Publication Summary for ARC Linkage Project: Optimal Source Control in Urban Water Cycle Management

PhD Theses

Citation	Abstract
Gardiner, Anne 2007, Implementing Water Sensitive Urban Design: the context of changing urban stormwater technologies in Australia, PhD Thesis, University of Newcastle, Australia	This thesis is concerned with the problem of implementing new sustainable practices in urban environments through an analysis of the response to and reworking of a proposed urban design strategy over two decades in Australia, from the early 1990's until the mid 2000's. The analysis fits within a Science Technology and Society (STS) perspective but also draws on urban studies, theories of socio-technical change, and the exercise of agency by professional groups. The term Water Sensitive Urban Design (WSUD) originated in Perth in the late 1980's and has been rapidly adopted into environmental engineering and development planning. The meaning of the term is variable, but it typically implies the use of source control and natural surface strategies for the management of stormwater for both its resource value and to improve the environmental impacts on receiving waters. However, it can incorporate broader aims, integrating the management of water into a consideration of the urban water cycle and the whole urban landscape. Implementation depends on the technical credentials of the new methods, but also receptive governance, engineering and development communities. This thesis addresses the position of engineers, developers, and governance bodies within their political and social context to elucidate the effects of each group on shaping the eventual outcome; redefining and constraining the integrated intentions of WSUD to make it compatible with the commercial process of land development, the constraints of local and state government and the ecological modernisation perspectives of the federal government. The hosting of WSUD by the water engineering community is juxtaposed against the lack of intellectual debate amongst planners. The influence of different tiers of government is described in terms of the mechanisms used to express their power and direct changing priorities in light of political intentions and drought. While great progress has been made in mediating environmental impacts and capturing rainwater for useful outcomes, little progress has been made in integrating water management into a consideration of other aspects of a desirable urban form. The current political climate promotes strengthened accountability and project managed responses to resource and environmental problems. This is not conducive to nurturing the integrated planning aspects of WSUD or encouraging debate over the form of urban stormwater management that is desirable in the long term.
Hardy, Matthew, J. 2008, Integrated Urban Water Management and the urbanCycle Modelling Framework, PhD Thesis, University of Newcastle, Australia	This thesis presents a journey exploring the issues and challenges facing the water sector in Australia and examines the potential of integrated urban water management (IUWM) to address many of these challenges. IUWM presents a new framework in which solutions to the provision of urban water cycle services can be sought. It enables new and innovative solutions currently constrained by the existing urban water paradigm to be implemented. In order to facilitate the broad acceptance of IUWM, strategies the availability and functionality of models to support the investigation of integrated solutions must be addressed. This thesis presents the urbanCycle modelling framework, developed in response to the growing and changing needs of the water management sector and in light of the need for tools to evaluate integrated water management strategies. The urbanCycle modelling framework is a new and innovative integrated modelling tool designed to specifically address the identified needs of new tools and the limitations of existing ones. The key concepts underpinning the urbanCycle framework are: the representation of all three urban water cycle service systems to an appropriate level of detail for integrated system modelling; the integration of those systems at a range spatial and temporal scales through embedded hierarchical networks; the adoption of continuous simulation and adaptive time-stepping; the development of a flexible water consumption model; the incorporation of end-use dynamics and alternative supply allocation; and the careful management of network and computational complexity. The thesis is concluded with practical investigation and clear demonstration of the many key functionalities and simulation capabilities of the urbanCycle modelling framework. The investigations are presented in such a manner as to illustrate the various levels of system representation, offered by urbanCycle, and explicitly highlight the manner in which they are integrated at the sub allotment, allotment, cluster and catchment scales.

