COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

OPTIMISING URBAN STREAM REHABILITATION PLANNING AND EXECUTION

TECHNICAL REPORT
Report **04/7**
August 2004

Tony Ladson

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CATCHMENT HYDROLOGY

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Bibliography

ISBN 1 920813 12 8

1. Stream conservation - Victoria - Melbourne. 2. Restoration ecology - Victoria - Melbourne. 3. Stream ecology - Victoria - Melbourne. I. Cooperative Research Centre for Catchment Hydrology. (Series: Report (Cooperative Research Centre for Catchment Hydrology); 04/7)

333.916216099451

Keywords

Urban areas
Streams
Restoration
Stream Flow
Geomorphology
Water quality
Hydrology
Habitats
Aquatic organisms
Stormwater management
Wetlands
Flood control

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Preface

The main goal of the Cooperative Research Centre (CRC) for Catchment Hydrology's River Restoration Program is to provide the tools and understanding that will allow the environmental values of Australia's streams to be protected and restored. Restoring streams following the impacts of urbanisation is a particular challenge. Most Australians live in cities and often highly value their local streams that are being degraded by the polluted runoff from the roads, roofs and driveways that are part of urban infrastructure. Urban streams suffer from larger and more frequent floods, higher pollutant loads, and greater disturbance than their rural counterparts. There is a large range of possible management interventions to restore urban streams, the problem is to determine those that will be effective.

Project 6.2 *'Optimising urban steam rehabilitation planning and execution'*, has explored a range of urban stream restoration approaches. Originally it was intended to undertake an experiment to test the effect of improving stream hydrologic conditions through changes to the design of a retarding basin. If flow in urban streams could be made more 'natural', that is, more like flow in rural streams, then perhaps stream health could be improved. On closer examination, improving hydrologic conditions looked a high risk approach because it left water quality and geomorphic impacts untreated. In fact a detailed review of existing information shows that none of the standard small-scale approaches to restoring urban streams are likely to be successful and a different approach is needed. The reasoning that led to this conclusion is an excellent example of the benefits of integrated, multi-disciplinary analysis.

So what should we do to improve the health of urban streams? A way forward lies in using the findings from work by Dr Chris Walsh and colleagues in a joint project between the Cooperative Research Centres for Freshwater Ecology and Catchment Hydrology. They have shown that the key predictor of ecological health is the area of impervious surface in a catchment that is directly connected to waterways by pipes. If frequent direct delivery of water and pollutants to streams can be decreased then stream health is likely to improve. This report concludes by discussing an experiment to test catchment-scale restoration approaches based on decreasing runoff frequency.

I fully support this experimental approach because it has the potential to greatly decrease the uncertainties that plague the selection and design of restoration works in urban streams. This new proposal is supported by data and modelling to allow the design of an intervention expected to succeed in improving stream health.

Mike Stewardson
Program Leader, River Restoration Program
CRC for Catchment Hydrology

Summary

This is the final report of Project 6.2 '*Optimising Urban Stream Rehabilitation Planning and Execution'*, part of the River Restoration program of the Cooperative Research Centre for Catchment Hydrology. Urban streams represent a special challenge to river managers because they are often highly degraded and subject to multiple impacts. At the same time, they may be greatly valued by the people that live in the surrounding suburbs.

As city infrastructure spreads over catchments there are effects on:

- Streamflow: floods become larger and more frequent; runoff volume increases; flow frequency increases, and base flows are generally lower.
- Geomorphology: stream bed and banks erode; the stream channel becomes much larger; and there may be excess or too little sediment.
- Water quality: there are increases in the concentrations of a range of pollutants and toxicants and increased loads to receiving waters.

These impacts affect stream ecology: macroinvertebate diversity decreases and populations become dominated by a small number of tolerant taxa; fish diversity decreases; pathogen concentration increases.

Often restoration efforts have focused on actions aimed at mitigating the effects of individual stressors at the stream-scale. This report discusses three possible interventions: 1) improvements to physical habitat; 2) changes to stream hydrology through retro-fitting retarding basins; and 3) efforts to improve water quality through the use of constructed wetlands.

If the objective of restoration is to improve in-stream ecological indicators then the effectiveness of these interventions is shown to be questionable. Others have shown that physical habitat improvement was not effective in improving stream biota in urbanised catchments in Melbourne's east. The effects of changes to hydrology are shown to be questionable because of scale issues. Constructed wetlands may have limited effect on, or may even degrade, low flow water quality despite being very effective at decreasing pollutant concentrations during storms.

If none of these restoration efforts are likely to work then what should be done? The answer lies in a catchment scale approach to restoration. Joint work by the CRCs for Freshwater Ecology and Catchment Hydrology has shown that the proportion of a catchment that consists of *impervious surfaces directly connected to waterways by pipes* is a good predictor of ecological condition. The problem for stream biota is that even small events of the order of 1 mm of rain will cause overland flow from impervious surfaces which will deliver water and pollutants to streams via the stormwater system. Restoration needs to focus on reducing runoff frequency by storing, infiltrating, evaporating, or transpiring rainfall, to prevent flow from small events.

There is strong evidence that reducing effective imperviousness will show improvements in stream health, but it is important to test this hypothesis. A large scale experiment is proposed to design and build an improved stormwater drainage system for a trial in two urbanised catchments in Melbourne's east.

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1. Introduction

Healthy streams are all alike;
every unhealthy stream is unhealthy in its own way

(with apologies to Tolstoy)

Urban streams represent a special challenge to river restorers. Often they are highly modified with numerous conflicting management demands. The past focus on using urban streams for drainage and flood control has left many in poor condition but, compared to rural streams, there are often more resources available for their care.

Urban stream health can be compromised by one, or a combination of factors, such as:

- Lack of physical habitat;
- Modified flow;
- Poor water quality;
- Lack of riparian vegetation;
- Barriers to migration of fish and other biota;
- Exotic plants and animals; and
- Channelisation, erosion and sedimentation.

Urban stream rehabilitation needs to address some or all of these factors so it is important to know which interventions will be the most effective and should therefore receive the highest priority.

Deciding on the most appropriate and cost effective interventions in urban streams is central to Project 6.2 '*Optimising urban stream rehabilitation planning and execution'*, part of the River Restoration program of the Cooperative Research Centre for Catchment Hydrology. This document is the final report of that project. The focus of this work has been on streams in and near Melbourne, Victoria but there are lessons for streams in most cities.

Project 6.2 has addressed aspects of urban stream management by looking at better ways to plan and carry out stream rehabilitation. The aims of this project were to: 1) assist in filling the knowledge gaps that reduce confidence in the effectiveness of rehabilitation plans and actions, and 2) assist priority setting at a catchment wide scale. Project activities, outcomes and outputs are detailed in this report and summarised in Appendix 1.

As documented in the original project agreement, our activities are being supported by related work undertaken by the Cooperative Research Centre for Freshwater Ecology, particularly by Dr Chris Walsh of Monash University. There have also been strong links with the Urban Stormwater Quality program of the Cooperative Research Centre for Catchment Hydrology led by Dr Tim Fletcher.

Catchment urbanisation has a major effect on streams as discussed in Section 2. There are well documented urban impacts on stream hydrology, geomorphology, water quality, and consequent effects on stream ecology and biology. Restoration aims to mitigate these impacts to improve stream health or condition. Section 3 explores a range of stream-scale restoration efforts including improvements to physical habitat, hydrology and water quality. The conclusion of this section is that these types of restoration activities are unlikely to be successful. Instead a catchment scale approach to restoration, through a large scale experiment, is proposed in Section 4.

2. Impacts of Urbanisation on Streams

Urbanisation has profound effects on streams, changing flow and sediment regime, channel size and substrate, and water quality. There are consequent impacts on stream biota.

2.1 Hydrology

Urbanisation usually results in a large change to hydrology which drives many other changes to the stream system. In summary, high flows and the total volume of runoff increase, and low flows are made smaller.

Increased Flood Frequency and Magnitude

Urbanisation causes up to a 10 fold increase in peak flows of floods in the range 3 months to 1 year with diminishing impacts on larger floods (Figure 1) (Tholin and Keifer, 1959; ASCE, 1975; Espey and Winslow, 1974; Hollis; 1975; Cordery, 1976; Ferguson and Suckling, 1990; Wong *et al.,* 2000).

Faster Flood Peaks

Runoff in urban streams responds more rapidly to rainfall compared to rural catchments (Mein and Goyen, 1988).

Increased Flow Volumes

More rainfall is converted to runoff in urban catchments both because of the increased impervious areas and increased runoff from pervious areas which are commonly irrigated by imported water. (Harris and Rantz,1964; Cordery, 1976; Ferguson and Suckling, 1990). There may also be additional rainfall over cities compared with adjacent rural areas (Landsberg, 1981).

Decreased Base Flow

The most common response to urbanisation is that base flow is decreased. More impervious areas means less opportunity for water to infiltrate so groundwater storage and discharge is reduced (Simmons and Reynolds, 1982). Less commonly, there may be increased base flow caused by leakage from the water supply system or extensive irrigation of gardens and parks which increases groundwater levels (Al-Rashed and Sherif, 2001; Nilsson *et al*., 2003).

