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PRIMARY RESEARCH PAPER

Influences of catchment and corridor imperviousness on urban stream macroinvertebrate communities at multiple spatial scales

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Abstract Resolving land cover hierarchy relationships in urban settings is important for defining the scale and type of management required to enhance stream health. We investigated associations between macroinvertebrate assemblages in urban streams of Hamilton, New Zealand, and environmental variables measured at multiple spatial scales comprising (i) local-scale physicochemical conditions, (ii) impervious area in multiple stream corridor widths (30, 50 and 100 m) along segments (sections of stream between tributary nodes) and for entire upstream networks, and (iii) total impervious area in stream segment sub-catchments and upstream catchments. Imperviousness was higher for stream segment sub-catchments than for entire catchments because of the agricultural headwaters of some urban streams. Imperviousness declined as corridor width declined at both segment and catchment scales reflecting the vegetated cover along most urban stream gullies. Upstream catchment imperviousness was strongly and inversely correlated with dissolved organic carbon concentration, whereas segment and upstream corridor scales were correlated with water temperature and pH. Corridor imperviousness appeared to be a stronger predictor than catchment imperviousness of Ephemeroptera, Plecoptera and Trichoptera taxa richness and the Quantitative Urban Community Index specifically developed to assess impacts of urbanisation. In contrast, imperviousness at all measured scales added only marginal improvement in assemblage-based models over that provided by the local-scale physicochemical variables of reach width, habitat quality, macrophyte cover, pH and dissolved oxygen concentration. These findings infer variable scales of influence affecting macroinvertebrate communities in urban streams and suggest that it may be important to consider local and corridor factors when determining mechanisms of urbanisation impacts and potential management options.

Keywords Stormwater · Riparian · Impervious area · Urbanisation · New Zealand

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Introduction

The term 'urban stream syndrome' has been coined to describe the state of ecological degradation consistently observed for city streams throughout the world (Meyer et al., 2005). Symptoms typically include taxonomically depauperate biotic communities dominated by tolerant taxa, poor water quality and degraded physical habitat. A major mechanism for these effects is urban stormwater which is channelled directly to streams via pipes that by-pass natural hydrological pathways, thereby leading to more frequent floods, rapidly changing hydrographs and higher peak flows (Walsh et al., 2005a). The erosive forces generated by this altered hydrology can cause channel incision and bank erosion, elevating fine sediment levels and resulting in increased water turbidity and smothering of streambed habitats (Chin, 2006). Stormwater flushes can also increase water temperatures significantly and elevate concentrations of nutrients and a wide range of contaminants in streams (Walsh et al., 2005a).

Upstream catchment imperviousness is often used as a surrogate measure of urban stormwater impacts, and impervious surfaces comprising around greater than 10% of catchment area can substantially compromise the capacity of urban streams to support healthy aquatic macroinvertebrate communities (Walsh, 2004), although impacts from levels as low as 4% total catchment imperviousness have been reported (Walsh et al., 2007). Indeed, in revising the impervious cover model, Schueler et al. (2009) proposed a curvilinear relationship that accounted for variability in ecological responses, particularly at the lower end of the imperviousness range. In support of this model, recent analyses across nine metropolitan areas in the USA revealed little evidence of an initial period of resistance by macroinvertebrate communities to urbanisation, leading to the conclusion that previously suggested thresholds of imperviousness area were not protective (Cuffney et al., 2010).

Recently, interest has accelerated in ecological restoration of urban areas given that cities are where most people interact with native biodiversity most often, and their ecological experiences in this setting help shape public expectations for the wider environment. However, for reasons outlined above, ecological rehabilitation of urban streams can be problematic because of the overwhelming influence of stormwater on stream ecology (Bernhardt & Palmer, 2007). Nonetheless, not all urban streams are the same and some can sustain significant biodiversity values in highly modified settings (Collier et al., 2009; Vermonden et al., 2009). This situation may potentially occur where the amount of impervious area directly connected to stream channels via stormwater pipes (so-called ‘effective impervious area’) has remained low (Walsh et al., 2005b) or stormwater discharges are attenuated along natural flow paths before reaching streams (Walsh & Kunapo, 2009). It is widely accepted that restoration of streams in urban catchments should start with attention to the catchment drainage system (Walsh et al., 2005b; Roy et al., 2006), although ecologically successful restoration in urban catchments will most likely require attention to both riparian zones and catchment drainage systems (Roy et al., 2005; Walsh et al., 2007).

Analysing the spatial arrangement of land use around streams, including riparian corridors, can enable patterns and thresholds to be resolved that are not apparent with larger scale analyses (King et al., 2005; Feld & Hering, 2007). Several studies have explored relationships between macroinvertebrate measures of stream health and a spatial hierarchy of land cover variables, primarily in agricultural catchments although Walsh & Kunapo (2009) investigated a continuous spatial hierarchy of attenuation along upland flow paths in an urban setting. Such studies in agricultural landscapes have noted stronger associations with riparian buffer and corridor attributes than for whole catchment attributes (e.g. Sponseller et al., 2001; Rois & Bailey, 2006), although the importance of catchment land cover optima is well recognised (Black et al., 2004; Death & Collier, 2010). Determining the scales over which urban impacts become manifest in stream ecosystems, particularly in relation to upstream catchment and stream corridor imperviousness, may provide helpful insights into defining the scale of management required to enhance urban stream health.

We investigated associations between macroinvertebrate assemblages and environmental variables measured at multiple spatial scales comprising (i) reach-scale physicochemical conditions, (ii) total impervious area in corridors with widths of 30, 50 or 100 m along stream segments and entire networks upstream of sampling sites, and (iii) impervious area in stream segment sub-catchments and upstream catchments. Stream ‘segments’ are defined as the section of channel on which sampling sites occurred between mapped tributary nodes. Our aims were firstly to assess if a particular spatial scale of total impervious area provided a stronger explanation of macroinvertebrate metric relationships and secondly to determine the relative significance of local scale physicochemical factors and impervious cover in accounting for biotic patterns in a spatially discrete set of urbanised streams in Hamilton city, North Island, New Zealand. We used regression analyses to infer the relative influence of impervious area measures on macroinvertebrate metrics and for investigating the position of imperviousness scale in a hierarchy of environmental factors. Non-parametric community–environment models helped identify combinations of physicochemical variables and imperviousness scales best explaining patterns of macroinvertebrate community composition. These analyses were used to infer scales of influence affecting key macroinvertebrate indicators of ecological health and community composition generally in these urban streams.

