3rd Australian Stream Management Conf. Proc. (2001) Eds Rutherford I, Sheldon, F, Brierley, G. Kenyon, C.

Developing predictive ecological capacity for a stormwater management decision-making framework

Christopher J. Walsh[1], Tim D. Fletcher[2], Tony H. F. Wong[2], and Peter F.Breen[1]

SUMMARY: A decision-making framework (DMF) for stormwater management based on a stochastic watershed model has been developed by the CRC for Catchment Hydrology. The DMF predicts stormwater flows and loads of pollutants (total suspended solids, phosphorus, nitrogen and gross pollutants) exported from urbanized catchments with varying types and levels of stormwater abatement techniques. The utility of the DMF is limited by the lack of prediction as to the effects of these changes on the ecology of receiving waters. This paper places the DMF within a conceptual model of stormwater physico-chemical impacts on stream ecosystems. Emerging methods are identified and described for inserting predictive models of ecological indicators (community composition) into the DMF, and to include the assimilative capacity of the stream ecosystem as part of the 'treatment train'. Current research using the catchment ecosystem approach to quantify in-stream biogeochemical processes is described, and areas of research need are identified, such as the effects of the spatial arrangement of catchment urbanization on stream ecology and the interactions between engineering solutions, stream condition and human behaviour.

THE MAIN POINTS OF THIS PAPER

- A mismatch of scale exists between models of stormwater-derived pollutants and ecological responses in receiving waters
- This scale mismatch may be reconciled by integrating the multiple urban impacts into two key elements of urban land use: catchment imperviousness and drainage connection
- Most stormwater abatement techniques equate to a reduction in drainage connection, which can be used to predict ecological responses
- Stormwater management needs to be investigated in the broader context of urban ecology

1. INTRODUCTION

Fletcher et al. (2001) developed a decision-making framework (DMF) for urban stormwater management, which uses a stochastic watershed modelling approach to predict the generation of stormwater flows and pollutant loads, based on specified catchment conditions (soil type, impervious area, land use). This system allows urban waterway managers to predict changes to water quality and hydrology resulting from altered land use and to develop best-practice stormwater strategies to avoid or ameliorate these changes. While urban stormwater managers are provided with an assessment of proposed stormwater strategies, the likely ecological impact of the modelled flow and pollutant regime is not identified. This is a significant shortcoming, given the ultimate objective of urban waterway management is the improvement of 'ecosystem health'.

The DMF predicts 'end-of-pipe' conditions (flow and water quality), with no prediction of the effects of these conditions on the ecology of receiving waters. In most urban situations, first-order streams are the smallest scale at which studies of aquatic ecosystem response to urban stormwater impacts are likely to be feasible. The catchments of such streams are typically an order of magnitude or two larger than the catchments of most stormwater abatement structures. Because of this mismatch of scale, a different approach to modelling of ecological response to stormwater impacts is required.

Urban stormwater runoff affects stream ecosystems in a variety of confounded ways. Increased imperviousness of the catchment increases runoff from storms, while reducing groundwater flows. Base flows of streams affected by urbanization are thus reduced while discharge increases in response to smaller storms: flood flows thus become more frequent and intense. Associated with the increased runoff are a variety of pollutants, ranging from suspended solids and nutrients to toxicants that impact on different species in different ways.

Quantifying biotic responses to specific urban-derived changes to hydrology, water quality and physical habitat is therefore an extremely large and complex pursuit. The large-scale, confounded nature of urban impacts suggests that large-scale integrative approaches may be more fruitful. In this paper, we place the problem of urban stormwater impacts on receiving waters in the larger context of urban ecology (sensu Grimm et al., 2000). We identify catchment imperviousness and drainage connection as the two elements of urban land use that are likely to be useful integrators of both the effects of stormwater impacts and of stormwater abate-

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[1] Cooperative Research Centre for Freshwater Ecology, Water Studies Centre, Monash University, Clayton Victoria 3800. Ph (03) 9905 4091, Fax (03) 9905 4196, e-mail Chris.Walsh@sci.monash.edu.au

[2] Cooperative Research Centre for Catchment Hydrology, Department of Civil Engineering, Monash University, Clayton Victoria 3800.

