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The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams

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ABSTRACT / Effective water quality management of streams in urbanized basins requires identification of the elements of urbanization that contribute most to pollutant concentrations and loads. Drainage connection (the proportion of impervious area directly connected to streams by pipes or lined drains) is proposed as a variable explaining variance in the generally weak relationships between pollutant concentrations and imperviousness. Fifteen small streams draining independent subbasins east of Melbourne, Australia, were sampled for a suite of water quality variables. Geometric mean concentrations of all variables were calculated separately for baseflow and storm events, and these, together with estimates of runoff derived from a rainfall-runoff model, were used to estimate mean annual loads. Patterns of concentrations among the streams were assessed against patterns of imperviousness, drainage connection, unsealed (unpaved) road density, elevation, longitude (all of which were intercorrelated), septic tank density, and basin area. Baseflow and storm event concentrations of dissolved organic carbon (DOC), filterable reactive phosphorus (FRP), total phosphorus (TP) and ammonium, along with electrical conductivity (EC), all increased with imperviousness and its correlates. Hierarchical partitioning showed that DOC, EC, FRP, and storm event TP were independently correlated with drainage connection more strongly than could be explained by chance. Neither pH nor total suspended solids concentrations were strongly correlated with any basin variable. Oxidized and total nitrogen concentrations were most strongly explained by septic tank density. Loads of all variables were strongly correlated with imperviousness and connection. Priority should be given to low-impact urban design, which primarily involves reducing drainage connection, to minimize urbanization-related pollutant impacts on streams.

Runoff from urban areas is one of the leading sources of water quality degradation in surface waters (U.S. Environmental Protection Agency 2000). Urbanization degrades stream ecosystems in a variety of ways that are not easy to separate: increased frequency and intensity of flood flows, decreased groundwater levels, increased stream bank erosion, and increased loads of pollutants (Novotny and Olem 1994), with resulting multiple impacts on aquatic ecosystems (Paul and Meyer 2001). In cities with separate storm and sanitary sewerage systems, stormwater runoff is the primary degrader of streams (Walsh 2000). Increased imperviousness (the proportion of a basin covered by surfaces impermeable to water, such as roofs and roads) and hydraulically efficient drainage systems typical of urban areas, result in increased frequency and intensity of flood flows, decreased groundwater levels, increased stream channel and bank erosion, and increased loads and concentrations of pollutants (Novotny and Olem 1994).

Pollutants running off urban areas are difficult to measure and regulate because they ultimately arise from a multitude of activities and are variable in time because of the effects of weather. Because of these difficulties, models that predict runoff and pollutant loads are required to estimate the impacts of urbaniza-

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tion in urban waterways and receiving waters (Duncan 1999). Furthermore, effectively managing the impacts of urbanization requires identification of the elements of urbanization that contribute most to pollutant loads. Although basin-scale features are recognized as important drivers of instream condition (Johnson and others 1997, Gergel and others 2002), the mechanisms of this behavior have not yet been clearly described (Duncan 1999, Brezonik and Stadelmann 2002).

Land-use zoning has commonly been used as a predictor of water quality (Soranno and others 1996, Carpenter and others 1998). However, assigning a pattern of pollutant output to a particular land use provides little insight into the processes impacting on aquatic systems, or how to manage that land use to reduce its pollutant output. The U.S. EPA's Nationwide Urban Runoff Program found land use to have little power in explaining site-to-site differences in pollutant loads (Novotny and Olem 1994).

Two elements of urban land use—basin imperviousness and drainage infrastructure—are major contributors to changes in hydrology arising from stormwater runoff (Leopold 1968). Relationships between imperviousness and water quality have emerged in recent years (Arnold and Gibbons 1996, May and others 1997, McMahon and Cuffney 2000), and a predictive relationship between pollutant loads and basin imperviousness has been promoted (Center for Watershed Protection 2003). However, correlations between pollutant loads and imperviousness tend to be weak. We postulate that the hydraulic efficiency of drainage infrastructure can explain a large proportion of the unexplained variation in the relationship between pollutant loads and imperviousness.

Drainage efficiency has long been recognized as an important determinant of hydrological change (Leopold 1968), accounting for up to 80% of the increase in peak discharge in urbanized basins (Wong and others 2000). However, no published studies have assessed the importance of stormwater drainage connection to pollutant loads or concentrations in receiving waters. This lack of basin-scale study is surprising, considering that most stormwater abatement techniques reduce drainage efficiency through infiltration or retention for treatment (Novotny and Olem 1994).

Our hypothesis of the importance of hydraulic efficiency of stormwater drainage is consistent with the suggestion of "effective imperviousness" as a better predictor of stream degradation than total imperviousness (Booth and Jackson 1997). Effective impervious areas are defined as those impervious areas directly connected to streams or receiving waters by pipes or lined channels. Because effective imperviousness is a subset of total imperviousness, a comparison of their relative importance is best achieved by comparing their independent parts. Effective imperviousness can be considered the product of total imperviousness and drainage connection (defined as the proportion of all impervious areas directly connected to streams). We aim to assess the relative importance of these two elements of effective imperviousness in explaining concentrations of pollutants.

We use geometric means of baseflow and storm event concentrations and a rainfall-runoff model to estimate loads of each water quality variable. We then assess whether the effects best explaining variation in concentrations among the 15 streams are the same as those best explaining loads. We propose that effective imperviousness is likely to be a good predictor variable of loads and concentrations for predictive models of the effects of urban land use.

