were below these guideline values and are thus within acceptable limits.

CONCLUSIONS

Stormwater treatment requirements were assessed by monitoring at two urban spatial scales: a lot-scale road surface and a low-density residential subdivision. Based on the faecal coliform indicator, disinfection is needed but the requirement for road runoff disinfection is less than that for the subdivision runoff. No BOD_5 or salinity (TDS) treatment is required and pH adjustment is anticipated to be an occasional requirement for road runoff only. The treatment targets are based on a non-potable use assuming unrestricted spray irrigation.

Hardness of the road and urban residential stormwater was rated 'very soft' (calcium carbonate <60 mg/L). This is a low hardness, which may increase the corrosion potential to treatment and irrigation equipment. The high turbidity and low alkalinity of the road runoff makes it relatively easy to treat with coagulants. The lower turbidity of the residential area runoff makes it a more difficult raw water to coagulate and addition of alkalinity or turbidity may be required. The proportion of low-density organic particles was greater in the residential runoff (median 50%) than the road runoff (median 25%) and this has implications to the particle removal efficiency of treatment systems based on settling.

It was found from a screening-level risk assessment that for road runoff, there is a medium risk of clogging by iron deposition within irrigation systems in the medium term (20 years' operation). The risk of soil degradation, as indicated by the SAR was found to be low in both road and subdivision stormwater. Median nutrient concentrations in road stormwater exceeded subdivision concentrations, but represent a low irrigation hazard. This outcome was also generally the case for metal concentrations.

Pesticide analyses were conducted on the road runoff (three samples) and of the 121 pesticide compounds tested, all except Simazine and Hexazinone were below their limit of detection. Although at detectable concentrations, the presence of these pesticides in the water samples was within Australian drinking water guidelines.

ACKNOWLEDGEMENTS

The author acknowledges the valuable assistance of Toowoomba Regional Council and Ipswich Water for provision of funding and sample analysis.

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First received 5 December 2011; accepted in revised form 23 February 2012