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Managing impacts of urbanisation on receiving waters: a decision support framework

Tim D. Fletcher[1], Tony H.F Wong[1], Hugh P. Duncan[2], John R. Coleman[3] & Graham A. Jenkins[4]

SUMMARY: Managing the impacts of urbanisation on receiving waters involves a complex process of investigation, evaluation and prioritisation of proposed strategies. Urban waterway managers have been hindered in this task, by inadequate information about the likely water quality emanating from catchments under various development scenarios. Similarly, managers have had limited ability to predict the performance of stormwater treatment measures, either singularly, or as part of an integrated stormwater management strategy. In an attempt to address these limitations, the CRC for Catchment Hydrology has developed a computer based decision support system called MUSIC (Model for Urban Stormwater Improvement Conceptualisation). MUSIC provides a suite of tools that allow urban waterway managers to formulate and evaluate alternative waterway management strategies. Future refinements to MUSIC will enhance its utility, and ultimately allow for the prediction of ecosystem responses to varying stormwater management strategies.

THE MAIN POINTS OF THIS PAPER

- Managing the impacts of urbanisation on receiving waters is a complex task; inadequate information about the performance and integration of stormwater treatment measures limits the effectiveness of management strategies.
- Most management frameworks and water quality standards have been event or deterministically based, failing to recognise the stochastic nature of stormwater impacts.
- The CRCCH Model for Urban Stormwater Improvement Conceptualisation (MUSIC) aims to addresses many of the current inadequacies in stormwater management decision-making.
- Application of MUSIC is discussed, along with its limitations and future development.

1. INTRODUCTION

Waterway managers face a complex task in assessing, prioritising, and addressing the impacts of land use on receiving waters, particularly in catchments affected by urbanisation. Urban stormwater management involves a catchment-wide approach to flow and water quality improvement. Until recently, there have been a number of significant gaps in prioritisation of urban waterway management activities, and in particular, management of urban stormwater impacts. Inadequate information about the performance of stormwater treatment measures (e.g. wetlands, vegetated swales, or gross pollutant traps) has created uncertainty about their merit, in the minds of urban waterway managers. Similarly, a lack of understanding about how various treatment measures fit together in an integrated manner can result in ad-hoc, single-focus approaches.

Compounding these inadequacies, water quality standards have tended to be deterministic and based on discrete events, failing to recognise the stochastic nature of interactions between hydrology and the physical and biochemical processes affecting the water quality of urban waterways. Recent research provides a platform for improving urban stormwater management. The CRC for Catchment Hydrology has developed a Model for Urban Stormwater Improvement Conceptualisation (MUSIC), which addresses many of the current inadequacies, and packages the results of this research into easily-applicable tools. This paper describes the operation of the model, the principal algorithms, and research activities undertaken in the CRC directed at further enhancing the system.

MUSIC provides a suite of models which allow urban waterway managers to (a) determine the likely water quality emanating from specific catchments, (b) predict the performance of specific stormwater treatment measures in protecting receiving water quality, (c) design an integrated stormwater management plan for each catchment, and (d) evaluate the success of specific treatment measures, or the entire catchment plan, against a range of water quality standards. MUSIC, currently being 'beta-tested' in Melbourne Water and Brisbane City Council (due for public release in early 2002), will assist those with a role in managing urban waterway health, to improve the efficacy of urban stormwater management programs.

2. RECENT DEVELOPMENTS IN URBAN STORMWATER RESEARCH

Successful environmental management of urban stormwater requires understanding of :

i. relationships between rainfall and runoff in the urban context,
ii. pollutant generation from differing land uses and catchment characteristics,
iii. performance of stormwater treatment measures, and how it may vary with design specifications,
iv. long-term performance of proposed stormwater strategies against water quality standards,
v. resultant impacts on receiving ecosystems, before and after implementation of the proposed stormwater strategy.

Recent research developments in the CRC for Catchment Hydrology have given substantial insights into the first four of these issues. The fifth - ecosystem responses - remains a substantial knowledge gap.

2.1 Urban rainfall-runoff

Chiew and McMahon (1997) developed a simple daily rainfall-runoff model (**Figure 1**) for urban catchments, where the majority of runoff is generated from impervious surfaces.

