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APPLIED ISSUES

Catchment urbanisation and increased benthic algal biomass in streams: linking mechanisms to management

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SUMMARY

1. Urbanisation is an important cause of eutrophication in waters draining urban areas. We determined whether benthic algal biomass in small streams draining urban areas was explained primarily by small-scale factors (benthic light, substratum type and nutrient concentrations) within a stream, or by catchment-scale variables that incorporate the interacting multiple impacts of urbanisation (i.e. variables that describe urban density and the intensity of drainage or septic tank systems).
2. Benthic algal biomass was assessed as chlorophyll *a* density (chl *a*) in 16 streams spanning a rural–urban gradient, with both a wide range of urban density and of piped stormwater infrastructure intensity on the eastern fringe of metropolitan Melbourne, Australia. The gradient of urban density among streams was broadly correlated with catchment imperviousness, drainage connection (proportion of impervious areas connected to streams by stormwater pipes), altitude, longitude and median phosphorus concentration. Catchment area, septic tank density, median nitrogen concentration, benthic light (photosynthetically active radiation) and substratum type were not strongly correlated with the urban gradient.
3. Variation in benthic light and substratum type within streams explained a relatively small amount of variation in log chl *a* (3–11 and 1–13%, respectively) compared with between-site variation (39–54%).
4. Median chl *a* was positively correlated with catchment urbanisation, with a large proportion of variance explained jointly (as determined by hierarchical partitioning) by those variables correlated with urban density. Independent of this correlation, the contributions of drainage connection and altitude to the explained variance in chl *a* were significant.
5. The direct connection of impervious surfaces to streams by stormwater pipes is hypothesised as the main determinant of algal biomass in these streams through its effect on the supply of phosphorus, possibly in interaction with stormwater-related impacts on grazing fauna. Management of benthic algal biomass in streams of urbanised catchments is likely to be most effective through the application of stormwater management approaches that reduce drainage connection.

Keywords: chlorophyll *a*, imperviousness, nutrients, stormwater drainage connection, streams

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Introduction

Eutrophication is a fundamental concern in the management of many waterbodies, particularly those draining urbanised catchments. Urban stormwater is a major factor in promoting eutrophic conditions and degrading stream health (Bliss, Brown & Perry, 1979; Heaney & Huber, 1984; Lee & Bang, 2000; Hatt *et al.*, in press). It not only degrades water quality but also increases physical disturbance through increased intensity and frequency of floods and reduced base flow, resulting in loss of habitat through channel erosion and sedimentation (Marsalek, 1991; House *et al.*, 1993; Rutherfurd & Ducatel, 1994; Novotny & Witte, 1997; Walsh, 2000).

The stormwater-related effects of urbanisation on streams therefore result from multiple interrelated impacts on water quality, hydrology and habitat (Baer & Pringle, 2000; Sonneman *et al.*, 2001). Understanding the links between catchment-scale factors (such as the density and design of urban land) and small-scale factors (such as nutrients, light, flow velocity, flood frequency and substrata) is required to formulate management strategies aimed at preventing the eutrophication of streams and other downstream waterbodies.

The response of benthic algae to interactions of small-scale or site-specific factors has been widely studied (Lohman, Jones & Perkins, 1992; Biggs, 1995; Elosegui & Pozo, 1998; Pan *et al.*, 1999; Dodds, Smith & Lohman, 2002). However, when investigating streams it is often necessary to take a broader view, because many site-specific factors are confounded by complex interactions. For example, flood frequency and nutrient supply have been found to be primary controls of algal biomass (Biggs, 1995) as, too, have light, nutrients and substrate (Elosegui & Pozo, 1998). Managers are likely to find it difficult to decide on the appropriate action for restoration when so many stressors and stimulants are considered important in shaping algal communities.

Investigating large spatial-scale factors, which integrate the small-scale interactions, may be more useful from a management perspective. The response of algae to catchment-scale variables has received less study but has recently become a growing area of interest in aquatic research. The few studies that have been done have suggested that large-scale factors are more important than small-scale factors in determining long-term production (biomass accrual: Biggs & Gerbeaux, 1993) and community composition (Snyder *et al.*, 2002). In addition, stream degradation often stems from broad-scale catchment features that may only be controllable at this level (Biggs & Gerbeaux, 1993). Relationships between benthic algae and land use (urban, agriculture, forest) have been investigated (Pan *et al.*, 1999; Leland & Porter, 2000; Munn, Black & Gruber, 2002; Snyder *et al.*, 2002), however these studies did not identify the components of land use that were creating the disturbance. To effectively manage the impacts of urbanisation, the components of urbanisation that are the main sources of stress must be identified (Walsh *et al.*, 2004).

Catchment imperviousness (the proportion of a catchment covered by surfaces impermeable to water such as roads or roofs) and efficiency of drainage connection have been hypothesised as the two key elements of urbanisation that determine the impact of stormwater on aquatic ecosystems (Walsh, 2000). Catchment imperviousness has been described as a predominant driver of stream degradation in urban areas, because of the commonly observed negative correlation between imperviousness and stream condition (Beach, 2001; Center for Watershed Protection, 2003). However, the hydrological impacts of imperviousness are strongly influenced by drainage connection, which is defined here as the proportion of impervious surfaces directly connected to streams by stormwater pipes (Leopold, 1968; Booth & Jackson, 1997; Poff *et al.*, 1997). Stormwater drainage connection has been found to be a strong explanatory variable independently of the effects of imperviousness for the loss of an invertebrate species of conservation significance (Walsh *et al.*, 2004) and for in-stream concentrations of phosphorus, dissolved organic carbon and for conductivity (Hatt *et al.*, in press). Here, we apply similar analyses to assess the relative explanatory power of imperviousness and drainage connection in explaining patterns of algal biomass in small streams on the eastern fringe of the Melbourne metropolitan area (population 3.5 million), Victoria, Australia.

The objective of this study was to determine if benthic algal biomass (measured as chlorophyll *a* [chl *a*] concentration) is better explained by small-scale factors within each stream or by catchment-scale variables that incorporate the more complex interactions of multiple impacts of urbanisation. Small-scale factors considered were benthic light [photosynthetically active radiation (PAR) reaching the stream bottom], substratum type and nutrient concentrations, in particular, dissolved inorganic nitrogen (DIN), filterable reactive phosphorus (FRP), total nitrogen (TN) and total phosphorus (TP). We first assess the proportion of variance in algal biomass that was attributable to variation in benthic light and substratum type, within and among streams of varying catchment urbanisation using analysis of covariance. We then use hierarchical partitioning (Chevan & Sutherland, 1991) to explore which of three catchment-scale, urban indicators (imperviousness, drainage connection and septic tank density), three large-scale, non-anthropogenic factors (catchment area, altitude and geographical location) and three small-scale factors (nitrogen and phosphorus concentrations and benthic light) best explained, independently and jointly, patterns of median (and geometric mean) algal biomass among streams. Hierarchical partitioning is the most appropriate method for exploring potentially causal or explanatory relationships between a dependent variable and a set of potentially collinear independent variables (Mac Nally, 2000).

