Using Directly Connected Imperviousness Mapping to Inform Stormwater Management Strategies

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ABSTRACT
Directly connected imperviousness (DCI) has been established as a catchment indicator of waterway ecological condition, and waterways with DCI above 2% have been shown to be in poor ecological condition. As a result, stormwater management needs to be undertaken to ensure a more natural hydrological cycle is maintained. Melbourne's rapid growth means there is increasing imperviousness in many areas. This is especially concerning where waterways are currently in excellent condition. Whilst protection of 'the best' is an important aspect of stormwater programs, restoration efforts are also required to achieve long-term goals. To ensure that limited budgets are spent wisely, an approach is needed to target catchments where management effort will produce the greatest returns. To this end, Melbourne Water in conjunction with partners has undertaken two related projects. Both use a DCI dataset in conjunction with a multi-criteria analysis to take into account other factors that influence river health and the efficiency of restoration/protection efforts. This paper presents an overview of these projects, providing an insight into the way they are informing stormwater management strategies.

KEYWORDS
Directly Connected Imperviousness (DCI); Stormwater management; Prioritisation.

INTRODUCTION
In Victoria, Australia, the emergence of "liveability" as a philosophy of state government, which aligns with international concepts of new urbanism, means that multiple objectives – such as health, wellbeing, comfort and amenity – need to be met by future investment in water management. As Melbourne Water's (MW) role in the management of stormwater through an integrated water management (IWM) approach grows, future programs must reflect these challenges and new philosophies.

Directly connected imperviousness (DCI, sometimes called effective imperviousness) is an indicator of urban stormwater impacts that has been established as a primary driver of degradation of ecological health in urban waterways (Walsh and Kunapo, 2009; Shuster *et al.* 2005). DCI is thus becoming increasingly important in planning works for MW, as well as refining standards for urban development. To ensure that limited budgets are spent wisely, an approach is needed to target catchments where management effort will produce the greatest returns for both protection and restoration works. To this end, MW in conjunction with partners has undertaken two related projects. This paper presents an overview of these projects, providing an insight into the way they are informing stormwater management strategies. Background to MW's stormwater management is first presented, including a brief summary of DCI as a concept. The paper then outlines how the

DCI data that has been mapped for Melbourne's region is used to inform two areas of stormwater management activities focusing respectively on the restoration and protection of waterways.

BACKGROUND

Human society is deeply dependent on water, and the ways we manage the water cycle strongly shape our environment. Traditionally, urban water management has often been separately considered in terms of potable water, stormwater, wastewater and catchment management. However, more holistic concepts, such as Water Sensitive Urban Design (WSUD, e.g. Melbourne Water, 2005; Wong, 2006a), IWM, and Water Sensitive Cities (e.g. Wong & Brown, 2009), are now emerging, which seek a more integrated approach to all parts of the urban water cycle. Population growth and climate change increase the challenge of providing a safe and reliable water supply. Accordingly, water supply diversification objectives still tend to dominate IWM, potentially resulting in insufficient consideration of outcomes for waterways.

Importantly, a shift in governance is required to deliver true IWM, including considerable changes to institutional arrangements, organisational management and investment structures (e.g. van de Meene *et al.*, 2011). Nevertheless, many organisations, such as local councils, water authorities, and the community have started to implement WSUD with varied levels of success and commitment.

Melbourne Water's WSUD Initiatives

MW manages water supply catchments, treats and supplies drinking water and removes and treats sewage in the Melbourne region. In addition, MW manages waterways and major drainage systems throughout the Port Phillip and Westernport region. The drainage system across the region is a separate system, and local stormwater drainage (typically catchments under 60ha) is managed by local government. MW is embracing the challenge of moving towards the delivery of its services under an integrated strategy and advocating for WSUD development. Achieving integrated service delivery will require step changes in the way these different services are delivered. MW in its role of caretaker of river health is seeking to provide leadership in defining waterways outcomes that need to be achieved in the implementation of IWM. An important component of this resides in the way stormwater is managed.

MW's approach to stormwater management over the last 10 years has focussed on nutrient reduction to its downstream receiving waters - Port Phillip Bay (and Westernport more recently). As stormwater is mostly generated on land that MW does not control, more holistic stormwater practices require a strong inter-organisational collaboration and commitment to the implementation of sustainable stormwater practices. Accordingly, MW has implemented stormwater programs aimed at supporting local government to implement sustainable stormwater practices.