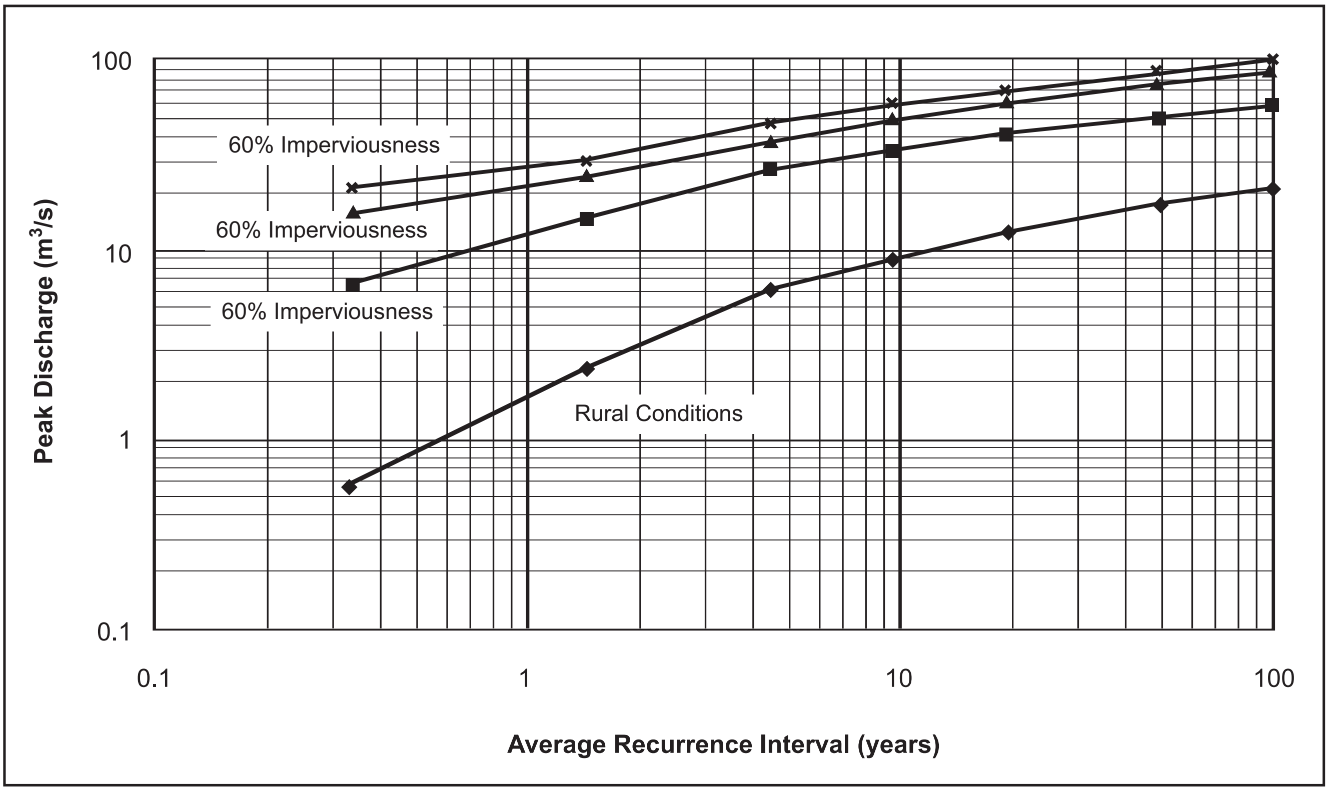

Figure 1. Effect on Flood Frequency Curves of Increasing Imperviousness. Source: (Wong *et al*., 2000)

Increased Runoff Frequency

Runoff occurs more frequently as the amount of impervious area increases. Small rainfall events of 1 to 2 mm will cause runoff from impervious surfaces (ASCE, 1975) but much more rainfall is usually required to produce runoff from grassland or forest (Pilgrim 1993). These larger rainfall events, which produce runoff in natural catchments, occur much less often than the small events that produce runoff from impervious surfaces.

2.2 Geomorphology

Case studies of urbanising streams show that common geomorphic responses include (US EPA, 2003):

- Stream incision;
- Sedimentation;
- Bank erosion;
- Stream enlargement;
- Increased sediment transport;
- Increased stream sediment loads; and
- Changes in channel shape.

Channel response can be complex because of changing sediment production as urban development proceeds. Initially sediment may be deposited in stream channels causing them to silt up and contract (Wolman, 1967a,b; Graf, 1975). Over time, sediment loads decrease and runoff from impervious surfaces increases which commonly leads to channel enlargement by both bed and bank erosion (Hammer, 1972; Hollis and Luckett, 1976; Neller, 1988; Booth, 1990; Trimble, 1997). Bed material may also increase in size because of armouring, or the stream may scour to bed rock or resistant clays (Arnold *et al.*, 1982; Pizzuto, 2000). Channel size may increase by up to a factor of ten times in highly urbanised areas (Morisawa and Laflure, 1982) and streams may not stabilise for many decades (Henshaw and Booth, 2000; Caraco, 2000).

Channel enlargement, bed and bank erosion have been noted in many of Melbourne's streams in urbanised catchments (Rutherfurd and Ducatel, 1994).

2.3 Water Quality

The water quality implications of urbanisation have been comprehensively reviewed by Duncan (1999; 2003) who analysed data from over 150 journal articles and reports. Compared with runoff from rural areas, urbanisation is usually associated with increased concentrations of:

- Suspended solids;
- Total phosphorus;
- Total nitrogen;
- Chemical oxygen demand;
- Biochemical oxygen demand;
- Lead;
- Zinc;
- Copper;
- Total coliforms;
- Fecal coliforms; and
- Fecal Streptococci

Urbanisation can also change stream temperature. In a study of five streams on Long Island, New York, Pluhowski (1970) showed that streams in urban catchments had higher summer temperatures, and lower winter temperatures, than rural streams, with little difference in the spring and autumn. The largest temperature changes were in summer with differences of up to 10^{o}C. Stormwater runoff also resulted in rapid changes in temperature of receiving streams. Causes of temperature differences included reduced shading, construction of lakes and ponds, and reduced groundwater inflows because of groundwater extraction. Temperature impacts of urbanisation on streams have also been reported in Melbourne (Walsh *et al.*, 2000; Hatt *et al.*, *in press*)

In urban areas where point sources are well managed, most pollutants will be transported to streams as part of urban stormwater particularly where there is a direct connection between impervious surfaces and waterways (Hatt *et al.*, *in press*).

2.4 Biology and Ecology

The changes to flow, channel form and the sediment regime, and water quality have a major effect on the biology and ecology of urban streams (Paul and Meyer, 2001). The best studied organisms are macroinvertebrates and the following effects have been noted:

- Decrease in overall invertebrate diversity;
- Decreases in sensitive taxa, such as *Ephemeroptera, Plecoptera,* and *Trichoptera*;
- Increases in relative abundance of non-sensitive taxa such as *Chironomidae* and *Oligochaetes*.

This effect has been noted in cities around the world (Klein, 1979; Schueler, 1994; May *et al*., 1997; Walsh, 2000; Paul and Meyer, 2001).

The effect of urbanisation on stream biota has been confirmed for Melbourne. In routine monitoring undertaken by Melbourne Water the aquatic life of most streams draining urbanised catchments is rated as poor or very poor (Melbourne Water, 2004). Walsh *et al*., (2001) found that benthic macroinvertebrate communities from catchments with imperviousness 1-51% were all severely degraded with high abundances of a few tolerant taxa.

3. Testing Possible Approaches to Restoring Urban Streams

Clearly the impacts of urbanisation on streams are multifaceted and changes to stream form and function can be profound. At the same time, urban communities are coming to value streams and their surrounds (Riley, 1988). Recent surveys in Melbourne showed there were over 50 million visits to local streams which were highly valued by residents (RWC, 1999). There are now increasing efforts to restore streams in Australia and elsewhere that are impacted by urbanisation.

A common goal is to improve stream 'health'. There seems to be consensus amongst ecologists that indicators based on the occurrence of macroinvertebrate taxa are appropriate health indicators because they are sensitive to a range of disturbances, are responsive, and relatively easy to measure. There are also a range of protocols for their assessment (e.g. Rosenberg and Resh, 1993; Chessman, 1995). In simple terms, healthy (abundant, diverse and sensitive) macroinvertebrate assemblages indicate healthy streams. In Victoria there are recommended values for a range of macroinvertebrate indices associated with environmental quality objectives (EPA, 2003).

Often urban stream restoration has focussed on a single aspect of streams that was thought to be limiting stream health. Our conceptual model was that if the critical limiting factor could be identified and treated, then stream health would be improved. A number of possible 'critical factors' were examined as described below.

3.1 Improvements to Physical Habitat

Often restoration has focussed on improvements to physical habitat by introducing riffles or woody debris to streams that have been channelised or have eroded because of the impacts of urbanisation on hydrology and sediment supply.

Should improvements to physical habitat be part of urban stream restoration efforts in Melbourne? If the lack of physical habitat is the limiting factor for macroinvertebrates then reintroducing riffles or woody debris to Melbourne's streams could make them healthier as measured by macroinvertebrate indicators. Planning procedures to improve the geomorphic conditions of urban streams were assessed and the 'Leitbild' procedure was applied to Monbulk Creek (Kiessner, 2003). See Appendix 2.

Work undertaken by the CRC for Freshwater Ecology investigated the success of habitat restoration in streams in the Melbourne area. Experimental riffles were placed in six urban lowland streams in the eastern suburbs of Melbourne and macroinvertebrates were monitored at these streams and in control streams. Monitoring took place before the placement of riffles and up to five years after placement.

There was limited response to addition of physical habitat and the riffles remained dominated by pollution-tolerant taxa typical of highly impacted streams (Walsh and Breen, 2001). Over a five-year period, some sensitive taxa were collected at least once in all of the new riffles, which indicates there were potential colonisers, but they did not persist (Walsh, Monash University, *pers. comm.*). Walsh and Breen (2001) concluded that the lack of response to the addition of physical habitat was because of catchment scale disturbances to water quality and hydrology.

Recent work in Melbourne Streams by Pappas (Arthur Rylah Institute, *pers. comm.*) and Perry (SAGES, University of Melbourne, *pers. comm.*) provide similar results. International examples also show that the effect of physical habitat restoration is small with few, if any, new taxa colonising the provided habitat (Larson *et al*., 2001; Walsh and Breen, 2001; Purcell *et al*., 2002; Suren and McMurtrie, *in review*) Where streams are impacted by urbanisation, addition of physical habitat seems unlikely to improve stream health (Walsh and Breen, 1999).