Methods

Study area

The central North Island city of Hamilton is New Zealand's seventh most populated city and is bisected by the Waikato River where the median discharge is 254 m^3/s (Environment Waikato, unpublished data). Around 15,000 years ago, deepening of the river channel induced spring sapping which caused erosion of adjacent underlying sand, silt, peat and gravel, eventually creating gullies that now accommodate over 120 km of stream within the current city boundary. Gully floor vegetation is frequently dominated by the deciduous exotic grey willow (*Salix cinerea*), though beneath this is often an understory dominated by indigenous plants including ferns, mahoe (*Melicytus ramiflorus*) and cabbage tree (*Cordyline australis*). Streams with headwaters outside the city boundary arise in low-gradient agricultural catchments that were formerly peat wetlands, whereas streams originating within the city have entirely urbanised catchments. Hamilton has a temperate, damp climate with mean annual rainfall of 1190 mm (1971–2000 data, accessed 20 July 2010 from www.niwa.co.nz), most of it falling between June and September. Mean annual temperature is 13.7°C and daily maximum temperatures range from about 22 to 26°C in January and February to 10 to 15°C in July and August.

Twenty-five urban stream reaches of 50–100 m length were selected for sampling from December 2005 to March 2006. All streams had residential or industrial development areas adjacent to the sampling sites and upstream to varying extents, although typically development did not extend fully to the stream edge due to the presence of parks and vegetated gullies. Stormwater discharges are typically directed through pipes directly into stream channels. Catchment areas upstream of sampling sites ranged from 4 to 2706 ha, with the Mangakotukutuku (nine sites) being the largest catchment followed by the Waitawhiriwhiri (two sites; 2221 ha). Seven sites occurred on Kirikiriroa stream tributaries (390 ha), whereas the remaining sites were distributed on small streams around the city.

Habitat assessment

Habitat quality was assessed using a qualitative index that provides an integrative score for riparian, bank, channel and instream conditions by visually evaluating nine attributes on a scale of 1 (lowest habitat value) to 20 (highest habitat value), with possible total scores ranging up to 180 (Collier & Kelly, 2005). Following the first site visits, it was apparent that cover by algae, iron floc, macrophytes as well as mosses was highly variable among sites. These were assessed for all sites on two subsequent visits using a 5-point cover scale (<5%, 5–25%, 26–50%, 51–75%, and >75%). Visual assessments of percentage streambed cover by large wood (>10 cm diameter), coarse particulate organic matter (CPOM; ca. >1 mm diameter), fine particulate organic matter (FPOM; ca. <1 mm diameter) and inorganic substratum size distribution based on the operational divisions of bedrock, boulder (>256 mm), cobble (65–256 mm), gravel (2–64 mm) and sand/silt/clay (<2 mm) were made on all dates. Streambed compaction was assessed after Pfankuch (1975) (1 = no packing/loose assortment easily moved; 2 = mostly a loose assortment with little overlap; 3 = moderately packed with some overlap; 4 = assorted sizes tightly packed and/or overlapping). Embeddedness was assessed after Platts et al. (1983) according to the percentage of gravel-boulder particles covered by fine sediment using the abundance classes described above.

Water quality parameters

Measurements of water temperature and conductivity (both WTW Cond 340i), pH (Shindengen ISFET

KS701 meter), and dissolved oxygen concentration as well as percent saturation (WTW Oxi340 meter) were made on three occasions at approximately monthly intervals from December to March. Water samples were collected in February 2006 and analysed after filtration where indicated (0.45 µm filter unless otherwise stated) following APHA (1998): total suspended solids (GFC filtration, dried at 103–105°C), NH_4-N (filtration, phenol/hypochlorite colorimetry, flow injection analyser), total Kjeldahl nitrogen (TKN; acid digestion, phenol/hypochlorite colorimetry), total organic nitrogen (TON; automated cadmium reduction, flow injection analyser), dissolved reactive phosphorus (DRP; filtration, molybdenum blue colorimetry, discrete analyser), total phosphorus (TP; persulphate digestion, ascorbic acid colourimetry, discrete analyser), dissolved organic carbon (DOC; filtration, catalytic oxidation, IR analyser), and dissolved iron (filtration, inductively coupled plasma mass spectrometry). Turbidity (Hach 2100N) and absorbance at 340 and 440 nm (filtration, 1 cm path length) were also measured.

Macroinvertebrates

Stream macroinvertebrates were collected in flowing water with a D-frame net (0.5 mm mesh) using established protocols (see Collier & Kelly, 2005, for further details). Collection involved kicking loose gravel-cobble substrate in front of the net, hand-brushing embedded substrate elements and wood, and jabbing the net among macrophytes (where present) and along stream edges with a similar amount of effort at all sites. Samples were preserved in ca. 70% isopropanol, and later processed by identifying at least 200 invertebrates (excluding pupae) from randomly selected sub-samples, followed by a search for unrecorded taxa in the rest of each sample, after Stark et al. (2001). Sub-sampling was achieved by dividing the processing tray into a grid and randomly selecting one cell for processing; additional cells were added until the desired number of macroinvertebrates was obtained with all animals in the final cell being removed. This process yielded an average of 213 individuals per site, with only one sample yielding <200 individuals.

Macroinvertebrate identifications were based on Winterbourn et al. (2000) (insects), Winterbourn (1973) (molluscs) and Chapman & Lewis (1976) (crustaceans). The level of taxonomic resolution was to genera for most insects and molluscs and ranged from family to phylum for other groups, as recommended by Stark et al. (2001). Total number of taxa, and the number of sensitive Ephemeroptera, Plecoptera and Trichoptera taxa (excluding Hydroptilidae which proliferate among filamentous algal growths; denoted as EPT*), were calculated from the macroinvertebrate data. In addition, we calculated the Urban Community Index (UCI) and its quantitative derivative (QUCI), developed to assist with discriminating among streams that largely lack sensitive species and are impacted by urban development, following Suren et al. (1998) and Boothroyd & Stark (2000). The UCI and QUCI metrics are derived from tolerance scores based on a Canonical Correspondence Analysis for taxa from a nationwide urban stream survey, with higher metric values denoting better condition, as follows:

$$\mathrm{UCI} = \sum_{i=1}^{i=S} \frac{a_i}{s} \times 20, \quad \mathrm{QUCI} = \sum_{i=1}^{i=S} \frac{(n_i \times a_i)}{N},$$

where a_i is the calculated tolerance value for the ith taxon, S the total number of taxa in the sample, n_i the abundance of the ith taxa and N the total abundance in the sample.