Significant progress has been made in terms of increased organisational capacity, implementation of projects and commitment to implementation of WSUD. However, the link between local stormwater quality treatments and the ultimate goal of river health improvement is often not immediate. Where other agendas such as responding to water security issues through provision of alternative water supply are prominent, it can thus be more difficult to adopt a strategic approach to stormwater management that appropriately considers and prioritises waterways benefits. Interestingly, a large proportion of councils at the downstream end of the catchment have adopted IWM plans and targets. These include stormwater targets in the form of nutrients load reductions and alternative water supply provision. Higher up in the catchments, the imperative to protect the bay is not as clear, and there is a strong need to better link stormwater management and waterway health to enable these councils to develop more integrated strategies.

Future Focus

From these initial initiatives, MW is now considering structuring the stormwater management element of its next 5 year investment plan on three regimes/programs – Protect, Restore, Enhance. Such an approach will help to ensure that every project or action implemented can be clearly linked to an environmental objective for waterways. A number of tools will be used to build the investment case and to prioritise stormwater management activities. DCI has been identified as a critical source of information to use in planning stormwater management and prioritising works.

Directly Connected Imperviousness (DCI)

Whilst other catchment and local-scale processes influence river health, waterways cannot be in good ecological condition where significant urban stormwater inputs are permitted to occur (Fletcher *et al.*, 2011, adapted from FISRWG., 1998). Stormwater is thus a limiting factor to river health. The stormwater drainage network has been identified as the most plausible pathway by which stream biota are degraded (Walsh & Kunapo, 2009; Wenger *et al.*, 2009).

DCI is defined as the proportion of the impervious surface of a catchment that is directly connected to a stream through a conventional drainage connection. DCI can be used to assess the scale of the stormwater management problem in a catchment (Walsh *et al.*, 2005, Walsh and Kunapo, 2009). Walsh *et al.* (2005) reported a steep decline in many ecological indicators from zero to a minimum level of ecological condition at 2-10% effective imperviousness (depending on the indicator). Walsh and Kunapo (2009) empirically determined the measure of attenuated imperviousness that best predicted macroinvertebrate assemblage composition in streams of eastern Melbourne: it is this measure that is used to estimate DCI in this study. Because of the different methods used, values of attenuated imperviousness are smaller than effective imperviousness used by Walsh *et al.* (2005). Walsh and Kunapo found that macroinvertebrate assemblages were maximally degraded by 1-3% attenuated imperviousness (see below), compared to 7-8% effective imperviousness reported by Walsh *et al.* (2005). Thus urban stormwater runoff has an increasingly severe impact on stream ecological condition from zero to ~2% DCI, with streams with more than 2% DCI being invariably poor ecological condition.

DCI can also be conceived as a measure of potential ecological value as (Fletcher *et al.*, 2011, adapted from FISRWG., 1998):

- all ecological indicators currently in use show a very steep decline with even very low level in stormwater runoff as measured by DCI, and
- spatial analysis has demonstrated a strong decline in macroinvertebrate diversity (and other ecological indicators) with increasing DCI, with no evidence of the existence of a minimum DCI value before an effect is observed (Walsh, *et al.*, 2005; Walsh & Kunapo, 2009)

MELBOURNE WATER'S USE OF DCI

Melbourne Water in conjunction with partners has undertaken two related projects to support the planning of stormwater management initiatives and their prioritisation. The first project aims to estimate changes in DCI as Melbourne grows over a 2030 and 2060 horizon, whereas the second aims to identify where reducing DCI will result in the greatest benefits in terms of length of waterways improved. Both projects use a common DCI dataset in conjunction with a multi-criteria analysis to take into account other factors that influence river health and the efficiency of restoration/protection efforts.

DCI Data Set

2006 DCI data. Melbourne Water has compiled a DCI dataset for its entire region (about 1.3M ha) following on a pilot project undertaken with research partners. The data was acquired based on:

- 16,000 hydrological subcatchments - established based on a digital elevation model - developed using 1 to 10m contours and piped drainage network discharging to streams
- Map of impervious surfaces – established based on fast look aerial photos (2005) with an infrared band of 35cm resolution along with a Normalised Vegetation Index (NDVI) used to automatically map impervious surfaces (followed by a manual verification process). A total imperviousness value was attributed to each subcatchment.
- For each impervious polygon from the impervious map, overland flow distances to the nearest pipe and/or stream were determined. MW and Local Government pipes (of 2006) were used to condition the elevation model to represent pipe network (see Walsh & Kunapo, 2009).
- The exponential decay function established by Walsh & Kunapo (2009), considered the most plausible predictor of stream macroinvertebrate assemblage composition, was used to determine DCI for each of the 16,000 subcatchments. The results were also attributed to MW's river network. DCI (%) for each subcatchment has been calculated as:

$$\sum_{\text{impervious polygons in subcatchment}} [\text{impervious polygon area x exp(-overland flow distance / 13.56)}]/ \text{subcatchment area}$$

This measure was termed attenuated imperviousness by Walsh & Kunapo (2009). In this paper, we term it DCI. However, it is not a true mechanistic measure of impervious surfaces with direct piped connection to the stream, but a statistically determined estimate of those impervious surfaces that are likely to have the greatest influence on stream ecology.