3.2 Retrofitting a Flood Retarding Basin to Improve Flow Conditions

Under urban conditions, floods are made more frequent and severe because runoff is increased in both volume and rate as a result of increased impervious areas. These changes in hydrology also cause changes in the hydraulic conditions experienced by macroinvertebrates such as velocity, shear stress, and depth of inundation. Changes in *hydraulic* habitat influence composition of the biota (Statzner and Higler, 1986). If the hydrology was more natural, i.e. more like it was before urbanisation; perhaps stream health would be improved.

The initial focus of Project 6.2 was on retrofitting a flood retarding basin in Melbourne to improve flow conditions. Retarding basins do reduce flood magnitude, but are designed to be most effective for large events usually above the two year ARI flood. Initial work suggested that it was smaller events, around six months to two years average recurrence interval, which were causing the flow stress that influenced biota (Breen, 1997). Perhaps retrofitting a retarding basin would improve the attenuation of these smaller floods and hence improve stream health.

This option was considered in detail including the development of conceptual designs and review of the literature on the effect of flow on biota (discussed in the next two sections). The implications for this review were not favourable for the proposed experiment (see below).

3.2.1 Effects of Flow on Biota

There is ample theory and empirical evidence that hydraulic conditions influence macroinvertebrate abundance and species richness and this provides support for interventions to improve stream health by changing flows.

It is well known that the response of taxa to flow conditions varies and many studies have looked at the behaviour of particular taxa in the field and in experimental flumes (e.g. Lancaster 1999; Robson *et al*., 1999). Fluid drag has been shown to have a significant effect on the energy budget of macroinvertebrates (Statzner *et al*., 1988) and flood disturbance is known to reduce benthic macroinvertebrate densities in some habitats (Irvine, 1985; Giller *et al*., 1991; Matthaei *et al*., 1996; Miller and Golladay, 1996) and the communities of streams subject to repeated flooding are often depauperate. (Death and Winterbourn, 1995).

As discharge increases, macroinvertebrates are subjected to a range of mechanisms that promote their removal and transport downstream. Drag and lift forces increase which will result in higher probability of dislodgement (Vogel, 1994). Air breathing taxa may not be able to resist entrainment in the flow or to swim against the increasing current. Increasing turbulence means flow becomes more three-dimensional and the magnitude and frequency of forces are less predictable. Sediment transport rates increase: at first smaller particles will be moved, potentially dislodging individuals, while at higher flows, the whole stream bed will be mobilised. The combined effect of hydraulic and sediment transport forces can be considered to provide a *flow stress* to stream biota.

An important unifying idea was proposed by Lancaster (2000) who developed an index (based on earlier work by Rader, 1997) that describes the impact of hydraulic forces on macroinvertebrate taxa using six traits in two groups; 1) self-control and 2) vulnerability. Self-control traits were intentional drift, mobility and drift distance (high scores to taxa that return quickly to the substrate once entrained, low scores to passive drifters). Vulnerability traits were preferred habitat, drag index and benthic exposure. A low value of the ratio of self control to vulnerability (the Lancaster Index) suggests that these taxa show weak resistance to flow disturbances. A high index suggest taxa that can resist flow disturbance. Of the six taxa studied by Lancaster (2000) *Gammarus pulex* (a freshwater shrimp) had the highest index value, which indicates control of movement in the stream and a low vulnerability for dislodgement. *Hydroptila sp*. (nonsessile caddisfly larvae) had the lowest index value and so will be easily affected by hydraulic stress.

As flow stress increases, taxa will begin to accumulate in refugia - areas where hydraulic forces and the negative effects of disturbance are reduced relative to the surrounding habitat (Lancaster, 2000). This can happen passively, as individuals are removed from high stress areas, or actively, by individuals seeking out desirable locations. Particular taxa will respond differently to flow conditions. For example, those inhabiting less exposed areas will be able to withstand hydraulic stress for longer. Similarly, active moving taxa may be quicker to find refugia. Air breathing taxa that have to leave the substrate are unlikely to resist entrainment unless they are good swimmers.

Lancaster (2000) showed that under moderate hydraulic stress those taxa with the lowest Lancaster Index accumulated in refugia (either by passive or active means). These taxa included *Polycentropus flavomaculatus*, (a caseless net spinning caddisfly) *Hydroptila sp*. and *Chironomidae* (larvae of non-biting midges). No refugia effects were found for taxa with a higher index value including *Baetis spp*. (mayfly nymphs), *G. pulex* or *Capnia*. *Bifrons* (a stonefly nymph) presumably because the flow stress studied by Lancaster (2000) was not sufficient to cause problems for these organisms which could control their location in the flow and were not vulnerable to being dislodged. Under higher stress, *G. pulex* were shown to use refugia (Borchardt, 1993). This index could also explain earlier results by Lancaster (1999) that showed *Oreodytes sanmarkii* (a dytiscid beetle) accumulated in refugia. This beetle is a poor swimmer and breathes air so is likely to be transported downstream and so will accumulate in refugia (even if just by passive means) under conditions of moderate hydraulic stress.

Although this has not been proven experimentally, under higher hydraulic stress, it may be expected that those taxa with a low index value would be washed out of the stream while those with a high index value would survive only in refugia. Perhaps, in an extreme flood, in those streams studied by Lancaster (2000), *G. pulex* would be last to hold on while all the other organisms where washed away. Still higher flows and even *G. pulex* would be dislodged.

Borrowing from toxicology, the effect of flow conditions on taxa is described in terms of a dose response relationship, which will vary for each taxon (Figure 2). For small spates there will be flow at which there is no observable adverse effect level. As the flow increases, refugia become increasingly important, until for large flows, all taxa may be removed.

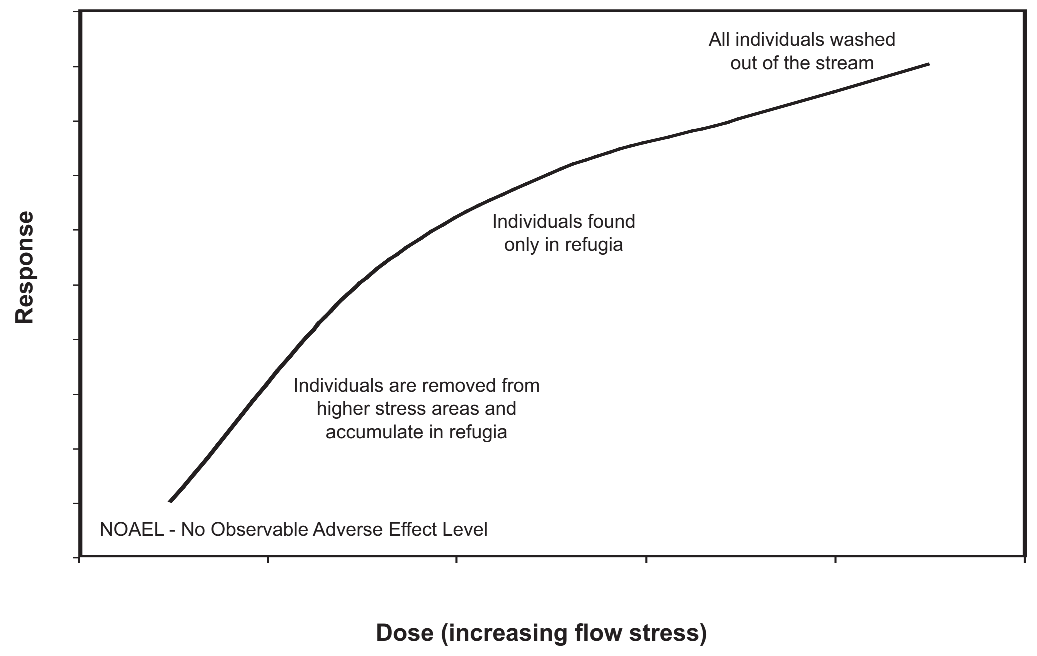

Figure 2. Effect of Increased Hydraulic Stress on Macroinvertebrate Taxa.

The frequency of high flow events is also important. There may be time for populations to recover between events if they are not too frequent or severe. As the magnitude and frequency of disturbance increases taxa that can't cope, or can't recover in time will be lost (see Appendix 3).

3.2.2 Flow at the Scale of Macroinvertebrates

Let's look more closely at the flow condition experienced by macroinvertebrates. Benthic macroinvertebrates reside within a roughness layer where the flow characteristics are determined by the free streamflow and the local arrangement, roughness and size of nearby bed particles (Figure 3). These flow conditions may include strong velocity gradients, turbulence and three-dimensional flow patterns (Vogel, 1996; Hart and Finelli, 1999; Nikora *et al*., 2001) (Figure 1). These near bed flow conditions may be impossible to predict where there is turbulence and complex bed topography. They are only approximately related to the average or free streamflow conditions where reasonable predictions can be made using standard engineering approaches to open channel flow calculations.

Fine-scale turbulent near bed flow conditions have been empirically related to macroinvertebrate occurrence. For example, Hart *et al*., (1996) measured flow conditions near to stones that were inhabited by black fly larvae (Figure 4). These larvae reside on stones and filter food from the passing flow. The flow conditions 2 mm above the stones were strongly correlated with larval abundance, while flow conditions 10 mm above the stones were not related to larval abundance or to flow conditions at a height of 2 mm. Clearly, changing flows by retrofitting a retarding basin is a blunt instrument when it comes to the local-scale hydraulic conditions experienced by macroinvertebrates.