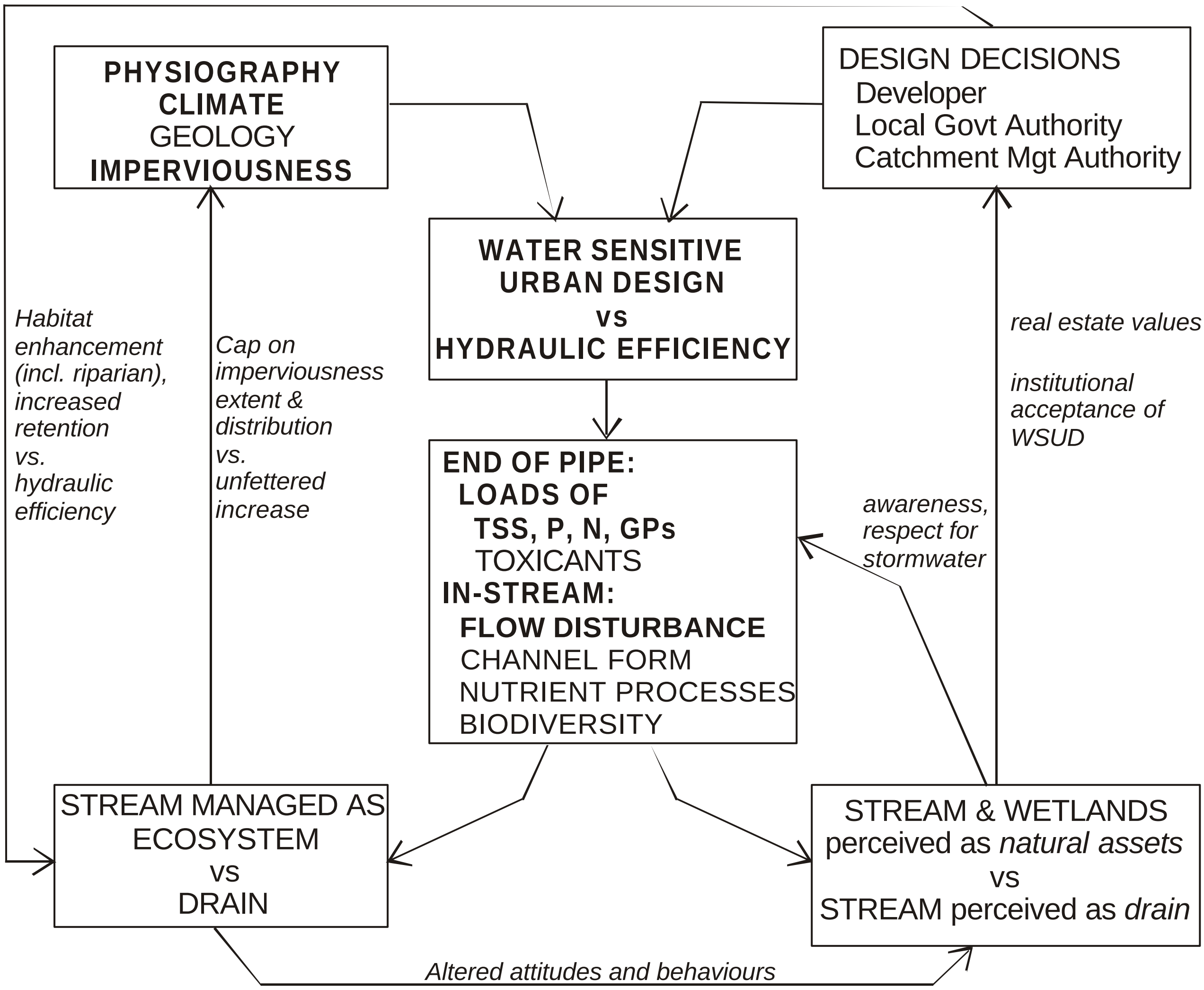

Figure 1: *A conceptual model of stormwater management in relation to the ecology of receiving streams and the ecology of the urban area.*

ment methods. Finally we demonstrate potential ways in which the DMF might be extended to include prediction of ecological condition of receiving waters.

1.1 The DMF in the context of urban ecology

Figure 1 places the DMF into a conceptual scheme for understanding urban ecological systems based on the general scheme of Grimm et al. (2000). This scheme shows that the features of the current DMF (in bold) appropriately use the coarse-scale environmental context as parameters for its models. The abatement techniques included in the DMF are primarily applied in the catchment (as opposed to in-stream), and largely involve reduction of the hydraulic connection between urban hard surfaces and the receiving waters. The conceptual scheme broadens the focus of the DMF to include the receiving stream and its biological components and processes.