Spatial analyses

Land cover data were obtained from 'mesh blocks' which comprise small geographic units of homogenous urban land classified as: 'green' (predominantly parks), 'industrial', 'residential' (high density housing), and intermediate classes of 'industrial-green', 'green-residential' and 'residential-green' reflecting different levels of urban land use intensity and associated parkland or gully. For example, most gully properties were classed as 'green-residential', whereas 'residential-green' sites were low density housing not associated with parks or gullies. Impervious areas were estimated by randomly selecting five scenes from each mesh block class and digitising hard surfaces (roofs, roads, driveways, etc.) from aerial photos at 1:1000 scale. A 'spatial intersection' between land cover and catchment areas was then performed to calculate the total impervious area within each catchment. We used total impervious area rather than effective impervious area since maps to enable stormwater tracking were not available, although our observations indicate most stormwater is discharged directly to streams.

A GIS 'buffering' procedure was used to identify impervious land cover for 30, 50 and 100 m corridors around stream segments where sampling sites occurred (referred to as segment corridors) and for all the river networks mapped upstream (upstream corridors; see Fig. 1). Segments were spatially discrete sections of stream occurring between tributary nodes mapped on the River Environment Classification network layer, which also delineated upstream and segment catchment boundaries (Snelder & Biggs, 2002). Thus, segment scale imperviousness measures reflected influences adjacent to and feeding laterally into the section of stream on which the sampling site occurred, whereas upstream measures reflected these influences and those from upstream corridors and catchment areas. The GIS buffering procedure also incorporated land cover for varying distances (30–100 m) above and below tributary nodes for assessment of corridor imperviousness; the effects of this analytical artefact on overall imperviousness estimates is considered minor.

Statistical analyses

Kruskal–Wallis test (Systat v.11; Systat Software Inc. 2004) was used to compare environmental parameters among the main catchments (Mangakotukutuku, $n = 9$; Kirikiriroa, $n = 7$) and other catchments combined ($n = 9$) to identify any differences in sampling site locations. Spearman rank correlation, after applying adjustment for the False Discovery Rate (McBride, 2005), was used for multiple comparisons to (i) assist with selection of key environmental variables for subsequent analyses and (ii) help identify environmental variables linked with different scales of imperviousness. Coefficients of determination (R^2) from linear and logarithmic regressions determined the strength of relationships between macroinvertebrate metrics and the different measures of imperviousness; logarithmic regressions were almost always higher and therefore only these are presented. Regression trees (Systat v.11) identified natural splits in macroinvertebrate metrics in relation to unconstrained environmental data and the relative position of imperviousness scale in a hierarchy of environmental factors. Trees explain variation of a single response variable by repeatedly splitting the data into more homogeneous groups, using combinations of explanatory variables (De'ath & Fabricius, 2000). A minimum count of five sites was allowed at any node, and the minimum proportion reduction in error for the tree allowed at any split and the minimum split value at any node were set at 0.05.

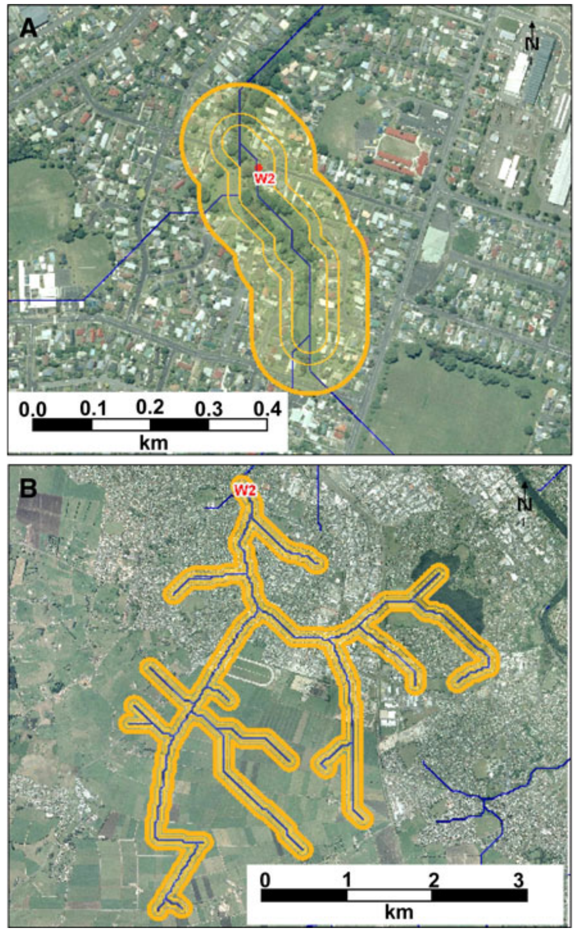


Fig. 1 Example of 30, 50 and 100 m wide corridors delineated along an urban stream for **A** the segment and **B** the upstream network of one sampling site

Non-metric multidimensional scaling (MDS) of percent invertebrate abundance was performed using Bray-Curtis similarity following 4th-root transformation (Primer v.6.1.13; Primer-E Ltd 2009) to determine patterns in macroinvertebrate composition. Spearman correlations >0.4 were used to illustrate trajectories of important physicochemical parameters and taxa related to the distribution of sites in two-dimensional ordination space. Analysis of

Similarities (ANOSIM) was performed to assess whether differences in macroinvertebrate communities could be attributed to the different catchment groupings described above. Environmental variables best explaining community composition were assessed using the BIOENV routine of Biota and/or Environmental Matching analysis in Primer. Environmental data were normalised and a Euclidean distance matrix calculated; the Bray-Curtis resemblance matrix was used for biota. Physicochemical variables were excluded if they were highly correlated ($r_s \geq 0.7$), were categorical variables that had low ranges (moss, FPOM, wood) or were included in other parameters (e.g. algae in Habitat assessment) to reduce environmental variables to 17, following Clarke & Gorley (2006). Environmental variables that were made available for BIOENV were width, depth, % CPOM cover, % sand/silt/clay, habitat score, % macrophyte cover, temperature, pH, conductivity, dissolved oxygen, suspended solids, NH_4-N, TON, DRP, DOC and Fe. Runs involved the use of physicochemical variables only, impervious measures only, and then physicochemical variables made available with each imperviousness variable forced into the analysis.

Results

Environmental parameters

Impervious areas ranged from 6 to 64% for upstream catchments and from 22 to 64% for segment subcatchments (Table 1). Average impervious area declined progressively as corridor width declined at both segment and catchment scales. All impervious measures were significantly intercorrelated ($P < 0.05$), although coefficients were lower for comparisons of catchment versus corridor imperviousness ($r_s = 0.45$–0.66) than for comparisons between segment and upstream corridor scales ($r_s = 0.65$–0.74). Cover by impervious surfaces was significantly different among the main urban catchments (Mangakotukutuku, Kirikiriroa) and other catchments combined at all upstream buffer scales, and for the 50- and 30-m segment buffers, with imperviousness lowest in the Mangakotukutuku catchment (Table 1). This difference largely reflected more Mangakotukutuku sites at the lower end of the imperviousness range; however, imperviousness maxima were similar among catchment groups (e.g. 58–64% for upstream and segment catchments).