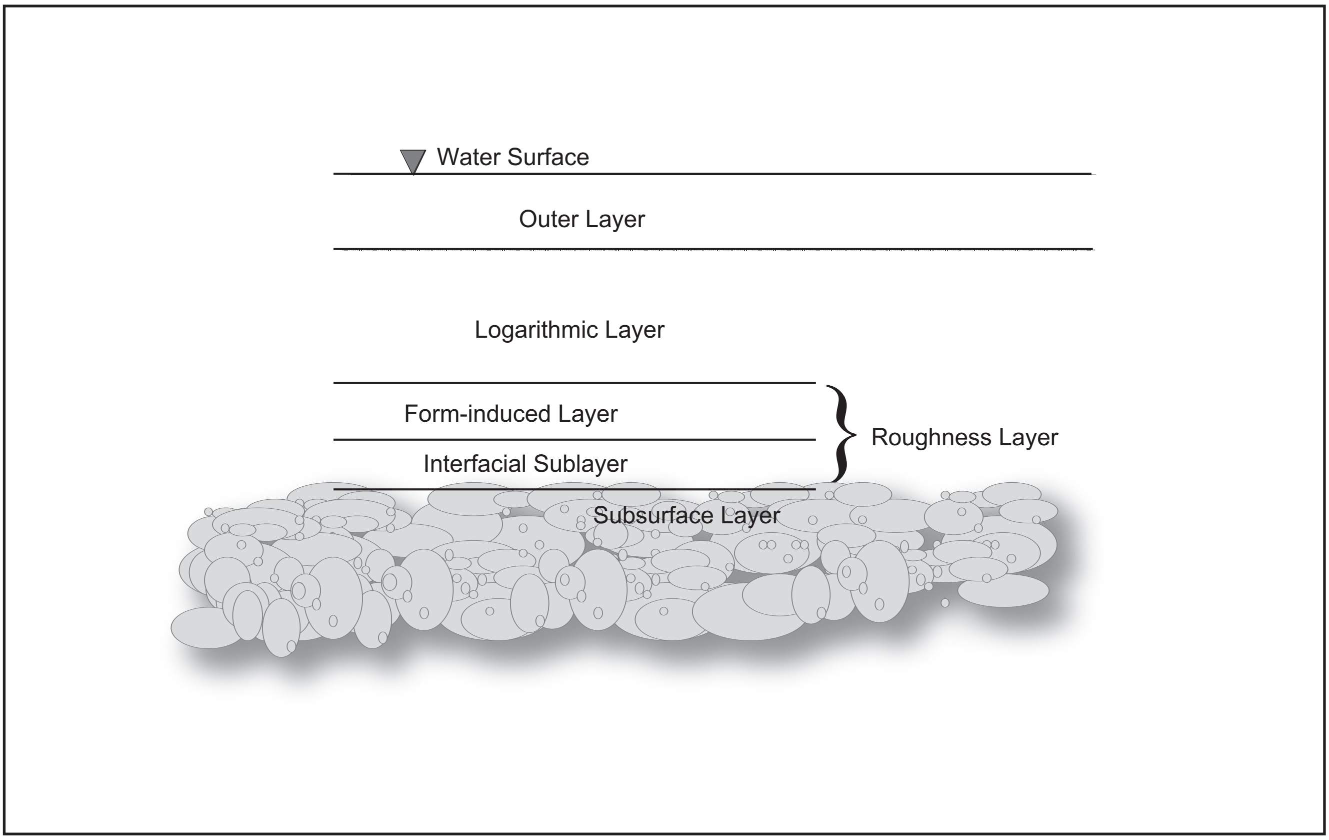

Figure 3. Description of Flow in a Stream Channel with a Permeable, Rough Bed. Source: (Nikora *et al*., 2001)

3.2.3 Implications for the Retrofit Experiment

Results from the literature review, and the earlier discussions of the riffle experiment, provide information that challenges the efficacy of a project that aims to improve stream health by retro-fitting a retarding basin to reduce the size of floods.

Retrofitting a retarding basin may reduce flow stress but will only improve stream health if flow stress is the critical problem. There are four reasons which suggest flow stress is not the ultimate factor limiting stream health in the urban streams we have looked at (mainly in Melbourne's east).

The first piece of evidence is that if flow stress was the only problem, we would expect to see patterns in the occurrence of macroinvertebrates. Taxa that are sensitive to flow should occur in refuge areas of the stream bed that are sheltered from turbulence, high velocities and transported sediment. Refugia, have been shown to accumulate sensitive taxa under laboratory experiments. However there were no evidence of sensitive taxa accumulating and persisting in refugia in Melbourne streams with high levels of urbanisation (Walsh *et al*., 2001).

The second line of reasoning is related to these findings. In situations of high flow stress (frequent, severe events) two types of taxa would do well, (a) those that can quickly recover from flow stress - their populations may be reduced by an event but they can reproduce rapidly before the next one, and (b) those that can cope with the stress e.g. those that prefer to live in refugia. In fact, the actual urban stream taxa are dominated by type (a) - those that can recover quickly, not type (b). This suggests there is more than one type of stress - the macroinvertebrates that can cope with flow stress are wiped out by water quality events (or

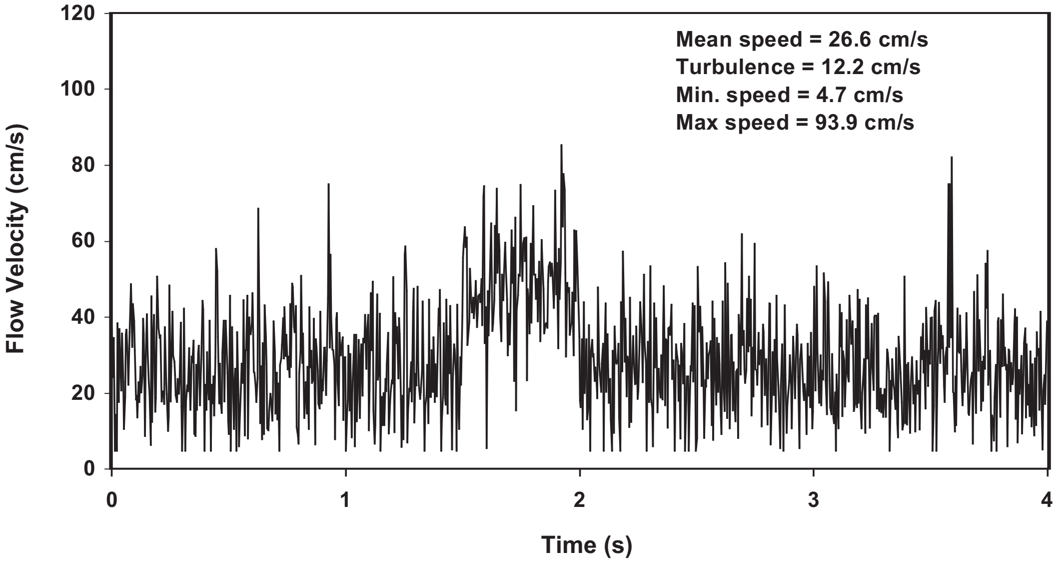

Figure 4. Four Second Velocity Time Series Collected Using a Hot-film Velocimeter.
Data were collected at 256 Hz at 2 mm above the surface of a natural stone inhabited by black fly larvae in Taylor Run (Chester County, Pennsylvania). Turbulence is measured as the standard deviation of the velocities.

Source: (Hart and Finelli, 1999)

some other stress). The only macroinvertebrates doing well are those that can recover quickly from disturbance. Reducing one source of disturbance, by retrofitting a retarding basin, would still leave other disturbances (e.g. pollution events) largely untreated.

Results from the CRC for Freshwater Ecology riffle experiment provide a third reason to suggest that we need to do more than fix the flow stress. When high quality refugia are added to a stream, some sensitive taxa appeared but were subsequently eliminated, probably by some stress other than flow (most likely water quality) since they were living in high quality refugia. Similar results were obtained in other projects dealing with physical habitat restoration (see Section 3.1).

The fourth reason to suggest flow stress is not the only critical factor is that urban streams with high quality refugia, have the same taxa as streams with poor or no refugia (Comparing the different streams sampled in Walsh *et al*., 2001). If flow stress was the only issue, we might expect to see some sensitive taxa where high quality refugia naturally exist.

These results suggest that urban streams are subject to multiple, frequent, and severe disturbances. This implies that an experiment aimed at changing flow could be a high-risk approach to testing factors critical to urban stream rehabilitation, as it would require a lot of resources to improve hydrology with no guarantee of an ecological effect.

3.3 Using Wetlands to Improve Water Quality

Improvements to physical habitat and hydrology have been shown to be unlikely to improve stream health; could an appropriate strategy be to improve water quality? A common initiative aimed to improve water quality in urban areas is the construction of wetlands which has been shown to reduce pollutant loads from storm events (Comings *et al*., 2000; Wong *et al*., 1999). Wetlands are a recognised part of conventional stormwater treatment approaches (Victorian Stormwater Committee, 1999). Melbourne Water is currently investing $4.5 million per year on major wetland projects and plans to construct two to three wetlands each year for the next ten years. At present, twenty-nine wetlands have already been constructed and eleven are under design or are planned (Bayley, 2004).

There has also been some criticism of wetlands. Helfield and Diamond (1997) argued that some pollutants may be temporarily stored in wetlands, rather than being permanently removed, and that some toxicants may have increased bioavailability. It has also been shown that shallow wetlands and ponds can increase diurnal temperature fluctuations in receiving waters (Pluhowski, 1970).

The effectiveness of wetlands in improving stream health was investigated in two projects co-funded by Melbourne Water. These projects were:

- A cooperative project with the Urban Stormwater Quality program of the Cooperative Research Centre for Catchment Hydrology to assess the effect of constructed wetlands on water quality (Fletcher and Poelsma, 2004);
- A cooperative project with the Cooperative Research Centre for Freshwater Ecology to assess the impact of wetlands on macroinvertebrate taxa (Walsh, 2004).