After Grimm et al. (2000), the scheme also includes the social elements that are an intrinsic element of any ecological study in an urban environment. Human behaviour will interact with the ecological impacts of stormwater. The attitudes and behaviour of people to stormwater will have a direct bearing on the potential loads of pollutants delivered to the stormwater system. These attitudes are likely to be altered by changes in the condition of receiving waters resulting from the application of water sensitive urban design (WSUD, sensu VSC, 1999). Such changes are likely to result in tangible economic benefits such as increased real estate values, which in turn are likely to increase and reinforce acceptance of water sensitive urban design by management authorities.

The connection between social patterns and ecology in urban systems (Pickett et al., 1997), points to the importance of social and ecological research being integrated in such systems. We return to this point when discussing research needs (section 3). However, our primary concern is to understand the links between end-of-pipe patterns and the subsequent in-stream ecological patterns and processes (contained in the central box of **Figure 1**).

2. ECOLOGICAL PREDICTION AND THE DMF

2.1 Predictive models of ecological indicators

The models in the DMF that predict reductions in concentration and load of a small range of pollutants following installation of stormwater treatment measures, such as swales or wetlands, are derived in part empirically, from experiments in small catchments. These experiments monitored the fate of pollutants entering stormwater treatment measures, and the quality of water discharging from them. The models developed are also related to theoretical models of physical processes, such as sedimentation theory (Fair and Geyer, 1954). Further refinement of the treatment models is being undertaken by the CRC for Catchment Hydrology (Fletcher et al., 2001).

Comparable small-scale models of biotic responses to changed pollutant loads are lacking. Despite considerable knowledge of the response of a relatively few species to a range of pollutants from ecotoxicological research, the responses of assemblages of biota to simultaneous changes in the concentrations of a variety of pollutants and altered hydraulic disturbance are poorly understood. Furthermore, such relationships are unlikely to be elucidated easily using toxicological approaches. Developing a predictive capacity for multivariate community composition that is compatible with the models of the DMF is a particular challenge.

A likely way forward in reconciling the scale mismatch between studies of stormwater impacts and ecosystem response lies in the hypothesis that efficiency of drainage connection strongly affects the relationship between macroinvertebrate community composition and catchment imperviousness (Walsh, 2000; Walsh et al., 2001). In the Melbourne hinterland, with little stormwater infrastructure, degradation of macroinvertebrate communities was well explained by the degree of catchment imperviousness. However, communities in catchments of moderate imperviousness in the hinterland were much less degraded than those in catchments of comparable imperviousness in the intensively drained metropolitan area (Walsh et al., 2001).

The link between these findings and the DMF models is that the stormwater abatement techniques used in the DMF all result in effective reduction in the degree of connection between impervious areas of the catchment and the receiving stream. If the degree of degradation in community composition can be related to catchment imperviousness and degree of connection, and the effect of each abatement measure can be expressed as a reduction in drainage connection, then a model can be developed that predicts change in community composition with altered drainage features in the catchment. Development of such models is in progress.

A first step in this process has been the adaptation of predictive models of macroinvertebrate community composition such as AUSRIVAS (Coysh et al., 2000) to assess the potential range of condition for a particular level of catchment imperviousness (Breen et al., 2000, **Figure 2**). The hypothesis currently being tested by research at the CRC for Freshwater Ecology is that a large proportion of the variance in O:E scores (or other measures of community composition for each level of catchment imperviousness is explained by the degree of drainage connection. It is thus hypothesized that application of stormwater abatement measures to a catchment (resulting in a reduction in drainage connection) should result in an increase in O:E scores for the stream draining that catchment (catchment imperviousness will remain unchanged).

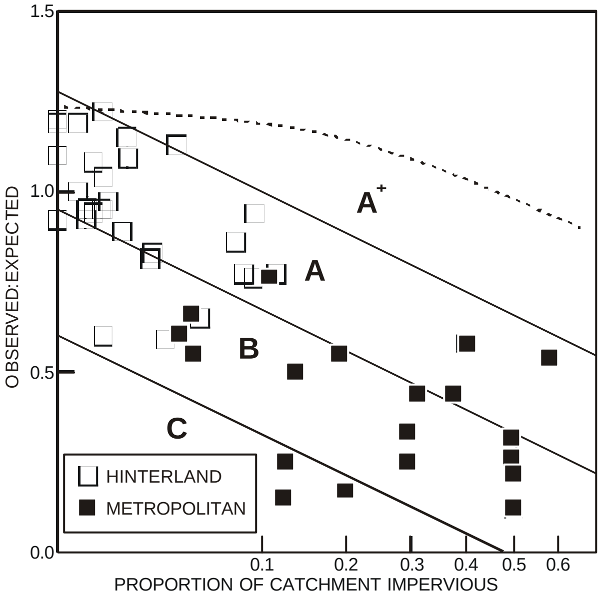

Figure 2: *Relationship between O:E ratio from the Victorian macroinvertebrate family AUSRIVAS model Marchant et al. (1997) and catchment imperviousness for sites in the Melbourne region. Bands ranging from very poor condition (C) to potential target condition for stormwater best management practices (A+) are proposed (adapted from Breen et al. 2000).*

