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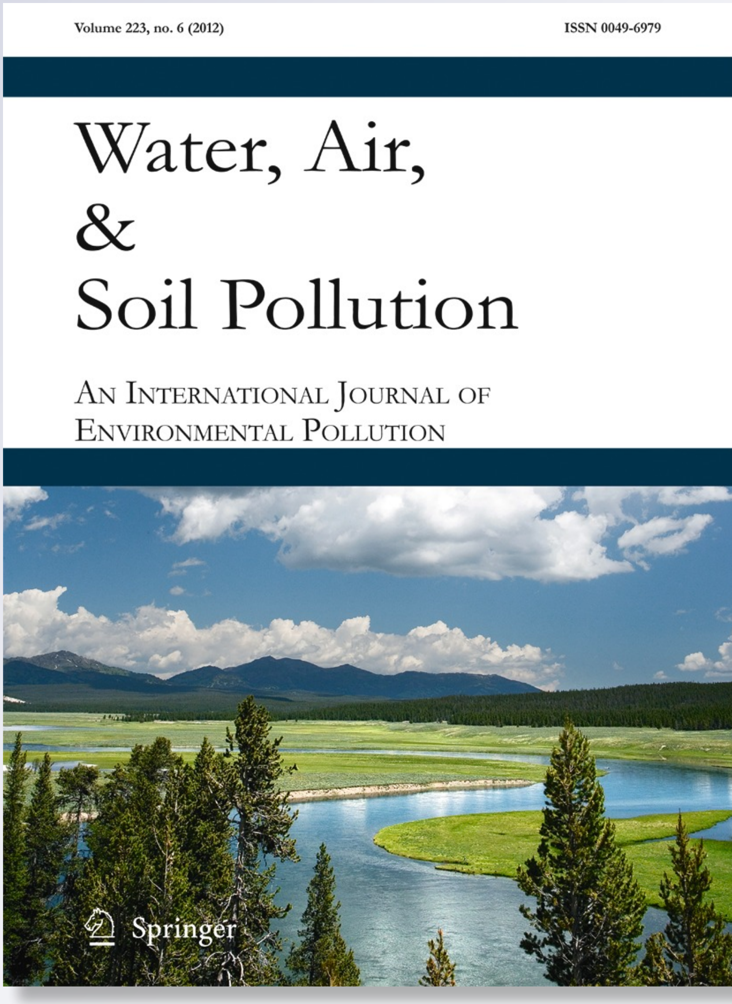

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Is Catchment Imperviousness a Keystone Factor Degrading Urban Waterways? A Case Study from a Partly Urbanised Catchment (Georges River, South-Eastern Australia)

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Abstract The extent of catchment impervious surface is recognised to be an important factor associated with the condition of urban freshwater streams. We tested the hypothesis that the degree of catchment imperviousness predicted the relative ecological condition of freshwater reaches within the network of streams and rivers in the partly urbanised Georges River catchment in temperate south-eastern Australia. The 2-year study involved two spring and two autumn assessments of water quality (chemical and physical) and ecological condition, using benthic macroinvertebrates, riparian vegetation and calculation of catchment imperviousness. The study revealed that highly urbanised streams had strongly degraded water quality and macroinvertebrate communities, compared to clean non-urban reference streams. We found three clear groups of sites with varying degrees of ecological condition, being categorised according to the level of catchment effective imperviousness (low <5.0 %, moderate = 5.0–18.0 % and high >18.0 %). Water pollution also varied according to these categories. A combination of two water chemistry attributes (total nitrogen and calcium), along with catchment imperviousness and riparian vegetation condition, were identified as being the factors most strongly associated with variation of macroinvertebrate communities. Based on our results, we recommend that protection of the ecological condition of streams should focus on not only water quality but also include catchment imperviousness and riparian vegetation condition.

Keywords Urban stream syndrome · Urban waterways · Aquatic macroinvertebrates · Water pollution · Imperviousness

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1 Introduction

The global trend towards greater urbanisation of the world's population is accelerating (Cohen 2003), and associated with this is an increase in the incidence and severity of urban environmental problems (e.g. McKinney 2006). The adverse impact of urbanisation on the 'health' of freshwater streams and rivers is just one consequence of the growing pressure that urban development has on the conservation of the natural environment. Studies have documented the decline of water quality in urban streams, particularly after heavy rain (e.g. Lee et al. 2002) when degradation to water quality typically occurs due to increased sediment loads, reduced light transmission, contamination by toxicants

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and nutrient enrichment that often leads to eutrophication (Walsh et al. 2004, 2005a, b). Walsh et al. (2001) studied aquatic invertebrates and water quality in urban and non-urban streams in the Melbourne area (south-eastern Australia) and found that communities of aquatic biota within degraded urban streams had reduced abundance (or absence) of pollution-sensitive species, increased abundance of pollution-tolerant species and a proliferation of invasive species when compared with clean non-urban reference sites. Similar findings have been made internationally. For example, a study of 30 streams in Georgia, USA, by Roy et al. (2003) established that the degree of urban land cover is linked to a negative macroinvertebrate response (reduced taxonomic richness).

Paul and Meyer (2001) used the phrase '*urban stream syndrome*' to describe the multiple networks of environmental problems which typify the degradation of urban streams. Central to the urban stream syndrome is the extensive modification of urban stream hydrology and increased frequency of small to medium high-energy surges of storm runoff (Booth and Jackson 1997). This, in turn, is related to changes in stream channel habitat and water quality (Gregory et al. 1992; Beavan et al. 2001). The widespread use of impermeable surfaces in urban catchments (e.g. Dunn and Leopold 1978; Walsh et al. 2001; Hatt et al. 2004), combined with highly engineered stormwater infrastructure, ensures that, instead of infiltrating catchment soils, as happens in natural catchments, runoff in most urban areas is quickly directed into the local urban stream. The extent to which this occurs is termed the 'imperviousness percent' of a catchment (Walsh et al. 2004). Rainfall in an urban catchment with a high level of imperviousness from widespread impermeable surfaces (such as roads and roofs) can quickly generate a high-energy inflow of stormwater into the catchment stream. This causes a multitude of negative physical and chemical changes to the stream habitat, such as channel scouring, pool infilling, elevated nutrient and sediment loads and altered flow regimes (Paul and Meyer 2001).