3.3.1 Assessment of Water Quality Changes

The Hampton Park Wetland, Hallam was chosen for sampling and water quality was monitored at the inflow, outflow and several intermediate points. Both storm events and base flow were monitored. Results to date are reported by Fletcher and Poelsma (2004).

In summary, the Wetland was effective in reducing loads and concentrations of Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN) during storms. But during base flows, with relatively clean water entering the wetland, concentrations and loads tended to increase. Although *most of the load* was treated by the wetland; *most of the time* water quality was made worse. This suggests that wetlands may not necessarily benefit downstream biota since they may experience reduced water quality most of the time even if the occasional extreme conditions are mitigated. It also suggests a possible conflict between the objectives of reducing loads to receiving waters, where wetlands are an effective tool, and mitigating the water quality environment experienced by biota where the role of wetlands is more questionable.

3.3.2 Impact of Stormwater Treatment Wetlands on Stream Macroinvertebrates

To test the impact of wetlands on stream biota, macroinvertebrates were sampled upstream and downstream of four Wetlands in Melbourne's east: 1) Hull Road Wetland off Olinda Creek, Lilydale; 2) Huntingdale Wetland on Scotchmans Creek, Oakleigh; 3) Heatherton Rd Wetlands, Dandenong North, a large off-stream wetland receiving base from Dandenong Creek, and 4) Hampton Park Wetland, Hallam where water quality was also monitored (see above). Preliminary results (based on samples from a single season) are reported by Walsh (2004).

One of the sites, Hull Road Wetland, takes water from a relatively un-urbanised catchment with effective impervious area less than 2%. The other three sites drained highly urbanised catchments with effective imperviousness ranging from 24% to 38% of catchment area.

For the three urbanised sites, there were localised changes in macroinvertebrate taxa immediately downstream of the wetlands that were consistent with the discharge of nutrient rich waters during base flows. This is consistent with the results from the water quality monitoring at the Hampton Park Wetland which suggested increased loads of TN and TP during base flow. Changes in macroinvertebrate taxa were not sufficient to change the scores of stream condition indicators such as SIGNAL.

For the Hull Road Wetland, there was a decline in SIGNAL score and reduced abundance of sensitive taxa downstream. Water quality testing suggested this was not related to reductions in dissolved oxygen, which might have been expected, but could be because of increases in temperature as water is heated in this shallow wetland.

The upshot of the preliminary results from these studies is that wetlands are unlikely to result in improvements to stream health as measured by indicators based on macroinvertebrates.

4. Proposal for a Large-scale Stream Restoration Experiment

So far, the discussion has been more about what interventions will not work to improve the health of urban streams rather than ways to achieve stream rehabilitation. However, there is a way forward, partly motivated by the results discussed here, but in larger part due to the work of Dr Chris Walsh and others in the Cooperative Research Centre for Freshwater Ecology in the project, '*Urbanisation and the ecological function of streams'* and Dr Tim Fletcher in the Urban Stormwater Quality Program of the Cooperative Research Centre for Catchment Hydrology. Together we have developed a framework for stream restoration based on new approaches to stormwater drainage (Walsh *et al.*, *in review*).

4.1 The Direct Connection of Impervious Surfaces to Waterways is a Key Degrading Process

The work by the CRCs for Freshwater Ecology and Catchment Hydrology Urban Program showed that in streams affected by urbanisation, it is the proportion of the catchment that consists of *impervious surfaces that drain directly to waterways* which is a strong predictor of a range of ecological conditions (Hatt *et al.*, *in press*; Taylor *et al.*, *in press*; Newall and Walsh, *in press*; Walsh, *in press*). The direct delivery of water and pollutants from impervious surfaces to streams causes problems for biota (e.g. Figure 5). Where there is opportunity for attenuation of these inputs, that is, where the link between impervious surfaces and streams is less direct, the damage to stream health seems to be mitigated. This work explains why it is also not generally possible to mitigate catchment scale

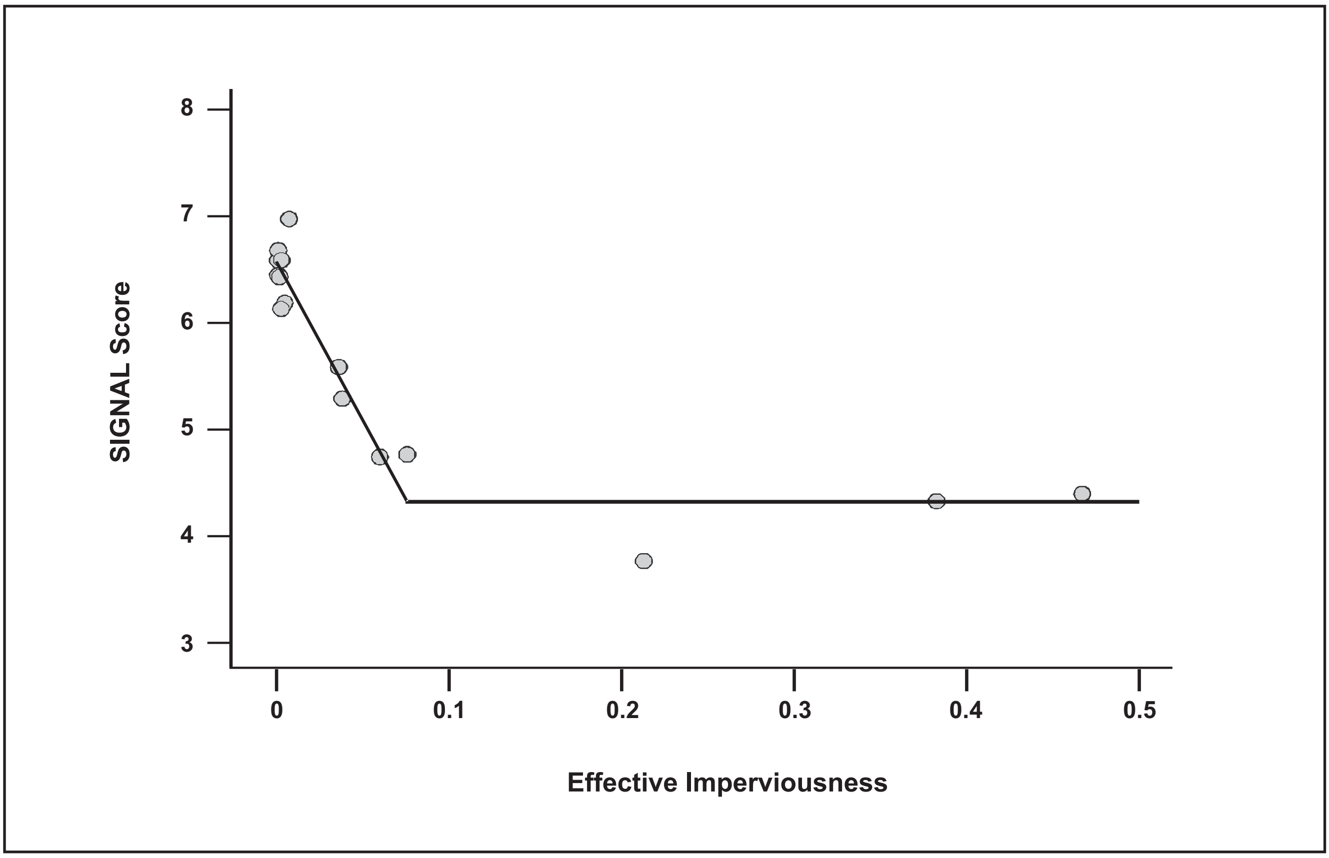

Figure 5. SIGNAL Score, a Measure of Ecological Health, Versus Effective Imperviousness - the Proportion of the Catchment Area that Consists of Impervious Surfaces that Drain Directly to Streams.

Source: (Walsh *et al.*, in review)

disturbance caused by urbanisation, by works at the stream-scale such as habitat improvement. Any local beneficial effects of these works are overwhelmed by the multiple impacts caused by direct runoff from urban areas (Walsh and Breen, 1999). Local scale restoration efforts fail to match the scale of the degrading process. Urban stream restoration, which aims to improve in-stream ecological indicators, needs to be focussed at the catchment scale (Hobbs and Norton, 1996).

Directly connecting impervious surfaces to waterways results in a large increase in runoff frequency. A few millimetres of rain falling on a car park or road will be sufficient to cause surface runoff that will flow into entry pits and then to streams via the urban drainage network. The same piped network will also efficiently deliver any chemical spills directly to streams.

A simple hydrologic model of a house block in Melbourne's east shows the effect of urbanisation on runoff frequency. Under forested conditions, daily rainfall of about 15 mm would be required to produce runoff which would occur about 15 days a year. Following development, where runoff from impervious surfaces such as roofs, roads and driveways is piped to waterways, only about 1 mm of rain is required to produce runoff which will now occur about 120 days per year (Walsh *et al*., in review).

4.2 Proposal for a New Type of Urban Drainage System

Our proposal is to test a new type of urban drainage system that mimics the natural hydrologic regime by intercepting the first 15 mm or so of rainfall without producing runoff. The intercepted water is infiltrated, evaporated, transpired or stored for later household use. Larger events will still cause disturbance to stream biota but at a frequency that is closer to natural conditions.

It is possible to predict the values of a range of ecological indicators based on the proportion of catchment area that is impervious and directly connected to waterways (the effective imperviousness) (Figure 5). Therefore, if a particular ecological condition is desired, it is possible to work out the allowable effective imperviousness. For degraded streams we are now investigating the feasibility of approaches that could be used to retrofit an existing suburb to achieve the required reduction in connected impervious area.