Holz, Linda, M. 2006, Beyond Weights and Discount Rates: Integrated Evaluation Tools for Sustainability Planning, PhD Thesis, University of Newcastle, Australia	A key issue for sustainability planning is how to integrate economic, social and environmental concerns in the process of evaluating possible management actions. This thesis is particularly concerned with evaluating natural resource management actions. Integrated evaluation tools may assist in weighing up multi-dimensional pros and cons of each management action. These tools aid decision making in two main ways; helping a decision maker to clarify his or her thoughts and suggesting preferable management options. Many integrated evaluation tools produce a ranking of options, from most to least preferred, in order to guide the choice of a management option. They achieve this by integrating impact assessment data, on how well management options perform economically, socially and environmentally, with a decision maker's value judgements. Multiple criteria decision analysis (MCDA) methods for example, often ask the user to specify what weight of importance each impact category should have in the appraisal of management options. If the impact data is in time series, a decision maker may be asked to consider how important future impacts are in comparison to short term impacts. The economic method of discounting future impacts is regularly utilised to aggregate a timeseries of impact data. This thesis looks beyond weighting and discounting, and explores tools which may better formalise value judgements about: balancing economic, social and environmental outcomes and; intergenerational equity. Such tools may be more effective in helping a decision maker to clarify his or her thoughts and in suggesting appropriate courses of action. A water resource case study is utilised to illustrate some of the alternatives identified. A major contribution of this thesis is a new integrated evaluation method referred to as Target Ordering. The Target Ordering method was developed in order to better identify which performance outcomes are most important to stakeholders and ensure user control of tradeoffs between impact categories, while retaining simplicity. This method is based on value judgements about how important target outcomes are, rather than how important the impact categories themselves are. That is, it is an alternative to weighting methods. The Target Ordering method is also extended to allow an aggregation of data across multiple time frames. That is, to provide an alternative to discounting.There seems to be a dearth of studies comparing how effective integrated evaluation tools are for helping users to think through and articulate their own preferences and to learn about the preferences of others. This thesis draws on existing research and presents new research, such that the effectiveness of weighting and non-weighting methods on these dimensions may be examined. Two experiments were conducted where a small number of water industry professionals utilised weighting and non-weighting tools to rank a large number of water management options. The non-weighting methods include Target Ordering and a graphical tool for facilitating an intuitive evaluation of management options. These tools are respectively classified as aspirational and holistic evaluation methods. Feedback was obtained from the participants through both surveys and interviews. The survey results indicate that the Target Ordering tool was significantly more useful than weighting methods for helping participants to articulate and apply their values to the problem. In general the Target Ordering tool was easier to utilise and was said to be more intuitive by some participants. The graphical tool was found to outperform a simple weighting method in facilitating users to think through and articulate their value judgements. No differences in usefulness of the graphical method and the Target Ordering method were found. Further experimental research is needed to compare how effective weighting, aspirational and holistic methods are in facilitating learning and communication of preferences in the decision making process.
Spinks, Anthony, T. 2007, Water Quality, Incidental Treatment Train Mechanisms and Health Risks Associated with Urban Rainwater Harvesting Systems in Australia, PhD Thesis, University of Newcastle, Australia	The increasing variability of rainfall in many Australian cities has recently highlighted major inefficiencies in the traditional centralised approach to urban water-cycle management. Rainwater tanks are fast becoming accepted as a best practice device in urban water-cycle management due to their ability to reduce mains water demand and reduce stormwater runoff. Unlike in rural areas, rainwater tanks in the urban environment can be interconnected with the municipal water supply via a trickle top-up system to allow the tanks to be plumbed in as a permanent supply for designated household end-uses. The greater the utilisation of tank waters within households the greater their contribution to increasing the efficiency of the urban water-cycle. However, what can be considered as appropriate utilisation of harvested rainwater is dependent upon the hygienic quality of the water and currently, very little is understood about the phenomena related to tank water quality. This thesis investigates three areas relating to water quality in urban rainwater harvesting (RWH) systems that were