Although Paul and Meyer (2001) suggest a level of 10 % or higher levels of imperviousness mark the onset of symptoms of the urban stream syndrome, other research points towards considerably lower levels. For example, Walsh et al. (2007) found that an impervious cover of 4 % and higher was a threshold at which fewer sensitive macroinvertebrate groups were collected in Melbourne (Yarra River catchment). Similarly, Stranko et al. (2008) reported an identical level of urban land coverage (i.e. 4 % impervious cover) where, at higher levels, Brook trout (*Salvelinus fontinalis*) is rarely found in Maryland streams. A study of macroinvertebrates in a number of different US study areas (Cuffney et al. 2005) took a different approach. They deliberately declined to nominate a level at which urban development began to have an adverse effect: 'Our data provided no evidence to suggest that there is a level of urban intensity that has no effect on invertebrate assemblages' (Cuffney et al. 2005).

Another facet of the poor environmental condition of urban waterways, outlined in the urban stream syndrome, is the degradation of stream channel and riparian vegetation. Increased intensification of urban land use has been associated with significant deterioration to stream channels and riparian vegetation (Lake and Leishman 2004; White and Greer 2004), the condition of which has been linked to the health of stream ecosystems. The function of stream channel and riparian vegetation often moderates the stream environment from unnatural changes in temperature, nutrients, sediment and flow regimes as well as providing food and habitat resources for aquatic life (Hession et al. 2000).

Stream biota (e.g. microbes, algae, macrophytes, invertebrates and fish) are often used to measure the degree of impairment of stream ecosystems due to urbanisation (Jones and Clarke 1987; Paul and Meyer 2001; Walsh et al. 2001; Chessman 2003a, b; Morgan and Cushman 2005). Freshwater macroinvertebrates are widely adopted as sensitive and effective indicators of the ecological condition of freshwater ecosystems (Beavan et al. 2001; Paul and Meyer 2001; Walsh et al. 2001). Identification of macroinvertebrates to the family and order level has been demonstrated to generate sufficient information for impact identification (Wright et al. 1995). Although less detailed information is provided, order-level identification has the additional advantage of being quick and easily performed by non-specialists, with a modest degree of instruction.

The primary objective of this study was to test whether the degree of catchment imperviousness was a key factor that was strongly associated with the ecological condition of freshwater invertebrate communities within a network of streams flowing within a partly urbanised and partly naturally vegetated catchment. We predicted

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that the level of catchment imperviousness was a keystone factor that influenced water quality and stream ecological condition. We also sought to determine which water quality and other environmental attributes were most closely associated with variation of stream ecological condition. To achieve these objectives, we sampled stream macroinvertebrates, water samples and catchment attributes over 2 years from a diverse range of freshwater waterways in urban and naturally vegetated catchments of differing levels of imperviousness across the Georges River catchment located in the south-west Sydney region of NSW, Australia.

2 Materials and Methods

2.1 Study Area

Located in south-western Sydney, the Georges River catchment covers an area of approximately 960 km^2 and holds a residential population of some 1.2 million people, making it one of the most highly urbanised catchments in Australia (SMCMA 2012). Although urban land use is widespread throughout the catchment, there are less extensive areas of industrial, agricultural, mining, and military lands. Approximately 45 % of the catchment contains large tracts of natural bushland (SMCMA 2012). The catchment is divided into two broad soil types: Wianamatta Shale in the western portion and Hawkesbury Sandstone in southern, northern and eastern catchments (Fig. 1). Land form typical of the Wianamatta Shale portion of the catchment is typically flat to undulating with incised creek lines. In contrast, the Hawkesbury Sandstone portion of the catchment is typified by flat ridge tops and deeply incised, steep and rocky gullies, which has limited urban development to ridge tops areas. The majority of the waterways flow within sandstone geology, with shale soils dominating the higher catchment elevations in the east and northern margins of the Georges catchment (Fig. 1).

2.2 Sampling Methods

Four sampling campaigns were undertaken during spring 2009, autumn 2010, spring 2010 and autumn 2011 in dry weather conditions at 31 freshwater monitoring sites spread across 22 waterways within the Georges River catchment (Fig. 2). Due to the remote and inaccessible nature of a large portion of the waterways within the catchment, site selection was based on the combination of accessibility and the need to be representative of the spectrum of land use and physical catchment and waterways across the catchment. Once this criterion was satisfied, the location of study sites was selected to represent the first-order headwater streams to lowland rivers. The exact location of sampling was randomised within each study site (a waterway 'reach' of about 100-m length). After sample sites were selected, the catchment imperviousness of each sampling site was calculated, and the site was 'grouped' according to the following categories. Thresholds for the categories of catchment imperviousness [percentage of effective imperviousness (% EI)] were defined as low, medium or high (low <5.0 %; moderate = 5.0–18 %; high >18.0 %). There were 8 sites in the 'low' category, 9 in 'medium' and 14 in 'high' (Fig. 2).

Catchment imperviousness was quantified using Environmental Systems Research Institute Arc-Map version 9.3.1 with sub-catchments delineated using 10 m contours. An impervious/pervious layer developed using remote sensing of Satellite Pour l'Observation de la Terre imagery on a 10×10 m grid was clipped by the digitised sub-catchment layer. Sub-catchment pervious/impervious areas were totalled, allowing the percentage of impervious surface to be calculated. It was assumed that all impervious surfaces were 'effective'. The degree of sub-catchment modification was determined using the percentage of 'effective imperviousness' calculated for the catchment of each sampling site.