Methods

Study area

Sites on 16 streams, draining independent sub-catchments on the eastern fringe of Melbourne, were chosen for the study (Fig. 1). These sites represent a rural to urban gradient, with primary land uses of forest or residential urbanisation. Catchments with large areas of intensive agriculture or sites downstream of sewage treatment plants were excluded from consideration to ensure the major anthropogenic disturbance in study streams was most likely urban stormwater runoff.

The 13 sub-catchments draining the Dandenong Ranges (0–22% imperviousness, with various degrees of connection: Fig. 1, Table 1) were not arranged along the east–west rural–urban gradient. Because of the scattered, mosaic nature of settlements with various degrees of infrastructure development in the Ranges, the sub-catchments' characteristics were not strongly associated with a geographical gradient. Physiographical and geological variation was minimised by locating sites within this small area of Victoria. One sub-catchment to the east of the main study area had near-zero imperviousness. Two heavily urbanised streams draining the eastern suburbs of Melbourne, west of the Dandenong Ranges, had high levels of imperviousness (39 and 42%) and connection (99 and 98%) (Fig. 1, Table 1).

Reaches of 50–80 m were selected that contained areas of both closed and open riparian canopy. Because more urbanised streams tended to have wider channels (through incision and bank erosion from increased runoff), they tended to have more open canopies. All sites had some areas of closed canopy. There were no tributaries or stormwater pipes entering the stream within any reach.

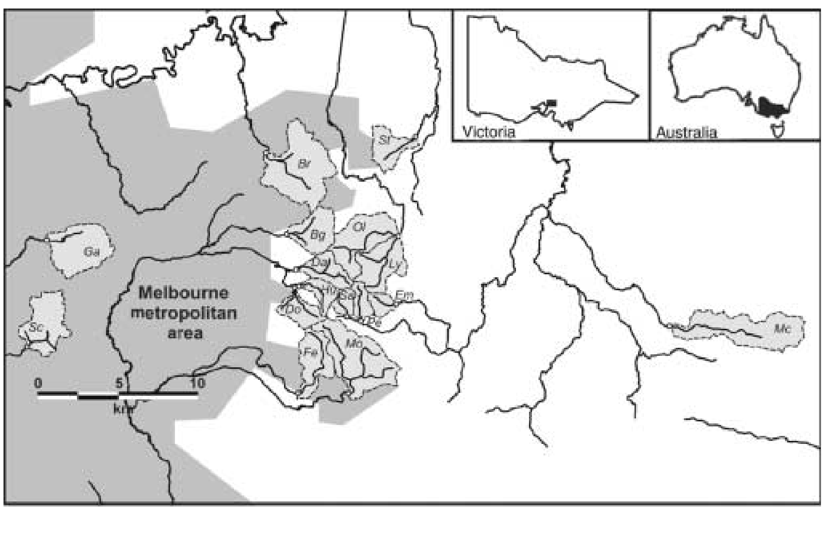

Fig. 1 Location of the 16 study sites (open circles) and their sub-catchments (lightly shaded with dashed lines). Stream codes are listed in Table 1. The 13 central sites drain the Dandenong Ranges on the fringe of the (darkly shaded) Melbourne metropolitan area.

Table 1 Summary of in-stream and catchment characteristics. Total number of chl *a* samples collected over the duration of the study (No.), median and maximum chl *a*, mean benthic light (photosynthetically active radiation, PAR) and depth, median filterable reactive phosphorus (FRP), median dissolved inorganic nitrogen (DIN), median total phosphorus (TP) and median total nitrogen (TN), percentage imperviousness (Imp), percentage drainage connection (Conn), septic tank density (Septics), catchment area (Area), altitude above sea level (Alt) and longitude (Australian map grid easting coordinate)

Stream-site	No.	Median chl. *a* (mg m^{-2})	Max chl. *a* (mg m^{-2})	Mean benthic PAR (mol m^{-2} day^{-1})	Mean depth (cm)	Median FRP (mg L^{-1})	Median DIN (mg L^{-1})	Median TP (mg L^{-1})	Median TN (mg L^{-1})	Conn (%)	Imp (%)	Septics (n km^{-2})	Area (km^{2})	Alt (m)	Longitude (m)
Scotchmans (Sc)	106	47	1232	1.6	42	0.012	0.3	0.05	0.61	99	39	0	8.1	78	335836
Gardiners* (Ga)	90	17	172	3.7	25	0.009	0.4	0.05	0.79	98	47	0	9.8	81	337030
Brushy (Br)	145	25	1184	3.9	26	0.027	0.6	0.11	0.97	89	22	38	14.8	82	350706
Ferny (Fe)	108	28	632	3.3	23	0.013	1.4	0.06	1.55	79	12	80	6.4	163	352696
Little Stringybark* (St)	87	20	258	3.4	19	0.012	0.2	0.03	0.58	58	10	48	4.5	137	360027
Bungalook (Bg)	110	27	357	7.5	9.5	0.160	1.7	0.35	2.00	57	6.8	53	5.8	133	351992
Dobsons (Do)	146	8.7	139	2.5	11	0.008	1.4	0.04	1.65	47	7.6	44	3.7	168	352500
Perrins (Pe)	110	2.0	47	2.8	6.6	0.010	1.7	0.04	1.90	20	5.3	75	2.2	327	356620
Dandenong (Da)	109	9.6	75	4.9	7.7	0.006	1.1	0.02	1.20	17	2.5	62	4.2	154	352585
Hughes (Hu)	111	5.9	131	3.5	5.8	0.006	1.4	0.03	1.60	12	3.5	63	2.8	173	352780
Monbulk (Mo)	108	14	158	1.0	15	0.035	1.6	0.09	1.90	11	3.2	69	13.5	159	355829
Sassafras (Sa)	147	1.8	47	2.2	6.8	0.004	1.8	0.03	2.10	8.3	8.0	141	1.9	370	355774
Olinda* (Ol)	90	5.1	39	2.1	13	0.002	1.6	0.01	1.90	3.0	3.9	88	9.1	222	358938
Emerald* (Em)	89	1.2	35	2.7	5.7	0.003	1.2	0.03	1.60	0	2.2	59	1.9	290	358831
Lyrebird (Ly)	147	4.0	121	3.2	8.1	0.003	0.3	0.04	0.82	0	0.1	0	7.2	222	358953
McRae* (Mc)	90	4.2	102	3.3	18	0.003	0.3	0.01	0.43	0	0.1	1.4	13.1	200	375893

*Not sampled in November–December 2001.