2030 and 2060 DCI scenarios. The base 2006 data allowed predictive modelling of total imperviousness into the future, and corresponding DCI using the method described above. A number of state government planning data sets were used to spatially predict increases in imperviousness for the 2030 and 2060 timing horizons. Data included the future location of 'activity centres' (high density development), the extent of land which can be rezoned from rural into urban – known as the urban growth boundary (UGB), and population predictions. The 2060 results are much less certain then the 2030 results due to availability of data.

Scenarios modelled relate to DCI under (1) no stormwater management (2) streetscale management and (3) precinct, streetscale and allotment treatment (reflecting different scales of stormwater management interventions). Total impervious area data recorded as part of MW's DCI data set was used to establish a relationship between existing total imperviousness and dwelling density. This relationship was then used to predict future total imperviousness based on proposed future dwelling densities which were estimated using state government "Victoria in Future 2008" population projection data. Spatial distribution of dwelling density was predicted using location of the revised UGB, sites identified for development in government planning (Urban Development Program, Melbourne Activity Centres and Principal Public Transport Network), and beyond the UGB, land likely to be unimpeded by environmental constraints.

PRIORITISING RESTORATION EFFORTS

MW is planning stormwater management activities to protect, restore and enhance waterways. The focus on restoration will aim to restore waterways through the retrofit of stormwater management measures. To ensure cost-efficient investment, this program will focus on waterways in which ecological condition is limited by stormwater inputs, and will investigate possible alignment with IWM opportunities to maximise environmental, social and economic benefits. The main approach for restoration efforts is partnership projects and capacity building. The two main types of activities undertaken will be to:

- Establish partnerships for co-investment in stormwater disconnection in a few targeted catchments. These catchments will be chosen using the prioritisation analysis outlined below.

- Support others (councils in particular) to adopt a more targeted approach to stormwater management retrofits that prioritise catchments with high-restoration potential over the short to medium-term. This will ensure that infrastructure renewal contributes to realising the restoration potential of urban streams in a strategic manner that will be most cost-efficient over the long-term. The prioritisation method used for MW's entire area of responsibility will be proposed to councils as a tool to use when developing an IWM strategy.

Analysis of current level of DCI to inform stormwater management in built areas

Overview. The objective of the DCI analysis is to define where catchment restoration through disconnection of directly connected impervious area will provide the greatest benefit to river health. The analysis comprises three stages:

1) Identify which catchments of our 16,000 sub-catchments dataset will provide the greatest benefit if disconnected (measured in terms of length of stream improved)
2) Aggregate catchments identified in 'manageable' size
3) Reality-check:
    - Identify other factors limiting river health (e.g. condition of riparian vegetation, water extraction, agriculture pollution, and urban development post 2006)
    - Identify opportunities (e.g. willing partners, potential to complement other river health activities targeting improvement of fauna and flora values)

At the time of writing, stage 2 and 3 were underway but not complete; this paper will focus on the stage 1 of the analysis.

Stage 1. Considering only the DCI data which is available for 16,000 subcatchments, rank the catchments in order of priority for treatment by disconnection. This ranking is based on the benefit expressed in terms of stream health improvement achieved.

In earlier work, Walsh and Fletcher (2006) showed that the stream health benefits of disconnection were strongly influenced by the order in which catchments were disconnected. Working in areas with relatively little existing DCI is more cost effective because the magnitude of the stream health response and the length of stream improved were both much larger. Furthermore, treating a particular subcatchment reduces the DCI of that subcatchment and the DCI of all the downstream subcatchments (since these catchments now have less impervious area upstream). This means the benefit obtained from treatment is influenced by what treatment has already been carried out. Intuitively we would expect to identify catchments on the edges of the city first, as highest ranked, and then gradually move into more urbanised areas are we treat additional DCI. Catchments listed for treatment will also tend to cluster since there is synergy in treating catchments along the same flow path from upstream to downstream. The ranked list of catchments was identified through an iterative process as follows:

a. Choose the optimal level of disconnection for each catchment (disconnection providing the highest benefit per unit of area disconnected)
b. Sort the list of catchments to identify the best catchment (*i.e.* providing highest benefit when disconnected at the optimal disconnection level)
c. Disconnect the best catchment (*i.e.* modify the DCI data set to reduce the DCI in the best ranked catchment to the level identified in a.)
d. Go back to step 2, identify the next best catchment
e. Produce a sorted list of catchments.

