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Urban stream rehabilitation through a decision-making framework to identify degrading processes and prioritize management actions

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SUMMARY: Rehabilitation of physical habitat in urban streams is unlikely to increase instream biological diversity if factors other than habitat simplification limit community development. We used a study of regional variation in macroinvertebrate communities to develop a model predicting which degrading processes limit community composition in urban streams. Organic pollution (as indicated by biochemical oxygen demand, BOD) and increased run-off (as indicated by proportion of catchment that is impervious)—both products of catchment-scale perturbations—were the best environmental variables to explain differences between communities in metropolitan sites and those in surrounding rural sites. We hypothesized that catchment-scale processes limited community development in metropolitan sites. This was supported by a second study that showed little change in community composition in metropolitan sites after the placement of artificial riffles, which were designed to increase habitat complexity. We thus propose a decision-making framework for urban stream rehabilitation, wherein community structure of a physically degraded site is assessed. If the community is similar to those of surrounding rural sites, site-specific physical habitat restoration is considered likely to be successful. If the community is similar to those of metropolitan sites, rehabilitation measures to improve water quality or hydrology are recommended as first priority. Levels of BOD and catchment impervious area are used to prioritize appropriate actions.

THE MAIN POINTS OF THIS PAPER

- Restoration of instream habitat will be unsuccessful if factors other than habitat simplification are limiting instream biotic communities.
- We hypothesize that development of invertebrate communities in urban streams may be limited by three main classes of degrading process: water pollution, hydrological disturbance, or habitat simplification.
- We propose a model for assessing which of these processes is the limiting factor at degraded sites, and a framework for deciding which management actions should be highest priority for stream rehabilitation.
- The model is proposed for active adaptive management. The model should be tested and refined by monitoring the results of its application.

1. INTRODUCTION

Most stream rehabilitation projects concentrate on the enhancement of physical habitat, either instream or through the restoration of riparian vegetation. Such projects, if their aim is to increase instream biological diversity, work under the assumption that the limiting cause of degradation of biotic communities is the loss of habitat complexity. The hope of such projects is that an increase in habitat complexity will result in increased biological diversity in the stream (Palmer et al. 1997). However restoration of physical habitat may not address the main degrading causes if those causes result from unrecognized larger-scale processes (Lewis et al. 1996).

The success of stream rehabilitation can be assessed by a variety of indicators: biotic or abiotic, structural or functional (Kelly and Harwell 1990). Macroinvertebrate community composition is increasingly being used as an indicator of water quality and 'stream health' (Norris and Norris 1995), and is therefore an appropriate indicator for the effects of stream management works. Here, we advocate the use of macroinvertebrate community composition, not only as an indicator of rehabilitation success, but as a tool for assessing the likelihood of success prior to rehabilitation works.

We present a model for assessing the dominant degrading processes at potential rehabilitation sites, using data for the Melbourne region. From this model, a decision-making framework is developed for prioritizing appropriate management actions to address these processes. The model is based on hypothetical relationships, and is presented in the spirit of active adaptive management. The model can be assessed and refined by monitoring the results of management actions.

2. WHICH DEGRADING PROCESSES LIMIT COMMUNITY DEVELOPMENT?

2.1 Methods

We propose a model derived from two studies that are soon to be published in more detail (Walsh and Breen in press, and other submitted papers). We provide here only a brief outline of the methods employed.

The first study was a regional survey of macroinvertebrate community composition at 49 sites on ten streams across the Melbourne region. Macroinvertebrates were collected using rapid bioassessment methods (Anon. 1994), processed in the laboratory, and identified to the lowest taxonomic level

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possible using available keys. Samples were collected from pools and riffles in spring 1994 and autumn 1995. Similarities in community structure between sites were represented using non-metric multidimensional scaling (MDS) based on Bray-Curtis similarity measures for presence-absence data.