Determination of benthic algal biomass

The reaches were surveyed and mapped, and the maps were used to select randomly spaced sampling points for each sampling date. Twenty to 40 algal samples were collected from 11 streams in December 2001 and 30–40 samples were collected from all 16 streams in February, July and November of 2002. A pilot study determined 20 samples to be sufficient to estimate the geometric mean biomass with a precision (standard error/mean) <0.22. The primary method for algal biomass estimation was the extraction of chl *a*. Soft substrata (e.g. sand and silt) were sampled with 2.2 cm diameter sediment corers. From large rocks and wood, a 2.2 cm diameter area was scrubbed with a purpose built sampler. Small rocks that were >2 cm diameter or pieces of wood that were >2 cm long, but too small to be sampled using the scrubbing sampler, were collected, and the surface area later determined with plastic wrap (Doeg & Lake, 1981). The (approximately 60 ml) algal slurry collected from the sampler was filtered through Whatman GF/F glass microfibre filters. All samples were frozen before chl *a* extraction and analysed according to Jeffrey & Humphrey (1975). Water depth, substratum type and method of sampling were recorded at each sampling point.

Determination of environmental variables

Impervious areas (buildings, roads and carparks) were mapped using geographical information system software. Building areas were quantified using gross-building-area data (City of Knox and Shire of Yarra Ranges councils), which were geocoded using land parcel data derived from the Victorian state-wide cadastral map data (URL: http://www.land.vic.gov.au/). For each building a polygon was created with an area 1.6 times the registered building area: a ground-truthed correction factor to account for eaves, driveways, pathways and garages/sheds on an average house block. The generated buildings layer was checked against digital aerial orthophotography (November 1999–February 2000, Melbourne Water Corporation), and any omitted buildings and carparks were digitised manually. Areas of sealed (paved) roads were derived from the Victorian 1 : 25 000 topographic map series (URL: http://www.land.vic.gov.au/) and the State Digital Road Network.

Council stormwater drainage and Melbourne Water Corporation pipe and channel data were used to delineate areas where impervious surfaces were directly connected to streams by pipes. All impervious surfaces in these areas were defined as connected. All impervious surfaces not connected to streams or channels by stormwater pipes were defined as unconnected. In several settlements on the ridges of the Dandenong Ranges, some impervious areas were drained by stormwater pipes, but these in turn drained to dry earthen or grassed channels. Walsh *et al.* (2004) treated these settlements as ambiguously connected, and two sets of analyses were run: one with ambiguous areas treated as connected and another with them treated as unconnected. In our study, only two sites were affected by this distinction, both draining a settlement on the main ridge of the Dandenong Ranges. As we are primarily interested in assessing the impacts of stormwater pipes directly delivering stormwater to streams, this settlement was considered unconnected.

Catchments for all sites were delineated using 10 m contours from the 1 : 25 000 topographic map series (URL: http://www.land.vic.gov.au/) and stormwater pipe data. Altitude and longitude (as Australian Map Grid easting coordinates) were estimated from the same topographic map series.

Locations of all septic tanks in the majority of the study area were obtained from the Shire of Yarra Ranges. The rest of the study area consisted of completely sewered metropolitan suburbs, and was assumed to have no septic tanks (M. Hudson, Yarra Valley Water, personal communication).

Catchment imperviousness was calculated as the proportion of total impervious area to catchment area. Connection was calculated as the proportion of connected impervious area to total impervious area in a catchment. Septic tank density was calculated as the number of tanks per km^2 in each catchment.

Median baseflow concentrations of nitrate/nitrite and ammonium (summed to calculate DIN, FRP, TP, TN and total suspended solids (TSS) were determined using the methods and data of Hatt *et al.* (in press).

Substrata collected for chl *a* analysis were classified as either hard or soft. Core samples (except for some clay: see below) were considered soft. Rocks and wood that were collected or scrubbed were considered hard. The classification of clay varied among samples and was based on the firmness and condition of the surface 5 mm. If the clay was very firm (identified when inserting the core) and not covered by silt or litter, the substratum was considered hard.

Benthic light climate

Because it was impossible to directly measure the light climate over each sampling point prior to sampling, benthic light climate over the period of algal accrual at each algal sampling point was estimated by interpolation using 'light maps' of each reach. Maps of light climate at the water surface were generated using geostatistical software (Robertson, 2000) from a grid of light measurements along each reach. For each sampling point, the estimate of light climate at the surface was adjusted to allow for attenuation through the water using the depth of the sampling point and an estimate of water attenuation in each stream.

Spatial variation in light climate at the water surface was estimated for each stream by analysing digital photographs taken with a 180° fisheye (hemispherical) lens (Canham, 1988; Frazer, Canham & Lertzman, 1999). Images were taken from first light until first appearance of the sun to prevent underestimation of canopy cover from direct sunlight reflecting off the leaves. Reflection of sunlight was found to be a problem in a pilot project, even with a uniformly overcast sky (cf. Sinoquet, Rakocevic & Varlet-Grancher, 2000). Images were taken in a regular grid along the reach (approximately 45 photos per stream) so that the maximum distance between two adjacent images was <2 m. A preliminary study along one reach showed that spatial autocorrelation of light estimates extended 4–10 m, suggesting that images at 2 m intervals would permit adequate interpolation of light estimates. The first and last photographs, at each stream, were taken at a reference location so adjustments could be made to account for increasing light levels during the photograph run.

Each image was analysed with the Gap Light Analyser (GLA) software (Frazer *et al.*, 1999). The period of algal accrual was estimated to be 3 weeks, and average daily light was calculated for the 3-week period before sampling. The average cloudiness index for the period was estimated from records of diffuse and direct light for Melbourne (Bureau of Meteorology) together with six light loggers (Odyssey™, Photosynthetic Irradiance Recording Sensor; Dataflow Systems Pty Ltd, Cooroy, Queensland, Australia) deployed across the study area. The GLA outputs were calibrated by cross-checking images taken at the same location as the *in situ* light loggers with average daily light recorded by the loggers. The average daily surface light at each algal sampling point for each sampling date was interpolated with Block Kriging analysis (Robertson, 2000).

Benthic light was estimated for each sampling point from the surface light estimate and water depth for each sample, and an attenuation coefficient for each stream. Attenuation coefficients were calculated as follows. During the December 2001 algal sampling period, a field fluorometer (Walz Diving PAM; Heinz Walz, Effeltrich, Germany) with a fibre optic probe was used to take *in situ* light measurements at each of the algal sampling points (above and below the water surface) at five sites. Water attenuation coefficients were calculated from the available light and the transmitted light (from the fluorometer) (Kirk, 1983). A relationship was developed between attenuation coefficients and median baseflow TSS concentrations for these five streams ($k = 0.0009S + 0.0488$, where k is the attenuation coefficient in cm^{-1} and S is the TSS in $mg\ L^{-1}$, $R^2 = 0.68$). Attenuation coefficients for the other 11 streams were estimated from this relationship based on their median baseflow TSS concentrations.

