Understanding Ecological Response in Urban Catchments

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Abstract

This paper presents the initial stages of a research program where concepts and methods are being developed for better understanding of ecological response in urban catchments. The aim of the research is to provide improved outcomes for integrated urban water cycle solutions and related ecosystems.

Important ecological concepts are introduced and discussed with the intention of providing more appropriate considerations for complex interactions between urban water infrastructure and ecosystems. These include the integrated nature of the urban water cycle, the importance of scale in studying ecosystems and providing solutions, the relativity of ecosystem improvements, and ecosystem stability. This paper then introduces a range of methods to be used in subsequent studies to investigate the ecological response of urban streams. These include the use of flow duration curves, peak flow frequencies and ecologically effective discharges, and also novel methods involving time series analyses to allow for non-stationary data and memory effects.

This work forms part of a research effort within eWater CRC investigating “innovative WSUD intervention strategies to counter deteriorating infrastructure and evolving urban form, and enhance ecosystem health.” It is intended that the work presented in this paper and related research will be used as part of a framework when implementing water sensitive urban design strategies and assessing likely impacts on connected ecosystems.

Introduction

The natural water cycle is profoundly changed by urban development and the hydraulic systems constructed to provide water services to towns and cities. Typically, the area of impervious surfaces is increased, whilst natural watercourses are replaced with pipes and channels designed to be hydraulically efficient to expedite the removal of water to downstream receiving water bodies.

This present paper forms part of a larger research project within the eWater Cooperative Research Centre where the objective is to discover and explore innovative solutions to urban water cycle problems. The nature of the research program requires a holistic systems approach, and to do this properly it is considered important to include the problems of deteriorating infrastructure, continuing degradation of ecosystems, evolving urban form and the compounding effects of drought and population growth. This paper, however, presents the beginnings of a research program where concepts and methods are being developed to better understand likely ecological responses in urban catchments from Water Sensitive Urban Design (WSUD) interventions to counter these impacts.

This discussion begins with an overview of important ecological concepts used to facilitate more appropriate considerations for complex ecosystems. The most important of which is the integrated nature of the urban water cycle, and how a change in any part of the urban water system may trigger responses in many other parts. This is particularly important when considering how urban water systems in Australia have historically been designed and managed as mostly separate water supply, wastewater and stormwater systems (Coombes and Kuczera, 2002). Ecosystem health has previously had limited consideration as part of the urban water cycle design process until the advent of WSUD methods.

A range of methods are introduced which will be used in subsequent studies to predict likely ecological responses in urban streams. These include the use of relatively simple approaches such as flow duration curves, peak flow frequencies and effective discharges, and also more complex and novel methods involving time series analyses to allow for non-stationary data and memory effects. Perhaps the most promising method is the use of an ecologically
effective discharge based on the work of Doyle et al. (2005). Case studies will ultimately be used to further establish the proof of concept for the use of ecologically effective discharges and to describe relationships to several ecological variables (including sediment, nutrients, macroinvertebrate mobilisation and periphyton growth and removal).

It is intended that the work presented in this paper will be used as part of a framework for investigation of WSUD strategies and assessing likely impacts on connected ecosystems.

**Ecosystem Health and Ecosystem Response**

From an ecological perspective it is the species richness that defines aquatic biodiversity and ecosystem health ($EH$) at time $t$. A change in species richness is an indicator of disturbance and can be described as the change in ecological health or an ecosystem response ($\Delta EH$). Equation 1 describes this.

$$EH_{t+1} = EH_t + \Delta EH$$

Equation 1

$\Delta EH$ can be further deconstructed to:

$$\Delta EH = \Delta HP + \Delta NP$$

Equation 2

where $\Delta HP$ is a change in Human Processes and $\Delta NP$ is a change in Natural Processes. Equation 2 assumes a linear superposition of effects, which may not be appropriate in all cases. In the context of an integrated urban water cycle, pertinent to the present research program, $\Delta EH$ can be limited to the changes in human processes, and is a function of the many possible changes in the provision of water services, described by Equation 3, where $ws$ is water supply, $sw$ is stormwater, and $ww$ is the wastewater cycle.

$$\Delta EH = \Delta HP = f(ws, sw, ww)$$

Equation 3

The development of greater understanding of ecological response in relation to urban water infrastructure provision can involve the use of expert knowledge processes and frameworks. Indeed, an objective of the research project is to streamline the link between ecologists and engineering methods as part of an integrated approach to solve urban water cycle issues, particularly when considering infrastructure options and WSUD intervention.