Macroinvertebrate samples were collected according to the Australian National River Health Program protocols (DEST et al. 1994; Chessman 1995, 2003b). This involved collection using a 'kick' net, with 250-µ mesh and square 30×30 cm net frame (Chessman 1995) to survey pool, edge and riffle habitat. Pool, edge and riffle sub-samples were combined into one homogenised sample to be representative of each study site. A total of 10 m of stream habitat was sampled within a 100 m section of each site. Samples were live picked in the field on a sorting tray for 30 min using forceps and pipettes, and animals were identified in the field to order level with exception of Collembola, Nematoda and Oligochaeta which were identified to class using ×30 magnification hand lenses and the recommended Australian taxonomic keys of Hawking and Smith (1997) and Gooderham and Tsyrlin (2002). The aim was to

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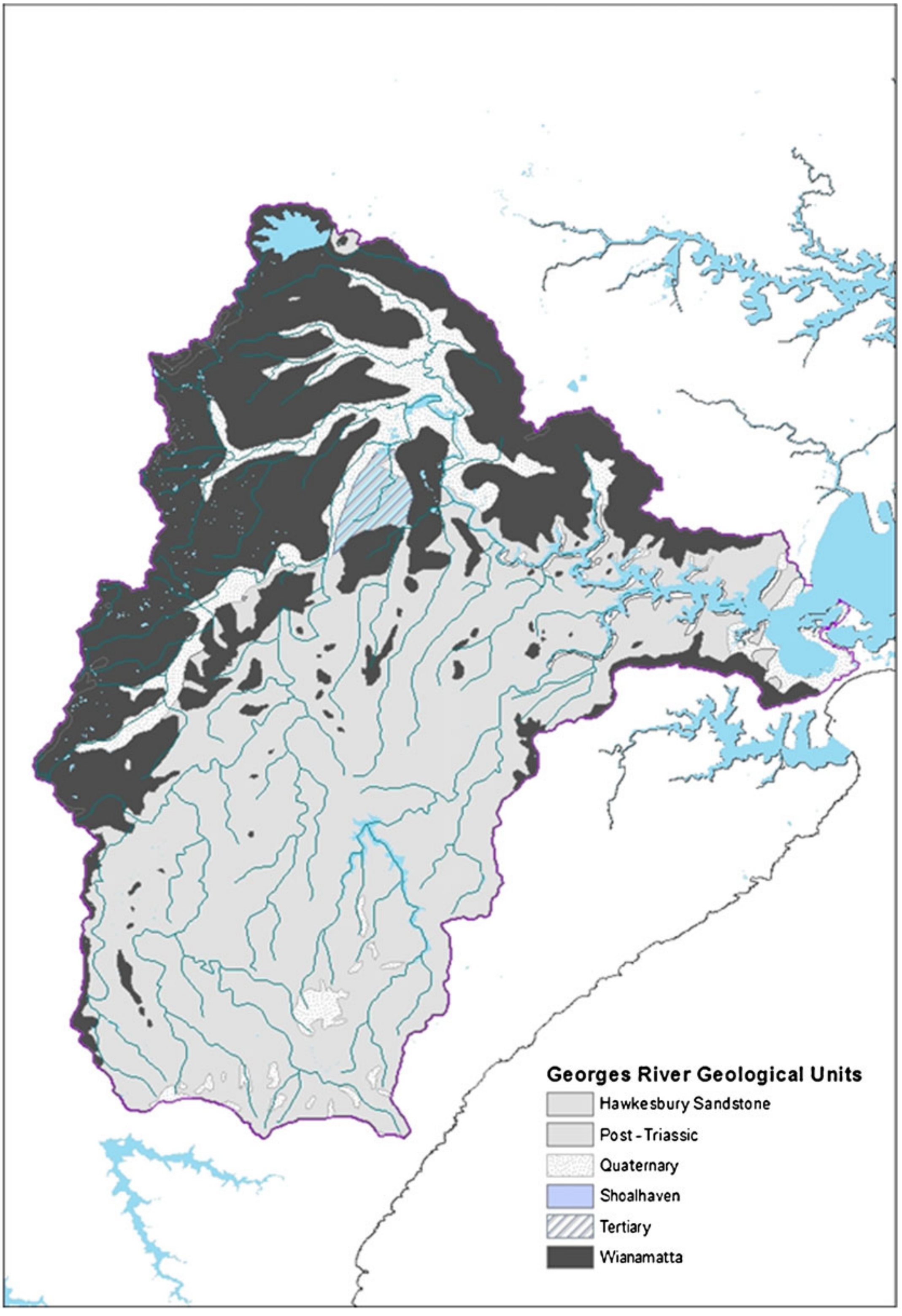

Fig. 1 Georges River catchment geology, south-western Sydney, NSW

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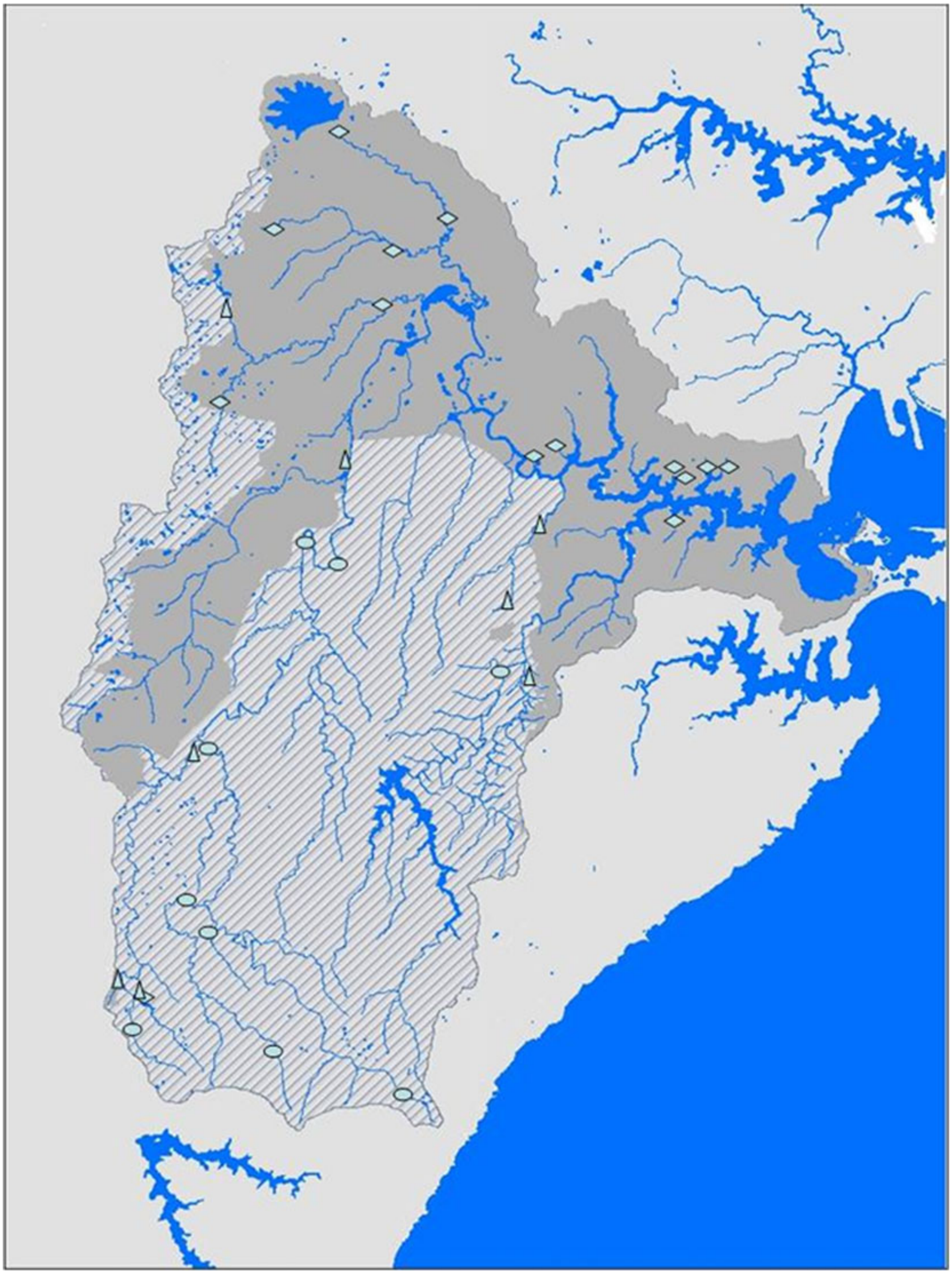