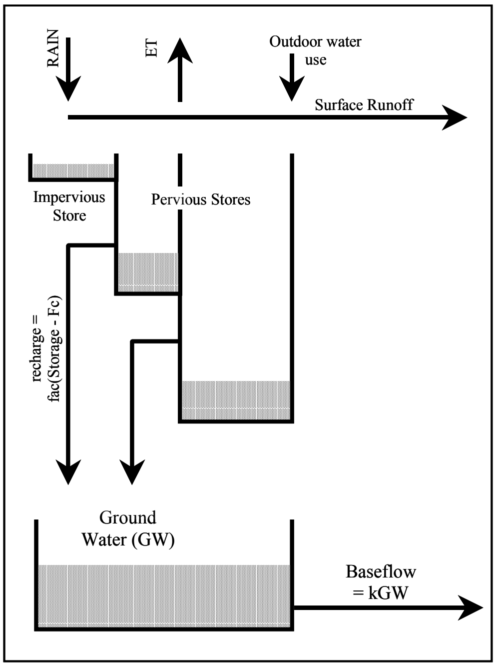

Figure 1: Conceptual daily rainfall-runoff model for urban catchments (source: Chiew et al. 1997).

In urban catchments, impervious areas will typically account for 20-70% of the total area. Further work by the CRC for Catchment Hydrology has allowed the output from this model to be disaggregated into smaller timesteps, which is important for modelling the behaviour of behaviour of stormwater hydrology and water quality in an urban environment.

2.2 Pollutant generation

The relationships between land use and the generation of pollutant loads to receiving waters is critical to understanding the nature of stormwater pollution, and to developing strategies to address it.

Duncan (1995) undertook a review of urban stormwater quality processes, and carried out a statistical analysis of urban stormwater quality from around the world (Duncan, 1999). The latter analysis presents statistical distributions of a range of pollutant concentrations in stormflow, for several broad land use categories including forested, agricultural and urban. More recent work extends the analysis to baseflow using the same methods. Mean concentrations are shown (**Table 1**) for Total Suspended Solids (TSS), Total Phosphorus (TP), and Total Nitrogen (TN).

Table 1: Summary of pollutant concentrations in relation to land use (source: Duncan, 1995).

		Mean concentration (mg/L)		
Land Use	**Flow**	**TSS**	**TP**	**TN**
Forest	Baseflow	7.9	0.034	0.73
	Storm	80.4	0.073	0.84
Agriculture	Baseflow	22.5	0.131	1.19
	Storm	187	0.536	3.90
Urban	Baseflow	13.7	0.152	2.09
	Storm	153	0.352	2.64

Urban waterway management authorities (e.g. Brisbane City Council and Melbourne Water) are now undertaking their own monitoring to refine these relationships for their own catchments. In this way, application of stormwater quality modelling will be most applicable to local circumstances.

2.3 Performance of stormwater treatment measures

Urban waterway managers understandably wish to be able to predict the performance of any stormwater treatment measures they may construct. The CRC for Catchment Hydrology has, over the last seven years, undertaken substantial research in this area.

Allison assessed the performance of Gross Pollutant Traps (GPTs), and developed guidelines for their use (Allison et al., 1996; Allison et al., 1997; Allison et al., 1998). Subsequent research has been undertaken to assess the performance of gross pollutant traps in sediment and nutrient removal (Walker et al., 1999).

The function of constructed wetlands in pollutant removal from urban stormwater has been extensively studied (e.g. Livingston, 1988; Bautista and Geiger, 1993; Duncan, 1998; Wong et al., 1998; Lawrence, 1999). This has resulted in a number of predictive models for stormwater performance, along with design guidelines (e.g. Duncan, 1997; Somes et al., 1998; Wong et al., 1998; Wong et al., 1999). The relationship of these predictive models to important design parameters (e.g. detention time, hydraulic loading[1]) has been helpful in refining design specifications for treatment wetlands.