**Scale, Detail and Stable States in Ecosystems**

The basic premise of the research is that ecological response is dependent on many interacting elements of the water system. Figure 1 shows how the urban water cycle fundamentally impacts on ecosystem health. The Figure shows that, for a regional scale system, there may be three different ecosystem responses within the one stream. The first is the (undisturbed) ecosystem upstream from urban impacts, the second is a result of water extraction (changed flow regime from water supply) and the third a result of water discharge (changed flow and water quality regime from both stormwater and wastewater) back into the system. Water quantities and qualities will be different for each of these and have corresponding ecological responses.
Figure 1: Diagram showing the many interacting elements of the urban water cycle.

There will also be many ecosystem responses within the urban catchment. Figure 2 shows how the response can be investigated as an “end of pipe” problem or as a distributed scale catchment problem. Unfortunately, most analyses and models (both ecological and infrastructure related) are at this “end of pipe” scale. This method does not account for the true complexity of the catchment and provides only “net effect” information. Information in this form is difficult, if not impossible, to deconstruct to the necessary detail to provide information on upstream processes and usually precludes the effectiveness of decentralised solutions. Small pieces of critical information may be glossed over or hidden amongst the mass of other information. Put simply, responsive solutions cannot be formulated to non-responsive data. How can decisions on countering deteriorating ecosystem health be made if there is only non-responsive data to infer decisions from? The rush to solutions fosters the oversimplification of such notions as sustainable development and ecosystem health, and favors the tendency to ignore the complexity of natural systems (De Leo and Levin, 1997). A distributed scale approach will be required for true ecosystem health and diversity solutions.

Figure 2: Alternate methods for monitoring and managing ecosystem response.
Figure 3 shows how important it is to also consider the relative gains that can be made with ecosystem health. With a certain flow increase, $X$, a stream may provide two ecological responses (1 or 2) depending on the relative ecosystem health at the time. That is, the ecosystem response will be different under different flow improvements.

An additional consideration for ecosystem health is the homeostasis of ecological communities. Some communities tend to return toward a steady state (or fixed structure) after disturbances such as floods (diagram 2 part b of Figure 3), whereas other communities may not return to the original state even if the original abiotic conditions are restored (diagram 2 part a of Figure 3) (adapted from Mitchell and Wallis, 1996, p. 3-6.). The identification of such thresholds is an active area of research within the ecohydrology community (Hinz et al., 2006).

Figure 3: Diagram (1) showing relative improvements in ecosystem health for a given flow increase; diagram (2) describing homeostasis and stability in community structures where a) illustrates multiple stable states A, B, C, D and E and b) illustrates a steady state system.

Figures 1, 2, and 3 present some important concepts for the effective investigation and use of ecological response models in combination with analysis of the urban water cycle. The changes on ecological health impact at any point where the natural hydrological or water quality regime is disturbed (Figure 1); the importance of scale and understanding the level of detail required to impact positively on ecological health (Figure 2); the improvements that can be made to an ecosystem is always relative, with one solution not always applicable to other systems (Figure 3, diagram 1); and acknowledging that it may not be possible to return an ecosystem to its original state even if all of the original conditions are restored (Figure 3, diagram 2).

**Methods for Investigating Ecological Response to WSUD Intervention**

Hydrological methods can be used to show how flow regimes change with different water management options. This information can then be related to instream ecological responses. The qualification on this, is that a good ecological indicator may not be immediately apparent for all systems (particularly in a heavily or uniquely disturbed urban environment), and some data exploration will be required to investigate appropriate ecological assessment techniques for use in multi-criteria analysis of the urban water cycle.