considered poorly understood. In Section I (Chapter 3) of this thesis, water quality was monitored across a range of RWH systems to allow tank water quality to be compared to official water quality guidelines and to municipal water supplies, as well as to assess design variables by comparing intersystem water quality variations. The water quality results of two field trials showed that harvested rainwaters generally did not comply with drinking water guidelines primarily due to the presence of coliform bacteria and E. coli, though did consistently comply with bathing water guidelines. Several design and environmental parameters were assessed for correlations with water quality parameters. Strong correlations were found between tank size and microbial parameters, with increasing tank size being associated with increasing concentrations. This was thought to be related to the greater frequency of top-up with chlorinated municipal supplies in smaller tanks as a result of more rapid emptying. Water quality was also found to be poorest immediately after rain events with improvements as storage time increased. Section II (Chapters 4 – 8) of this thesis investigated a series of mechanisms within RWH systems that influenced intra-system water quality

	variations, termed here 'the incidental treatment train'. The mechanisms investigated were defined as incidental in that they were not deliberately installed or established for the purpose of improving water quality and were potentially common to all RWH systems. Investigations into the incidental treatment train confirmed that a number of speculated processes were indeed occurring. Within the water column of several rainwater tanks, both spatial and temporal variations in water quality were observed. Spatial water quality variations were seen through the stratification of microbial concentrations, with higher concentrations observed in the upper layers of the water columns. Temporal variations in water quality were observed through repeated sampling of the water column in specific tanks, providing evidence of the existence of incidental treatment mechanisms within the tanks. Heterogeneous microbial populations were also observed in the water columns with several species having been previously identified as containing some form of bioremediation potential. The hypothesis that biofilms would develop on the internal walls of tanks and would demonstrate the potential to improve water quality was also shown to be true. Microbial communities were observed to develop on galvanised iron, polyethylene and glass slides at varying depths within a rainwater tank. Viable cell counts in these biofilms were found to be three orders of magnitude greater than concentrations in the water column, while culturable cell counts were found to be over four orders of magnitude greater within the biofilms. Greater concentrations of cells were generally observed in the biofilms grown in the lower layers of the water column while minimal variations in concentrations were observed between slide materials. A mixture of bacteria was detected within the biofilms and a core group of 5 species were found on each material. Plastic and metal-slide biofilms contained species exclusive to those materials, indicating that slide material did have a bearing on the species present. Biofilms were found to have a substantial capacity for removing heavy metals from the water column. This phenomenon was observed for all of the heavy metals that were analysed. The most significant accumulation rates were observed with lead, for which concentrations within biofilms were consistently 2,000 – 10,000 times greater than concentrations in the water column. The process of sedimentation and the accumulation of sludge were observed in many rainwater tanks. It was found that sediment was not distributed evenly across the base of rainwater tanks and greatest accumulation occurred directly under the inlets. Extremely high concentrations of heavy metals were found in sediments from all tested tanks. Lead concentrations in sludge ranged up to 6.6g/L, equating to magnifications of up to 340,000 times the concentrations found in water columns. This highlights the importance of the role of passive sedimentation in rainwater tanks and provides impetus for tank design to optimise the effectiveness of this process. The ability of two types of sludges to act as flocculants when re-suspended was also tested but found to be of minimal practical benefit. A number of factors were thought to influence the risk and extent of sludge re-suspension relating to design and environmental variables. The potential of domestic hotwater systems (HWS) to produce waters of sufficient hygienic quality for showering was of great interest in this research project. From the major field studies, massive reductions in bacterial concentrations were achieved when harvested rainwaters were passed through a range of domestic HWS. A minimum of three log-reductions or 100% inactivation was achieved for E. coli in HWS operating at 55°C or above. HWS operating at 60°C produced comparable quality to municipal water supplies in both regions. Laboratory-based thermal destruction analyses were conducted on a range of common indicator and pathogenic organisms to ensure susceptibility of these organisms to heat inactivation. Rapid inactivation of all pathogens was achieved at temperatures relevant to domestic HWS (55°C – 65°C). E. coli was found to possess the greatest heat