Less research has been undertaken on other stormwater treatment measures, such as vegetated swales, biofiltration and infiltration systems. However, a worldwide review of these systems, along with recent field experiments conducted in Melbourne and Brisbane, is beginning to fill this gap (Wong et al., 2001). Importantly, this research is demonstrating the unified nature of many stormwater treatment processes, allowing modelling approaches to be simple and efficient (refer to Section 3).

2.4 Performance against water quality standards

In addition to being able to predict the performance of individual treatment measures, urban waterway

[1] Hydraulic loading, q, is a measure of flow rate per unit area; q=Q/A. It is usually expressed in m/a.

managers require the ability to estimate the overall performance of proposed stormwater strategies, and to compare the performance of alternative strategies. To be realistic, this assessment needs to be based on performance over long-time periods, under varying climatic and water quality conditions.

Until recently, the derivation and application of water quality standards has largely been deterministic or event-based. This approach does not adequately consider the dynamics of stormwater impacts. More recent guidelines use a frequency-based approach, where a threshold value is specified, along with a maximum frequency of exceedance (ANZECC and ARMCANZ, 1999). This approach allows for more realistic long-term evaluation of performance.

Combining the rainfall-runoff algorithms developed by Chiew with the predictive models of treatment performance developed by Wong et al. (2001) gives urban waterway managers access to long-term prediction of stormwater management strategies.

3. MODEL FOR URBAN STORMWATER IMPROVEMENT CONCEPTUALISATION

3.1 MUSIC Interface

Whilst the developments in urban stormwater research outlined in section 2 are important, their adoption by waterway managers is likely to be dependent on their accessibility and ease of use. Recognising this, the CRC for Catchment Hydrology has developed the Model for Urban Stormwater Improvement Conceptualisation (MUSIC).

Based on a simple icon-driven interface (**Figure 2**), urban waterway managers can formulate their proposed waterway management strategy on a map or plan, creating a 'treatment train' of stormwater treatment measures. MUSIC will simulate the performance of the proposed strategy on an event or continuous basis using historical and/or stochastically generated data of flow and pollutant concentration.

The performance can be examined via a range of output options, including time-series graphs of flows and pollutant loads or concentrations, statistical summaries, or cumulative probability plots (**Figure 3)**. Water quality standards can be applied to any of these outputs to allow easy interpretation of performance. Output can also be exported, for use in other software (e.g. statistical analysis software).

The most important feature of MUSIC is the ease with which urban waterway managers can evaluate the short- or long-term performance of alternative strategies. For example, the potential reduction in area required for a stormwater treatment wetland (often a critical issue in constrained sites), by the pre-treatment of inflows with an upstream grass swale, can be easily evaluated. This will help to facilitate effective priority-setting and analysis, resulting in more efficient and effective stormwater management strategies

Figure 2: MUSIC interface, showing layout of stormwater treatment strategy, and background

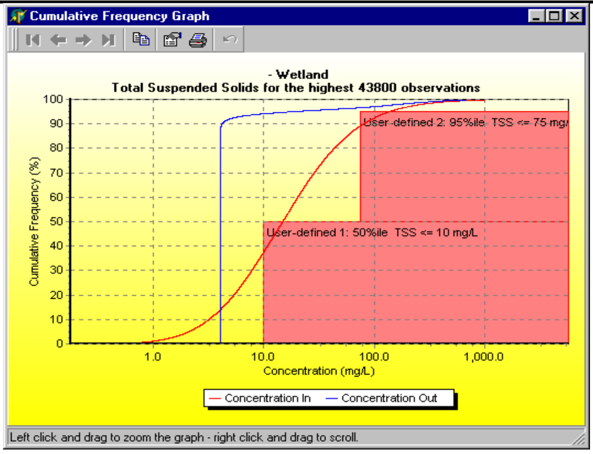

Figure 3: Cumulative probability plot output, showing water quality standards (shaded boxes).

3.2 The Universal Stormwater Treatment Model

Sitting behind the user-friendly interface of MUSIC is the modelling 'engine', called the Universal Stormwater Treatment Model (USTM).