Examples of hydrological analysis techniques for ecological response to be used at the outset of the present research project will include simulating how flow regimes may alter after some type of WSUD intervention. One way to do this is with flow duration curves and flow frequency distributions. Figure 4 shows how the stormwater flow duration curves for a catchment can change with WSUD intervention. For this example, data were obtained from the computer program UrbanCycle (Hardy et al., 2005), which was used to continuously

![Diagram 1](image1)

![Diagram 2](image2)
simulate the performance of an urban catchment of 9.2 hectares in a suburban Newcastle area consisting of 89 residential dwellings. Data is described as pre intervention, using traditional stormwater infrastructure (curbs, channels and pipes), and post intervention, using innovative WSUD devices (in this case rainwater tanks to capture roof runoff to augment mains water supply). More information on UrbanCycle and this particular UrbanCycle model can be obtained from Hardy (2007). Note the significant reduction in stormwater runoff events as a result of the intervening rainwater tanks. Shown on the Figure, for demonstration purposes, is a 10% frequency reduction for flow magnitudes of approximately 100 L/s. Important information relating to the potential changes in stream geomorphology, inundation levels, and likely frequency of inundation can be obtained from such data analysis.

Figure 4 also presents the frequency distribution of the peak stormwater discharges. Again, a notable difference is observed, especially at the lower discharge values. This reduction of flow “flashiness” is exactly what is prescribed as one of the main methods to combat the effects of urbanisation to promote ecosystem health (Coombes et al., 2002; Hatt et al., 2004; Meyer et al., 2005; Walsh et al., 2005).

A very clear feeling of how ecology is influenced by hydrology can be obtained by using the concept of “ecological effective discharge” (Doyle et al., 2005). Ecological effective discharge, $Q_{eff}$ analysis is a generalisation of the ideas behind the definition of the geomorphologic effective discharge. That is, the discharge that transports most of the sediment or does most of the work in shaping the cross section in a stream. This discharge is a combination of frequency of occurrence and flow magnitude, and is obtained by multiplying the flow duration curve (probability density function of discharges) with the parameter rating curve (in this case sediment) that gives a relation between discharge and the parameter (Figure 5). The same rationale has been applied to nutrient export and retention, nutrient loads, particulate organic matter, dissolved organic carbon, periphyton growth and removal, macroinvertebrate mobilisation and physical habitat availability (Doyle et al., 2005).

The approach has great potential because subsequent analysis can be carried out on the effective discharges instead of having to resort to the whole probability distribution. Changes in hydrologic regime due to, for example, urbanisation or stream regulation, will have an effect on the probability distribution of the discharge and that in turn will be reflected in a change of the effective discharge. The concept can also be used to identify ecological processes dominated by base flow, moderate floods (recurrence interval of years) or extreme floods (recurrence interval of decades to centuries).
Discharge, $Q$

(A) Frequency of Discharge, $F(Q)$

(B) Sediment Load, $S(Q)$

(C) Effective Discharge Curve, $F(Q) \times S(Q)$

Figure 5: Plot showing concept of effective discharge, adapted from Doyle et al. (2005).

This methodology may be useful when applied to equilibrium systems in which the discharge data can be considered a stationary random statistical variable. Unfortunately, this represents an important limitation for Australian conditions where multi decadal variability is common and also precludes the consideration of other short term “memory” effects which are fundamental for some ecosystem responses. A number of ecological processes respond to a sequence of flow conditions rather than to individual events and this effect is not completely captured by the statistical analysis. Several ways of relaxing these assumptions will be explored in future work by incorporating other methodologies like spell analysis (time between dry and wet periods) (Donald et al., 1999), residual mass flow analysis (McMahon and Mein, 1986), and number of rain days (Coombes, 2002). Figure 6 gives an example of two of these methods.

Figure 6 uses the daily time series stormwater data for a random 3 year period from the UrbanCycle model described previously. Only three years of data is used in order to simplify the presentation of data. Shown is the number of flow events or “peaks” that have occurred for each year of the time series that fall above the root-mean-square (RMS) value of that time series. The RMS value could be substituted with a more ecologically significant value, such as a 3 month ARI. Any significant change from year to year in the number of peaks may have ecological consequences.