Channel width averaged 2 m and was similar to wetted width due to the incised nature of most channels (Table 1). Depth and substrate composition were variable among sites but on average streambed substrates were dominated by weakly compacted fine sediments. Accumulations of organic matter and cover by aquatic plants and iron floc were low on average (<25%), although a wide range of conditions was encountered, as was also apparent in the habitat quality scores. Significant differences among the main urban catchments were detected for % sand/silt/clay which was lowest at sites outside the Mangakotukutuku and Kirikiriroa catchments, and cover by wood and CPOM which were both highest in the Mangakotukutuku (Table 1).

Summer water temperatures were generally <20°C on three monthly occasions, pH was circumneutral, and ionic concentration (indicated by conductivity) and oxygen concentrations were variable among sites (Table 1). Waters were generally turbid with suspended sediment concentrations averaging 10 g/m^3. DOC concentrations averaged around 7 g/m^3 and were as high as 25 g/m^3, partly reflecting the leaching of organic soils in sites with upper catchments draining former wetlands outside the city boundary. Both DOC and dissolved iron concentrations were highly correlated with absorbance ($r_s = 0.78$–0.87, $P < 0.001$, $n = 25$).

Significant differences among the main urban catchments were detected for water temperature and pH, being highest in 'other' streams and the Mangakotukutuku sites, respectively, although the range of values recorded was limited (Table 1). No significant differences were detected among catchments for the nutrients measured at summer low flow (Table 1). Upstream catchment imperviousness was inversely correlated with bed cover by CPOM and water quality variables reflecting organic colour and nutrient concentrations (absorbance, TKN, TP, DOC), although only DOC was statistically significant following adjustment for multiple comparisons (Table 2). In contrast, both segment and upstream corridor scales were, respectively, positively and negatively correlated with water temperature and pH, with correlations generally highest at the 30 and 50 m corridor scales.

Table 1 Summary of environment variables at the 25 urban sampling sites

	Mean	SD	Min.	Max.	Catchment differences (*H*)
Impervious area					
US_{Catch}	40.1	16.7	6	64	ns
US_{100}	31.8	14.4	7	62	14.2***
US_{50}	26.9	14.9	6	61	14.8***
US_{30}	23.8	15.4	6	61	13.5***
SEG_{Catch}	48.0	10.9	22	64	ns
SEG_{100}	36.2	12.4	12	60	ns
SEG_{50}	25.4	15.1	9	56	7.9*
SEG_{30}	19.9	16.1	9	56	10.8**
Habitat					
Channel width (m)	2.01	1.28	0.70	5.00	ns
Wetted width (m)	1.80	1.20	0.50	4.50	ns
Depth (m)	0.31	0.18	0.05	0.80	ns
Sand/silt/clay (SSC) (%)	69	32	10	100	6.3*
Total habitat score (out of 180)	92	21	46	129	ns
Compaction (1–5)	1.76	1.01	1.00	5.00	ns
Wood (1–5)	1.24	0.52	0.00	2.00	9.5**
Coarse particulate organic matter (CPOM) (1–5)	1.44	0.71	0.00	3.00	9.1*
Fine particulate organic matter (FPOM) (1–5)	1.44	0.96	0.00	5.00	ns
Filamentous algae (1–5)	1.56	0.75	1.00	3.50	ns
Macrophytes (1–5)	1.48	0.98	1.00	4.50	ns
Moss (1–5)	1.08	0.31	1.00	2.50	ns
Iron-floc (1–5)	1.94	1.36	1.00	5.00	ns
Water quality					
Temperature (Temp.) (°C)	16.8	1.4	14.9	20.5	9.5**
Dissolved oxygen (DO) (%)	75.1	14.2	36.5	91.6	ns
Dissolved oxygen (DO) (g/m^3)	7.3	1.4	3.5	9.1	ns
Conductivity (Cond.) (μS/cm at 25°C)	213.7	119.5	147.3	769.6	ns
pH	7.3	0.4	6.2	7.8	17.7***
Turbidity (NTU)	19.2	16.0	2.4	53.0	ns
Absorbance (340 nm)	0.10	0.10	0.02	0.39	ns
Absorbance (440 nm)	0.02	0.02	0.00	0.07	ns
Total suspended solids (g/m^3)	10.1	9.6	0.3	39.0	ns
NH_4-N (g/m^3)	1.09	4.14	0.01	20.80	ns
Total Kjeldahl nitrogen (TKN) (g/m^3)	1.70	4.51	0.21	23.00	ns
Total organic nitrogen (TON) (g/m^3)	1.40	1.04	0.14	4.84	ns
Dissolved reactive phosphorus (DRP) (g/m^3)	0.05	0.06	0.00	0.21	ns
Total phosphorus (TP) (g/m^3)	0.15	0.16	0.02	0.54	ns
Dissolved organic carbon (DOC) (g/m^3)	6.9	6.3	0.9	25.4	ns
Dissolved iron (Fe) (g/m^3)	1.04	0.95	0.07	3.02	ns

Kruskal–Wallis test statistics (*H*) for comparisons among catchment groups (Mangakotukutuku, Kirikiriroa, other sites) are shown. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; subscript numbers denote corridor widths

ns Non-significant, *US* upstream, *SEG* segment, *Catch* catchment

Table 2 Spearman correlation coefficients between physicochemical parameters and impervious measures

	US_{Catch}	SEG_{Catch}	US_{100}	US_{50}	US_{30}	SEG_{100}	SEG_{50}	SEG_{30}
CPOM	**−0.55**	−0.51	−0.52	−0.49	−0.44	−0.18	−0.30	−0.41
Temperature	0.28	0.35	0.43	**0.59**	**0.63***	0.46	**0.57**	**0.57**
pH	−0.47	**−0.54**	**−0.66***	**−0.67***	**−0.60**	−0.50	**−0.56**	**−0.63***
Absorbance (340 nm)	**−0.53**	−0.06	−0.28	−0.09	−0.04	−0.07	−0.15	−0.21
TKN	**−0.56**	−0.05	−0.09	0.08	0.12	0.05	0.03	0.00
TP	**−0.60**	−0.12	−0.12	0.02	0.06	−0.02	0.02	0.01
DOC	**−0.76****	−0.25	−0.41	−0.20	−0.13	−0.16	−0.24	−0.28

Only those parameters are shown with at least one pairwise correlation significant at $P < 0.1$ (bold) following adjustment for False Discovery Rate ($n = 25$). *$P < 0.05$; **$P < 0.01$. Conventions as for Table 1