Statistical analysis

Two analyses were used to explore the patterns of variance in benthic algal biomass. First, an analysis of covariance was used to assess the proportion of variance explained by within-stream variation, compared with between-stream variation. Secondly, factors that explain variation between streams were explored using hierarchical partitioning (Chevan & Sutherland, 1991).

An analysis of covariance was performed on four data sets (one from each sampling period) to assess the proportion of variance in $\log_{10}$-transformed chl *a* explained by small-scale variation in benthic light and substratum type compared with differences among sites. Stream (11 levels in December 2001, and 16 levels thereafter) and substratum (two levels, soft and hard) were treated as fixed factors and benthic light, which was estimated for each sample, was the covariate. Random sampling resulted in a different number of each substratum type in each reach on each sampling occasion. The range in light values also varied between sampling periods, due to seasonal variation. Samples with >8 mol m^{-2} day^{-1} were excluded from the analysis to ensure equality of the covariate range across sites. Where possible, a subset of six hard and six soft substrates was randomly selected for inclusion in the analysis to minimise variation in replication size. In a few cases only five of one substratum were available in one stream. Heterogeneity of slopes in relationships between benthic light and chl *a* was assessed by testing the three interaction terms combined (stream × light, substratum × light and stream × substratum × light) against the residual mean square (Quinn & Keough, 2002). Significance was accepted at $P < 0.05$. The proportion of variance explained by each term in the analysis was estimated using ω^2 (Quinn & Keough, 2002).

Relationships between environmental variables and mean and median $\log_{10}$-transformed chl *a* on each sampling period were assessed using multiple linear regression. For each sampling period, a hierarchy of 512 regression models was calculated using all combinations of nine environmental variables: imperviousness, drainage connection, septic tank density, catchment area, altitude, longitude, mean benthic light, median phosphorus concentration and median nitrogen concentration. These analyses were conducted once with phosphorus and nitrogen assessed as FRP and DIN, respectively, and again as TP and TN. We were thus able to assess Dodds' (2003) assertion that TN and TP were better indicators of trophic state.

Hierarchical partitioning of the regression models was performed with R^2 as the goodness-of-fit measure (Walsh & Mac Nally, 2003). This analysis distinguishes those variables that have high independent correlations with the dependent variable as opposed to a variable that may have a strong univariate correlation with the dependent variable by virtue of its correlation with other variables, but little independent effect (Mac Nally, 2000). Variables that independently explained a larger proportion of variance than could be explained by chance were identified by comparison of the observed value of its independent contribution to the explained variance (I) to a population of Is from 500 randomisations of the data matrix (Mac Nally, 2002). Significance was accepted at the upper 95% confidence interval (Z-score ≥ 1.65: Mac Nally, 2002; Walsh & Mac Nally, 2003). As the results of the analyses on medians and those on geometric means were nearly identical, only those for medians are presented.

The following transformations were performed to minimise the influence of outliers and to ensure that residual distributions approximated normality: FRP, TP and TN were $\log_{10}$ transformed; imperviousness and catchment area were fourth-root transformed; and drainage connection, septic tank density and altitude were square-root transformed. Correlation strengths are reported based on the transformed data.

Bungalook Creek and to a lesser extent Monbulk Creek were identified as having high FRP and TP concentrations that were unlikely to be caused by stormwater inputs. In the former, phosphorus was the only pollutant recorded at high levels, suggesting a non-stormwater origin (Hatt *et al.*, in press). The high phosphorus concentrations in Monbulk Creek were likely to be a result of inputs of wastewater from houses immediately upstream. These wastewater inputs were unrecognised during site selection. To assess the effects of these outliers, analyses were repeated with these streams omitted.

Results

Relationships between environmental variables

Urban density as indicated by sub-catchment imperviousness was positively correlated with drainage connection ($R^2 = 0.79$) (Fig. 2). Drainage connection displayed a large spread (0–80%) over a small range of imperviousness (2–12%), apart from five sub-catchments, two with near zero imperviousness and no connection and three that were highly impervious and almost completely connected. Sub-catchment imperviousness and longitude were negatively correlated ($R^2 = 0.71$). However, this relationship was primarily influenced by two highly urbanised sites to the west and one near-zero impervious sub-catchment to the east of the main study area. Altitude ranged from 80 to 370 m and was more strongly correlated with connection ($R^2 = 0.56$) than imperviousness ($R^2 = 0.34$). Urban density was not well correlated with septic tank density or catchment area (Fig. 2). Median FRP and TP were positively correlated with imperviousness ($R^2 = 0.50$ and 0.38, respectively) and connection ($R^2 = 0.78$ and 0.49, respectively), but DIN and TN were poorly correlated