The environmental variables that best explained patterns of community structure were found using the BIOENV procedure of Clarke and Ainsworth (1993). In this paper, the relationship between the three 'best' variables and community composition is represented by the best-fit attributes of correlations between each variable and the two axes of an MDS ordination (Belbin 1993).

Three environmental variables are discussed in this paper. Twentieth percentile electrical conductivity (EC) was calculated from 14 monthly measurements (Nov 1994-Dec 1995). Median five-day biochemical oxygen demand (BOD) was sampled and calculated as for EC. Proportion of the catchment that was impervious (impervious area) was estimated from the proportion of random points on aerial photographs (VicImage 1992 1:16000 colour) that fell on impervious surfaces. Catchment areas were calculated from VICMAP 1:25000 topographic maps.

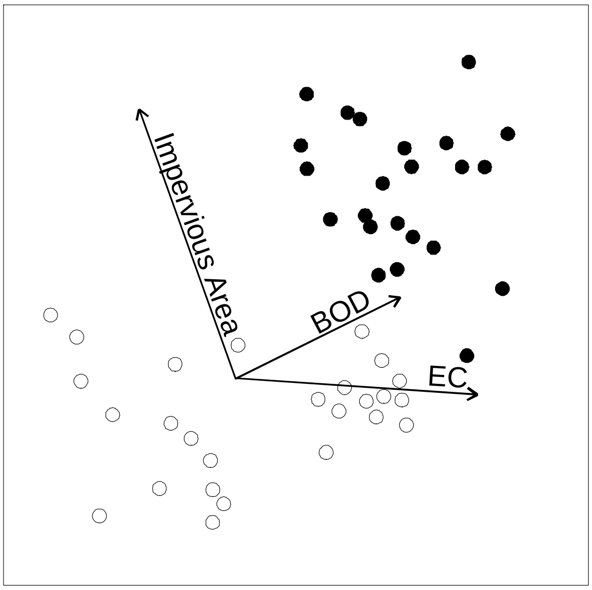

Figure 1. Non-metric multi-dimensional scaling ordination based on macroinvertebrate presence-absence at 49 sites on ten streams in the Melbourne region (two habitats, two seasons combined). Metropolitan sites (shaded), rural sites (open). Correlations between the ordination and the three best explanatory environmental variables are shown.

The second study was an experiment assessing the effect of artificial rock riffles on small lowland urban streams. Channelized, incised reaches, at seven sites on seven streams draining separate catchments in the eastern suburbs of Melbourne were selected as experimental units. Graded-rock riffles were placed in three reaches, large rock lining in two reaches and two reaches were left as controls. Macroinvertebrates were sampled quantitatively in and around the locations of the riffles twice before and twice (seven and nine months) after riffle placement.

2.2. A model of degrading processes

Three groups of macroinvertebrate communities were consistently found across Melbourne streams (Figure 1): two rural groups and a group of sites that fell entirely within the Melbourne metropolitan area. Communities of the metropolitan group were species-poor compared to the rural groups, and were dominated by pollution-tolerant taxa.

Patterns of community structure across the two groups of rural sites were best explained by EC (Figure 1). In metropolitan sites, there was some evidence that urban stormwater slightly diluted the more conductive streams to the west of Melbourne, and slightly increased the EC of less conductive streams to the east of Melbourne (Walsh, unpublished data).

However, EC did not explain the separation of rural and metropolitan streams well. This separation was best explained by the combined effect of two variables directly related to urbanization: impervious area and BOD (Fig. 1). These two variables correspond to two major classes of disturbance attributable to urbanization. Increased impervious area results in increased run-off, and is thus a good indicator of increased hydrological disturbance. BOD indicates levels of organic pollution. In urban streams, it is likely to be correlated to the wide range of pollutants associated with urban run-off. Site-specific variables associated with physical habitat of the site (e. g. riparian cover , mass of fine sediments, stability, conveyance, and entrenchment) did not explain the differences between urban and rural communities as well as BOD and impervious area.