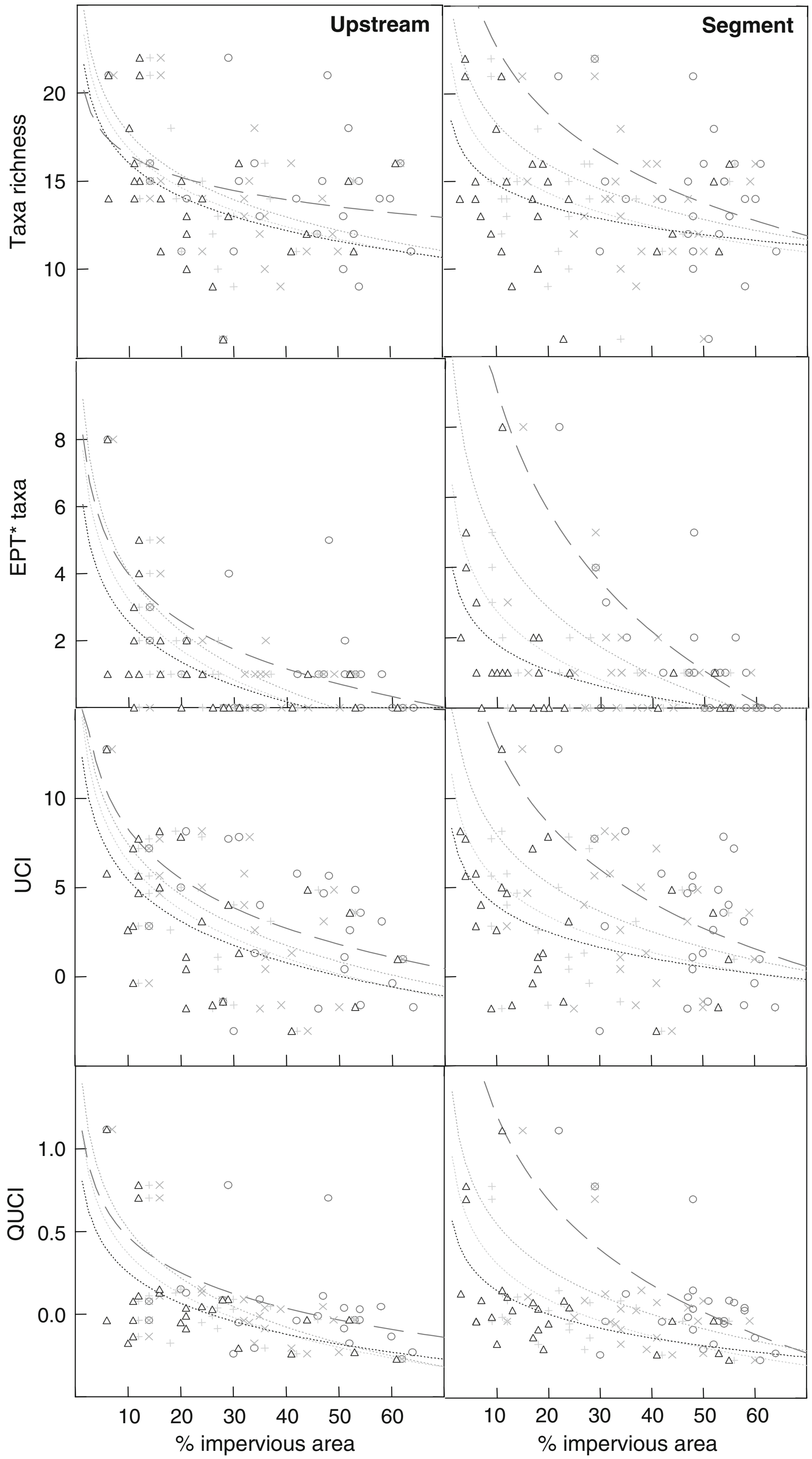
Macroinvertebrates

Macroinvertebrate communities of these urban streams were dominated numerically by *Potamopyrgus* (Hydrobiidae) and Oligochaeta (>20% of total numbers), followed by the chironomid taxa *Polypedilum* and Orthocladiinae (ca. 9%), and the simuliid *Austrosimulium* (5%). All other taxa comprised less than 3% of abundance at any site. The four dominant taxa were also found at most (>80%) sites, with the first two-named being found at all sites sampled. Other taxa found at more than half the sites were the introduced mollusc *Physa*, Acari and the dipteran Muscidae. Twenty-one taxa were found at <10% of sites, including six Diptera and four Trichoptera taxa, and three taxa each of Ephemeroptera, Mollusca and Hemiptera. In total, 57 taxa were recorded across all 25 sites, with site richness ranging from 6 to 22 taxa. Few EPT taxa were present on average, although eight taxa were recorded at one site.

Logarithmic regression lines fitted to four macroinvertebrate metrics indicated declining condition with increasing imperviousness irrespective of spatial scale (Fig. 2). Considerable scatter was evident for taxonomic richness and UCI across all scales, with relationship outliers most evident for catchment scale impervious measures. Examination of patterns in R^2 values for these regressions confirmed relatively weak relationships across all scales for taxa richness and UCI, and stronger relationships for most imperviousness measures in relation to EPT* taxa and QUCI (Fig. 3). Most catchment measures had higher R^2 at the segment scale, whereas corridor measures were higher at the upstream network scale. R^2 values declined with decreasing corridor width for EPT* richness and QUCI (Fig. 3). Regression trees identified initial natural splits in the metrics that corresponded to 50 m segment corridor imperviousness for EPT* richness and QUCI (<12% imperviousness for both) followed by splits reflecting dissolved oxygen and DRP concentrations, respectively (Fig. 4). In contrast, the initial split for taxa richness reflected water temperature followed by 50 m upstream corridor imperviousness and then conductivity, and for UCI splits were pH followed by water temperature and TP (Fig. 4).

The stress value for the MDS analysis of percent abundance data indicated a fair representation of sites in two-dimensional space (Fig. 5). The ANOSIM Global *R* statistic comparing communities among catchments was not statistically significant ($R = 0.073$, $P > 0.05$). Trajectories of impervious cover measures were higher towards the top left of the ordination and were closely aligned to the trajectory for temperature and inversely to trajectories for instream organic matter cover, habitat quality, dissolved oxygen levels, pH and DRP concentration (Fig. 5). Macroinvertebrate taxa displayed an array of relationships with site location in ordination space, with all correlated EPT taxa (indicated by asterisks in Fig. 5) and the Diptera taxa Tanyderidae, *Austrosimulium* and Eriopterini inversely related to imperviousness trajectories. Another dipteran, the midge Tanytarsini, was positively related to measures of impervious area, as were dytiscid beetles. The molluscs *Potamopyrgus* and *Musculium*, along with two chironomid taxa, leeches (Hirudinea), flatworms (Platyhelminthes) and oligochaetes, appeared more closely aligned with trajectories related to substrate composition and channel width.