Methods

Study Area

Sites on 15 first- or second-order streams with similar riparian cover, draining independent subbasins of similar area, spanning the eastern edge of the Melbourne metropolitan area, Victoria, Australia, were chosen for the study (Figure 1). These sites represent a rural-to-urban gradient and were selected to encompass as wide a range as possible of both imperviousness and drainage connection (Figure 2, Table 1). In selecting sites, we also aimed to minimize variation in physiographic and climatic conditions, and to minimize spatial confounding of subbasin characteristics. As a result, most streams were located within the Dandenong Ranges, east of Melbourne. One of these streams had near zero subbasin imperviousness. A second near-zero impervious subbasin further to the east of the Dandenong Ranges was also chosen. Eleven other Dandenong Ranges streams ranging in imperviousness from 2.2% to 12% were selected. Two streams with heavily urbanized subbasins were selected in the suburbs to the west of the ranges (Figure 1).

To ensure that urban stormwater runoff was the major anthropogenic impact in the study streams, only subbasins with primary land-uses of urban or forest were selected. Subbasins with intensive agriculture were excluded. A second possible impact across the study area that we have assessed is polluted subsurface flow from poorly maintained septic tanks.

Determination of Subbasin Characteristics

Seven environmental variables were considered as potential correlates with water quality variables (Table

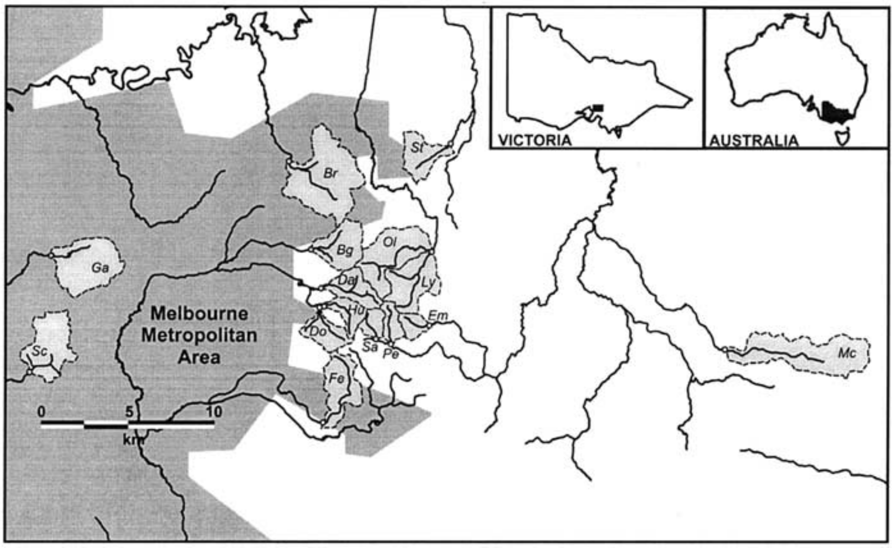

Figure 1. Map of the study area. The shaded area indicates the Melbourne metropolitan area. The fifteen subbasins chosen are outlined with dashed lines.

1). Four were indicators of potential impacts of urban land use: imperviousness (the proportion of basin area covered by impervious surfaces), drainage connection (the proportion of impervious surfaces directly connected to streams by pipes or lined channels), septic tank density, and unsealed (unpaved) road density (area of unsealed roads to basin area). Three variables, basin area, elevation, and longitude were potentially correlated variables that may more strongly independently explain observed patterns than anthropogenic impacts.

Elevation and longitude (measured as kilometers east of the most westerly site) were estimated from the Victorian 1:25 000 topographic digital map series (URL http://www.land.vic.gov.au). Basin areas were delineated using 10-m contours from the topographic map data and local government digital data of stormwater drainage lines. Septic tank density was determined using a local government database of septic tank locations. Impervious areas (and unsealed road areas) were mapped using digital road data, local government building area data, and aerial orthophotography. The connection status of impervious areas was estimated from proximity to stormwater drains, allowing for local topography, and was checked by ground truthing. The methods of determination were described in more detail by Walsh and others (2004). In that study, areas drained by stormwater pipes, but in turn draining to dry earthen or grassed channels, were treated 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. Because we are primarily interested in assessing the impacts of stormwater pipes directly delivering stormwater to streams, this settlement was considered unconnected.

Data Collection

Water quality was sampled at the 15 sites during baseflow and storm events from September 2001 to March 2003 (Table 1). Samples were collected every 2 weeks, along with additional storm event samples from September 2001 to November 2002. After November 2002, only storm event samples were collected. To avoid biasing results with respect to time of day, samples taken every 2 weeks were collected from the 15 sites in a random order on each sampling trip. Event sampling occurred on a response basis with the aim of capturing the variation in water quality experienced between and within storm events. Event sampling took two forms: (1) single grab samples taken at all sites; and (2) multiple samples taken manually at Em, Fe, Ga, Ly, Ol, and Sc (Table 1). In addition to the manual sampling, autosamplers connected to a float switch (Sigma Model 900 Standard Portable Sampler) were installed at Br and Do in September 2002 to sample storm events. Samples collected by the autosamplers were processed within 36 hours of collection.

Water quality variables measured were water temperature, pH, electrical conductivity (EC), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), filterable reactive phosphorus (FRP), ammonium (NH_4^+), nitrate/nitrite (NO_x) and dissolved organic carbon (DOC). Analyses were undertaken by the NATA