The mechanisms promoted in the removal of stormwater pollutants encompass physical, chemical and biological processes. Given the intermittent nature of stormwater inflow, physical processes associated with detention for sedimentation and filtration (through vegetation or an infiltration medium) are the principal mechanisms by which pollutants are first intercepted. Subsequent chemical and biological processes can influence the transformation of these pollutants during the inter-event period. MUSIC has placed particular emphasis on modelling the physical processes during storm events in the first instance.

The various stormwater treatment measures by which pollutants are first intercepted and detained are described with a unified model, the Universal Stormwater Treatment Model (USTM). Grass swales, wetlands, ponds and infiltration systems are considered to be a single continuum of treatment based around flow attenuation and detention, and particle sedimentation and filtration.

Grass swales are simply ephemeral vegetated systems operating at a higher hydraulic loading than constructed wetlands. Constructed wetlands are simply shallow densely vegetated systems, compared to ponds which are characterised by deeper open water and fringing vegetation. Hydraulic loading, vegetation density and areal coverage, hydraulic efficiency and the characteristics of the target pollutants (eg. particle size distribution and contaminant speciation) largely influence their differences in performance. Similarly, infiltration systems are simply vertical filtration systems compared to the horizontal filtration systems of grass swales and wetlands, reliant on enhanced sedimentation and surface adhesion (promoted by biofilm growth) for removal of fine particles.

The validity of this unified conceptual approach to simulating the operation of stormwater treatment measures can be demonstrated by empirical analysis of observed water quality (predominantly TSS) improvements in swales, wetlands, ponds and infiltration basins during storm events and also by fitting observed storm events water quality data from these treatment systems to a universal stormwater treatment model (Barrett et al., 1998; Wong et al., 1999; Wong et al., 2001; Wong et al., in prep). While it is acknowledged that there are many complex and interacting biological and chemical processes affecting water quality in aquatic systems, the USTM provides an efficient mechanism by which urban catchment and waterway managers can predict and assess the performance of stormwater treatment measures.

Refinement of the USTM will be undertaken by the CRC for Catchment Hydrology over the next five years, and is discussed in Section 5.

3.3. The k-C* model

The USTM utilises a first-order kinetic decay model (the "k-C* model") to simulate the behaviour of pollutants as they pass through treatment measures. This model has commonly been used in predicting the performance of wastewater treatment facilities (Kadlec and Knight, 1996; Kadlec, 2000), and is now being applied in stormwater treatment (Wong et al., 1999; Wong et al., 2001).

As a pollutant moves through a treatment facility (e.g. wetland, swale, or infiltration system), its concentration tends to move by an exponential decay (at a rate, *k*) process towards an equilibrium value or background concentration (C*), as shown in Eqn 1.

$$(C_{out} - C^*) / (C_{in} - C^*) = e^{-k/q} \qquad \textbf{Eqn 1.}$$

where C^* = background concentration (mg/L),
C_{in} = input concentration (mg/L),
C_{out} = output concentration (mg/L),
k = (decay) rate constant
q = hydraulic loading (m/a)

The rate of decay, *k*, and the background concentration, C*, are both influenced by the pollutant characteristics, particularly particle size and settling velocity distributions. It is therefore apparent that a treatment measure which targets large particles (such as a sedimentation basin), will have a high decay rate (because large particles settle quickly). They will also have a high background concentration (because the finer particles are kept in suspension by the typically high flow velocities and short detention times in such measures).

Refinement of the parameters for the k-C* model, to suit local conditions (particle size distributions in particular) and treatment measure design specifications, is currently being undertaken.

4. APPLICATION OF MUSIC

It is anticipated that MUSIC, when it is released early in 2002, will be widely used in the urban waterway management industry. Land development consultants will, for example, be able to simulate the performance of proposed subdivision layouts and drainage design. Whilst MUSIC is not a detailed design tool, it will allow users to examine the consequences of changing basic design parameters of a particular stormwater treatment measure (e.g. wetland surface area, or height of vegetation in a swale). It is hoped that this will help to promote innovation and best practice.

Waterway management authorities will use MUSIC to review proposals from land developers, and to test alternate scenarios. They may also use MUSIC at the very early stages of subdivision planning, to formulate the basic stormwater management strategies.