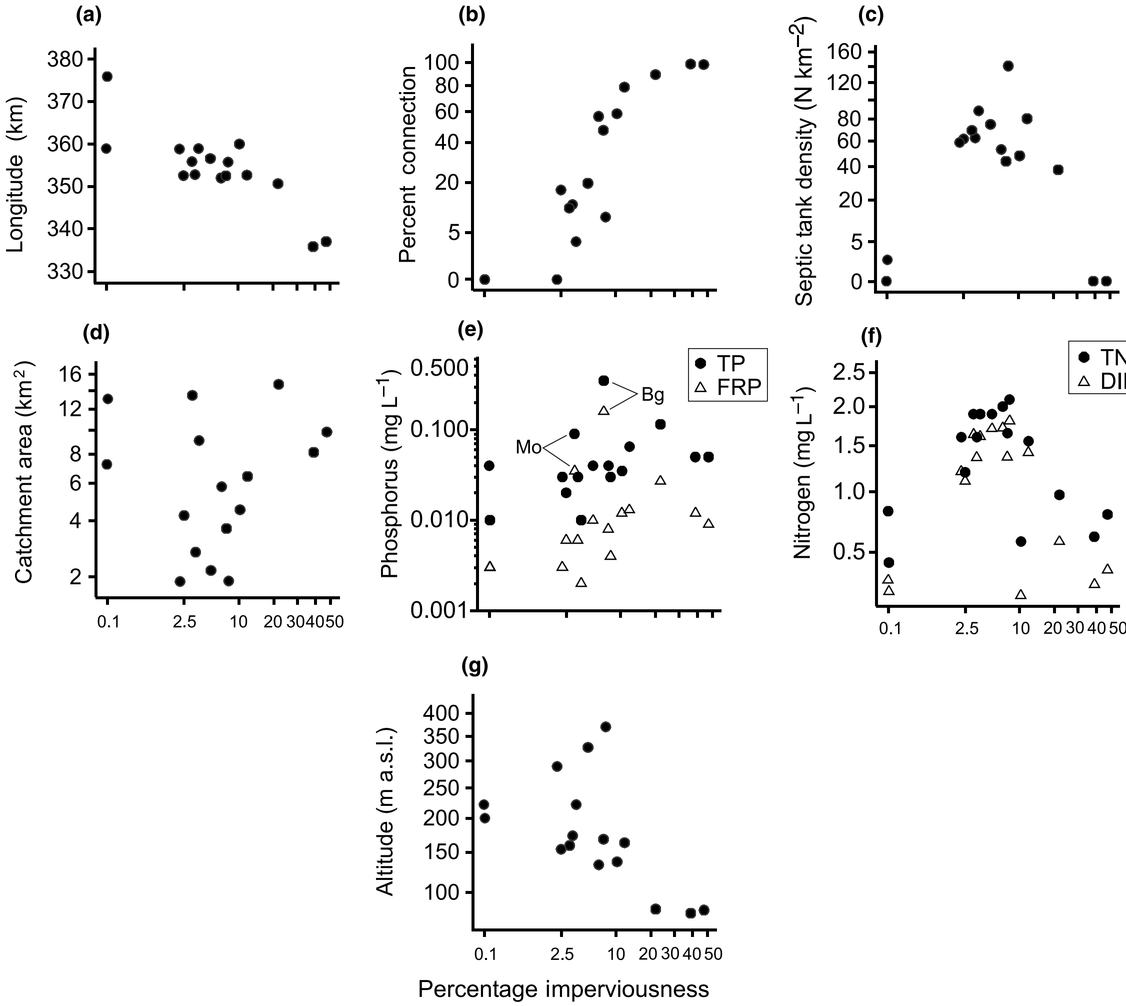

Fig. 2 Relationships between six catchment-scale variables in 16 study sites. (a) longitude (Australian map grid easting coordinate), (b) percentage drainage connection, (c) septic tank density, (d) catchment area, (e) total (TP) and filterable reactive phosphorus (FRP), with two outliers indicated (site codes as in Table 1), (f) total (TN) and dissolved inorganic nitrogen (DIN) and (g) altitude, all plotted against percentage catchment imperviousness.

with the general urban density gradient (Fig. 2). The general urban gradient was therefore broadly correlated with imperviousness, connection, median phosphorus concentration and the inverse of altitude and longitude.

Benthic light varied among sites, but was not strongly correlated with the urban gradient (Fig. 3). The pattern of benthic light contrasted with the pattern for surface light, which tended to be greater in the more urban sites, because of the wider channels and more open canopies (Fig. 3). However, this trend in surface light was counteracted by the tendency of streams draining more urbanised catchments to be deeper (Table 1). Thus benthic light was more attenuated by water in streams of more urbanised catchments.

The proportions of hard and soft substrata were not related to the urban gradient. Nine of the 16 streams had a relatively even mix of soft and hard substrata (within 10% of being an even mix). Of the remaining streams, five were dominated by hard substrata ranging from 61 to 72% hard, and two streams, Hughes and Lyrebird creeks, were dominated by soft substrata, 67 and 65%, respectively. Two incised streams, Bungalook and Little Stringybark creeks, were composed predominantly of clay substrate. Sand was the dominant soft substratum in four streams: Scotchmans, Gardiners and Brushy, located in the

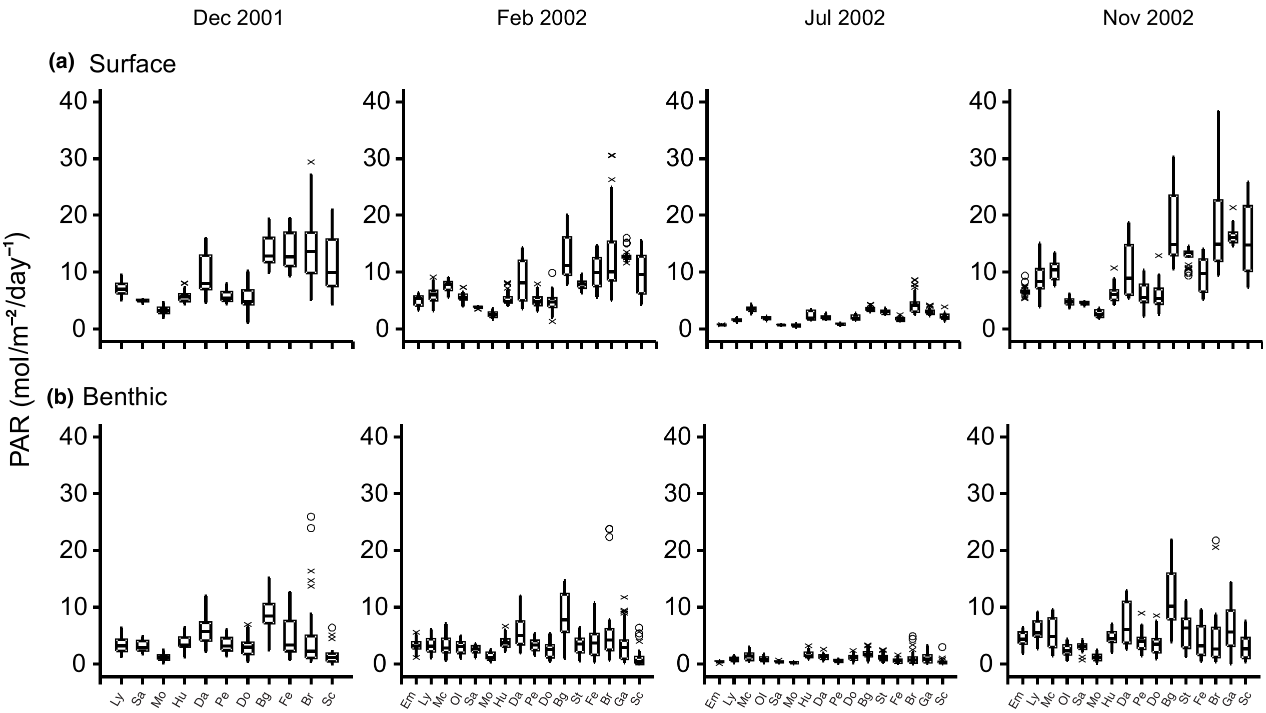

Fig. 3 Box plots of surface light (photosynthetically active radiation, PAR) and benthic light for each stream for the four sampling periods. Sites are ordered with increasing drainage connection, which was a strong correlate of the urban gradient.

most highly urbanised sub-catchments, and McRae Creek with zero imperviousness. A mix of silt and fine sand dominated the soft substrata of the remaining sites, all within the Dandenong Ranges.