resistance capacity of the tested organisms, which was shown in the field studies to be inadequate for surviving domestic HWS. Bacillus sp. were found to be the most common survivors in both laboratory analyses and field tested HWS. This was expected due to the spore-forming ability of Bacillus though was not considered alarming due to negligible potential for these organisms to cause disease transmission through water systems. The use of rainwater in HWS was therefore concluded to pose minimal human health risks, though HWS should be maintained at a minimum of 60°C in accordance with current Australian Standards to ensure human safety. The third and final section (chapter 9) evaluates the health risks of utilising harvested rainwater for non-drinking purposes and critiques the inadequacies of the current guideline framework for regulating urban RWH systems. A review of the literature relating to pathogen transmission pathways and water-borne outbreaks of disease from rainwater tank and non-rainwater tank supplies revealed that the risk of serious illness from drinking untreated harvested rainwaters is relatively low due to the exclusion of the major disease vectors (cattle and human faeces) from roof catchments. Previously reported epidemiological studies and an analysis of outbreak frequency supported this conclusion. A review of the current framework of water quality guidelines revealed a deficiency in their relevance to non-potable utilisation of harvested rainwaters. Specific guidelines were therefore developed and proposed for three categories of secondary-use and recommendations were made for developing robust drinking rainwater guidelines. In essence, this thesis has argued that a series of incidentally occurring treatment mechanisms contribute significantly to producing a high quality freshwater resource and that with an appropriate guideline framework, the fuller and more appropriate utilisation of this sustainable water resource for secondary uses including showering and bathing, toilet flushing, laundry and washing, and outdoor irrigation applications, should be achieved.

Selected Journal and Conference Papers

Number	Citation	Abstract
2	Gardiner A. and Hardy M., 2005 'Beyond Demonstration Mode: The Implementation of WSUD in Australia' (December 2005), Australian Planner.	Water Sensitive Design (WSUD) is a planning philosophy, developed in Western Australia in the early 1990s, for the integration of water cycle management with a specific consideration of the ecological impacts and resource potential of urban stormwater. Some critics argue that WSUD has been adopted by the development industry as a set of distinct structural solutions and the wider potential is being lost. This paper is based on interviews with an opportunistic sample of developers who have identified their approach as conforming to the principles of WSUD. All of the developers expressed a common motivation of improved planning with a sustainability focus as the reason for adopting WSUD. However, their ability to achieve integrated outcomes was limited by a number of factors. These included the increased effort required in the planning stages and difficulties in negotiating with councils and obtaining planning approval particularly in regards to maintenance uncertainties. Two government developers (Landcom and VicUrban) as well as two private developments on environmentally sensitive land demonstrated the highest degree of integration and linkages with the surrounding region. They also had the longest planning processes and were the most willing to impose covenants and conditions on future uses of the land. For commercial developers to be expected to adopt the additional planning burden of WSUD, regulatory reform is required. Tighter environmental approval standards tied to regional initiatives would assist in creating a framework that favours progressive development practices.
1	Gardiner A., 2006 The Effects of WSUD on Urban Form: A Statement about Australian Urban Life, Urban Drainage Modeling and Water Sensitive Urban Design 2006 Conference, April 2006, Melbourne	This paper uses a range of evidence to examine the urban form created through applying WSUD in Greenfield subdivision. 'New Urbanism' (the creation of walking scale urban villages) was a key feature of its origins but is certainly not evident in outcomes. Swale constructions, detention basins and wetlands by their nature take up considerable public space and often are presented within an informal 'natural' aesthetic. This is frequently along road verges, in 'mutifunction' corridors and entrance roads that emphasizie a semi-rural aesthetic associated with affluence in Australian culture. WSUD in Australia, in contrast, to integrated water management in Europe and North America, has been adopted in conjunction with an informal aesthetic accentuated by Xeric landscaping practices (the use of low water requiring and native plants). While this has been described as contributing to an 'untidy' aesthetic, it is increasingly valued as a demonstration of ecologically responsible values. The second theme, communal space reallocation, is consistent with the increasing privatisation of space and 'cocooning' of families within large houses with private recreation facilities. These trends demonstrate aspects of our lifestyle choices and values, but validate car dependant estates through a demonstration of environmental credibility and are not transferable to higher density sites.