One promising approach is through the use of rainwater tanks. Roofs represent a large proportion of the impervious surface in urban catchments and installing rainwater tanks can decrease the amount of connection between these surfaces and streams. Instead of contributing to runoff, water collected in rainwater tanks can be used inside households. Rainwater tanks also offer benefits of reduced requirements for mains supply, savings in stormwater infrastructure because of reduced peak runoff rates, and decreased pollutant loads to waterways. However additional strategies will be required as there are practical limits to the change in effective impervious area that can be achieved through the use of rainwater tanks (Cornish, 2003).

The limited benefits of rainwater tanks mean that strategies for decreasing the connection of roads and car parks, to streams, are also important. Permeable pavements are one option. In most cases it won't be feasible to replace existing paved areas, that are in good condition, with permeable pavements, but a long term strategy of using permeable pavements for new or maintenance work will gradually decrease connected impervious area. It's also important not to forget driveways and parking areas on private property. Runoff from these areas often flows directly to streams, via the stormwater system, so there will be benefits from using permeable pavements instead of standard approaches. Perhaps there could be an incentive program to encourage people to implement environmentally sensitive driveways. Other retrofit options include rain gardens and ponds, trenches or pits that facilitate infiltration. Increasing infiltration in urban areas is generally desirable because base flows in streams will be restored. Of course, if there are slope stability issues, infiltration may have to be avoided.

The aim of these works, which are focused on reducing runoff frequency means that small-scale, source control approaches are favoured over end of pipe schemes. The requirement to retain the first 15 mm of rainfall produces volumes of water that are difficult to manage once catchment areas increase beyond a cluster of houses. To be feasible in most cases, retrofit works must be designed for house block to streetscape scale.

4.3 Testing the Approach

Although there is strong evidence that reducing effective imperviousness will result in improvements in stream health, it is important to test this hypothesis. We are concentrating our work on Melbourne's suburbs where streams are in moderately degraded ecological condition. These suburbs are good candidates for intervention because a relatively small change in the amount of connected impervious surface could tip them from being unhealthy back to being healthy and it is possible to design an experiment that has a large effect size. This can be explained by looking at Figure 5. There is a rapid change in stream health for values of effective imperviousness less than about 8%. Above about 8% streams are 'unhealthy' and are not further degraded by increases in the amount of effective impervious area. Therefore the largest response to restoration efforts, that aim to decrease effective imperviousness, will be in catchments that plot on the steeply sloping part of Figure 5 rather than along the sill. Using this criterion, the first sites for investigation have been in the catchments of Dobsons Creek and Little Stringybark Creek that drain the Dandenong Range in Melbourne's east (Cornish, 2003; Horton, 2004). There are also streams nearby that can be used as experimental controls, and before data for both control and treated streams.

Our original plan, in Project 6.2, was to conduct an experiment in urban stream restoration based on changing flows, but that project was abandoned following our investigation (see Section 3.2.3). The experiment proposed here has a much greater chance of success for the following reasons (see Walsh *et al*., (*in review*) for details):

- Data collected in Melbourne's streams supports the link between effective imperviousness and stream condition;
- It is possible to model the effect of changes in effective imperviousness and stream biota;
- These models allow the design of an experiment that has a large effect size so stream response should be detectable amongst the noise of natural variation;
- Preliminary analysis suggests the experiment is technically feasible;
- There are opportunities for replicates and controls which should allow reliable inference from results; and
- Urbanisation is a catchment scale disturbance and this approach works at the same large scale.

Funding and community support are now being sought to redesign the drainage systems in the two candidate catchments. It is also hoped that this experimental approach will be key activity of the eWater Cooperative Research Centre, should it be funded.

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Appendix 1. Summary of Activities, Outcomes and Outputs of Project 6.2

Table A1.1 Project Activities, Outputs and Outcomes Based on Issues from the Project Agreement

Issue from Project Agreement	Activity	Output	Outcome
Setting clear rehabilitation targets	Workshop to review Melbourne Water's waterway management strategic plan (with CRC for Freshwater Ecology)	Report summarising comments from workshop (Cottingham *et al*., 2002)	Melbourne Water to consider revising their waterway management strategic plan
Improve priority setting	Two workshops to refine STREAMS, the Melbourne Water waterway management and priority setting model (with CRC for Freshwater Ecology)	Agreement with Melbourne Water staff at the workshop about the capabilities and limitations of streams. Draft report (Walsh *et al*., 2002)	Melbourne Water to consider refinements to STREAMS
	Discussions with the Aquatic Services Team at Melbourne Water about the quality of data used as input to deciding priorities. Input into a proposal to improve data collection methodology.	Proposal by Melbourne Water Aquatic Services Team to develop an Urban ISC	Melbourne Water to consider developing and implementing the Urban ISC
	Research on planning procedures for urban stream rehabilitation	Thesis by Josef Kiessner on the Lietbild rehabilitation planning approach (Kiessner, 2002)	Melbourne Water to consider changes to planning procedures
	Research on priority setting	PhD thesis by Myriam Ghali (in preparation)	
	Collaborative work with CRC for Freshwater Ecology on incorporation of results from research on drainage connection into urban stream restoration	See below	
Application of ecological and physical principles (particularly connection) to rehabilitation planning	Preliminary application of connection indicators by CRC for Freshwater Ecology suggests they are a useful approach (Walsh *et al*., 2002)	Proposal to develop and test connection indicators in the Melbourne area (see Walsh *et al*. in review).	Project included in second round CRC for Catchment Hydrology Project 4B and an associated CRC for Freshwater Ecology project
A procedure to optimise the rehabilitation investment by testing which targets are achieved for various scenarios	Familiarisation with STREAMS the Melbourne Water waterway management and priority setting model. Two workshops with CRC for Freshwater Ecology to refine STREAMS	Agreement with Melbourne Water staff at the workshop about the capabilities and limitations of streams. Draft report (Walsh *et al*., 2002)	Melbourne Water to consider refining STREAMS
Identify what can be achieved (in environmental terms) by altering various variables in an urban catchment.	Literature review on the response of biota to flow	Presentation to Melbourne Water on Feb 11, 2002, plus summary in this report.	Work suggested that retrofitting a retarding basin is a high risk strategy to achieve environmental improvement. Outcome was a change in direction of Project 6.2 away from modifying hydrology to looking at water quality improvement first.

Table A1.2 Performance against Milestones Listed in the January 2001 Project Agreement

Date	Milestone	Status	Comment
Feb 2001	Research fellow and steering committee appointed	Completed	Tony Ladson appointed. Melbourne Water, program 6 and external experts used for project steering as appropriate
	Design of experimental protocol decided	Completed	Water quality improvement by NHT wetlands adopted at steering committee meeting in Feb 2002
	Potential planning procedures reviewed, and approach selected	Completed	Leitbild planning approach selected and reviewed in Kiessner (2003)
May 2001	Field sites selected	Completed	Three NHT wetlands selected for monitoring. Monbulk Creek catchment chosen for Leitbild study
Aug 2001	Pre-treatment monitoring completed. Structural works in detention basins designed and construction begun	Completed	NHT wetlands to be used rather than detention basins
	Workshop to define goals	Completed	Three workshops held with Melbourne Water in Jul and Aug 2002
Oct 2001	All structural works and monitoring gear in place	Completed	Monitoring gear in place at NHT wetland sites
	Complete rehabilitation plan for review	Completed	Complete plan documented as part of a graduate project (Kiessner, 2002)
Feb 2002	Steering committee meeting. Preliminary report on results to date	Completed	Meeting (on Feb 11, 2002) adopted proposal to monitor water quality improvement, based on recommendations from work to date
	Begin modelling of catchment variables to test scenarios	Completed	Rehabilitation analysis undertaken in Kiessner (2003)
Dec 2002	Final report and workshops	Completed	Workshops held in Feb 2002 and Nov 12 2002 latest results discussed with Melbourne Water Feb 2004. Completion report prepared

Appendix 2. Summary of Research on Stream Rehabilitation Planning Applied to Monbulk Creek

Published in *Catchword*, (Cooperative Research Centre for Catchment Hydrology newsletter, August 2002).

Report by Tony Ladson.

Project 6.2: Optimising urban stream rehabilitation planning and execution

Evaluating stream rehabilitation planning.

Activities in work on evaluating stream rehabilitation

One of the key activities of this study has been the work undertaken by Josef Kiessner, a visiting student from the University of Agriculture in Vienna, Austria. Josef came to the University of Melbourne to complete his final year project and worked for 9 months from September, 2001 to May, 2002 on urban stream restoration planning. He has now returned to Austria and is writing up his thesis.

Monbulk Creek - research focus

Josef's focus was on Monbulk Creek which flows through an interesting mix of urban and rural development in Melbourne's eastern suburbs. The upper reaches are in a relatively natural condition, draining the Dandenong Ranges National Park around Kallista and Sherbrooke. Downstream there is urban development through Belgrave. Then the creek flows through agricultural land in Lysterfield and new urban areas in Ferntree Gully and Rowville before joining Corhanwarrabul Creek and onto Dandenong Creek just north of Wellington Road.

The lower reaches of Monbulk Creek are subject to many of the pressures that are typical of urban streams, yet there are also opportunities for rehabilitation. This is because there is limited development on some of the floodplain, areas of rural land upstream, and a retarding basin that has the potential to protect the creek from the changes to hydrology caused by urban development around Belgrave. Melbourne Water has also recently been rehabilitating the creek in parallel with construction of a golf course. Willows have been removed, and a series of rock chutes has been built to control bed erosion and to provide in-stream habitat for the aquatic life in the clay-bedded Monbulk Creek.

Research task

Josef's task was to look at planning approaches that could be used to further improve the health of Monbulk Creek. In particular his work involved an application and assessment of the type-specific approach (Leitbild concept), a planning approach that has been developed in Austria to re-establish ecological integrity in riverine landscapes (Jungwirth et al. 2002). This approach focuses on restoring some of the natural attributes of a particular stream rather than providing generic recommendations for restoration. The Leitbild concept was developed in response to deficiencies in past restoration projects that include poor project design and planning, lack of integration of different disciplines, or scaling issues, and inadequate monitoring.