Fig. 2 Sample sites and urban/non-urban areas of the Georges River catchment. *Grey* = urbanised area, *Crosshatching* = non-urban area, *diamonds* = high percentage of EI, *triangles* = moderate percentage of EI, *circles* = low percentage of EI

maximise taxon richness, using the rapid assessment 'SIGNAL' approach developed by Chessman (1995). Order-level identification of freshwater macroinvertebrates has been demonstrated to be suitable for detecting major water pollution impacts (e.g. Wright et al. 1995; Bowman and Bailey 1997).

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Four macroinvertebrate biotic indices were calculated for each macroinvertebrate sample: percentage of Ephemeroptera, Plecoptera and Trichoptera (EPT) (Cairns and Pratt 1993), taxonomic richness (Rosenberg and Resh 1993), Shannon index (Krebs 1989) and order-level SIGNAL 2 scores (Chessman 2003b).

In conjunction with macroinvertebrate sampling, a calibrated TPS 90FLMV field meter was used to measure the water quality attributes of electrical conductivity (EC), dissolved oxygen percentage saturation (DO %), turbidity (TU) and pH. In addition, grab samples were collected for laboratory assessment of total nitrogen (TN), total Kjeldahl nitrogen (TKN), oxidised nitrogen (NOx-N), total phosphorus (TP), total alkalinity (Alk), carbonate (CO_3), bicarbonate (HCO_3) and hydroxide (OH). Additionally, calcium (Ca), chloride (Cl), sodium (Na), magnesium (Mg), potassium (K) and sulphate (SO_4) were analysed from autumn 2010 onwards (i.e. three of four sampling occasions). Samples were analysed using standard methods (APHA 1998) by a commercial National Associations of Testing Authorities accredited laboratory.

The ecological condition of stream channel and riparian vegetation condition was surveyed at each monitoring site in spring 2009 using the 'Rapid Appraisal of Riparian Condition' (RARC) Version 2 (Jansen et al. 2004). The RARC method uses a suite of 15 indicators of riparian condition divided into sub-indexed categories that reflect the functional aspects of the physical vegetation community and landscape features of the riparian zone (Jansen et al. 2004). Due to the variability of access to survey sites, a standardised approach was taken, whereby a maximum of 100 m of stream bank with four transects at right angles to the channel were surveyed. Each transect was limited to a maximum of 40 m.

2.3 Data Analysis

A one-factor analysis of variance (ANOVA) was used to investigate whether macroinvertebrate biotic indices (SIGNAL 2, percentage of EPT (% EPT), richness and Shannon index) varied according to imperviousness category (low, medium or high). Multivariate analysis was used to assess and compare the macroinvertebrate community response to catchment and waterway disturbance. Multivariate analysis has been demonstrated to be a powerful and useful approach to evaluate the ecological condition of macroinvertebrates exposed to freshwater pollution (e.g. Marchant et al. 1994; Wright et al. 1995). Non-metric multidimensional scaling (NMDS) was performed on a similarity matrix that was calculated with cube root-transformed macroinvertebrate data, using the Bray–Curtis dissimilarity measure (Clarke 1993; Warwick 1993). Two-dimensional ordination plots were generated to give a representation of the dissimilarity among samples. Data were grouped by degree of catchment imperviousness (high, medium and low) to test for macroinvertebrate assemblage differences by two-way analysis of similarity (ANOSIM) (Clarke 1993), with season of sampling (spring and autumn) the second factor. In the ordinations, the influence of particular families to ecological differences between imperviousness groups was quantified using the similarity percentage procedure.

The BIOENV procedure (Clarke and Ainsworth 1993) was used to assess pH (variable 1), EC (variable 2), DO percent (variable 3), NOx-N (variable 4), TU (variable 5), TKN (variable 6), TN (variable 7), TP (variable 8), Alk (variable 9), CO_3^{2-} (variable 10), HCO_3^{-} (variable 11), SO_4^{2-} (variable 12), Cl (variable 13), Ca (variable 14), Mg (variable 15), Na (variable 16), K (variable 17), riparian habitat quality (RARC; variable 18) and catchment percentage of EI (variable 19) and to determine which variables were most highly correlated with variations of Georges River catchment macroinvertebrate assemblages. The multivariate analyses were achieved using the software package PRIMER version 5 (Clarke 1993). One-way ANOVA was conducted to test whether variation of catchment or water quality attributes (as identified by the BIOENV procedure as being highly correlated with invertebrate assemblages) existed between imperviousness categories (low, moderate or high).

3 Results

A total of 16,431 freshwater macroinvertebrates from 19 taxonomic groups (generally orders) were collected in the 2-year study. Diptera was the most widely detected and abundant group with 1,128 (14.6 % of the total abundance), then Odonata with 1,054 (13.6 %) and Hemiptera with 884 (11.4 %). The majority (64.1 %) of invertebrates detected were insects. A total of 1,394 (18.0 %) invertebrates were collected from the sensitive EPT orders.