3	Hardy, M.J., Kuczera, G. and Coombes, P.J., 2005. Integrated urban water cycle management: the urbanCycle model. Water Science & Technology, 52(9): 1-9.	Integrated urban water cycle management presents a new framework in which solutions to the provision of urban water services can be sought. It enables new and innovative solutions currently constrained by the existing urban water paradigm to be implemented. This paper introduces the UrbanCycle model. The model is being developed in response to the growing and changing needs of the water management sector and in light of the need for tools to evaluate integrated watercycle management approaches. The key concepts underpinning the UrbanCycle model are the adoption of continuous simulation, hierarchical network modelling, and the careful management of computational complexity. The paper reports on the integration of modelling capabilities across the allotment, and subdivision scales, enabling the interactions between these scales to be explored. A case study illustrates the impacts of various mitigation measures possible under an integrated water management framework. The temporal distribution of runoff into ephemeral streams from a residential allotment in Western Sydney is evaluated and linked to the geomorphic and ecological regimes in receiving waters

4	Hardy, M.J., Jefferson, C., Coombes, P.J. and Kuczera, G., 2003. Integrated Urban Water Cycle Management: Redefining the Boundaries, 28th International Hydrology and Water Resources Symposium, Wollongong, NSW.	Integrated urban water cycle management presents a new framework in which solutions to the provision of urban water services can be sought. It enables new and innovative solutions currently constrained by the existing urban water paradigm to be implemented. This paper introduces the UrbanCycle model. The model is being developed in response to the growing and changing needs of the water management sector and in light of the need for tools to evaluate integrated watercycle management approaches. The key concepts underpinning the UrbanCycle model are the adoption of continuous simulation, hierarchical network modelling, and the careful management of computational complexity. The paper reports on the integration of modelling capabilities across the allotment, and subdivision scales, enabling the interactions between these scales to be explored. Preliminary modelling has been undertaken using UrbanCycle to investigate the temporal distribution of runoff into ephemeral streams from a residential allotment in Western Sydney and the results presented explore the impacts of various mitigation measures possible under an integrated water management framework. The significance of the impacts of urbanisation at short time scales is reported upon and linked to its role in changing geomorphic and ecological regimes in receiving waters.
5	Hardy, M.J., Kuczera, G., Coombes, P.J., Barbour. E. and Jurd, K., 2007. An Evaluation of the Performance of the application of the urbanCycle Model to a Gauged Urban Catchment, Rainwater and Urban Design 2007, Sydney, Australia.	This paper details and evaluates the application and performance of the urbanCycle integrated urban water cycle modelling framework, on a gauged urban catchment. The urbanCycle modelling framework, developed at the University of Newcastle, was used to develop a model of the Kotara Roof to Creek Project catchment, located in Newcastle NSW. The Kotara Roof to Creek Project is being jointly conducted by Newcastle City Council, Hunter Water Corporation, The University of Newcastle, and the (former) NSW EPA Stormwater Trust. A primary aim of the project was to develop a suburban scale demonstration site for implementation of Integrated Urban Water Cycle Management (IUWCM) techniques, within an established urban area. Additionally the project was developed in an attempt to address the environmental impacts downstream of the Kotara catchment. The evaluation of the urbanCycle model focuses on its ability to capture and represent the underlying hydrology of the catchment and explores the relationship between this and the model's performance and capabilities in predicting the impacts of the introduction of a simple IUWCM strategy. The insights and comparisons available through the application of continuous simulation are also examined and compared and contrasted against those of design event modelling and recommendations on the application of the model are made.