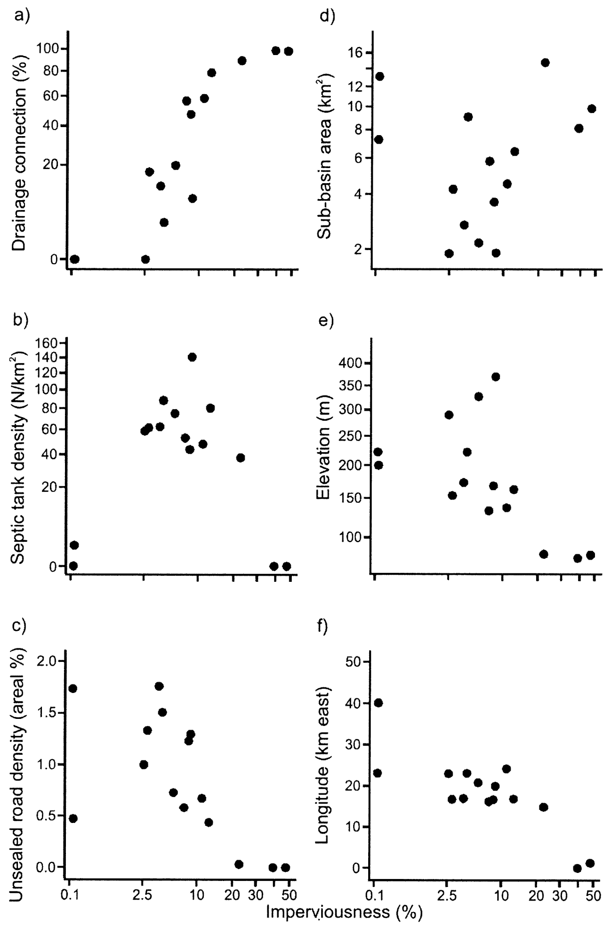

Figure 2. Relationships between percentage imperviousness and (**a**) percentage drainage connection, (**b**) septic tank density, (**c**) unsealed road density, (**d**) subbasin area, (**e**) elevation and f) longitude, in the 15 study sites. Consistent with analyses, axes have been transformed.

accredited (URL http://www.nata.asn.au/) Water Studies Centre analytical laboratory, using standard methods and quality control/assurance procedures (Table 2) (Water Studies Centre 2001).

Staff gauges were installed at each site, and flow heights were recorded when water quality samples were taken. Flow was estimated at each site using an appropriate hydraulic model, constructed with HEC-RAS 3.0 (Hydrologic Engineering Centre 2002), or Manning's equation if a suitable culvert was near the sampling location. The hydraulic models were calibrated with limited flow measurement data (velocity measurements undertaken using a flow meter: Hydrological Services, Model C.M.C 20).

Data Analysis

Factors explaining patterns in concentrations. Median and geometric mean concentrations for each site were calculated separately for baseflow and storm-event data. Samples taken every 2 weeks were classified as being taken in either baseflow or storm-flow conditions, using a two-step process. First, frequency analysis (using the data density distributions) was used to identify the threshold between baseflow and storm flow. Seasonal variation was then taken into account by examining the flow data over time, and identifying whether a variable threshold should be applied across seasons. In most cases, there was very little or no seasonal influence.

For each date on which multiple samples from a storm event were collected, a flow-weighted mean concentration (EMC in mg/L) was calculated, as follows (Eq. 1):

$$EMC = \frac{\sum_{1}^{n}((t_{i+1} - t_i) \times 0.5(Q_j + Q_{j+1})(c_i + c_{i+1}))}{\sum_{1}^{n}((t_{i+1} - t_i) \times 0.5(Q_j + Q_{j+1}))} \tag{1}$$

where: n = number of samples collected during the event, t_i = time sample i was taken, c_i = concentration for sample i, and Q_j = flow at time t_i.

Because EMCs were not calculated for all streams, geometric mean and median storm-flow concentrations were calculated in two ways for analysis. First, means and medians were calculated using only storm-flow data from the two-weekly sampling. Second, the mean and median for each site were calculated using the set of concentrations from all single storm-flow samples from the two-weekly data, together with all EMCs calculated for that site. The number of baseflow and storm event samples collected, and EMCs calculated for each site are shown in Table 1.

The relationships between concentrations (baseflow and storm event, median and geometric mean) of all water quality variables and the seven subbasin variables were assessed using multiple linear regression. Analyses were undertaken on transformed data in order to minimize the influence of outliers and to ensure that residual distributions approximated normality. Imperviousness and subbasin area were fourth-root transformed, while drainage connection, septic tank density, elevation, median NO_x and temperature, and the geometric means of DOC and temperature were square-root transformed. Longitude, median TN, and pH were untransformed. Median DOC, EC, FRP, NH_4^+, TP and TSS, and all other geometric means were all $\log_{10}$-transformed. All reported correlation strengths are based on the transformed data.

Table 1. Summary of subbasin characteristics: subbasin area (Area), longitude (distance east of the most westerly site), elevation, imperviousness (Imp), drainage connection (Conn), septic tank density (Septics), percentage of the subbasin covered by unsealed roads (U Roads) and the number of baseflow, storm event grab samples collected and event mean concentrations (EMC) calculated

Subbasin name	Area (ha)	Longitude (km)	Elevation (m)	Imp (%)	Conn (%)	Septics (N/km^2)	U Roads (%)	No. samples: Base flow	Event flow	EMC
Bungalook Ck (Bg)	579	16.2	133	6.8	57	52.8	0.58	21	13	—
Brushy Ck (Br)	1479	14.9	82	22	89	37.8	0.03	19	11	11
Dandenong Ck (Da)	424	16.8	154	2.5	17	61.5	1.33	20	11	—
Dobsons Ck (Do)	365	16.7	168	7.6	47	43.8	1.23	21	17	7
Hughes Ck (Hu)	275	16.9	173	3.5	11	62.5	1.76	15	15	—
Emerald Ck (Em)	188	23.0	290	2.2	0	58.6	1.00	20	9	1
Ferny Ck (Fe)	642	16.9	163	12	79	80.4	0.44	29	9	1
Gardiners Ck (Ga)	982	1.19	81	47	98	0	0	19	12	1
Lyrebird Ck (Ly)	724	23.1	222	0.1	0	0	1.74	18	15	1
McRae Ck (Mc)	1310	40.1	200	0.1	0	1.4	0.47	16	18	—
Olinda Ck (Ol)	907	23.1	222	3.9	3.0	88.2	1.51	18	13	1
Perrins Ck (Pe)	218	20.8	327	5.3	20	74.9	0.73	19	13	—
Sassafras Ck (Sa)	189	19.9	370	8.0	8.3	141	1.30	20	11	—
Scotchmans Ck (Sc)	812	0.00	78	39	99	0	0	17	14	1
Little Stringy bark Ck (St)	451	24.2	137	10	58	47.9	0.67	19	18	—