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All biotic indices (richness, percentage of EPT, Shannon index and SIGNAL 2) varied highly significantly according to the category of catchment percentage of EI (Table 1). The mean level of each index was highest at the lowest category of catchment imperviousness (< 5.0 % EI) and was lowest at the highest category of catchment imperviousness (>18.0 % EI; Fig. 3).

Multivariate analysis revealed that the order-level macroinvertebrate community structure of Georges' catchment stream samples varied highly significantly according to the classification of catchment imperviousness (high, moderate or low percentage of EI). The two-dimensional NMDS ordination showed that the low (<5.0 %) EI sites clustered discretely and separately from the moderate (5.0–18.0 %) and high (>18.0 %) EI sites, with minor overlap (Fig. 4a). ANOSIM confirmed the significance of the ecological differences apparent in macroinvertebrate communities between the three categories EI (global $R=0.411$, $p<0.001$). Season of sampling (Fig. 3b) was not associated with any ecological differences (global $R=-0.005$, $p=0.57$). Pairwise ANOSIM comparison of communities between each class of waterway

Table 1 Factors associated with Georges River macroinvertebrate assemblages (according to BIOENV analysis), catchment and riparian habitat and water chemistry ANOVA results (F values, probabilities and degrees of freedom) and summary statistics (range and mean) from streams grouped according to level of disturbance (low, medium or high) in freshwater reaches of Georges River catchment waterways sampled in October–November (spring) 2009 and April–May (autumn) 2010 and October–November (spring 2010) and April–May (autumn 2011)

Source of variation	F value (p), degrees of freedom	Level of waterway and catchment disturbance					
		High		Medium		Low	
		Range	Mean	Range	Mean	Range	Mean
Biotic indices							
SIGNAL 2	158.8 (***) 2,120	1.7–5.0	2.7	3.0–5.3	4.1	4.2–6.5	5.1
EPT (%)	128.8 (***) 2,120	0–20.3	2.3	0–48.5	15.7	7.3–62.8	33.0
Richness	54.3 (***) 2,120	2–12	7.1	6–14	10.3	6–14	10.8
Shannon	22.0 (***) 2,120	0.4–2.1	1.4	0.9–2.2	1.7	0.7–2.2	1.8
Catchment and riparian habitat							
RARC score	17.3 (***) 2,28	14.5–37	23.6	29.7–40.5	35.7	30.5–43	37.1
Sub-catchment effective impervious (% EI)	45.0 (***) 2,28	19.1–70.7	45.7	6.2–18.4	12.4	0–3.26	1.5
Water Quality							
pH (pH units)	36.3 (***) 2,120	5.97–8.99	7.52	5.85–8.85	7.64	4.07–7.78	6.11
Salinity (µs/cm)	13.7 (***) 2,120	108–3,310	825	101–2,680	874	68–370	163
Dissolved oxygen (% saturation)	18.4 (***) 2,120	0–122.5	60.7	53.7–132.3	84.0	55.5–124	86.5
Total phosphorus (µg/L)	12.2 (***) 2,120	5–940	150	5–210	42.5	5–215	39
Total nitrogen (µg/L)	24.1 (***) 2,120	200–6,900	1240	50–1,800	532	50–400	196
Oxidised nitrogen (µg/L)	3.9 (*) 2,120	5–1,790	351	5–5,400	362	5–500	41.2
Total Kjeldahl nitrogen (µg/L)	15.8 (***) 2,120	5–6,900	925	0–800	325	50–400	180
Turbidity (NTU)	3.5 (*) 2,120	0.05–485.3	31.1	0.05–45.3	8.0	0.05–50.9	3.59
Alkalinity (mg/L)	7.9 (**) 2,89	22–876	143.7	12–865	226.1	0.5–106	17.3
Bicarbonate (mg/L	5.8 (*) 2,59	22–872	130	12–586	222.4	0.5–64	13.7
Chloride (mg/L)	4.6 (*) 2,59	5–699	119.3	5–165	81.5	23–65	35.8
Sulphate (mg/L)	18.2 (***) 2,59	2–71	25.6	5–23	14.5	2–19	6.2
Calcium (mg/L)	37.8 (***) 2,59	4–58	20.0	3–25	8.1	0.5–12	2.2
Potassium (mg/L)	19.2 (***) 2,59	1–7	3.8	1–6	2.9	0.5–3	1.25
Magnesium (mg/L)	8.0 (**) 2,59	1–49	9.6	1–8	3.4	1–5	2.9

*$p<0.05$; **$p<0.001$; ***$p<0.0001$

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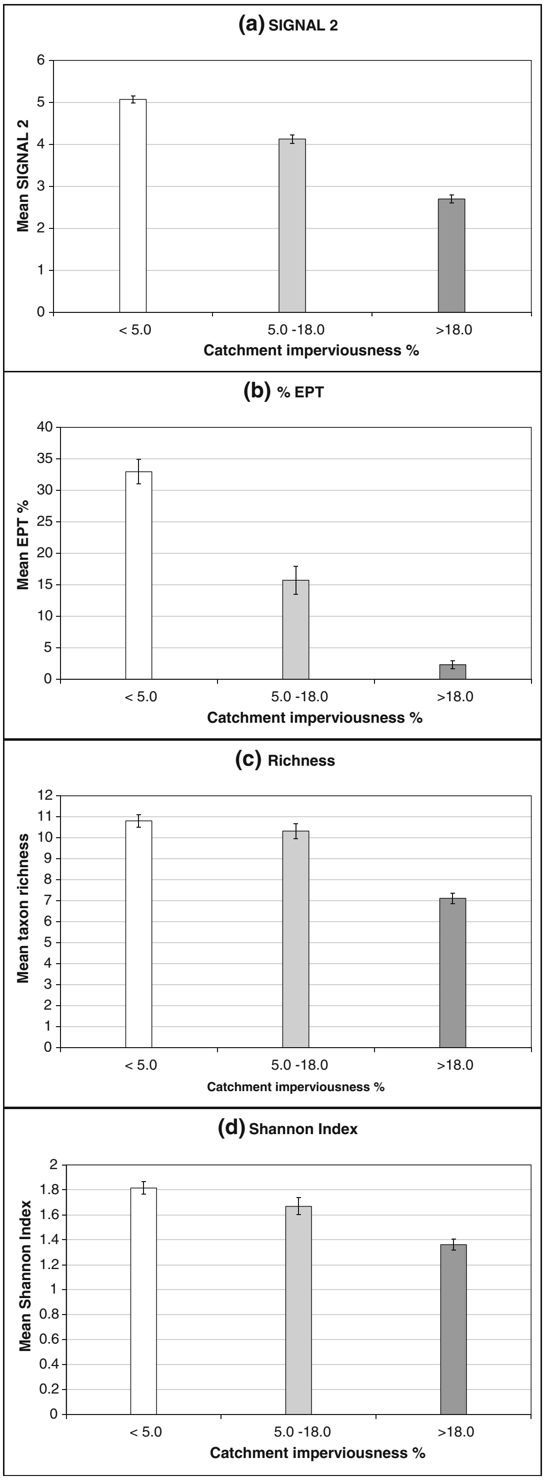