Fig. 2 Logarithmic regressions between four macroinvertebrate metrics and impervious area for upstream network and stream segment catchments (*open circle*; *dashed line*), and buffers of 30 m (*open triangle*), 50 m (*plus*) and 100 m (*times*) widths (*dotted lines*)



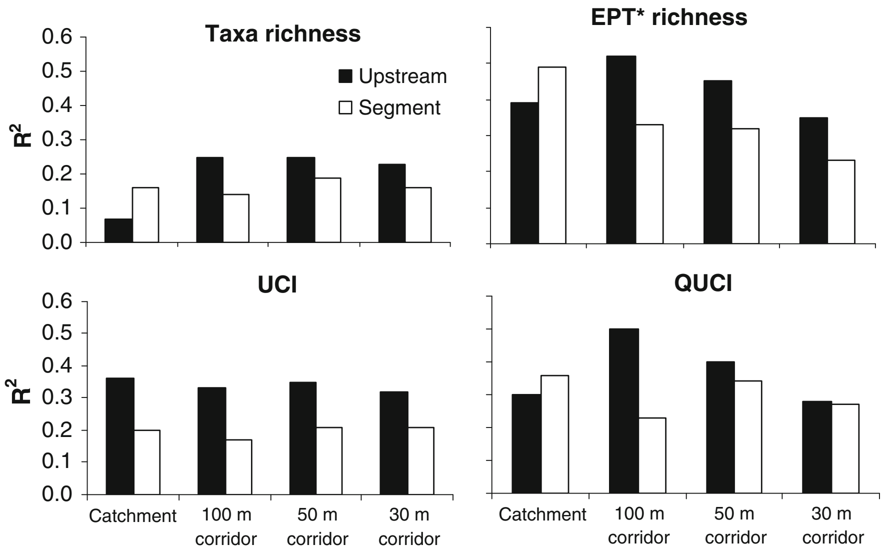


Fig. 3 Coefficients of determination (R^2) from logarithmic regressions (see Fig. 2) at multiple spatial scales

Non-parametric community–environment models derived using the BIOENV procedure yielded correlations ranging from 0.37 to 0.48. The strongest BIOENV model using physicochemical variables only (correlation 0.44) selected width, habitat quality index, macrophyte cover and pH as explanatory variables. When only measures of imperviousness were made available to the model, upstream 100 m corridor imperviousness provided the most parsimonious model but with a much weaker correlation (0.23). The physicochemical variables listed above were also selected when upstream catchment and upstream 100 or 50 m corridor imperviousness were forced into the model, and with the addition of dissolved oxygen concentration for other corridor scales (upstream 30 m and segment 30, 50 and 100 m). Highest correlations were detected for the physicochemical model with upstream or segment catchment imperviousness included (correlations 0.47–0.48), whereas lowest correlations were evident at the 30 m upstream corridor and 50 and 30 m segment corridor scales (correlations = 0.37–0.39).

Discussion

Relationships with impervious area

Many studies attempt to isolate land cover factors affecting stream macroinvertebrate communities by sampling along a stressor gradient that incorporates a range of contrasting land use types such as forestry, agriculture and urbanisation (Helms et al., 2009; Walters et al., 2009). Urban streams typically harbour a relatively narrow range of taxa and physicochemical conditions, making the discrimination of specific factors influencing ecological health within these environments challenging when streams are embedded in a much broader stressor gradient. In such circumstances, constraining the gradient and utilising designer metrics targeting the particular land cover of interest (e.g. Suren et al., 1998; Carter et al., 2009a) can be useful approaches for inferring mechanistic linkages. Furthermore, ecological responses to urban development may be influenced by historical land use legacies that leave enduring impacts (Brown et al., 2009; Carter et al., 2009b), highlighting the importance of constraining the sampling gradient to sites with similar antecedent land cover. The present study focussed on streams with catchments formerly dominated by agricultural land use/cover, but now with varying levels of urban stress characterised by degree of catchment or corridor imperviousness.

A core set of a few widely distributed and tolerant macroinvertebrate taxa was found in many Hamilton city streams, although the numbers of total taxa and EPT taxa varied widely among sites. Higher impervious area was inversely associated with selected richness and condition metrics, and the relative abundances of several Diptera and EPT taxa, a relationship widely reported elsewhere at least for EPT faunas (Helms et al., 2009; Walters et al., 2009;