AUSRIVAS and similar models predict community composition in undisturbed conditions and estimate deviation from that condition in sites reputed to be disturbed. Direct analysis of change in community composition in relation to urban-rural gradients is likely to be a more useful approach to modelling the ecological effects of urbanization. Principal curve analysis (De'ath, 1999) is a powerful method for describing change in multivariate community composition in response to strong environmental gradients typical of urban-rural gradients.

Figure 3a shows a principal curve projected onto the first two principal components of macroinvertebrate composition in 49 sites in the Melbourne region. The data were described in full by Walsh et al. (2001). Here, the analysis was conducted on presence-absence of the 121 taxa that occurred in >3 sites. The curve was a spline smoother with 5.6 degrees of freedom (the mean degrees of freedom of cross-validated splines for each taxon) (De'ath 1999). The starting configuration was the first axis of an MDS ordination based on Bray-Curtis dissimilarities. Environmental gradients are portrayed by plotting environmental variables against distance along the principal curve (**Figure 3b**). Here, median electrical conductivity and catchment imperviousness are as described by Walsh et al. (2001), and sediment zinc data for 31 of the 49 sites were gathered from various sources (Lewin, 1997; Pettigrove, 1999; V. Pet-

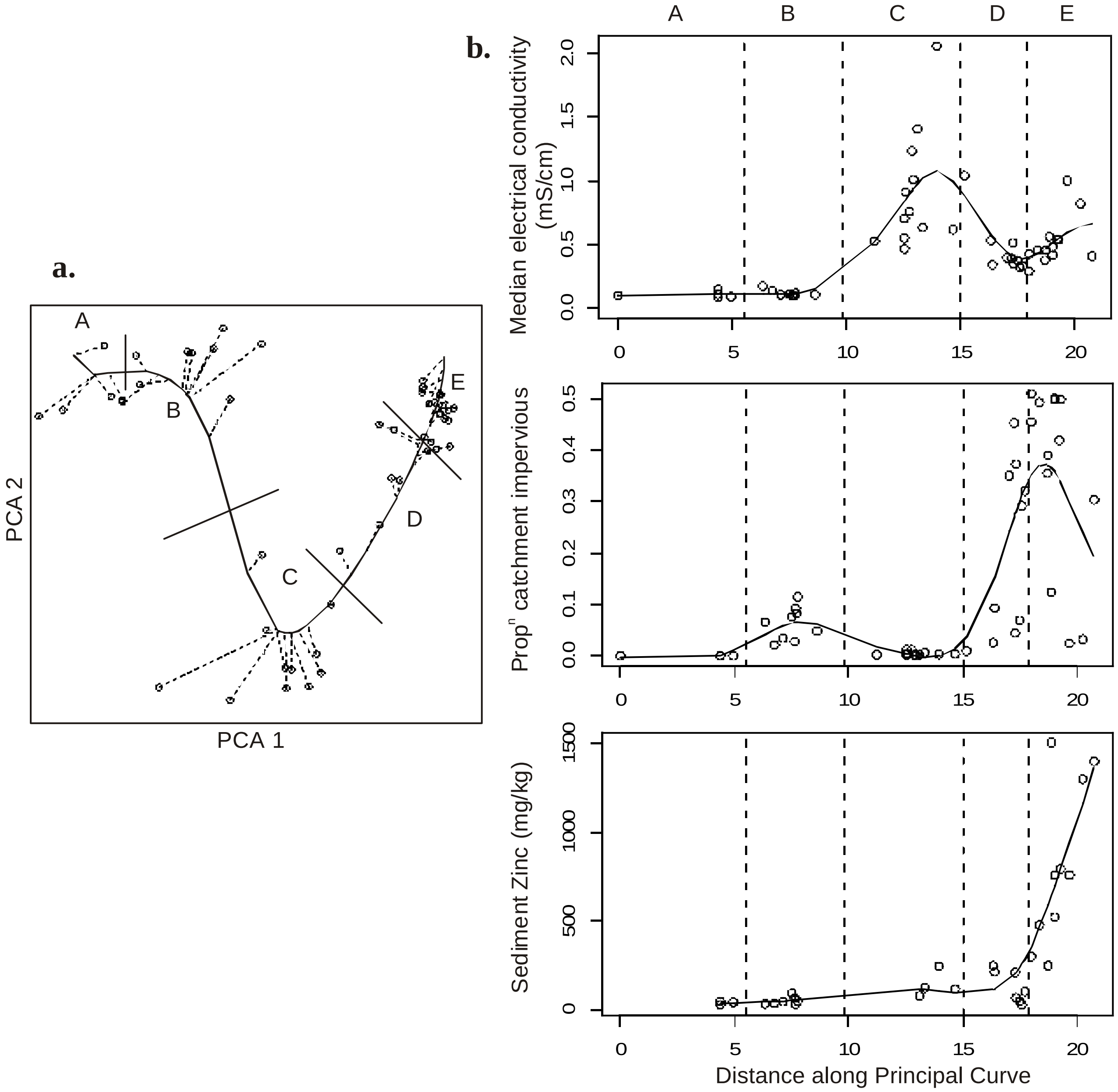