Fig. 3 Mean (±SEM) biotic index results (**a** SIGNAL 2; **b** percentage of EPT; **c** Richness; **d** Shannon) from macroinvertebrate samples collected from the Georges River catchment (2009–2011). Categories according to the percentage of catchment imperviousness (<5; 5–18; >18)

disturbance confirmed that the largest ecological difference was detected between low and high catchment EI sites (R statistic=0.642, p<0.001). The next largest difference was between high and moderate catchment EI sites (R statistic=0. 338, p <0.001). The ecological differences were lesser, but still significant between the moderate and low catchment EI sites (R statistic=0.283, p< 0.001).

Significant differences between riparian and channel vegetation condition was found to exist across the three disturbance categories (Table 1) with the lowest RARC scores recorded at high EI sites (mean = 23.6) followed by moderate EI sites (mean = 35.7). The highest RARC scores were recorded at low EI sites (mean = 37.1; Table 1).

Major differences were evident between the water chemistry of the three groups of stream imperviousness categories (Table 1). Low impervious streams were generally acidic (mean pH 6.11). The higher impervious streams were generally alkaline (mean pH 7.52 and 7.64). The mean electrical conductivity of medium and high impervious (mean = 874 and 825 µs/cm) was more than four times as high as that recorded for low impervious streams (mean = 194 µs/cm) (Table 1). Nutrient levels were generally progressively higher at streams of higher imperviousness (Table 1). Total phosphorus concentrations were similar at low and medium impervious streams (mean = 39 and 42.5 µg/L) compared to high impervious streams (mean = 150 µg/L). Mean total nitrogen levels were more closely associated with the level of imperviousness (high = 1,240 µg/L, medium = 532 and low = 196).

For all ionic attributes, mean levels were significantly higher at medium and high EI streams (Table 1). Calcium and bicarbonate levels showed the greatest differences between the lowest and the two groups of higher EI streams (Fig. 1). Mean calcium concentrations were more than nine times higher in highest EI streams (mean 2.2 and 20 mg/L) than in lowest EI streams (mean 2.2 mg/L). Bicarbonate levels were more than 9.5 times greater in medium EI streams (mean 222 mg/L) than low EI streams (mean 13.7 mg/L; Table 1).

BIOENV analysis revealed that the most important combination of factors associated with variation in macroinvertebrate assemblages in the Georges River

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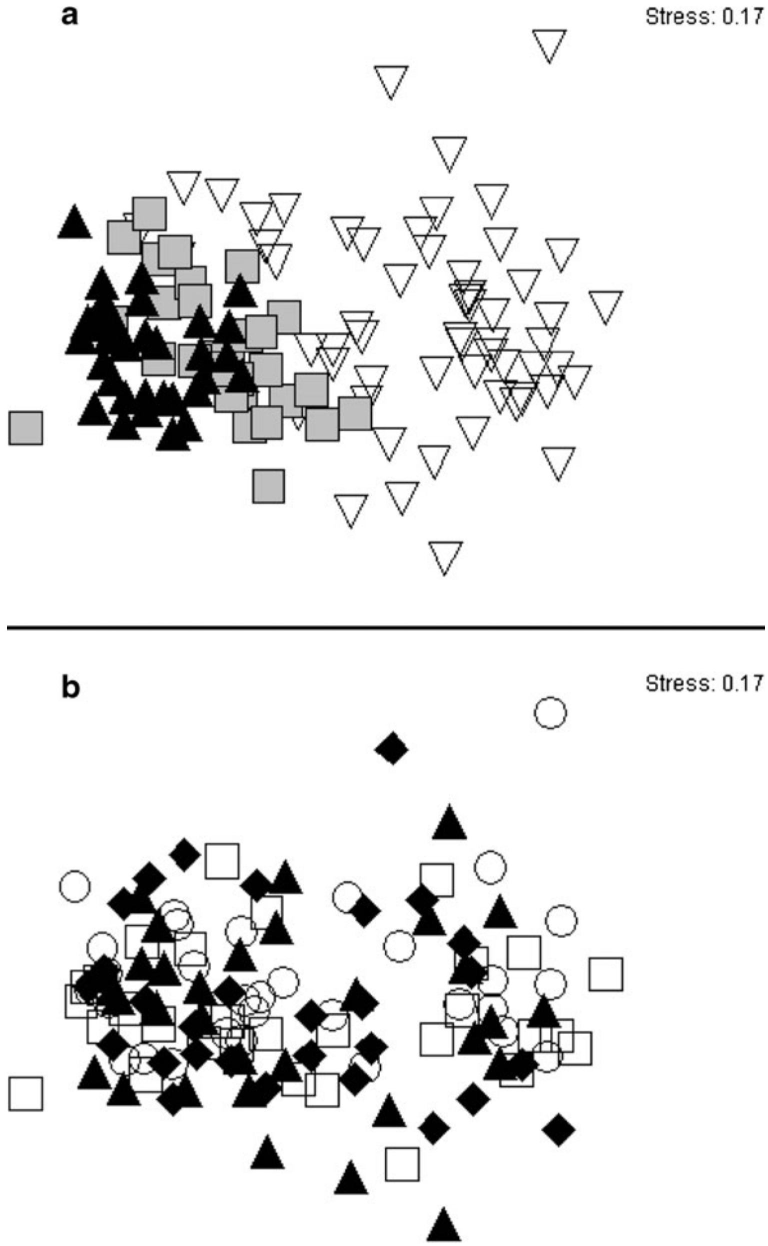

Fig. 4 NMDS two-dimensional ordination of macroinvertebrate communities samples collected from the Georges River (2009–2011). (*Top*) samples categorised according to catchment imperviousness (low = *black triangles*; moderate = *grey squares*; high = *unshaded triangles*). (*Bottom*) samples categorised according to sampling period (Spring 2009 = *unshaded circles*; autumn 2010 = *black diamonds*; spring 2010 = *unshaded squares*; autumn 2011 = *black triangles*)

catchment study were the four factor combinations of riparian habitat condition (RARC), catchment EI, TN and Ca (Table 2).