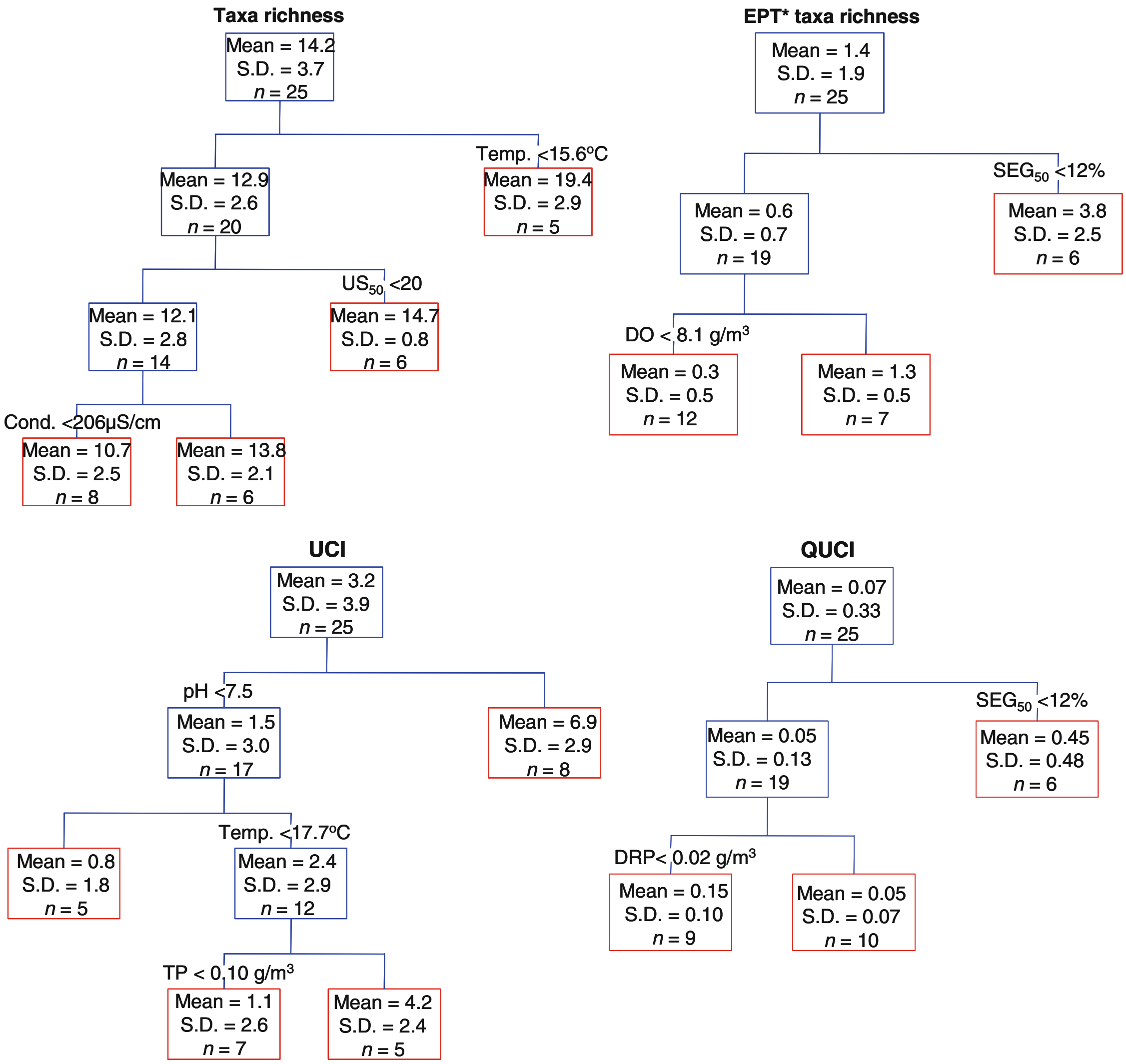


Fig. 4 Regression trees of four macroinvertebrate metrics using measures of imperviousness at multiple spatial scales and measured physicochemical parameters. Conventions as for Table 1

Cuffney et al., 2010). A range of water quality and habitat-related factors was also implicated as influencing macroinvertebrate metrics and community composition, with temperature and pH identified as the primary factors in a hierarchical analysis for taxa richness and UCI, and pH along with habitat quality score, stream width, macrophyte cover and dissolved oxygen concentration identified in biota-environment models. Relationships with similar physicochemical parameters have also been reported in other studies of urbanising watersheds. For example, Walters et al. (2009) reported correlations between nutrient levels and baseflow water temperature for different macroinvertebrate community indicators. Cuffney et al. (2010) reported conductivity was among the variables showing strong associations with urban intensity, and elsewhere it has been found to be a useful integrator of cumulative urban disturbances on water quality (Wang & Yin, 1997; Wenger et al., 2009). Associated water quality influences, along with reduced baseflow and increased sedimentation leading to the development of stagnant pools and accumulations of organic matter, can contribute to low dissolved oxygen levels in urban streams (Wenger et al., 2009). Reduced agricultural influences were apparent in more highly urbanised

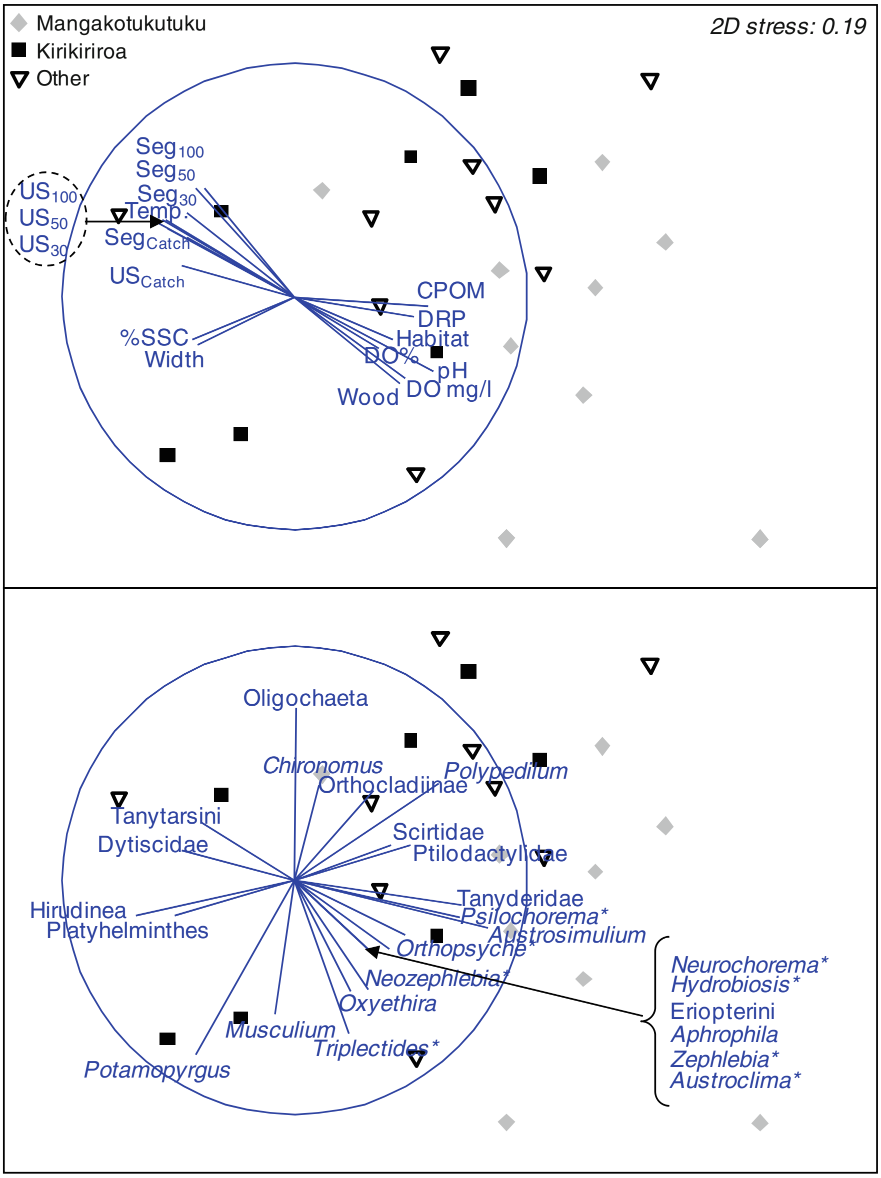


Fig. 5 Non-metric multidimensional scaling plots based on percent abundance macroinvertebrate data showing the distribution of sites in two-dimensional ordination space in relation to highly correlated (>0.4) environmental variables (*upper plot*) and macroinvertebrate taxa (*lower plot*). * = EPT* taxa. Other conventions as for Table 1

catchments where measured nutrient concentrations tended to be lower, supporting the conclusion of Brown et al. (2009) that relationships between urban intensity and nutrient levels partially depend on other land uses. We did not set out to measure concentrations of dissolved metals, which can be high in urban stormwater discharges (e.g. Williamson, 1998), relying on imperviousness measures to broadly capture the relative magnitude of such factors.