6	Hardy, M.J., Coombes, P.J. and Kuczera, G., 2004. An investigation of estate level impacts of spatially distributed rainwater tanks, International Conference on Water Sensitive Design, Cities as Catchments, Adelaide, Australia.	The impact of spatially distributed rainwater tanks on stormwater peak discharges in hypothetical catchments in four Australian capital cities is explored. While the impacts of retention storage at the allotment scale have been investigated there is a need to better understand how the impacts at an allotment scale influence runoff dynamics at increased scales such as that of the subdivision and catchment. Effects of catchment scale on the performance of distributed storages in reducing peak discharges from a 2.5, 5, 7.5 and 10 Ha residential developments was evaluated. Analysis for the 3 month to 100 year ARI design storm event for durations ranging from 5 minutes to 72 hours was performed for both no storage and distributed storage (use of rainwater tanks) scenarios and critical duration peak discharges recorded. A methodology to estimate initial storage available prior to a design event is outlined. For the hydraulically efficient urban catchment used in this study and at the range of scales investigated, the reduction of peak discharge was found to be scale independent. The effects of the use of a hydraulically efficient traditional drainage system where seen as a major factor in minimising catchment attenuation. It is expected that a larger and or less hydraulically efficient catchment would yield different responses. The impact of spatially distributed storages was found to be essentially a function of three variables. The storage volume available prior to a rainfall event, the rainfall intensity and the temporal distribution of that rainfall, in so much as its distribution governs the timing of and shape of runoff hydrographs. Given the direct relationship between these variables and geography and climatic conditions the observed variation across the cities investigated can be understood. Primarily the effectiveness of retention storage on reducing peak discharge was observed to decreases with increasing average rainfall intensity. The complexity of the interactions that can occur when spatial distributed retention storages are applied at the allotment scale was also

		highlighted. The alterations of peak discharges, times to peak and critical durations that can occur through the use of distributed retention storages generate cascading effects that can alter significantly the rainfall runoff regime of the catchment in which they are applied. Due to the complexity of these interactions at scales beyond simple clusters of allotments there is significant difficulty in conceptualising these interactions and they are best considered as a complex joint probability problem. Given this complexity a continuous simulation framework is proposed as a more suitable basis than design storms for modelling purposes.
7	Jefferson, C., Holz, L., Hardy, M., Berghout, B., Coombes, P. J., and Kuczera, G. "Multi-Objective Optimisation of the Urban Water Cycle Management Using a Parallel Genetic Algorithm." 2004 International Conference on Water Sensitive Urban Design, Adelaide, Australia, 309--320.	With the engineering profession moving towards integrated design and management strategies for urban water cycle systems, the simulation models that are being utilised within the industry are becoming increasingly complex. Integrated management leads to a greater number of decisions and objectives. As the complexity increases in the decision and objective space, the time required for engineers to determine the most suitable strategy for a given project also increases. This results in traditional search approaches, such as trial-and-error, becoming impractical to implement. The presence of many conflicting objectives means that there is no longer one unique optimal solution but a myriad of solutions lying on the Pareto frontier. Once the objective space exceeds two or three dimensions two significant issues arise. Firstly, it becomes very difficult for engineers to apply trial and- error to navigate around the decision space in an effort to identify a set of Pareto optimal solutions within the objective space and secondly, it is difficult for engineers to manually determine where a particular solution lies relative to other obtained solutions in the objective space. This paper introduces the concept of Pareto optimality and recommends the ε-dominance approach used for maintaining a Pareto optimal archive and population updating. Also outlined is the application of a parallel computing multi-objective genetic algorithm that has been used to automatically and efficiently search for Pareto optimal design and management strategies for various urban water cycle scenarios. It presents results from a case study which involved the optimisation of restriction rules for a regional water authority's bulk supply system. Also discussed is the role of multi-objective optimisation in urban water management.