Variation in algal biomass

Differences among sites accounted for much more of the variance in algal biomass than did light and substratum composition in all seasons sampled (Table 2). Benthic light was positively correlated with algal biomass in all months and the slope of the relationship was consistent among streams and between substratum types (non-significant combined interaction term for: (i) December 2001: $F = 1.65$, d.f. = 21, 84, $P = 0.06$, (ii) February 2002: $F = 1.22$, d.f. = 31, 126, $P = 0.23$, (iii) July 2002: $F = 0.71$, d.f. = 31, 128, $P = 0.87$, (iv) November 2002: $F = 1.03$, d.f. = 31, 24, $P = 0.44$). In all months, the effect of benthic light on chl *a* was small compared with the variance between sites (Table 2). The effect of substratum composition was also small compared with the variance between sites, but where significant substratum effects did occur, hard substrata supported greater algal biomass than soft substrata (Table 2).

Median chl *a* ranged from 1.2 to 47 mg m^{-2} (Table 1). Two of the streams with the highest catchment urbanisation, Scotchmans and Brushy creeks, reached maximum chl *a* concentrations of 1230 mg m^{-2} (February 2002) and 1180 mg m^{-2} (November 2002), respectively. Gardiners Creek, also with a highly urbanised catchment but with lower median FRP concentrations (Table 1), did not reach such high biomass levels (maximum of 172 mg m^{-2}).

Total phosphorous and TN independently and jointly explained less variation in median chl *a* than did FRP and DIN. Therefore, only the hierarchical partitioning analyses using FRP and DIN are presented. The results of hierarchical partitioning were unchanged when the streams identified as having high phosphorus concentrations were omitted from the analysis.

Median chl *a* concentration was positively correlated with urban density, as indicated by the large amount of variance that was jointly explained by the inter-correlated variables connection, imperviousness, altitude and FRP (Fig. 4). However, independent of

Table 2 Analysis of covariance tables for $\log_{10}$ chlorophyll *a* (mg m^{-2}) for 11 streams in December 2001, and 16 streams in February, July and November 2002

	December 2001, $R^2 = 0.67$					February 2002, $R^2 = 0.58$					July 2002, $R^2 = 0.67$					November 2002, $R^2 = 0.67$				
Effect	SS	d.f.	*F*	*P*	ω^2 (%)	SS	d.f.	*F*	*P*	ω^2 (%)	SS	d.f.	*F*	*P*	ω^2 (%)	SS	d.f.	*F*	*P*	ω^2 (%)
Stream	18.4	10	17.7	<0.001	52.1	22.9	15	10.7	<0.001	39.3	24.7	15	15.4	<0.001	47.6	29.8	15	16.9	<0.001	54.2
Substratum	2.0	1	19.4	<0.001	12.8	0.3	1	2.2	0.142	0.6	0.8	1	7.8	0.006	3.0	0.4	1	3.2	0.076	1.2
Light	1.0	1	9.6	0.003	6.9	2.2	1	15.5	<0.001	7.0	2.7	1	25.1	<0.001	11.2	0.7	1	5.7	0.018	2.6
Stream × substratum	0.9	10	0.9	0.536	−0.3	4.8	15	2.2	0.008	9.5	3.2	15	2.0	0.019	7.8	2.5	15	1.4	0.151	3.4
Residual	10.9	105			28.6	22.5	157			43.6	17.0	159			30.3	18.2	155			38.6

SS, sum of squares; d.f., degrees of freedom; ω^2, percentage of total explained variance (Quinn & Keough, 2002).

this joint correlation, drainage connection explained more of the variation in algal biomass than was explicable by chance, in all seasons. Altitude was the only other significant independent correlate; in February, July and November 2002.

On all sampling occasions, median chl *a* concentration was more strongly correlated with drainage connection than with imperviousness (Table 3), which independently explained a small proportion of the variance (Fig. 4). Mean benthic light, septic tank density and DIN all explained very little variance (Fig. 4).

Discussion

The urban density gradient (characterised by drainage connection, imperviousness, and also correlated with altitude and median phosphorus concentration) strongly explained patterns of algal biomass. Streams in more urbanised catchments supported more benthic algae than streams with less catchment urbanisation, indicating a decline in ecological condition.

The degradation of in-stream habitat and water quality in urbanised catchments is not the result of a single cause. Rather, it is the cumulative effect of multiple sources of stress that are responsible for the decline in stream condition (May & Horner, 2002). Imperviousness has traditionally been the focus for predicting and explaining declines in water resource integrity (Beach, 2001; May & Horner, 2002; Center for Watershed Protection, 2003). However, in this study drainage connection was a stronger explanatory variable for algal biomass than was imperviousness. Altitude was the only other factor to independently explain significant proportions of variation in algal biomass (in three of the four sampling periods). A natural altitude gradient in algal biomass, as suggested by the River Continuum Concept (Vannote *et al.*, 1980), is possible. However, independent of the altitude effect and of the general urban gradient, drainage connection explained a large proportion of variance in algal biomass.

The importance of the catchment-scale effect of drainage connection is in contrast to the relatively small amount of variance independently explained by small-scale variables. Nevertheless, the impacts of urbanisation on benthic algae must act through small-scale mechanisms. Urbanisation reduces infiltration of water through the loss of natural forest cover,