From these correlational findings, we hypothesized that communities of metropolitan sites are limited by catchment-scale processes. The second study aimed to test if increasing habitat complexity in such streams affected macroinvertebrate community composition. The hypothesis of catchment-scale limitation would be supported if habitat complexity had little effect on community composition.

All five sites into which riffles or rock-lining were placed, supported degraded urban macroinvertebrate communities that grouped with the metropolitan sites of the first study. Their affinity with the metropolitan group was unchanged before, and up to nine months after riffle placement (Walsh and Breen in press). The effects of habitat remediation on macroinvertebrate community composition were thus not detectable at a regional scale. The lack of observed change after habitat enhancement in the metropolitan streams suggests that habitat simplification (from which these sites suffered) was not the limiting factor for macroinvertebrate community development at these sites. These findings do not conflict with the hypothesis of catchment-scale limitation. However, it is possible that remoteness from sources of colonizers is limiting the success of this habitat remediation (Cairns 1990). This possibility will be assessed by further monitoring of the experimental sites.

Sites in the rural group supported more diverse macroinvertebrate communities, which included species sensitive to pollution. We hypothesize that catchment-scale perturbations to water quality and hydrology are less likely to be limiting the development of such communities. Physically degraded sites that support such communities are better candidates for site-specific habitat rehabilitation than those that group with metropolitan sites (Walsh and Breen in press).

We have identified three classes of degrading process that might limit community development in urban streams. Habitat simplification is implicitly targeted in any restoration project that increases habitat complexity at a site. For metropolitan sites with degraded macroinvertebrate communities, we believe that habitat simplification is unlikely to be the primary limiting factor, and have identified indicators of two classes of catchment-scale urban disturbance. BOD indicates general urban pollution, particularly organic pollution. Impervious area indicates altered hydrology resulting from increased run-off in urban areas. These three classes of degrading process lead to three classes of management action that can be taken to address each process.

3. MANAGING DEGRADING PROCESSES

3.1. Habitat simplification

We assume that the site to be assessed has been selected as a potential candidate for site-specific habitat restoration, and therefore suffers from some level of habitat degradation. The purpose of the proposed decision-making framework is to decide if habitat restoration is likely to be successful in improving macroinvertebrate community composition, and if not, what management actions should take priority.

Habitat simplification in urban streams may arise from catchment-scale changes to impervious area resulting in increased volume and speed of run-off. Increased discharge often causes enlargement of the natural channel and changes in substrate composition (Brookes 1994). A large proportion of urban stream management therefore involves stabilization of eroding beds and banks. Such works could be conducted in ways to enhance instream habitat (Hey 1994), but the cause of the channel instability indicates that hydrological controls may be a more effective way to improve instream habitat. Urban streams are also often subject to severe habitat simplification by engineering works, usually aimed at improving hydraulic efficiency to prevent flooding. The pervasiveness of habitat simplification in urban streams makes it an obvious object of rehabilitation actions. We would argue for caution. If site-specific habitat restoration is considered desirable, a range of methods have been described (Newbury and Gaboury 1993; Hey 1994; Large and Petts 1994), although not all of these may be appropriate for lowland streams in Australian sedimentary landscapes.

3.2. Pollution

Streams flowing through urban areas may be subject to pollution from both point sources, such as industrial effluent and treated or untreated sewage and diffuse sources such as stormwater. Because almost all of the Melbourne metropolitan area is sewered separately from the stormwater system, its streams are largely protected from sewage effluent, except occasionally during periods of high rainfall (Anon. 1997a). Most of the pollution suffered by Melbourne’s urban streams is likely to arise from urban stormwater (Anon. 1988). Stormwater typically carries a wide range of contaminants including fine sediments, heavy metals, nutrients, and a wide range of organic matter and associated microbes that demand oxygen. Organic pollution as indicated by BOD has been identified here as a useful indicator of stormwater-derived pollution.