Other influential factors identified by BIOENV analysis were Cl, Mg, TU, TKN and DO percentage saturation (Table 2). All water quality and catchment attributes that were identified by BIOENV (Table 2) varied significantly according to the category (low, moderate or high) of catchment EI (Table 1). Apart from DO percentage saturation and RARC, all mean values were highest at the high EI (>18 %) group of site (Table 1).

4 Discussion

This study found that freshwater aquatic ecosystems across the Georges River catchment varied from near pristine to highly degraded, based on freshwater macroinvertebrate communities and water quality. The

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Table 2 Summary of results from the BIOENV procedure correlating invertebrate assemblage structure with physicochemical (pH, EC, DO, TU, TN, TP, TKN, NOX-N, Total Alk, Cl, Ca, K, Na, CO_3, HCO_3, SO_4 and Mg), percentage catchment effective imperviousness (% EI) and riparian quality score (RARC score)

k variable	Bio-physical riparian variables contributing to maximum ρ	BIOENV maximum ρ ρ=rank correlation
4	**RARC score, % EI, total nitrogen, calcium**	**0.650**
5	RARC score, % EI, chloride, calcium, turbidity	0.646
3	RARC score, % EI, calcium	0.646
4	RARC score, % EI, calcium, turbidity	0.645
4	Chloride, calcium, RARC score, % EI	0.645
5	Turbidity, calcium, magnesium, RARC score, % EI	0.640
4	TKN, calcium, RARC score, % EI	0.639
5	Total nitrogen, magnesium, calcium, RARC score, % EI	0.638
3	RARC score, dissolved oxygen %, total nitrogen	0.637
2	RARC score, % EI	0.637

From streams in the Georges River catchment sampled in spring 2009, autumn 2010, spring 2010 and autumn 2011. Combinations of riparian variables (*k*) yielding the highest rank between variables (correlation ρ) are shown. *Bold* indicates the best combination (maximum ρ)

macroinvertebrate assemblages and water quality attributes varied significantly according to catchment percentage of EI categories (low, moderate and high). The waterways in the most degraded ecological condition were typically those of highly urbanised catchments. The results indicate that waterways, draining urban catchments of the Georges River, are highly degraded and are consistent with the urban stream syndrome (Paul and Meyer 2001). The most degraded communities were characterised by the absence or rarity of taxa sensitive to degraded water quality (such as mayflies 'Ephemeroptera').

As the percentage of impervious surfaces within a subcatchment increased, the condition of macroinvertebrate assemblages, riparian vegetation and water quality declined. The biotic indices (richness, SIGNAL, percentage of EPT and Shannon index) and community structure (NMDS ordination) all indicated that macroinvertebrate communities became more degraded at waterways of progressively higher categories of imperviousness. These results were similar to those of Donohue et al. (2006) who observed an inverse relationship between benthic macroinvertebrate community structure and the degree of catchment urbanisation of rivers and streams in Ireland. Likewise, Jones and Clarke (1987), Walsh et al. (2001) and Paul and Meyer (2001) observed reduced richness of pollution-sensitive macroinvertebrate taxa and increased abundance of tolerant taxa in urban streams.

The degree of alteration of macroinvertebrate communities was associated with the degree of human modification within the catchment. Our study found that a relatively minor degree of catchment percentage of EI (*c* 5 %) was associated with the onset of ecological and water quality impairment. This finding builds upon the work of Walsh et al. (2007) who also found that a similar threshold (4 %) of imperviousness also applied to macroinvertebrate communities in the Yarra River catchment in Victoria (south-eastern Australia). In addition, our findings are similar to those in a study of streams in Maine (USA), which identified a threshold of 6 %, and higher levels of imperviousness were linked to a decline in stream invertebrate communities (Morse et al. 2003). Our results are supported by a recent macroinvertebrate study of urban and natural streams in northern Sydney (Davies et al. 2010a) where the catchments of clean non-urban streams had an average impervious cover of 1.5 % and urban streams had an average of 29.5 %. The study by Davies et al. (2010a) had no streams with a catchment percentage of EI between 3.6 and 19.7 %, which limited their detection of the critical 'tipping point' at which macroinvertebrate communities steeply declined at progressively higher levels of imperviousness.

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We used multivariate analysis of the macroinvertebrate community combined with water quality and riparian health indicators, using the PRIMER BIO-ENV procedure. This identified the top ranking factors that were most highly correlated with variation in macroinvertebrate communities across the Georges River catchment. The combination of factors that were most highly correlated included percentage of EI, riparian vegetation condition (RARC), calcium and total nitrogen. The ecological condition of riparian vegetation was much lower at sampling sites in the most highly modified catchments, typical of streams in highly urbanised catchments. We observed that many urban streams in the study sometimes had almost no native riparian vegetation due to the dominance by invasive weeds and past land use activities. Studies on sandstone-derived low-fertility soils in northern Sydney (similar to the current study area) have linked stormwater and nutrient enrichment with invasion of stream riparian zones by exotic plant species (Lake and Leishman 2004). Riparian vegetation is of particular interest as it is a factor that can be rehabilitated by natural resource managers, such as local council authorities. The importance of riparian vegetation to urban macroinvertebrate communities, expressed as 'riparian integrity', was also found by Walsh et al. (2001). Other Australian and international studies have also made similar conclusions (Walsh et al. 2004; Donohue et al. 2006; Walters et al. 2009; Miserendino and Masi 2010).