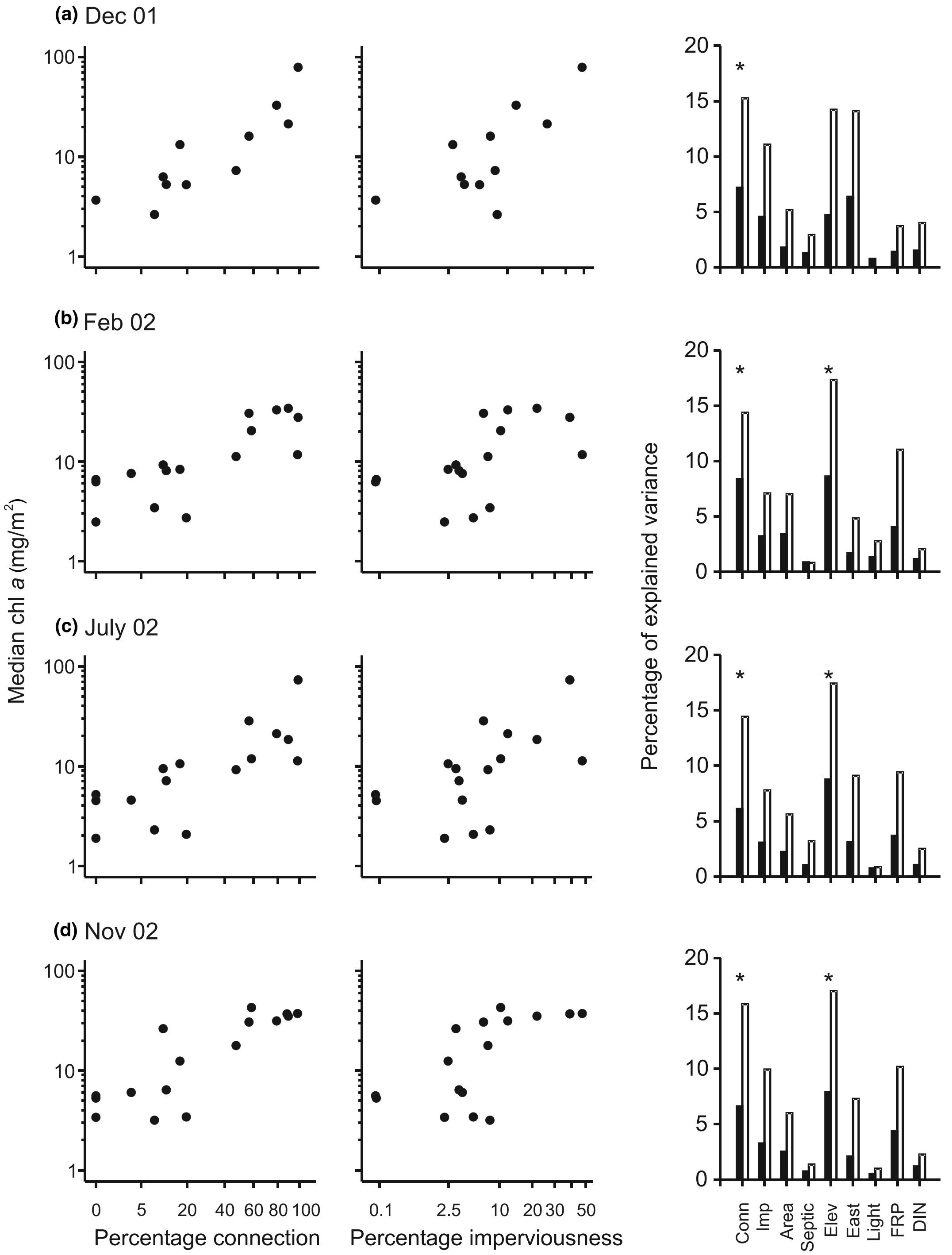

Fig. 4 Median chlorophyll *a* at 16 streams for four sampling periods plotted against percentage drainage connection and percentage imperviousness. Bar graphs display the percentage of variation that is explained by the nine urban indicators. Solid bars are the independent contribution and open bars are the joint contribution to the explained variance. *Significant independent contributions at $P < 0.05$.

increased impervious surfaces, reduction and fragmentation of riparian corridors and stormwater drainage connection. Drainage systems pipe stormwater directly from impervious surfaces into receiving waters thereby short-circuiting the 'natural' passage of water and bypassing soil infiltration and riparian

Table 3 Strength of correlations (R^2) between chl *a* concentrations and environmental variables for each sampling period. Full models are multiple regression models using nine environmental variables (one using FRP and DIN and a second using TP and TN)

	December 2001	February 2002	July 2002	November 2002
Imperviousness	0.52	0.28	0.32	0.42
Connection	0.75	0.62	0.60	0.71
Septics	0.14	0.05	0.12	0.07
Catchment area	0.23	0.28	0.23	0.27
Altitude	0.63	0.71	0.76	0.79
Longitude	0.69	0.18	0.35	0.30
TP	0.09 (0.23)	0.14 (0.38)	0.13 (0.24)	0.24 (0.42)
FRP	0.17 (0.50)	0.41 (0.49)	0.38 (0.41)	0.46 (0.56)
TN	0.22 (0.27)	0.03 (0.13)	0.06 (0.16)	0.12 (0.15)
DIN	0.19 (0.23)	0.09 (0.21)	0.10 (0.25)	0.11 (0.27)
Light	0.02	0.11	0.05	0.05
Full model (TP, TN)	0.99 (1.0)	0.91 (0.98)	0.86 (0.94)	0.95 (0.95)
Full model (FRP, DIN)	0.99 (1.0)	0.89 (0.97)	0.87 (0.91)	0.93 (0.99)

Values in brackets are correlations with the outliers, Monbulk and Bungalook creeks, removed.

processing (Groffman *et al.*, 2002). This bypassing of the riparian zone and other parts of the catchment can have multiple interrelated impacts on stream systems.

Hydrology

Hydrologic changes associated with urbanisation primarily stem from the efficient delivery of surface runoff to streams by stormwater pipes. The lack of soil infiltration results in an increased discharge volume into receiving streams and hence, increased peak flows. In urbanised catchments small rain events can result in a substantial increase in stream flow, in contrast to the predevelopment condition where a small rain event may not have produced runoff (MacRae, 1996). Flow disturbance can induce scouring and erosion of the stream bank and streambed. Erosion may widen the stream channel and damage an already reduced riparian zone. Drainage connection can also reduce baseflow levels through reduced levels of infiltration in the catchment leading to a reduction in groundwater recharge (Reininga & MacDonald, 2002). While imperviousness contributes to these hydrology-related impacts, the efficiency of stormwater drainage (i.e. drainage connection) can account for a large proportion of the change in runoff resulting from urban land use (Wong, Breen & Lloyd, 2000). However, if water is permitted to run off onto pervious areas for infiltration rather than into pipes, the impacts may be greatly reduced (Tourbier, 1994).

In our study, streams with higher flow disturbance had higher chl *a* concentrations, therefore the negative influence of hydraulic disturbance (i.e. the loss of biomass through sloughing and substratum instability) cannot be a primary cause of algal growth patterns as suggested in other studies (Biggs & Close, 1989; Steinman *et al.*, 1990; Biggs, 1995; Biggs & Thomsen, 1995). In November 2002, two of the most urbanised streams, Scotchmans Creek and Gardiners Creek, were sampled 1 day after an approximately one in 30-day rain event. Although we expected a reduction in chl *a* concentrations, they were still higher in these streams than in the less urbanised streams. Filamentous green algae, promoted by high phosphorus concentrations, were dominant in these streams and their long strands are particularly susceptible to sloughing (Biggs, Goring & Nikora, 1998). Following the November 2002 event, mats of algae were still observed on rocks, so the flood disturbance did not result in the complete removal of benthic algae. It has been suggested that if a spate only causes partial destruction, exponential growth of algae could occur soon after (Biggs & Thomsen, 1995), and sub-scouring spates (those that do not remove algae from substrata) could stimulate filamentous algal growth in nutrient-rich streams (Humphrey & Stevenson, 1992). Hydraulic disturbance from a large rain event must initially cause a reduction in algal biomass due to sheer stress but this may be tempered by a more rapid rebound in biomass accrual at highly enriched sites (Lohman *et al.*, 1992).

Light

The generally positive correlation between benthic light and algal biomass within streams suggests that light was, at least in part, limiting algal growth. Thus strategies to reduce algal biomass in urban streams by restoring riparian vegetation (Suren, 2000) are likely to have some effect. However, the effect of light in the small streams of eastern Melbourne was small compared with inter-stream differences that were attributable to differences in catchment urbanisation. Thus management strategies aiming to reduce catchment-derived stormwater impacts are likely to be more effective than riparian restoration.