The benefit of disconnection was defined in terms of length of river improved, with improvement or benefit for a given subcatchment (SCi) measured in meters by:

$$\sum_{SCi} \Delta DCI_{SCi} \text{ x weight } (DCI_{after}) \text{ x stream length}_{SCi}$$

where the weight is a function of DCI_{after} defined by the decay curve shown in Figure 1 (best function fit using the relationship established by Walsh & Kunapo (2009)).

The output of this stage of the analysis is a list of 1,000 subcatchments ranked (equivalent to 3000ha DCI removed) by benefit provided by disconnection. The map below shows this preliminary result.

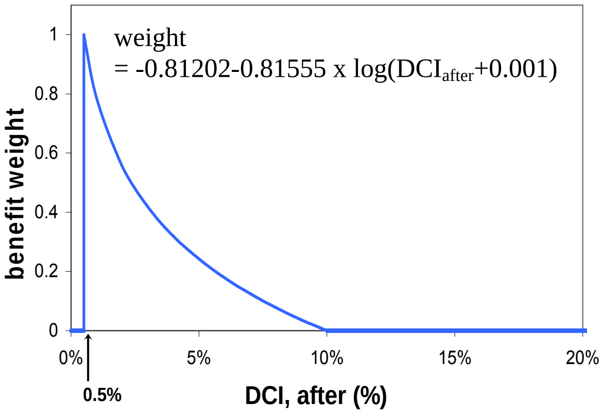

Figure 1. Benefit weighting decay curve

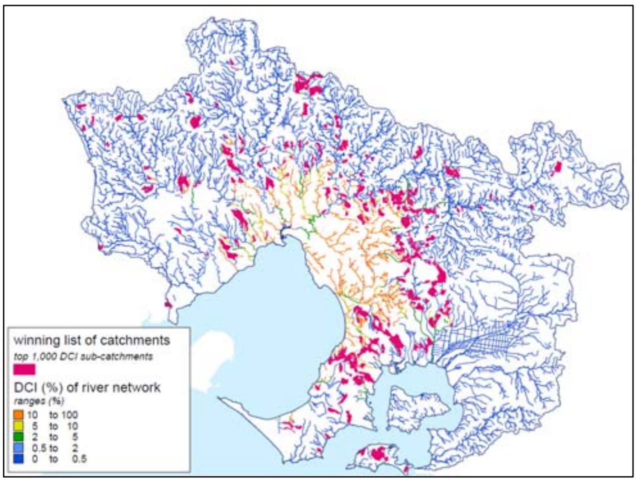

Figure 2. Map showing (in pink) the 1,000 subcatchments providing the highest benefits to river health if disconnected.

Use of scenarios

The scenarios data is particularly useful for producing visual material demonstrating the benefits of investment in restoration over the long-term with the aim to assist decision makers. Figure 3 below shows how regulation for renewal type development can actually start to decrease existing DCI assuming that current DCI levels are not increased. It also demonstrates that reducing DCI through on-going road renewal works will have a significant impact on waterways condition over-time.