A spell analysis is also shown in Figure 6, where consideration is given to the duration between ecologically significant flows (or how long low flows have been evident) and how large a flow deficit has been accumulated. Wet and dry periods are shown in the Figure and are described by plotting the data about some ecologically significant value, in this case the mean. The mean could be substituted with any other ecologically significant threshold or environmental flow value. An analysis of this type shows when above or below average stream flow conditions are being experienced. A sequence of dry or wet periods, their
duration and magnitude will provide useful ecological information. Durations of dry events are shown in Figure 6 as D1, D2 and D3.

**Discussion**

Understanding ecological response to WSUD intervention in urban environments is a multidisciplinary problem, and so an important aspect of the present work will be to encourage and establish a space for dialogue between ecologists and engineers. Ecologists will need to make recommendations for inclusions in any analysis and assist in the decisions of what is realistic or not. How to better include the role of ecologists in the process will be fundamental to any successful ecological response model. The urban water cycle should be inclusive of disciplines other than engineering.

A tentative framework for the analysis of ecosystem response can be described by:

$$
\Delta EH = f(scale, Q, \tau - \tau_c, Q_{eff}, RMS, D)
$$

where $Q$ is flow discharge, $\tau - \tau_c$ is the system distance with respect to an identified threshold, $Q_{eff}$ is the ecological effective discharge, $RMS$ the root-mean-square of the discharge data, and $D$ is some measurement of the accumulated effects of dry and wet periods.

The major issues of ecological health in urban environments have largely been identified (Engineers Australia, 2006) as being based around toxicants (heavy metals, hydrocarbons, pesticides), nutrients (phosphorus, nitrogen, carbon), oxygen demanding material (organic material), physical contaminants (suspended solids), changes to environmental flows (streamflow levels and frequency), microbial pathogens (enteric viruses, bacteria, protozoa, helminths) and aesthetic contaminants (gross or visible contaminants, litter, nuisance algal related scums, anaerobic related scums and odours). Whilst there is research required for better understanding the processes of contaminant mobilisation and transporting pathways to urban water systems, it is the focus of the present study to investigate processes, in terms of ecological response, when contaminants arrive and changes to flows are made within receiving waters. The cause-effect relationships in urban aquatic ecosystem health are still not understood in the necessary detail to provide optimal outcomes for infrastructure solutions. Nevertheless, development of ecological response models in conjunction with innovative WSUD intervention strategies will be most effective in providing the integrated solutions required.

The present study will endeavour to determine gaps in knowledge and measured parameters required to include ecosystem response in the integrated design of urban water infrastructure. From the outset, however, it is intended to consider every feasible assessment method for ecological response in the development of methods. This may include, but not be limited to, any combination of macro-invertebrates surveys, assessment of hydrological regime, assessment of hydraulic regime, geomorphologic character, water quality assessment, bioaccumulators, vegetation surveys and micro-organism surveys.

Effort will be directed into the development of a type of expert knowledge process or framework to help guide others in finding solutions to particular ecosystem responses, within an urban water cycle context. This may include assessment frameworks and the application of frameworks, along with possible assessment tools. To be pragmatic, outputs from the present research program will not necessarily provide single solutions. It is envisaged that multiple solutions may be available to any given problem, and this gives rise to the use of a Pareto optimisation approach. Such an approach will provide a frontier of solutions to choose from, based on the best engineering and science available. This will be a significant departure from the prevailing single preferred solution philosophy.
Conclusions
This paper has presented the initial stages of a research program that aims to establish better methods to integrate likely ecological responses into WSUD intervention strategies. There are limited methods currently available to adequately design for the necessarily decentralised, and more sophisticated water infrastructure solutions. This paper asserts the need for an integrated approach to urban water cycle issues. The examples presented in this report have illustrated a need for a holistic approach, however, further work will be required including investigations into what constitutes timely or optimum WSUD solutions, investigating various innovative WSUD approaches, investigating different ecological and infrastructure responses; and how to feedback new information into the solution process. Investigations will evolve to consider whether or not it is ultimately possible to provide general characterisations of ecological response and research will also include investigations into output reliability and resilience.

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References