Figure 3: *a) Bi-plot of first two principal coordinates of macroinvertebrate presence-absence in 49 sites in the Melbourne region. The solid line is the principal curve through the data and the fit of each site on the curve is indicated by dotted lines. The five site groupings A-E are discussed in the text. b) Distance along the principal curve plotted against electrical conductivity, catchment imperviousness and sediment zinc concentration. The line of best fit for each graph is a cross-validated spline smoother.*

tigrove, Melbourne Water Corporation, personal communication).

Site groups correspond to those discussed by Walsh et al. (2001). Groups A and B were the eastern hinterland sites, A being the 5 sites with no catchment urbanization. Group C comprised the more saline, lower rainfall sites of the western hinterland. Groups D and E comprised the species-poor metropolitan sites within which Walsh et al. (2001) did not distinguish any strong environmental gradients. However, principal curve analysis reveals two distinct groups within metropolitan sites: those with low to moderate sediment zinc concentrations (D), and those with high concentrations (E).

Relationships such as these may serve as a basis to predict community composition under varying levels of urban-derived disturbances, and therefore to predict the ecological effects of a particular level and type of catchment development. The importance of sediment metal concentrations in determining changes among species-poor communities suggests that in-stream biotic improvements may only occur after both amelioration of stormwater runoff impacts in the catchment and further instream actions to remove contaminated sediments. Relationships between sediment metal contamination and drainage connection have yet to be determined.

Diatom community composition varies more directly with nutrient concentrations than is the case for macro-