5. FUTURE DEVELOPMENTS

The beta-version of MUSIC is currently being tested by Brisbane City Council and Melbourne Water. Both organisations are using MUSIC to evaluate land development applications, and to develop their own stormwater treatment strategies in priority catchments. Results of this testing will be incorporated into a revised version of MUSIC, to be released early in 2002. The feedback so far has been very positive.

However, there are many gaps in knowledge relating to stormwater management, and the CRC for Catchment Hydrology will be undertaking research to address these. Further refinement of MUSIC will be the focal point of the CRC's urban stormwater research activities over the next five years:

5.1 Prediction of ecosystem responses

MUSIC currently allows waterway managers to predict the performance of a given stormwater management strategy against national, state or local water quality standards. It does not, however, allow them to predict the consequential ecosystem response.

This is a major gap which is being addressed in partnership with the CRC for Freshwater Ecology, who are also undertaking substantial work in this area. Further discussion of the approach to be used in developing these models is provided in Walsh et al. (this volume).

5.2 Refining the k-C* model for local conditions

Selection of appropriate values for k (decay rate) and C* (background concentration) has a significant influence on the predicted performance of a stormwater treatment facility. Work is underway (Wong, unpublished manuscript) to relate these values to particle size and settling velocity distributions, which in turn, can be determined for local conditions.

It is thus envisaged that subsequent versions of MUSIC will allow users to enter the particle size distribution for their catchment, and the model will adjust the k and C* parameters accordingly. This will substantially refine the prediction of TSS removal, as well as TP removal, given its close association with fine particles (Lloyd and Wong, 1999). For TN, which tends to exist in stormwater often in the soluble form, the relationship with particle size is less important. It is likely that biological processes are important for TN removal, and this will be investigated.

5.3 Refining models of inter-event periods

Much of the research into the detailed behaviour of pollutants in stormwater treatment facilities is based on event conditions. As previously discussed, it is likely that the relative contribution of physical, chemical and biological processes will be different during event (stormflow) and inter-event (baseflow) conditions. Refinement of the USTM to reflect these differences will be undertaken.

5.4 Improved models for gross pollutant traps and buffer strips

Currently, the algorithm which describes the performance of gross pollutant traps (GPTs) is based on a limited dataset, from only one GPT type. Current research being undertaken in partnership with Brisbane City Council and Melbourne Water will allow more sophisticated models to be developed. Similarly, the algorithms which describe buffer strip performance are based on empirical data, and do not account for all characteristics of the buffer (e.g. vegetation, slope). Research will be undertaken to improve these algorithms.

5.5 Stormwater characterisation

Improving understanding of relationships between a catchment's land use, physiography, and the characteristics of stormwater emanating from that catchment, will be important for designing stormwater treatment measures, and understanding ecosystem responses. For example, particle size distributions, which vary greatly across Australia, have been shown to be an important determinant of treatment performance (Fletcher et al., 1997; Lloyd and Wong, 1999). Current research is expanding the database of stormwater characteristics across Australia, and will be incorporated into subsequent versions of MUSIC. Currently, adequate data are available are only available for modelling of TSS, TP, TN and gross pollutants. Future versions will predict performance for an increased range of pollutants.

5.6 Lifecycle costing and non-structural measures

Prioritisation of stormwater management strategies requires information on lifecycle costs. This is also necessary to compare the costs and savings of 'water sensitive urban design' against traditional approaches. Comparatively little research has been undertaken in this area; this gap will be addressed, with an 'economic module' inserted into MUSIC.

Evaluation of the effectiveness of non-structural elements of stormwater management is also required by urban waterway managers. However, there is a lack of information in this area, which will be targeted by CRC research projects over the next five years.

6. CONCLUSIONS

Significant limitations to the effective management of urbanisation impacts on waterways exist. They include poor understanding of water quality emanating from catchments under differing land use, and a lack of ability to predict the performance of a range of treatment measures. The CRC for Catchment Hydrology, in attempting to overcome these, has developed a Model for Urban Stormwater Improvement Conceptualisation. When released early in 2002, MUSIC will provide urban waterway managers with an effective tool for formulating and evaluating alternative stormwater management strategies. Ultimately, it is hoped that this will help to reduce the impacts of urbanisation on aquatic ecosystems.

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