A Vision

The first task in this approach is to define a vision or 'leitbild'. This vision is based on what the stream was like before European settlement and is reconstructed from historical records and, if available, current less impacted sites. For Monbulk Creek, data were available from historical maps and descriptions of the area from early settlers. Early Parish plans from 1855 and 1856 indicate that the lower Monbulk Creek, downstream of Nixon Road (Melway 83J2) to the confluence with Ferny creek, was a vast Tea-tree swamp. There was no defined stream channel in some sections. Early settlers describe the area as being poor and scrubby (Coulson 1959).

Status quo condition

The next step is to assess the status quo, or current condition, and to compare it with the reference conditions to determine deficits and demands. Data on the status quo condition were available from investigations of Melbourne Water Corporation that include a report on geomorphology and a Waterway Activity Plan. Additional investigations were made through field work which comprised mapping, photo documentation, discharge measurements, and the application of an Austrian field protocol to evaluate the geomorphology. Josef modified this protocol as necessary to make it suitable for Australian conditions.

Quantitative data, including cross sections, width to depth ratio, width and depth variance, were collected in the field. The draining of the Tea-tree swamp, catchment clearing, construction of a defined stream channel, rural and urban development is revealed by changes in parish plans, historical documents, a sequence of aerial photographs and the annual updates of the Melway street directory.

Assessing the status quo included a detailed assessment of stream hydrology and hydraulics to predict channel stability from the frequency of bankfull flow, and the corresponding stream power and shear stress. Bankfull discharge was estimated from field measurements of channel size and slope, along with selection of a Manning's n value. Bankfull discharge frequency was determined from a partial flood frequency analysis of flows from the gauge on Monbulk Creek in Tecoma, which is upstream of the retarding basin at Birdsland Reserve. For a given recurrence interval, the discharge downstream of the retarding basin was calculated using a RORB model.

Bankfull flow is expected to occur with a frequency of 1 to 2 years for streams that are in balance with their water and sediment inputs. Similarly, bankfull stream power is expected to be about 35 W/m2 for stable streams (Brookes, 1988) while critical values for bankfull shear stress can be calculated from bed material size. Where the actual values depart from the critical values, stream processes are likely to alter the size and slope of the channel. Although these methods are all approximate, in combination they are likely to be a reasonable approach to predicting where channel adjustment is most likely. These areas have now been mapped along Monbulk Creek.

Target view for Monbulk Creek

The next step in the type-specific approach to stream restoration is to develop an "operational leitbild" or target view. This aims to move the stream toward reference conditions while recognising that it may not be desirable or achievable to make the stream completely natural. This target view guides the development of a rehabilitation design that takes account of the specific characteristics of the stream and aims to restore key features that have been lost. The operational leitbild considers the social and economic constraints that may prevent complete restoration. It is also important to identify the features that should be protected from further degradation and the current geomorphic trajectory.

For the Monbulk Creek, Josef is developing a target view and rehabilitation plan to restore some of the features of the stream that existed under natural conditions. In particular this involves increasing the frequency of connection between the stream and the floodplain and restoring some of the wetlands and Teatree swamps. Unfortunately, it's a little late to incorporate these features into the new Waterford Valley golf course but perhaps they could guide the next development upstream.

As well as developing his Monbulk Creek plan, Josef is evaluating the type-specific approach, commenting on its suitability for Australian conditions and identifying any modifications that may be required. One finding is that the formal assessment of reference conditions provides a method to overcome the difficult step of setting goals for stream rehabilitation. The approach has also confirmed the need to identify, and if possible address, the processes leading to stream degradation(see Hobbs and Norton. 1996). It is not enough to just provide a list of activities required to restore streams, as these will never be successful unless the cause of the degradation is mitigated.

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Appendix 3. Lessons from a Simple Model of Disturbance

Summary

A simple mathematical model of disturbance suggests that frequent disturbance favors taxa with a high intrinsic rate of increase. This is likely to correlate with rapid growth, small size at adulthood, rapid maturation to adult stage (short life cycles), continuous emergence and large numbers of offspring (Fisher *et al.*, 1982; Resh *et al.*, 1988).

If, in a particular stream, these type of taxa dominate they are likely to indicate frequent disturbance, but, without other information, they cannot suggest the cause of the disturbance.

Where disturbance is frequent and severe, the history of disturbance determines the population size at any particular time. The population is always recovering from the previous disturbance not fluctuating around some equilibrium level. This implies that a time series of population measurements is necessary to understand disturbance and that measurements at a single time will only yield very limited information.

Explanation

Consider a macroinvertebrate taxa growing according to a simple logistic population model

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \qquad (1)$$

where N, is the population, K is the carrying capacity, r the intrinsic rate of increase, t is time.

Expressing this as a difference equation.

$$\frac{\Delta N}{\Delta t} \approx r\Delta t N\left(1 - \frac{N}{K}\right) \qquad (2)$$

$$N_2 = N_1 + \Delta N$$

Where the subscripts refer to time 1 and time 2 respectively. A graph of a population following a logistic growth equation is shown in Figure 1

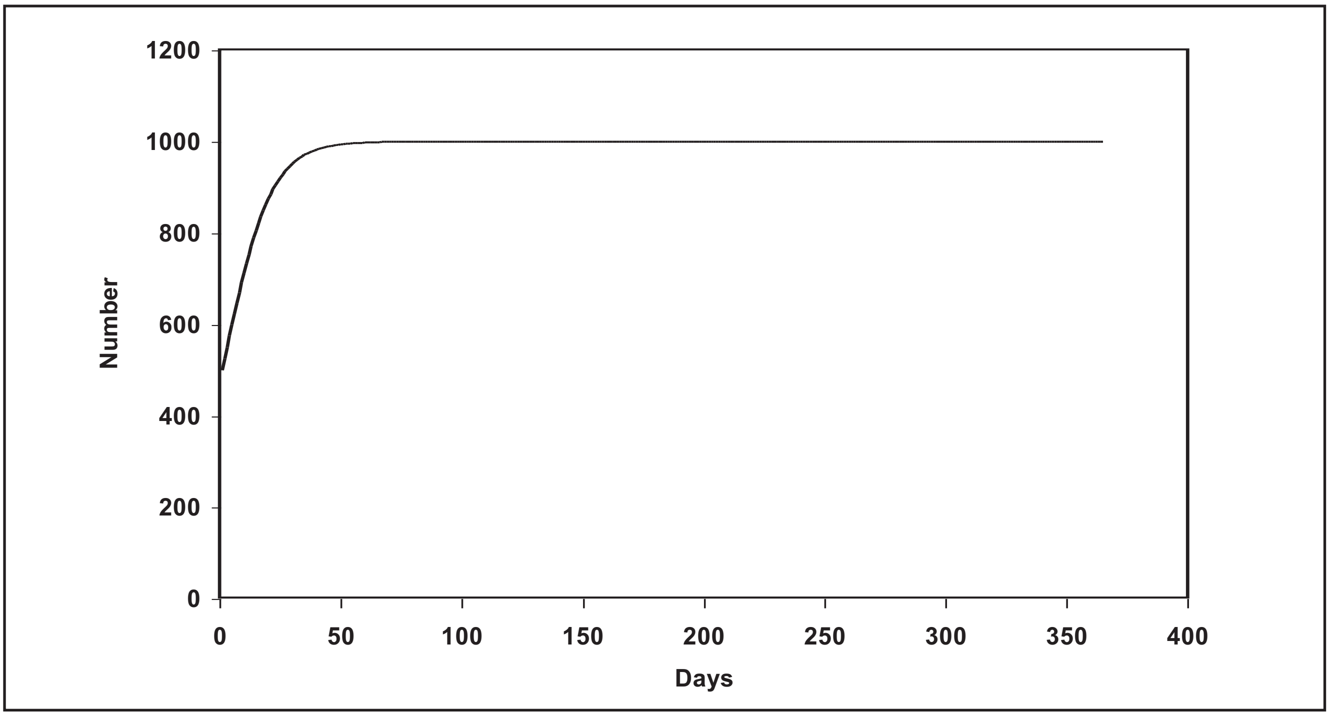

Figure 1. Logistic Population Growth *r=0.1m N(0) = 500, K = 1000,* time step of 1 day.

Now consider the population affected by large disturbances that occur randomly and result in a reduction in population of H. Let the probability of occurrence of the disturbance, on any particular day be P.

$$N_2 = N_1 + \Delta N - HN_1$$

Where H depends on P and the time, t.

Modelling H as a severe disturbance, say the loss of 90% of the population (perhaps caused by a large flood or a severe water quality incident) means the population will be reduced but will grow back toward the carrying capacity K. The effect of infrequent disturbances means the population has time to recover (Figure 2). As disturbances become more frequent there is less opportunity for recovery (Figure 3), until the carrying capacity is seldom reached Figure 4 and the chance of extinction increases Figure 5.

The model suggests that the response of biota to disturbance is a function of the severity of the disturbance, P and the intrinsic rate of increase of the species, *r*. Other factors being equal, species with higher *r* values will survive longer as the frequency and magnitude of disturbance increases, possibly through effects such as urbanisation. The P/r ratio indicates the severity of disturbance for a particular taxa.