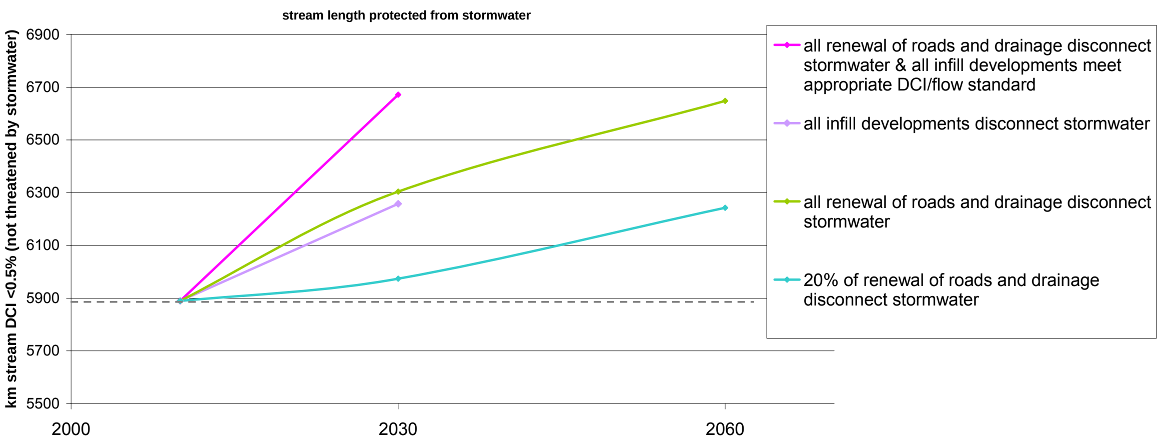

Figure 3. Evolution of the kms of stream which DCI is less than 0.5% under a range of management scenarios.

PRIORITISING PROTECTION EFFORTS

Melbourne is growing rapidly in population. The Port Phillip and Westernport region covers 12,000 square kilometres and is home to 80% of Victoria's population. The Victorian Government's *Melbourne 2030* strategy predicts that Melbourne's population will grow from 3.7 million in 2006 to 5.5 million by 2036, an increase of 1.8 million, requiring an estimated 780,000 additional homes to be built in over 20 years to meet the anticipated population increase. Urbanisation (e.g. greenfield developments, but also sealing of rural roads) is the most serious threat to waterways currently in good ecological condition, as the continuation of current practices will see the decline of the ecological condition of many of our waterways. It is thus the aim of MW to protect waterways from stormwater threats so that their ecological condition does not decline as a result of inadequate stormwater management. The protection of waterways in good or excellent ecological condition is the main outcome at stake in the protection focus of stormwater management activities. At the time of writing, the tools for prioritising the protection of waterways were still being developed.

Use of DCI analysis

One approach to prioritization being considered is to calculate the benefits of disconnecting each catchment from the 2030 DCI level to its 2006 levels. The catchment that when restored from 2030 to 2006 levels of DCI results in the greatest improvement in stream health is the catchment that should have the highest priority for protection now. The next step is to alter the 2030 dataset to set this catchment's DCI levels to the 2006 levels and then run the analysis again to iteratively identify the next most important catchment to protect. This procedure will produce a ranked list of catchments that need to be protected now.

This ranking can also be approached from the present rather than the future; *i.e.*, taking the 2006 dataset and, catchment by catchment, changing the DCI to what it would be in 2030. This will allow the catchment to be identified that if developed, would cause the maximum damage to stream health. Similarly we can identify a range of catchments that, if developed, will have little impact.

As for the analysis undertaken for prioritisation of restoration works, this analysis will need to be complimented by a reality-check or multi-criteria assessment to ensure that other river health influences, opportunities and limitations are considered to present a robust prioritisation method.

Use of DCI scenarios

Predicting broadscale changes in DCI based on likely development across the region (and assuming current stormwater management standards) has proven a powerful way of demonstrating the significant decline in stream condition and hence the urgent need for a revision of the stormwater policy framework to protect existing values. A range of maps and graphs have been developed to support a stronger focus in protecting waterways from stormwater in new developments. A sample of the maps realised based on the DCI scenarios data are shown in figure 4 below.