A range of methods for improvement of water quality in urban settings has been described (Anon. 1997b; Anon. 1998; Lawrence and Breen 1998). The methods employed should match the scale at which the degradation of water quality occurs (Table 1). The use of constructed ponds and wetlands feature prominently in many stormwater control approaches. Helfield and Diamond (1997) discuss potential problems in using constructed wetlands for multiple purposes in urban environments. The objective of urban stormwater treatment ponds and wetland designs should be to optimize the retention of pollutants, and in doing so, other potential beneficial uses may be compromised. For example, the accumulation of toxicants in wetland sediments may limit the value of the system as wildlife habitat. We thus recommend that the primary function of stormwater treatment ponds and wetlands be water quality improvement.

3.3. Hydrological disturbance

Increased impervious area associated with urbanization results in increased volume and speed of run-off (Brookes 1994). A model developed by Wong et al. (1997) predicted that a discharge equivalent to a rural five year average return interval (ARI) event would

Table 1. Appropriate methods for management of pollution and hydrological alteration in urban streams at two scales.

Degrading process	Scale	
	Point source/Small subcatchment	Large subcatchment/catchment
Water pollution	Source control • Erosion, sediment and chemical washoff control/reduction • Maintenance and upgrading of sewerage infrastructure • Wetlands/ponds constructed at local drain outlets[1,2]	Regional water quality management • Retention and use of floodplains • Wetlands/ponds constructed in regional flood retarding basins[1,2,4]
Hydrological alteration	Water-sensitive urban design (to control flow changes for <1.5 yr pre-urban ARI events) [1,3] • On site detention • Swale drains • Local distributed storage/detention	Flood protection (to control flow changes for 1.5- 100 yr pre-urban ARI events) [1,3] • Retention and use of floodplains • Flood retarding basins

[1]Anon. 1998; [2]Lawrence and Breen 1998; [3]Wong et al. 1997; [4]Breen et al. 1994.

occur at an ARI of 4.3 months in a catchment that was 20% impervious, 1 month if 40% impervious, and 11 days if 60% impervious. Much smaller floods (1.5-2 years ARI) have been reported as bank-full, or channel-forming flows (Gordon et al. 1992). Bank-full flow is likely to cause the most frequent significant hydraulic disturbance to biota on the stream bed. The aim of urban flow management should be to decrease the frequency of flows of that magnitude to near pre-urbanization levels (Anon. 1998). Control of flows less than pre-urban 1.5 year ARI is best achieved at the local scale, whereas control of flows greater than 1.5 ARI may be achieved at larger scales using flood retarding basins (Table 1).

4. A DECISION-MAKING FRAMEWORK FOR PRIORITIZING MANAGEMENT

The following framework is based on hypotheses arising from a regional dataset of macroinvertebrate community composition around Melbourne. Although we believe the general approach would be applicable in other cities, caution should be exercised in applying the suggested criteria elsewhere. The framework assumes that a major target of stream rehabilitation is an increase in benthic macroinvertebrate species richness. For sites supporting degraded urban communities, this would require a shift in community composition towards that of 'rural' communities.

For each potential rehabilitation site, assessment of three measures is required:

1. Macroinvertebrate samples collected, processed and identified using the methods used for the regional dataset. A minimum of one sample from one habitat is required, but we recommend samples from two habitats in two seasons. With more than one sample, the consistency of association with a group of sites can be assessed. Data from the test site should be added to the appropriate regional dataset (e. g. a spring riffle sample should be added to the regional set of spring riffle samples). Ordinations should be used to identify the group to which the test site is most similar.
2. Five day BOD, preferably measured on ten or more occasions over at least four seasons, so that a median can be calculated.
3. Percentage of catchment that is impervious. This can be estimated manually using recent aerial photographs and topographic maps, but the process is much quicker with GIS capabilities.