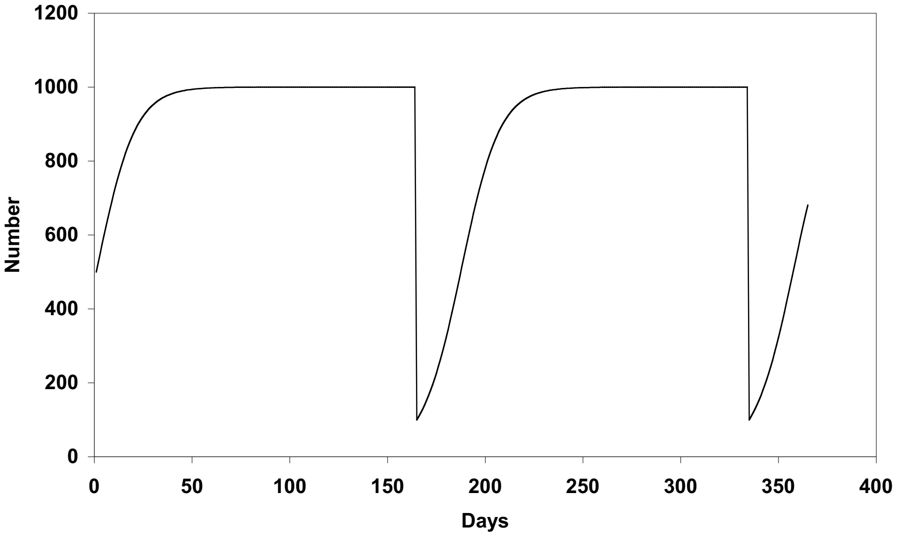

Figure 2. Population Affected by an Infrequent, but Severe Disturbance. *N(0) = 500, K = 1000, H = 0.9* i.e. 90% reduction in the population when there is a disturbance, *r = 0.1, P = 0.005* ie probability of a disturbance on any day is 0.005 (1.83 disturbances per year on average). The ratio *P/r = 0.05.*

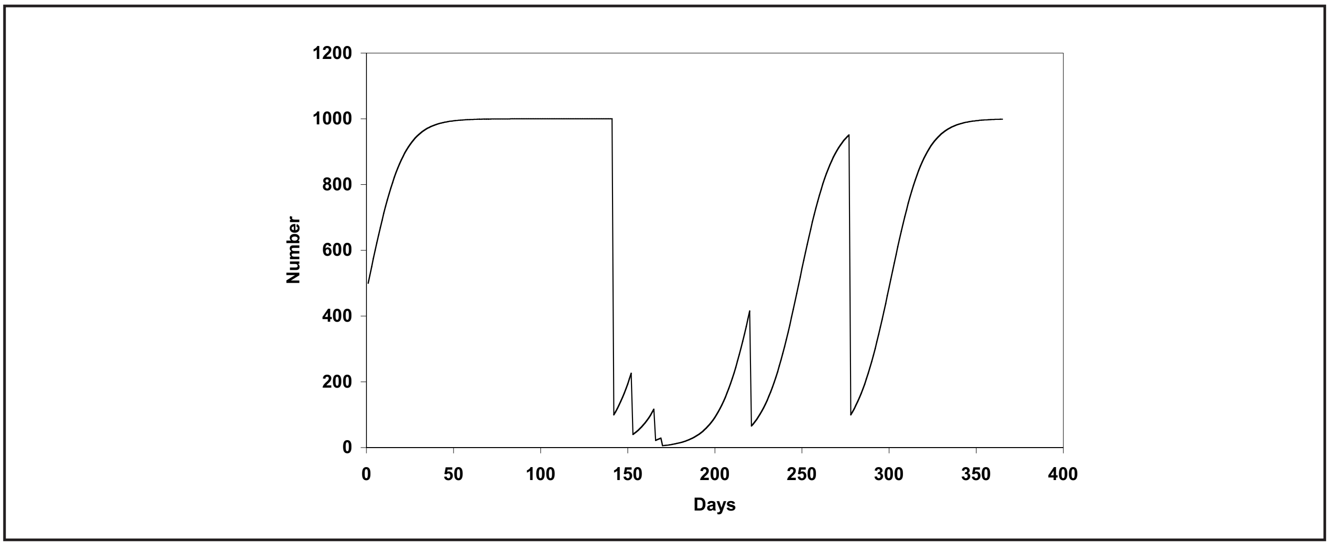

Figure 3. Similar to Figure 2 except disturbances are more frequent *(P/r = 0.1)*

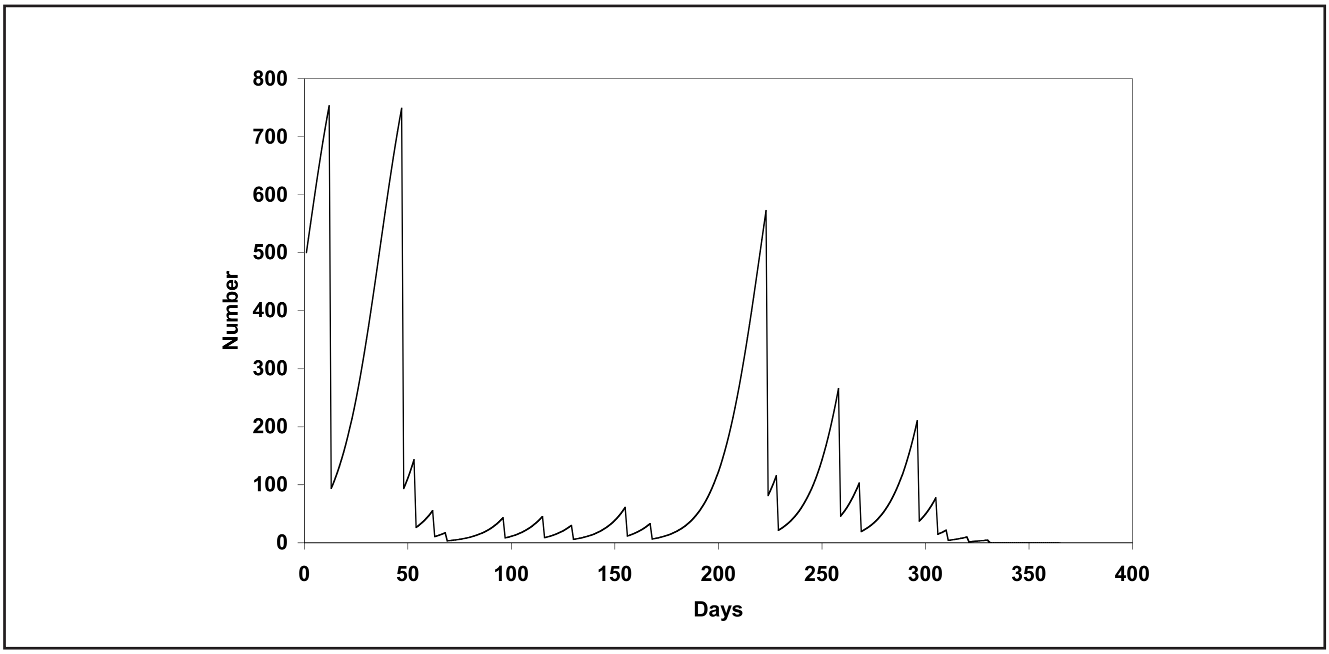

Figure 4. Similar to the previous figure except disturbance is more frequent. The disturbance frequency determines the population and there is a risk of extinction (P/r = 0.5).

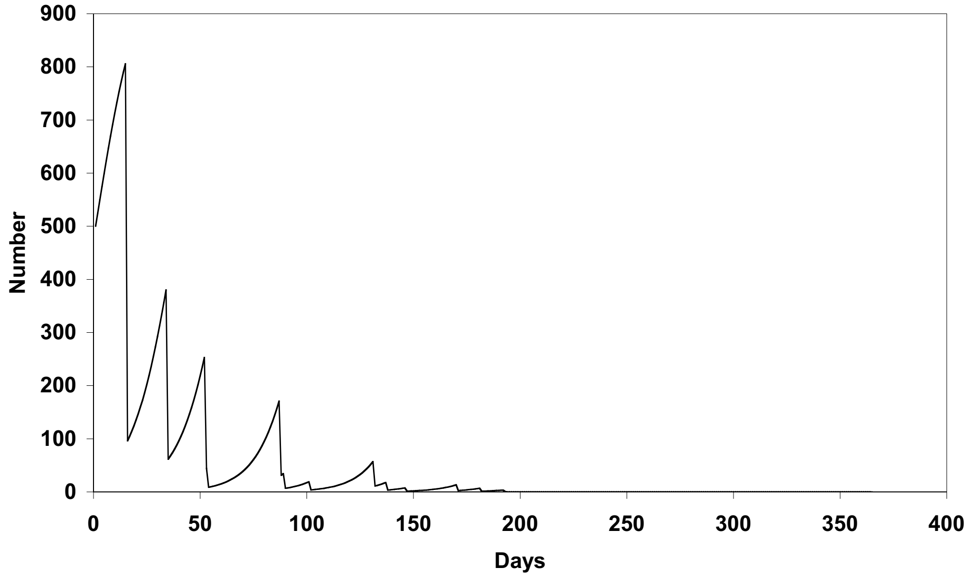

Figure 5. As the Disturbance Frequency Increases Still Further, the Population Does Not Have Time to Recover and is Driven to Extinction *(P/r = 1)*.

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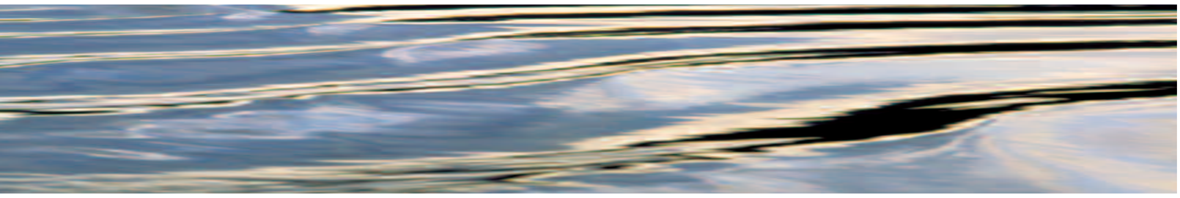

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