Table 2. Water quality variable collection and processing methods

Variable	Method of collection and processing	Detection limit
TSS, EC	Unfiltered, clean polyethylene bottle, refrigeration prior to laboratory analysis (AMHA-AWWA-WPCF 1998)	TSS: 0.5 mg/L
Total nutrients (TN,TP)	Unfiltered, clean polyethylene bottle, acidified, laboratory analysis (Hosomi and Sudo 1986)	0.02 mg/L
Nutrient species (NH_4^+, NO_x, FRP)	Filtered (0.2 μm) into clean polyethylene bottle (*in situ* for manual samples; in laboratory for samples collected by autosamplers), frozen prior to laboratory analysis (AMHA-AWWA-WPCF 1998)	0.001 mg/L
DOC	Filtered (0.2 μm) into clean polyethylene bottle, acidified, laboratory analysis (AMHA-AWWA-WPCF 1998)	1 mg/L
pH, temperature	Measured *in situ* using Horiba U-10 Water Quality Checker	—

DOC, dissolved organic carbon; EC, electrical conductivity; TN, total nitrogen; TP, total phosphorus; FRP, filterable reactive phosphorus; NH_4^+, ammonium; NO_x, nitrate/nitrite; TSS, total suspended solids.

Hierarchical partitioning of R^2 values was used to determine the proportion of variance explained independently and jointly by each variable (Chevan and Sutherland 1991, Mac Nally 2000). This method allows identification of variables whose independent correlation with the dependent variable is strong, in contrast to variables that have little independent effect but have a high correlation with the dependent variable resulting from joint correlation with other independent variables. Variables that independently explained a larger proportion of variance than could be explained by chance were identified by comparison of the observed value of independent contribution to explained variance (I) to a population of Is from 500 randomizations of the data matrix. Significance was accepted at the upper 95% confidence limit (Z-score ≥ 1.65: Mac Nally 2002, Walsh and Mac Nally 2003).

One of the subbasins (Bg) was found to be an extreme outlier in terms of phosphorus concentrations. Analyses for phosphorus were therefore conducted with Bg included and again with it omitted. We postulate that the phosphorus loads in Bg originated from a nonstormwater origin, because FRP and TP were the only variables for which Bg was an outlier.

Calculation of standardized pollutant loads. Annual loads of each water quality variable were estimated using geometric mean concentrations for base flow and storm flow at each site, together with a modeled estimate of total base flow and storm flow volumes. A subdaily rainfall-runoff model (Model for Urban

Stormwater Improvement Conceptualisation: Wong and others 2002) was used to generate base flow and storm flow volumes for each basin. The rainfall-runoff model, based on the algorithms of Chiew and McMahon (1999), was run using a 12-minute timestep, based on a standardized rainfall record (Melbourne rainfall for the period January 1, 1990 to December 31, 2000: mean annual rainfall = 648 mm, mean annual areal potential evapotranspiration = 1051 mm). The exact quantum of, and geographic variation in, annual rainfall, is not important to this study. Our aim is to quantify the pattern between effective imperviousness and pollutant loads, for a given (constant) level of rainfall. Actual loads measured at any location will of course be influenced by rainfall volume and distribution at that location. Although total annual rainfall varies across the 15 basins, our objective was to determine the relative differences in loads between basins of differing effective imperviousness, rather than to quantify absolute differences in loads, as a function of climatic variation. The rainfall-runoff model was run using an impervious store (based on our estimates of effective imperviousness), and a single pervious store, with store properties (impervious area initial loss, pervious area capacity and initial storage, groundwater recharge and drainage rate) held constant. Estimated runoff volumes were therefore solely driven by the estimates of effective basin imperviousness.

Loads were calculated based on two sets of mean storm-flow concentrations, calculated in the two ways described previously to ensure that exclusion of EMCs made no difference to the results. Derived loads were scaled to a per-hectare basis, for standardized comparison between subbasins. The strengths of correlations between the elements of effective imperviousness and pollutant loads were compared qualitatively with the correlations for pollutant concentrations. No statistical testing of the relationships between pollutant loads and impervious area has been undertaken, because the two variables are necessarily correlated (i.e., the modeled flow is itself a function of imperviousness). Nonetheless, the patterns of loads among the 15 sites allow us to examine whether the effects of effective imperviousness on runoff volumes override other factors that may have been stronger correlates with concentrations.

Results

Relationships Between Environmental Variables

Subbasin imperviousness and drainage connection were correlated (Pearson correlation coefficient, $\rho = 0.89$; Figure 2a). This correlation was primarily influenced by subbasins Sc, Ga, and Br (Table 1) with high imperviousness and drainage connection and subbasins Ly and Mc (Table 1) with near zero imperviousness and no drainage connection. However, drainage connection varied widely across a small range of imperviousness among the Dandenong Ranges sites. Imperviousness was significantly negatively correlated with unsealed road density ($\rho = -0.65$; Figure 2c) and longitude ($\rho = -0.84$; Figure 2f). The latter correlation was strongly influenced by two highly urbanized subbasins in the west (Sc and Ga; Table 1) and a single subbasin in the east (Mc; Table 1); among the sites in the Dandenong Ranges, imperviousness was not strongly correlated with longitude. Elevation was moderately correlated with subbasin imperviousness ($\rho = -0.58$; Figure 2e) and more strongly correlated with drainage connection ($\rho = -0.75$). Septic tank density showed a unimodal relationship with imperviousness: septic tanks were sparse both in basins of low and high subbasin imperviousness, but more abundant in the moderately urbanized basins (Figure 2b). Subbasin area was not strongly correlated with imperviousness ($\rho = 0.13$, Figure 2d) or drainage connection ($\rho = 0.28$). Therefore, of the seven variables considered, five (imperviousness and drainage connection, and the inverses of elevation, longitude, and unsealed road density) were intercorrelated indicators of urban density.