Forcing impervious area measures into models to explain community composition increased explanatory power only slightly over the physicochemical model. Similarly, Helms et al. (2009) reported that physicochemical and habitat variables better explained macroinvertebrate community metrics than hydrological variables, in part reflecting urbanisation around small streams in Georgia, USA. They suggested that this was because macroinvertebrates might be more closely associated with indirect rather than direct effects of altered hydrology due to their close association with benthic habitats, small size and short generation times. While there can be colinearity among multiple stressors activated by urbanisation and surrogate measures such as impervious area

(Carter et al., 2009b), factors influenced by upstream catchment land use or local habitat conditions appeared to more strongly reflect macroinvertebrate community patterns than direct measures of imperviousness in the present study.

The strength of relationships observed in this study with impervious area ($R^2 > 0.5$ for some macroinvertebrate metrics and r_s up to 0.48 for environment-biota models) is comparable with that reported for other studies examining influences of urbanisation on stream macroinvertebrate faunas (e.g. Walsh et al., 2007; Brown et al., 2009). Given that geological and climatic conditions were similar across sites, unexplained variation in our analyses could be partly accounted for by a number of more spatially constrained factors, including differential legacy effects, variations in the degree of stormwater connectivity (i.e. effective or attenuated impervious areas vs. total impervious area), and variable levels of riparian influence where legacy and stormwater influences were muted. For two outlier sites in the catchment imperviousness/EPT* taxa plot, effective impervious area appeared lower than that suggested by catchment imperviousness, possibly due to attenuation by overland flow. We are not aware of this occurring at our other sites, although it was not possible to track stormwater connections upstream of all sampling locations. As noted earlier, the type of former land use was similar among sites in the present study, but the magnitude of this legacy may have varied due to the timing of land use conversion.

Effects of scale

Average impervious area declined progressively as corridor width declined at both segment and catchment scales because most urban streams flow through narrow, vegetated gullies. Similarly, segment catchments tended to be more heavily urbanised than upstream catchments because some streams had agricultural headwaters. As a result, upstream catchment imperviousness was more strongly related to nutrient and dissolved organic carbon concentrations. Higher percentage catchment impervious area was associated with lower CPOM cover on the streambed, potentially reflecting faster processing rates in urban environments (Meyer et al., 2005) and/or reduced retention due to hydrological disturbances (Walsh et al., 2005a). In contrast, pH and water temperature were more strongly related to corridor imperviousness. This relationship could partly reflect the influence of riparian shade moderating elevated temperatures that can occur during summer baseflows because of increased air temperatures in urban centres (Wenger et al., 2009). Potential reasons accounting for higher pH where imperviousness was lower are unclear, but may be related to application of lime to peat soils to reduce acidity in upper agricultural catchments that were formerly wetland (Edmeades et al., 1985).

While physicochemical conditions yielded most of the explanatory power for patterns in community composition and were also highlighted in regression trees as primary factors influencing taxonomic richness and the UCI, EPT richness and the QUCI were more strongly influenced by imperviousness, with corridor influences stronger than catchment imperviousness. The scale of these influences varied amongst analyses, particularly in terms of whether segment or upstream networks were most influential, but nevertheless appeared strongest at 50–100 m corridor widths. Similarly, Sponseller et al. (2001) evaluated relationships between land cover and macroinvertebrate assemblages at catchment and various stream corridor scales in Appalachian headwater streams, Virginia, USA, and identified land cover within 200 m of the stream as that most closely related to the observed biotic pattern. Rois & Bailey (2006) reported that land use within 30 m of the stream was more highly related to diverse macroinvertebrate communities at the reach scale than the upstream network scale in small Ontario, Canada, catchments, with catchment land cover unrelated to observed biotic diversity. Aside from water temperature, the generally weaker effect on macroinvertebrate metrics at the 30 m corridor scale compared to other corridor scales in our study suggests that near stream imperviousness was less influential on urban stream ecology than broader corridor influences.

Corridor imperviousness could potentially reflect several processes influencing streams in urban settings. Higher imperviousness along stream corridors could indicate fewer opportunities for stormwater attenuation along off-channel flow paths which can mitigate stormwater effects over tens-of-metres where pipes do not transmit runoff directly to streams (Walsh & Kunapo, 2009). As noted earlier, we suspect this may have been a mechanism influencing two sites in our study, although most streams appeared to have direct stormwater connections. Low corridor imperviousness indicates more vegetated land along streams, although it does not discriminate between forest and parkland. The role of riparian vegetation in moderating urban impacts on streams has been the focus of some discussion. Wasson et al. (2010) considered that riparian forests can be effective for mitigating urban land cover impacts at the catchment scale for a range of European rivers, and Atkinson et al. (2010) concluded that the preservation of functional riparian zones can be an effective way of protecting water quality and enhancing environmental and social outcomes. Urban streams with high amounts of riparian forest have been reported to sustain unexpectedly high biodiversity levels in Maryland, USA (Moore & Palmer, 2005). However, such studies have been criticised for not accounting for spatial correlations between urbanisation and riparian land cover (Walsh et al., 2007). The protective effects of riparian forest for stream ecosystems are reduced where stormwater drainage systems bypass riparian zones, and ecologically successful restoration will require attention to both riparian zones and urban catchment drainage (Roy et al., 2006; Walsh et al., 2007; Walsh & Kunapo, 2009).

Conclusions

These analyses infer variable scales of influence potentially affecting macroinvertebrate indicators of ecological health in urban streams and suggest that local and corridor scales may need to be considered along with catchment land cover when developing environmental management approaches. Although macroinvertebrate community composition appeared more closely linked to measured physicochemical variables than directly to imperviousness, local-scale conditions were likely mediated by stormwater influences in combination with upstream land management and to some extent riparian conditions through water temperature moderation. Unexplained variation in our analyses could be partly accounted for by a number of more spatially constrained unmeasured influences, including differential legacy effects, extent of stormwater connectivity and variable levels of riparian shade. Irrespective of scale, this study highlights that total impervious area accounts for a limited amount of variation observed in biological datasets in urban streams, underscoring the need for more detailed analyses of ecological processes to support urban stream management.

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