Benthic light was not correlated with urban density in our study (Fig. 3b), as a result of two opposing effects: increased surface light with increasing catchment urbanisation (Fig. 3a), together with increased attenuation through greater depths of water (Table 1). This trend may be observable beyond this study area. Stormwater impacts produce morphological changes to stream channels that reduce the shading effect of riparian vegetation, through channel enlargement (e.g. Gregory, 1987), and it is possible that our observation of increased mean depth could also be a widespread phenomenon.

Nutrients

Terrestrial vegetation and soil microbial communities intercept and process pollutants moving in surface runoff and groundwater flow (Groffman *et al.*, 2002). Riparian zones, in particular, can function as nutrient sinks (Groffman *et al.*, 2002). This helps to prevent the movement of pollutants into streams from catchment land uses. When piped drainage infrastructure is in place, riparian zones and non-riparian parts of the catchment have less opportunity to influence the quality of stormwater, as pollutants are discharged directly from impervious surfaces into receiving waters.

We postulate that nutrient stimulation resulting from piped stormwater runoff is the major mechanism explaining the strong correlation between connection and algal biomass. Dodds (2003) suggested that TP : TN would be a better indicator of nutrient limitation than DIN : FRP because of the highly variable ratios of dissolved to particulate nutrients in many streams. All our streams other than the three most impacted (Br, Sc and Ga) had TN : TP ratios of >20 w : w indicating that phosphorus was the most likely limiting nutrient in most of our streams.

Phosphorus was likely to have had a primary role in limiting algal growth in the seven streams that had median FRP concentrations less than 8 $\mu g\ L^{-1}$ (all <20% drainage connection, Table 1). The minimum concentration required for maximum biomass accrual has been proposed as 8–50 $\mu g\ L^{-1}$ (Horner *et al.*, 1990; Borchardt, 1996). FRP was strongly correlated with drainage connection (Hatt *et al.*, in press), and more highly connected streams all had median baseflow FRP levels >8 $\mu g\ L^{-1}$, suggesting more frequent release from phosphorus limitation. A model of biomass concentrations in 25 runoff-fed streams (Biggs, 2000) predicted a linear increase in biomass accrual with FRP concentrations of 1–30 $\mu g\ L^{-1}$, which corresponds with the range of median concentrations observed in our study. However, connection was a stronger independent correlate with algal biomass than was FRP. Therefore, median baseflow FRP may not integrate factors driving algal biomass accrual as well as drainage connection does.

If bioavailability of phosphorus was the primary determinant of the observed increase in algal biomass with increasing urban density, one hypothesis to explain the stronger correlation with connection could be that median baseflow FRP is not an appropriate statistic to indicate bioavailable phosphorus. If FRP were limiting, the development of biomass may be dependent on the diffusional supply of FRP into the developing algal assemblage (Borchardt, 1996). Water column concentrations may not reflect micro-scale conditions of relevance to the algae when water velocity is highly attenuated within algal assemblages (Dodds & Biggs, 2002). The effect of more frequent sub-scouring flow events may relieve nutrient deficiency through increased nutrient concentrations and a reduction in the boundary layer around algal cells and mats. A better indicator of nutrient supply might be a measure of the frequency of high flows rather than baseflow median concentrations. Phosphorus concentrations were found to be higher during high flows than during base flows in these streams (Hatt *et al.*, in press). Frequent small flow events, that are more common with increasing connection, are likely to be beneficial to algal growth in urban streams through an increased supply of phosphorus during an accrual cycle (Biggs & Close, 1989).

A second hypothesis to explain the stronger correlation with connection than with FRP could be that algal biomass is determined by non-linear interactions between phosphorus availability and indirect effects of stormwater-related disturbances on grazing fauna, resulting in varying grazing pressures at different levels of connection. Experiments could be designed to test the importance of stormwater impacts on grazers and on nutrient concentrations and the interaction of these factors on algal biomass.

Drainage connection and catchment management

From a management perspective, the mechanisms by which drainage connection affects algal biomass are of little importance because all can potentially be controlled by management of drainage connection itself. The identification of drainage connection as the most likely cause of increased benthic algal growth alters the options likely to be considered by urban waterway managers aiming to control algal growth. Our work suggests that riparian planting to increase channel shading may reduce algal growth, but in the context of an urbanising catchment, management of the catchment itself is likely to be more effective.

Previous attempts to characterise catchment-scale drivers of stream degradation have focused on catchment imperviousness (e.g. Center for Watershed Protection, 2003), and some authors (Beach, 2001; Center for Watershed Protection, 2003) have been pessimistic about the potential for structural stormwater management to mitigate impacts of imperviousness. In contrast, our study strongly suggests that stormwater management practices that reduce drainage connection are likely to help reduce benthic algal growth. New approaches to urban design (termed low-impact design in the U.S.A., and water sensitive urban design in Australia) use a range of stormwater treatment measures at different scales, all of which reduce connection by maximising retention, infiltration or treatment of stormwater (Coffman, 2002; Lloyd, Wong & Porter, 2002; May & Horner, 2002; Reininga & MacDonald, 2002). If, as postulated above, the increased frequency of small stormwater flows from pipes is a major cause of increased algal growth, then perhaps a primary aim in disconnection of the drainage system should be to ensure, as much as possible, that flow through pipes to the stream does not occur for frequent, small rain events.

The explanatory models derived from hierarchical partitioning identify the most likely causal factor from those variables included in the model. By considering imperviousness and drainage connection as separate, independent variables, we have demonstrated the potential importance of drainage connection for the streams of eastern Melbourne, in which connection ranged widely over a relatively small range of imperviousness (2–12%). For the subsequent development of predictive models, it is likely that effective imperviousness (Booth & Jackson, 1997), the product of connection and total imperviousness, will prove a better predictor variable over a wider range of total imperviousness. This variable integrates the 'connection' effect and the urban gradient effect, both of which were found to be important correlates of benthic algal biomass.

Currently, because low-impact design has not been applied over wide areas in any city, it is unlikely that many catchments of >12% imperviousness have been built with low levels of connection. However, reduction of surface flows to zero for most rain events is possible (using dispersed biofiltration systems) in suburban residential developments of typical density (Lloyd, Wong & Chesterfield, 2002). If such design was applied at a catchment scale, streams draining them could potentially have flow regimes and water quality close to the predevelopment condition. We therefore postulate that low-impact developments of >12% imperviousness should result in reduced benthic algal biomass compared with catchments of the same imperviousness but with traditional stormwater drainage systems. The growing adoption of low-impact approaches to urban design presents opportunities for catchment-scale experiments to test this hypothesis.

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