Factors Explaining Patterns in Water Quality Concentrations

Because the results for median and geometric mean concentrations were nearly identical, only geometric means are reported. Similarly, only storm event mean concentrations calculated using EMCs are reported because patterns for storm event mean and median concentrations were unchanged if EMCs were included in calculations. For most water quality variables, patterns were the same for baseflow and for storm event concentrations: where there was a difference, it is noted below.

Temperature, EC, and concentrations of DOC, FRP, TP, and NH_4^+ all increased with subbasin imperviousness (Figure 3). More than half of the explained variation in these water quality parameters was jointly explained by imperviousness, drainage connection, elevation, longitude, and unsealed road density: variables that were intercorrelated indicators of urban density. Independently of that joint correlation, drainage connection explained more of the variance in TP (storm event only), DOC, EC, and FRP than could be explained by chance (Table 3, Figure 3). Elevation was also a strong independent correlate of variance in EC

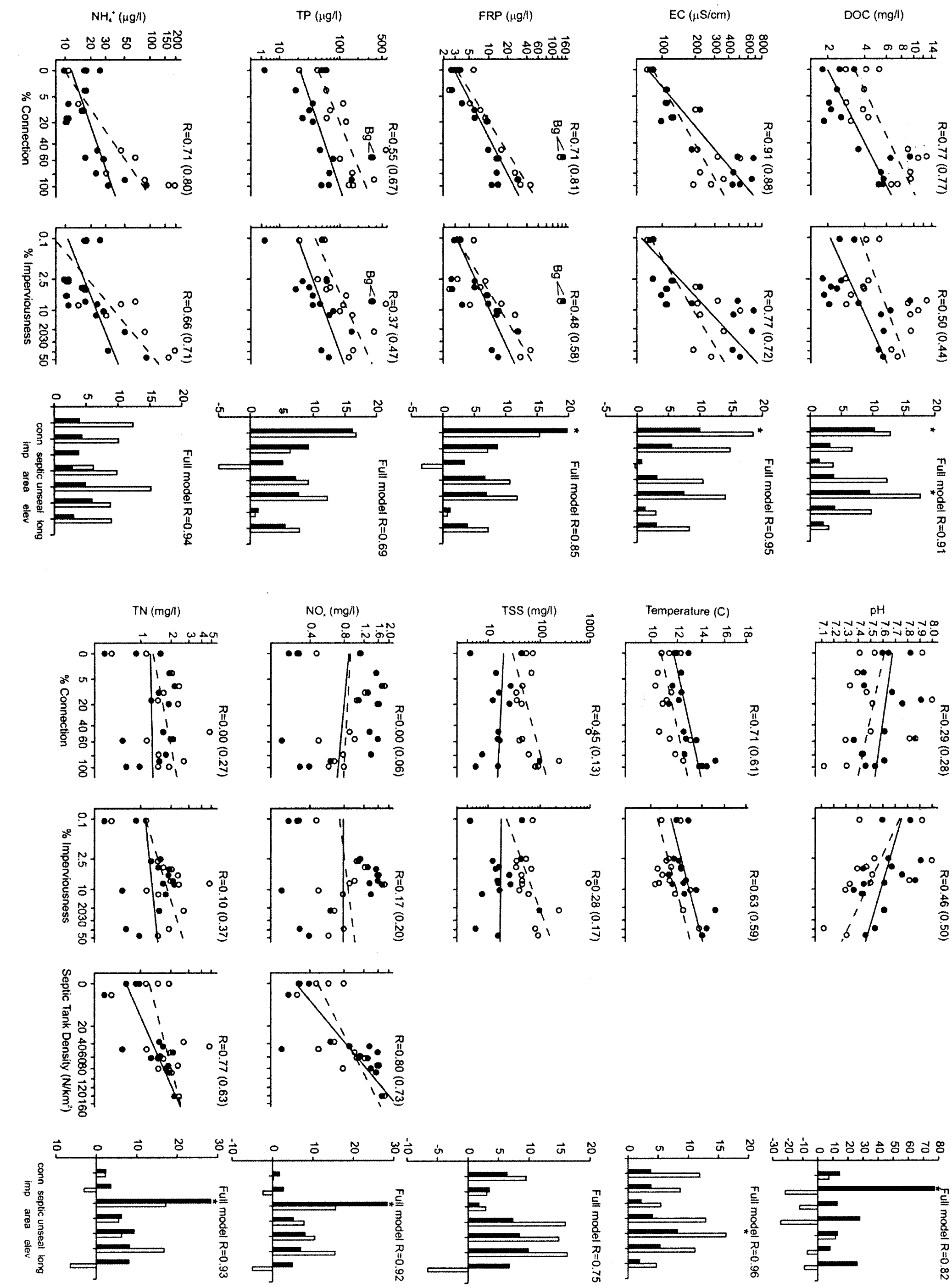

Figure 3. Relationships between geometric means of baseflow (closed circles, solid regression lines) and storm event (open circles, dashed regression lines) concentrations and three environmental variables. R values for baseflow concentrations (storm event concentrations in parentheses) for each graph and for the full model (all seven environmental variables) are indicated. Consistent with analyses, axes have been transformed. The bar charts indicate percentage of explained variance in baseflow concentrations explained by each of the seven environmental variables (conn, connection; imp, imperviousness; septic, septic tank density; unseal, unsealed road density; elev, elevation; area, subbasin area; long, longitude) independently (solid bars) and jointly (open bars) as determined by hierarchical partitioning. Variables marked with an asterisk were identified as significant independent correlates. Negative joint variance indicates that the other variables are "suppressors" of the variable in question (Chevan and Sutherland 1991). DOC, dissolved organic carbon; EC, electrical conductivity; FRP, filterable reactive phosphorus; NH_4^+, ammonium; TP, total phosphorus.