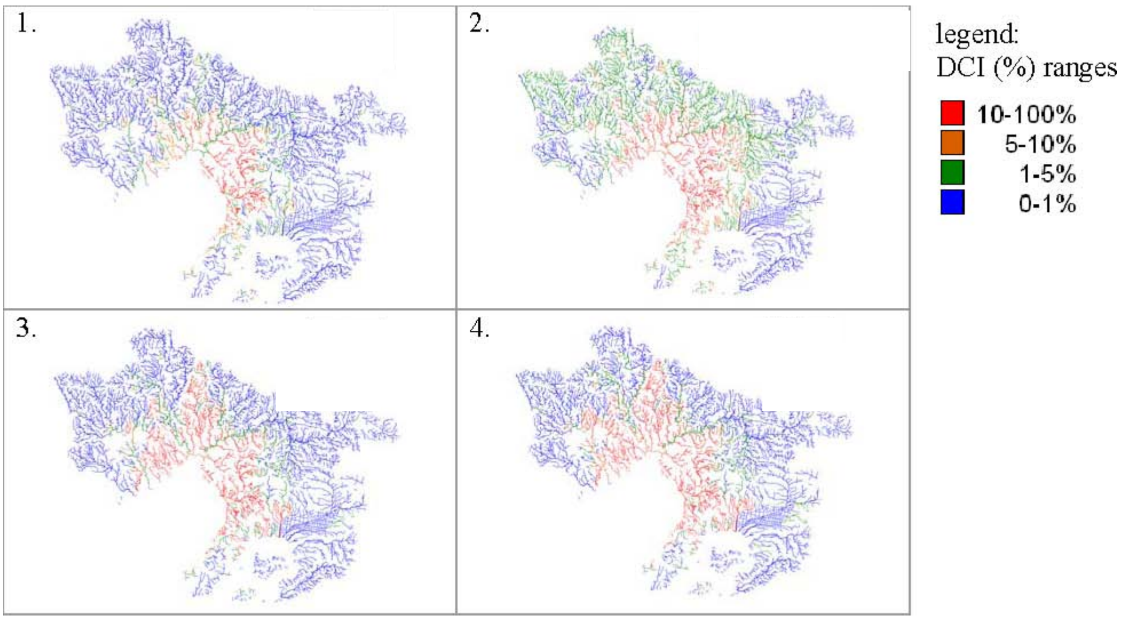

Figure 4. DCI of Melbourne streams for different scenarios: 1. 2006 2. connection of all DCI (poor retrofit practices) 3. 2030 in business as usual (BAU) conditions 4. 2060 in BAU conditions

CONCLUSIONS

The outcomes of this work will generate a significant re-focus of stormwater management in Melbourne. Its corollary is applicable to other contexts where urban stormwater runoff (which DCI indicates) is recognised as a major limiting factor to the ecological health of waterways. As discussed throughout this paper, management of stormwater is a critical aspect of IWM in that stormwater can be managed to both restore/protect waterways and deliver alternative water supply and liveability outcomes. Given the scale and timeframe of this issue, it is important for MW to prioritise its stormwater management effort. The DCI mapping and analysis described in this paper provides a solid basis to focus interventions where it will provide highest benefits. This work also provides useful communication tools that will help MW advocate both internally and externally (particularly to state government) the need for policy and regulation to better protect streams from the impacts of urban development and the potential to restore streams over the long-term.

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REFERENCES

FISRWG (1998). *Stream corridor restoration; principles, processes and practices*: Federal Interagency Stream Restoration Working Group (GPO Item No. 0120-A: SuDocs No. A 5 7.6/2:EN 3/PT.65 3. ISBN-0-934213-9-3.

Fletcher, TD, Walsh, CJ, Vietz, G, Hatt, BE, Thompson, R, Stewardson, M, Burns, MJ & Hamel, P (2011). Appendix 4: Stream Ecology (Literature Review) *in* Blueprint 2011. Stormwater management in a Water Sensitive City. Centre for Water Sensitive Cities, Melbourne, Australia.

Melbourne Water (2005). *WSUD Engineering Procedures: Stormwater*. CSIRO publishing, Australia.

Shuster, W., Bonta, J., Thurston, H., Warnemuende, E. & Smith, D. (2005) Impacts of impervious surface on watershed hydrology: a review. *Urban Water Journal,* **2,** 263–275.

van de Meene, S., Brown, R.R, and Farrelly, M.A. (2011*)*. Towards Understanding Governance for Sustainable Urban Water Management, *Global Environmental Change.* 21(3): 1117-1127

Walsh, C. J., Fletcher, T. D., & Ladson, A. R. (2005). Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society, 24*(3), 690-705.

Walsh, C. J. and Fletcher, T. D. (2006) *Water Sensitive Urban Design: can it really protect the environmental quality of receiving waters?* Proceedings of the 2nd Conference on Sustainable Water in the Urban Environment, Queensland, Australia.

Walsh, C.J. and Kunapo, J. (2009). The importance of upland flow paths in determining urban effects on stream ecosystems. *Journal of the North American Benthological Society,* **28,** 977-990.

Wenger, S. J., Roy, A. H., Jackson, C. R., Bernhardt, E. S., Carter, T. L., Filoso, S., *et al.* (2009). Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. *Journal of the North American Benthological Society*, 28, 1080-1098.

Wong, T. H. F (2006a). An overview of Water Sensitive Urban Design practices in Australia. *Water Practice & Technology,* 1(1), IWA publishing online - http://www.iwaponline.com/wpt/001/0018/0010018.pdf.

Wong, T., and Brown, R. (2009). The Water Sensitive City: Principles for Practice. *Water Science and Technology*. **60**(3): 673-682.