The framework is summarized in Figure 2. The first stage involves assessment of the affinities of the macroinvertebrate community of the test site to the regional dataset. If the test site groups with the rural group, our model predicts that the community of that site is not limited by disturbances to water quality or hydrology, and is therefore a good candidate for site-specific habitat restoration. The appropriate management action for such a site would be to plan and carry out appropriate site-specific physical rehabilitation (Newbury and Gaboury 1993; Hey 1994; Large and Petts 1994).

If the test site groups with the urban group, the model predicts catchment-scale disturbances to be limiting community development at the site. The most appropriate management action is then assessed by inspecting levels of BOD and impervious area at the site. (A third possibility at this first stage of the framework is that the test site falls outside the regional ordination, in which case the test site data or the model will need reviewing.)

In the Melbourne regional dataset, rural and metropolitan groups differentiated clearly based on BOD and impervious area alone (Figure 3). All rural sites had low values for both variables, but metropolitan sites showed much greater variation in the two measures. The rural sites (which support communities hypothesized not to be limited by catchment-scale disturbances to water quality or hydrology) were characterized by impervious areas <12%. And all but four lowland sites with zero or near-zero impervious area had median BOD of <1.5 mg O_2/L. Conversely, all but one of the metropolitan

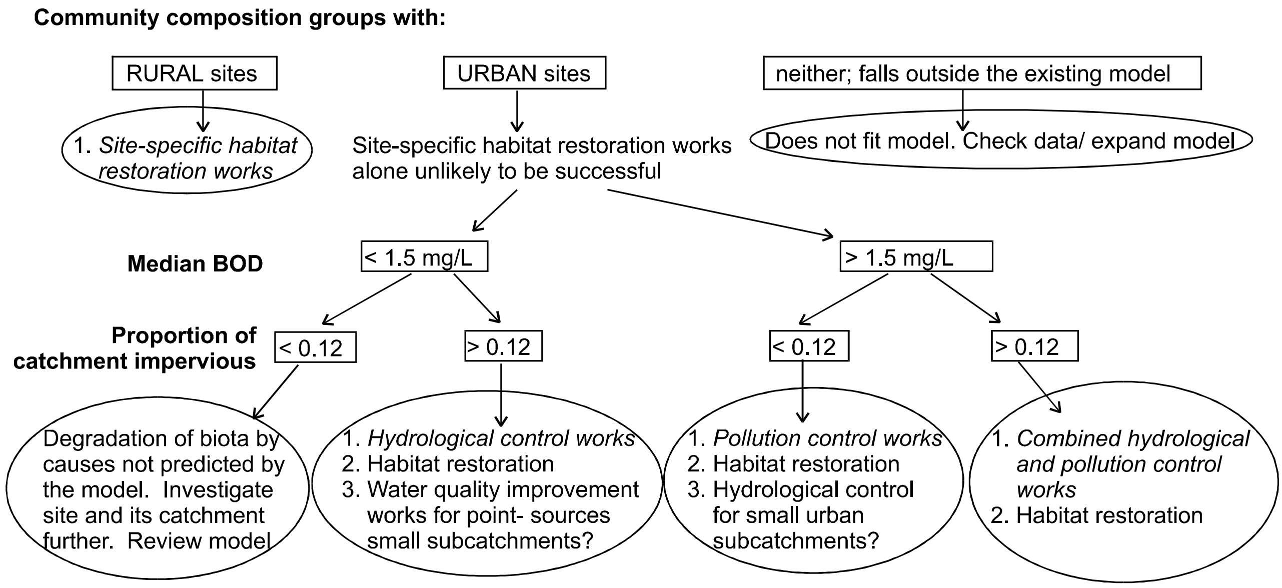

Figure 2. Decision-making framework for setting rehabilitation priorities in Melbourne streams.

communities had BOD ≥1.5 mg O_2/L or a high level of impervious area (Figure 3). As a first estimation, we use these values as 'critical' values for prioritizing management actions. Further investigation of the relationships of these variables (and those correlated to them) to community composition is required.