Table 3. Strength of correlations between median concentrations (base flow and storm event) and the two major indicators of subbasin urbanization and variables identified by hierarchical partitioning as being significant independent correlates.[a]

Water quality parameter	Pearson correlation coefficient				Significant independent correlates	
	Base flow		Storm event			
	Conn	Imp	Conn	Imp	Base flow	Storm event
DOC	0.76	0.50	0.77	0.44	Conn, Elev	Conn, Elev
EC	0.90	0.77	0.88	0.72	Conn	Conn, Elev
FRP	0.71	0.48	0.81	0.58	Conn	Conn
NH_4^+	0.71	0.67	0.80	0.71	—	—
NO_x	−0.17	−0.07	−0.06	0.20	Septic	Septic
pH	−0.29	−0.46	−0.28	−0.50	Imp	Imp
Tem	0.71	0.63	0.61	0.59	Elev	—
TN	−0.04	0.09	0.28	0.38	Septic	Septic
TP	0.55	0.38	0.67	0.47	—	Conn
TSS	−0.45	−0.29	0.13	0.17	—	—

[a]conn, drainage connection; imp, imperviousness; Elev, elevation; Septic, septic tank density; TN, total nitrogen; TP, total phosphorus. For other abbreviations, see Table 2.

(storm event only), temperature (baseflow only), and DOC (Table 3, Figure 3).

For DOC, EC, FRP, and TP, the correlation with drainage connection was stronger than with imperviousness. The correlations with imperviousness were strongly influenced by the most and least impervious sites, with wide variation within the intermediate imperviousness range (Figure 3). Omission of the outlying Bg from phosphorus analyses generally improved the fit of relationships but did not alter the significance of the independent contributions of the environmental variables.

For pH and TSS, the overall correlations with imperviousness, drainage connection, or other environmental variables were weak. Imperviousness was the strongest independent correlate of variance in pH (Table 3).

NO_x and TN were not strongly correlated with imperviousness or drainage connection, but were strongly correlated with septic tank density ($\rho = 0.80$ and 0.77, respectively), which independently accounted for more than a quarter of the explained variation in both NO_x and TN (Table 3, Figure 3).

Patterns in Mean Annual Loads

Mean annual loads of all water quality variables were strongly positively correlated with both imperviousness and drainage connection (and therefore effective imperviousness: Figure 4). This was the case even for those variables for which concentrations were not strongly correlated with imperviousness or connection: NO_x, TN, and TSS. In contrast to the case for concentrations, NO_x and TN loads were poorly correlated with septic tank density. The strengths of correlations were similar regardless of the method used for calculating mean concentrations (i.e., with and without EMCs).

Discussion

Concentrations

Urbanization was the most likely primary determinant of stream water quality degradation. Both drainage connection and imperviousness, as subbasin scale indicators of urban density, explained much of the observed variation in pollutant concentrations. In particular, we hypothesize that efficiency of runoff delivery from impervious areas is a cause of increased EC and concentrations of DOC, EC, FRP, and TP. Drainage pipes bypass subsurface pathways of water flow, both in the riparian and nonriparian sections of basins, resulting in direct transportation of stormwater to receiving waters, with little or no terrestrial processing of nutrients and pollutants. This bypassing, and the associated reduction in water table levels, result in riparian vegetation being "hydrologically isolated" from uplands and streams, further reducing the opportunity for riparian zones to influence the quality of stream water (Groffman and others 2002).

Several water quality indicators were more strongly correlated with drainage connection than with imperviousness, suggesting that, at least at low levels of imperviousness, stream water quality degradation is controlled more by the manner in which impervious areas are connected to receiving waters than by the presence of impervious areas alone. Previous studies (e.g. Bannerman and others 1993, Schueler 1994, Booth and