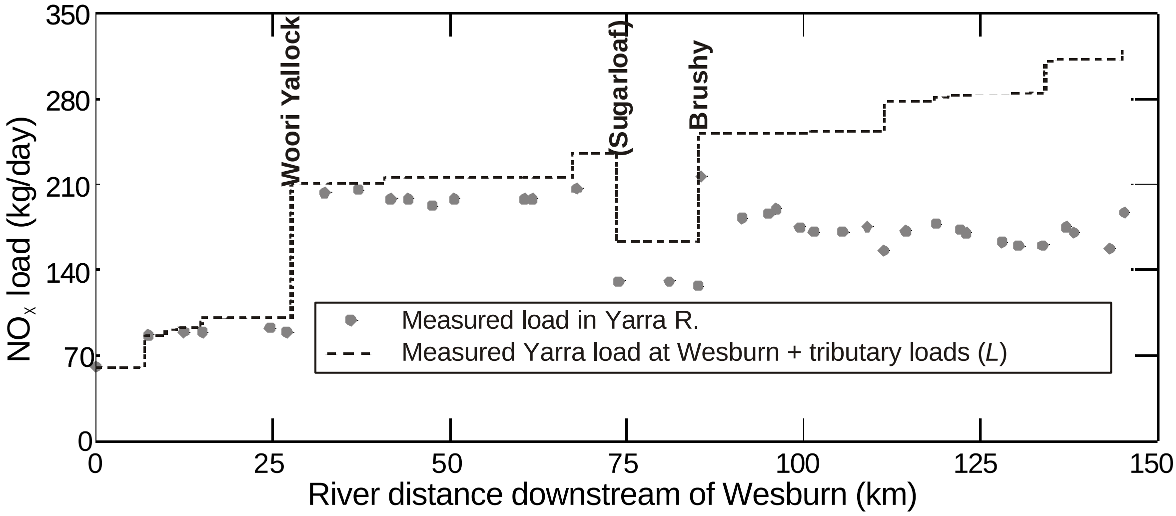

Figure 3: *Loads of nitrogen as nitrate/nitrite in the Yarra River, Victoria, measured on 6 November 1998 from Wesburn (0 km) to the estuary (145 km). The dashed line indicates the Yarra load at Wesburn + tributary inputs. Woori Yallock and Brushy creeks were the largest sources during this base flow period, while a large load was removed from the river for the Melbourne water supply at the Sugarloaf pumping station (C. J. Walsh, P. F. Breen, S. Bourguès, M. Grace and Melbourne Water Corporation, unpublished data).*

invertebrates (Sonneman et al., 2001), and also has the potential to be applied directly in the DMF with relation to reduction of nutrient loads. This could involve a similar analysis as described above or by the derivation of transfer functions for community composition in each region (e.g. Winter and Duthie, 2000).

While structural measures of ecosystem health such as community composition have been shown to be useful indicators of urban degradation and of other anthropogenic disturbances, the relationships between the structure of biotic communities and ecological processes are less well understood. Current research in the CRC for Freshwater Ecology is investigating the relationship between urban land use and the processing of nutrients in streams. Profound changes in nutrient process rates are obvious in streams of highly urbanized catchments because of the elevated nutrient concentrations, and the likely increase in nutrient export relative to instream assimilation and loss.

However, in catchments of low-moderate urbanization, where changes to nutrient processes are likely to be less obvious, the effect of drainage connection may have strong effects on nutrient processes. Small streams in particular have been identified as important systems explaining the loss of large amounts of nitrogen from instream water (Alexander et al., 2000). This feature of streams suggests another area for which this research can contribute to the DMF. If streams are important in the assimilation and loss of nutrients (and other pollutants), then expansion of the DMF to larger catchments will require modelling streams as part of the 'treatment train'.

2.2. Receiving waters as part of the 'treatment train'

Current research in the CRC for Freshwater Ecology aims to quantify the extent of assimilation, loss and transport of nutrients (particularly nitrogen) and other pollutants in small streams of varying catchment urbanization in the Melbourne region. Previous work on the Yarra River in Victoria has shown that attenuation of nutrient loads along a large river can be significant during base flow conditions, particularly in the more urbanized segment of the river following input of increased nitrogen and phosphorus loads from sewage treatment plants (**Figure 4**). Similar findings for small streams would require additional models in the DMF to account for loss of nutrients along streams. The rate of in-stream loss is likely to be related to the extent and nature of urbanization, in particular catchment imperviousness and drainage connection.

3. AREAS OF RESEARCH NEED

Current and past research on the effects of urbanization on stream ecology has focused on the integrative effects of catchment imperviousness (and more recently drainage connection). These approaches have generally used urban to rural gradients often combined with the watershed ecosystem approach (*sensu* Likens, 2001). An area of study more commonly applied in urban areas to terrestrial ecology is that of patch dynamics (Grimm et al., 2000) This concept has important application to urban-impacted aquatic systems, particularly at the landscape scale. For example, further research is required into the effect of spatial distribution of urbanization on generation of pollutant loads and stream ecology. Such information could lead to the development of a DMF that explicitly accounts for the spatial arrangement of urbanization and subsequent stormwater treatment strategies.

Perceptions and attitudes of land and catchment managers and the broader community have the potential to profoundly affect the success or failure of stormwater management actions. To our knowledge, the sociology of these interactions is an area of research not currently being pursued in Australia, certainly not in an integrated approach with ecological studies. The utility of the DMF will be enhanced by an understanding of the effect that human behaviour can have on the success of stormwater abatement methods. How can positive feedback loops (**Figure 1**) be optimized to improve human behaviour with regard to stormwater? Is human behaviour a more important factor in catchments where stormwater abatement measures have not been applied?

The need for integrated physical, ecological and sociological research is clear.

4. CONCLUSIONS

This paper identifies the paths to be followed to develop predictive ecological capacity for an existing stormwater management decision-making framework. Key challenges are the reconciling of a scale mismatch between the ecology of receiving waters and the catchments of stormwater abatement measures. Existing and soon to be developed ecological models show promise in being applicable to the DMF. Ultimately the DMF could be improved by its integration with both ecological and sociological research.

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