Total nitrogen concentrations were more highly elevated (mean 1,240 μg/L) at sites of high imperviousness (percentage of EI>18 %) compared to moderate (mean 532 μg/L) and low imperviousness (mean 196 μg/L) streams. This finding supports the validity of water quality guidelines for protection of ecosystem health of upland streams in south-eastern Australia (ANZECC 2000), which specify a maximum guideline of 250 μg/L for the protection of aquatic ecosystems. Although identified as a factor of lesser influence, total Kjeldahl nitrogen was also found by BIOENV to be associated with variation of invertebrate communities across the Georges River catchment. The source of nitrogen could come from numerous catchment sources, such as sewage discharges or leakages, landfill leachate, agricultural and garden runoff. Although no comparable TN or TKN data is available, previous water chemistry studies in the Sydney area have detected elevated nitrate levels in urban catchments (Hayes and Buckney 1995) and downstream of treated sewage discharges (Markich and Brown 1998). None of the waterway sampling sites in this study were located downstream of any sewerage treatment plant discharge points. The very high mean total nitrogen levels at highly disturbed streams deserve further investigation to determine likely catchment sources.

The emergence of water-sensitive urban design (WSUD) (Walsh et al. 2005a, b) places a strong emphasis on conserving water and reducing the surge of catchment runoff being directed from urban areas through the stormwater drainage system and into local waterways. This study provides evidence that geochemistry may also be a significant contributor to the degradation of urban waterway ecosystems from concrete stormwater infrastructure. Mean calcium concentrations at the group of highest imperviousness streams (20.0 mg/L) was more than nine times that of the group of low imperviousness streams (2.2 mg/L). This is a very similar finding to the observed differences in calcium concentrations measured in northern Sydney urban and non-urban reference streams (Davies et al. 2010b; Wright et al. 2011). This provides support to the theory suggested by Davies et al. (2010b) and Wright et al. (2011) that concrete stormwater infrastructure provides both a source and pathway of unnaturally elevated levels of anions and cations to urban streams, including calcium, leaching from the concrete material. We observed during our field sampling that concrete materials form the predominant construction material of Georges River catchment urban stormwater structures, such as pipes, gutters and culverts. We also observed that concrete was a ubiquitous material responsible for a large coverage of urban land surfaces such as footpaths, roads and car parks. Australian water quality guidelines (ANZECC 2000) currently provide no guidance for calcium concentrations, and this finding adds support for the development of guidelines, particular as intensification of urban lands, and provision of concrete stormwater infrastructure is a major landuse change across coastal south-eastern Australia. We acknowledge that further investigation is required to fully understand the source of and impact that increased ionic concentrations have on aquatic ecosystems and encourage future WSUD development to consider these factors.

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The BIOENV procedure identified chloride and magnesium (along with calcium) as important ionic water chemistry attributes associated with variation in aquatic ecosystems of the Georges River catchment. The levels of chloride and magnesium recorded in this study, particularly at the most highly modified sites, were higher than what was recorded in an earlier study of water chemistry of Sydney area streams (Hayes and Buckney 1995). The source of the changes to ionic composition deserves further investigation and may, in part, be due to changes in the hydrology of urban stream catchments. The Gibbs (1970) model for explaining differences in worldwide ionic composition of surface water highlighted the importance of evaporation and crystallisation processes. The proliferation of impervious surfaces of urban catchments, lack of vegetation shading streams and limited vegetated areas for water infiltration to soil and groundwater may enhance the influence of water evaporation in urban catchments. Changes to the ionic composition of freshwaters are not reflected in Australian water quality guidelines (ANZECC 2000) but are emerging as being highly influential to aquatic ecosystems, as Potapova and Charles (2003) showed with the association with algal diatoms across freshwaters in the USA.

The riparian vegetation (RARC) was one of the most influential factors to aquatic ecosystem condition. Highly disturbed sites (generally, also having the highest imperviousness) were characterised by highly degraded riparian zones with little to no natural canopy structure. Vegetation understory was commonly depleted and often ground cover consisted of mainly exotic grasses and invasive weeds. Additionally, these riparian zones lacked terrestrial habitat features, such as dead trees, hollows and accumulation of leaf litter (*personal observation*). The importance of calcium and magnesium sediment levels (in addition to phosphorus) to riparian vegetation communities was discovered in a study of riparian vegetation in urban and non-urban streams in northern Sydney by King and Buckney (2000). Further investigation into the catchments sources and ecological consequences of modified ionic composition of freshwater streams is recommended.

Order-level identification may be regarded as a coarse tool for the assessment of stream biodiversity, but it provides the advantage of immediate assessment in the field, with obvious time and resource savings. We also note that the method is less damaging as macroinvertebrate samples are quickly returned to the stream following on-site assessment, rather than being killed and preserved in ethanol for later laboratory identification. A more detailed (e.g. family, genus or species) level of identification would be much more expensive and slower and would be out of the reach (in terms of technical skills or financial costs) for many natural resource managers (Wright et al. 1995). Our current study has shown that order-level assessment, in conjunction with water quality, catchment imperviousness and assessment of riparian vegetation condition, was a powerful and effective approach for detecting large-scale changes in freshwater systems. This methodology also offered insight into the factors 'driving' the degradation of aquatic ecosystems. Our field collection methodology was an easily performed rapid assessment process that many natural resource managers and consultants could easily undertake with some fundamental training and support. An additional study is investigating the costs and benefits of family versus order-level of taxonomic resolution in this study area.

5 Conclusions

Our results supported the hypothesis that catchment imperviousness is a key factor associated with the ecological condition of urban and partly urbanised freshwater streams. In addition to imperviousness, our research also revealed that the condition of channel and riparian vegetation and two water quality attributes (total nitrogen and calcium) were key influential factors associated with macroinvertebrate assemblages. The Georges River catchment offers an unusually diverse range of waterways of differing environmental conditions. Its catchment is partly covered by urban development from the southern and south-west portions of the Sydney metropolitan area, the most populous urban settlement in Australia. The major source of poor water quality and degraded ecological stream communities is urban development, which covers approximately half of the catchment. The Georges River catchment, as with many other catchments throughout the world, faces a number of challenges in the future, the first of which is to ensure that the cleanest streams in the catchment are protected. These streams have very high conservation

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significance, particularly given their proximity to such a large urban development. The second challenge is to help urban stream managers protect and improve the environmental condition of urban streams that are already modified and environmentally degraded.

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