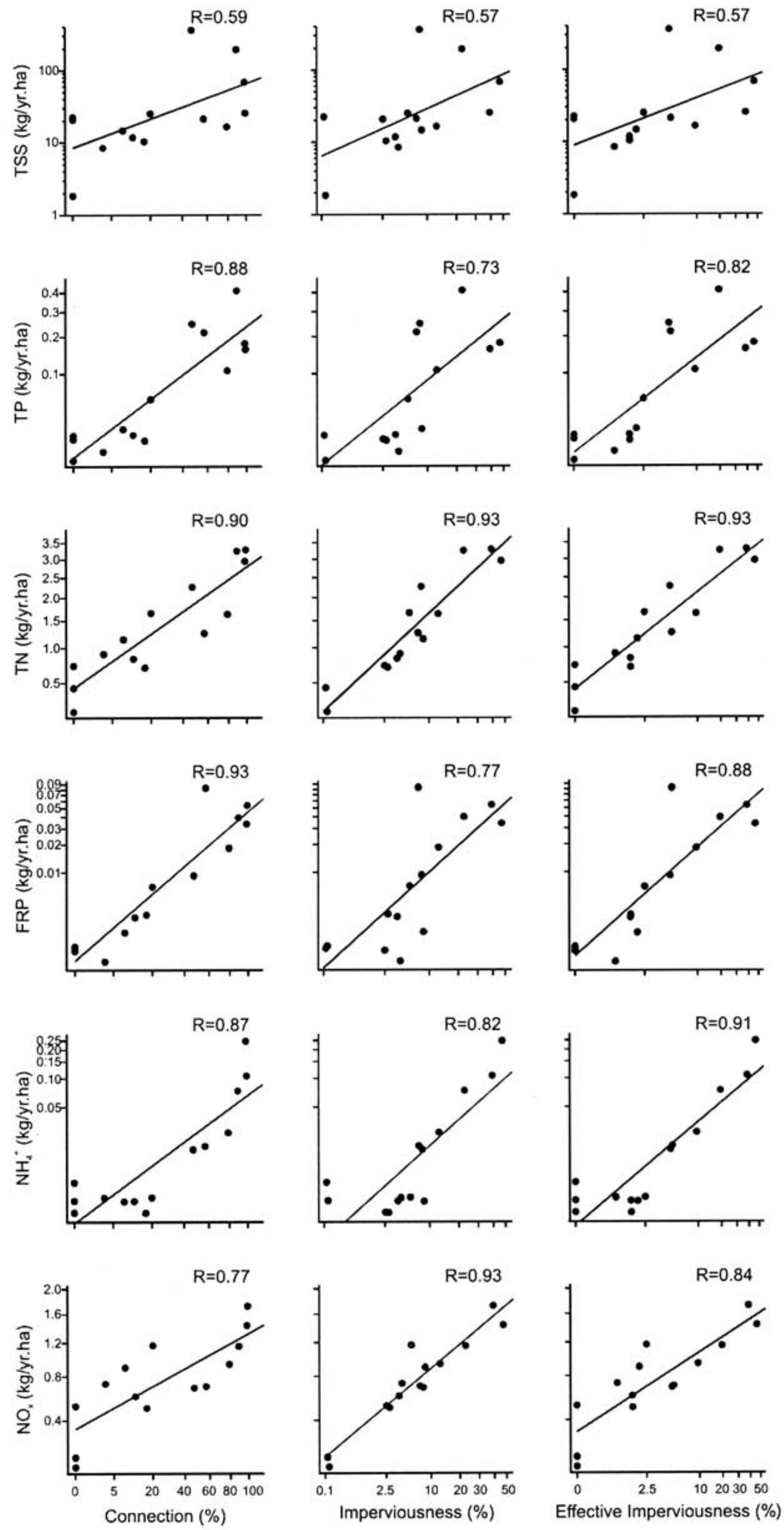

Figure 4. Relationships between mean annual loads (estimated using single event samples and event mean concentrations) and drainage connection, imperviousness, and effective imperviousness. FRP, filterable reactive phosphorus; NH_4^+, ammonium; NO_x, nitrate/nitrite; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids.

Jackson 1997) have acknowledged the potential importance of the degree to which impervious areas are directly connected to streams, but the relative importance of such connection has not been well investigated.

The importance of drainage connection as a correlate with concentrations of several variables, independently of the correlation with imperviousness, suggests that drainage connection may be an important cause of observed variation in water quality among streams with similar levels of imperviousness. Because drainage connection is independent of the amount of impervious area being drained by the stormwater pipes, it is surprising that connection was a stronger overall correlate with several variables than was imperviousness. The observed strong relationship suggests that even very small proportions of impervious area are capable of increasing pollutant concentrations, as long as there is a delivery mechanism between the impervious area and the stream. The strength of the correlations with drainage connection may have been a result of the structure of our dataset. Most of the variation in water quality was among sites in a relatively narrow range of imperviousness (0–12%), with a wide range of drainage connection. It is likely that, for a wider range of total imperviousness, effective imperviousness would be a stronger predictor of water quality degradation than drainage connection alone.

Drainage connection was important even for baseflow concentrations, suggesting that there may be sources of pollutants discharging to the stream via the stormwater drainage system even when there is no direct rainfall runoff. It is possible, however, that this pattern may be caused by residence time in streams exceeding time between events. No published previous studies have compared baseflow and high flow concentrations; typically, all samples have been grouped together (but see Meador and Goldstein 2003, where concentrations were flow-weighted) or only baseflow (e.g. Johnson and others 1997) or EMCs (e.g. Brezonik and Stadelmann 2002) have been considered. We suggest that both baseflow and storm flow should be considered separately because, although it is storms that contribute the majority of pollutant loads in these streams, baseflow concentrations are important to the stream ecosystem, because these are the conditions experienced by the stream biota most of the time.

The strong positive relationship between urban density and EC in the streams of eastern Melbourne is consistent with the proposition that urbanization alters both the rate of ionic flux through basins and the ionic composition of the total dissolved solids loads in runoff (Prowse 1987). Prowse (1987) attributed increased salinity in streams with increased basin urbanization to a combination of urban sources such as atmospheric deposition, building materials, and highways, and to accelerated chemical denudation of the basin. Our finding that drainage connection independently explains a large proportion of the variation in EC suggests that enhanced stormwater drainage efficiency further increases the transport of ions from urban sources to streams. Efficient stormwater drainage also decreases groundwater recharge (Rose and Peters 2001, Groffman and others 2002). The resultant reduced interaction with groundwater may also at least partly explain this relationship between drainage connection and EC.

Suspended solids concentrations in streams around the world have been reported to be weakly correlated with density of urban land use, with higher concentrations flowing from urbanized basins than from forested basins (Duncan 1999). In our study, TSS concentrations were not strongly correlated with urban density, and if the three geographical outliers (Sc, Ga, Mc; Table 1) were excluded, TSS was negatively correlated with urban density ($\rho = -0.64$ with imperviousness and $\rho = -0.74$ with connection). This pattern, contrasting with world trends (Duncan 1999), is likely to be an artefact of the marine sedimentary geology of the slopes of the Dandenong Ranges, which produces high silt loads. It is possible that the effects of increased imperviousness and piping or lining of drainage channels in these basins may have resulted in lower than natural TSS concentrations.

Septic tank density was the dominant influence on NO_x concentrations. Subbasins with the highest septic tank densities also had the highest concentrations of NO_x and the highest proportions of nitrogen present as NO_x. These high NO_x concentrations are unlikely to have a strong, direct impact on biota in streams draining *Eucalyptus regnans* forests (such as those studied here) because these streams tend to contain naturally high NO_x concentrations (Attiwill and others 1996) and uptake is likely to be limited by the very low phosphorus concentrations.