Sites with high levels of both BOD and impervious area are subject to large-scale impacts of urbanization. At such sites, pollution arising from stormwater, and higher run-off arising from large areas of impervious surface are undoubtedly linked. Before physical rehabilitation of habitat in such streams is likely to be successful or stable, catchment-scale rehabilitation measures should be undertaken to ameliorate degradation of water quality and hydrology. Retarding basins, which incorporate

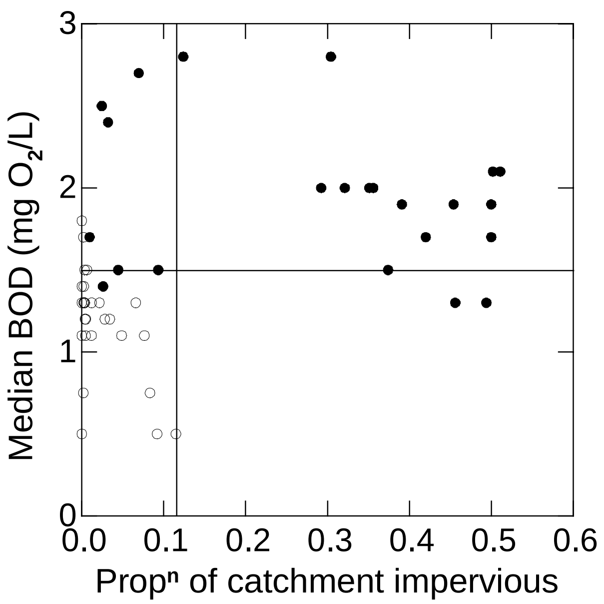

Figure 3: Median BOD and proportion of catchment that is impervious for sites on ten streams around Melbourne. Symbols as for Figure 1. Hypothesized critical levels of each variable are indicated.

ponds or wetlands designed for pollution abatement are required as first priority (Figure 2).

Sites with high levels of BOD but little impervious area in their catchments are likely to be affected by pollution from point-sources or small sub-catchments (or possibly non-urban sources). For point-source pollutants, source control is the best action. Where this is not possible, small-scale constructed wetlands at drain outlets are appropriate. If the source is a highly impervious urban subcatchment, combined hydrological and pollution control may be more appropriate. Once reduction of BOD is achieved, site-specific habitat restoration is more likely to be successful.

Sites with relatively low BOD but high levels of impervious area, primarily require hydrological control, but the situation will require assessment on a site basis. The two sites that fall into this category in Figure 3 are on highly urbanized streams with other sites that recorded higher BOD levels. The nature of the rehabilitation measures recommended for the other sites on these streams would also apply to these sites.

Sites with degraded macroinvertebrate communities, but with relatively low BOD and impervious area are not well explained by this model. Such sites warrant closer investigation. Degradation of the community may be explained by water quality problems not associated with organic pollution, such as a toxic industrial effluent, or by sediment pollution, which has not been included in the model. If no explanation is found, the model may need revising.

5. CONCLUSIONS

The model and framework presented here are a proposed first step towards more efficient use of resources in rehabilitating urban streams. The model is based on preliminary hypotheses that require testing. The usefulness of the model can also be assessed through monitoring the results of management actions, and comparing the results to the predictions of the model. We thus propose iteratively developing more efficient management practices through active adaptive management of urban waterways.

The key hypothesis is that catchment-scale degrading processes limit the development of communities that are typical of metropolitan sites. If management actions are taken to ameliorate the indicated disturbances to water quality or hydrology, the model predicts a shift in community composition towards that of communities at rural sites. It also predicts that site-specific physical habitat restoration alone will not achieve such a shift.

We have not presented evidence that increase in habitat complexity increased species richness in rural communities. We have inferred that the rural communities discussed here are not likely to be limited by poor water quality or altered hydrology, and thus propose that the hypothesis of limitation through habitat simplification is best tested at such sites.

6. ACKNOWLEDGMENTS

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