Hierarchical partitioning has proved a useful method for identifying environmental variables that are most likely to be causal drivers of pollutant concentrations in streams. This method differs from the more commonly used stepwise model selection methods to relate broad anthropogenic (e.g., land-use/land cover) and nonanthropogenic features (basin area, slope, elevation) to water quality (Johnson and others 1997, Brezonik and Stadelmann 2002). Stepwise methods of model selection are generally regarded as flawed and prone to produce spurious models (Mac Nally 2000). Other methods that have been used to identify the causes of patterns include factor analysis (Wayland and others 2003), principal components analysis, and cluster analysis (Meador and Goldstein 2003). However, these approaches are used to combine variables into smaller subsets rather than to identify the individual features that are potentially causing degradation of stream water quality.

Loads

Loads of all water quality variables were strongly correlated with effective imperviousness and its constituent elements. The estimates of storm runoff volumes (derived from effective imperviousness) were highly influential in determining estimated loads of pollutants. As a result, the loads of variables such as NO_x, for which concentrations were strongly explained by septic tank density, were more strongly explained by effective imperviousness.

The most commonly used indicator of urban land-use in the past has been total imperviousness (Center for Watershed Protection 2003). However, the distinction between total and effective imperviousness has not been explicit in many studies (Booth and Jackson 1997): typical values of effective imperviousness have been used rather than direct measurement. In general, total imperviousness has been used because it is quicker to measure and does not require extensive knowledge of the drainage infrastructure (Center for Watershed Protection 2003). Our finding of drainage connection as the dominant independent correlate with concentrations of several important pollutants and as a strong correlate of loads of all pollutants suggests that the direct determination of effective imperviousness will greatly increase the predictive power of models of urban effects on water quality.

Approaches by other researchers to modeling the effects of urbanization on pollutant loads have ranged from the application of a single export coefficient for each urban land-use type (Soranno and others 1996) to empirical estimation of loads in several basins that were then related to land use (Charbeneau and Barrett 1998, Sokolov and Black 1999, Brezonik and Stadelmann 2002). Although such models have proved useful in gross estimates of loads from multiple-use basins (Soranno and others 1996, Sokolov and Black 1999), correlations between land use indicators and loads or EMCs have generally been found to be weak. Hence, these models are of little use in identifying the most important elements of urban land use causing increased pollutant loads and concentrations (Charbeneau and Barrett 1998, Brezonik and Stadelmann 2002). Models using total imperviousness and drainage connection as predictor variables have greater potential management utility, because connection in particular is an attribute of urban land that is able to be manipulated through alternative drainage design.

Management Implications

The importance of drainage connection as an explanatory factor for both concentrations and loads of a range of pollutants points to the need for alternative approaches to stormwater management. The aim must be to break the direct linkage between impervious areas and the receiving waters. Opportunities for implementing drainage changes exist both at-source and "end-of-pipe," but distributed, at-source measures may provide the best opportunities for maintaining natural hydrology (Wong and others 2000). Options include retrofitting stormwater drainage systems in existing urban areas, and incorporating low-impact design (LID, also called water-sensitive urban design: Lloyd and others 2002) into new developments to prevent degradation of receiving waters.

In our study, we were unable to find any streams that drain subbasins with both imperviousness greater than 12% and low levels of drainage connection. However, because drainage connection was an important correlate independent of imperviousness, we postulate that effective water quality control will be possible by minimizing drainage connection in basins with higher levels of imperviousness, up to a point. The scope to disconnect impervious areas will diminish as total imperviousness increases. In highly impervious basins (e.g., dense inner-city areas), maintaining impervious areas as disconnected will be more difficult, although stormwater harvesting and recycling offer some potential.

Our findings suggest that reduction of drainage connection in urbanized basins should result in reduced loads of all pollutants exported by the streams. However, for some variables, reduction of concentrations might be of more importance to the stream ecosystem itself, and this may point to management priorities other than the reduction of drainage connection. For instance, we postulate that the reduction of nitrogen loads in urbanized streams of our study will be most effectively achieved through reduction of drainage connection, but reduction of nitrogen concentrations will be most effectively achieved through replacement of septic tank systems in the Dandenong Ranges.

The spatial scale dependency of landscape attributes has not been well resolved to date (Soranno and others 1996). Although other studies have demonstrated the importance of considering both the whole-basin context and local site attributes, few have assessed the relative importance of factors at basin and riparian scales. Those that have considered scale factors have focused on land use (e.g., agricultural, urban) rather than particular physical attributes (e.g., impervious cover), generally with inconclusive results. For example, Johnson and others (1997) found that riparian characteristics better explained some water quality variables whereas the whole basin better explained others, and this was season dependent. They also noted that, in highly modified basins, riparian areas may simply reflect dominant basin land uses. For urban streams, the relevance of the condition of riparian zones is likely to be reduced, because traditional stormwater drainage pipes bypass these zones, reducing their influence on in-stream water quality (Groffman and others 2002). Adopting a basin scale approach is appropriate for urban streams because diffuse pollution by definition stems from broad-scale features and therefore can most readily be controlled at this scale.

Our hypothesis that the widespread application of LID across basins will result in much-reduced pollutant concentrations and loads could be tested by experimental assessment of basin developments with and without LID, monitoring water quality before and after development. An alternative, but related approach would be the experimental assessment of the retrofitting of already developed basins without LID. Such experiments will require a commitment to adaptive management on the part of urban land managers and developers.

The explanatory models developed in this study could form the basis of predictive models (sensu Mac Nally 2002) of loads and concentrations using larger data sets from this and other regions. Such models could be refined by quantification of the influence of impervious surface type (i.e., is it more important that some surfaces, such as roads, be disconnected than others, such as roofs), and by more intensive storm event sampling. The resulting quantitative predictive models of the effects of drainage connection and imperviousness on water quality will permit the development of better guidelines for urban design and for prioritizing restoration efforts.

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