8	Jefferson, C. E., Holz, L. M., Hardy, M. J., and Kuczera, G. "Integrated Urban Water Management: Combining Multi-Criterion Optimization and Decision Analysis." Computing in Civil Engineering 2005, Cancun, Mexico, 165.	This paper outlines research being undertaken to develop new tools for investigating the opportunities integrated water management offers. With the engineering profession moving towards integrated design and management strategies for urban water cycle systems, the simulation models that are being utilized within the industry are becoming increasingly complex. Moreover, the number of decisions and objectives to be considered is growing and as a result traditional approaches, such as trial-and-error, for finding the most suitable approach become impractical. The presence of many conflicting objectives means that there is no longer one unique optimal solution but a myriad of solutions lying on the Pareto frontier. This work explores the potential for multiple objective optimization to identify the Pareto frontier and subsequent computer aided interactive decision analysis to explore the frontier. The paper presents a simple water supply case study in order to illustrate these concepts.
9	Holz, L., Kuczera, G. and Kalma, J.D, 2006 Multiple Criterion Decision Making: Facilitating a Learning Environment, , Journal of Environmental Planning and Management, Vol. 49, No. 3, 455 – 470.	Effective decision making for sustainability requires consideration of multiple evaluation criteria. A numerical weight, assigned to each criterion, is the most common tool used to formalize preferences in Multiple Criteria Decision Making (MCDM). However, there are methods other than applying weights, which can be used to explore and articulate preferences. Two such groups have been identified as aspirational and holistic methods. The authors are interested in establishing if the different approaches to MCDM vary in their ability to facilitate a learning environment. There has been little examination of how this might best be achieved. An attempt is made to set out some hypotheses about which characteristics of MCDM tools may best support such learning. Additionally, three MCDM tools, representing the weighting, aspirational and holistic methods, are evaluated through a workshop for their ability to support individual learning. This includes a new tool, referred to as Target Ordering, which explores preferences through criteria targets rather than applying a weight to the criteria themselves.
10	Holz, L., Kuczera, G. and Kalma, J.D. 2005 Beyond weights and discounting: decision analysis tools for integrated	An evaluation of management options can be supported with formal decision analysis tools which attempt to integrate objective and subjective information. There seems however, to be little exploration of decision analysis tools beyond

	planning. Sustainable Development and Planning II (1), Bologna, Italy.	weights and discounting for the formalisation of value judgements. This paper argues that we need to look beyond weights and discounting for tools which may better reflect value judgements about: intergenerational equity and; balancing economic, social and environmental outcomes. The paper presents some alternative tools for articulating value judgements in integrated assessment.
11	Holz, L., Kuczera, G. and Kalma, J.,2004 Sustainable Urban Water Resource Planning in Australia: a decision sciences perspective, International Conference on Water Sensitive Urban Design, Adelaide	This paper explores the promotion of sustainability in the current methodologies of urban water planning in Australia. A number of factors have been blamed for the perceived lack of sustainability promoting outcomes in urban water management. There seems however, to be little discussion on how to systematically evaluate how well solutions meet the multiple objectives of stakeholders. This paper argues that the absence of transparent integration of multiple objectives and inadequate recognition of uncertainty and multiple value systems in the decision support tools used in urban water management, makes standard decision making tools unsuitable for evaluating the sustainability of possible plans. It presents an argument that the current manner in which urban water strategies are prioritised allows for only one value system, one 'rationality', which is not necessarily consistent with the principle of sustainability. It outlines weaknesses in the two most commonly utilised quantitative decision support techniques; cost-benefit analysis (CBA) and multiple criteria analysis (MCA), and indicates how these may be overcome. This paper argues for new prioritisation tools which bridge the divide between 'calculation' and 'communication'. These new tools are vital for linking instrumental rationality (efficient achievement of known ends) with stakeholder dialogue on appropriate goals for urban water management. This approach would synthesise a planning process which more effectively addresses sustainability concerns. Finally the paper argues a case for a new conception of integrated resource planning. This new planning process takes an integrated approach to meeting multiple societal goals, rather than efficiently achieving one goal at a time and intertwines goal setting and strategy examination.
12	Spinks, A. T., Dunstan, R.H., Harrison, T., Coombes, P., & Kuczera, G., 2006, Thermal Inactivation of Waterborne Pathogenic and Indicator Bacteria at Sub-boiling temperatures, Journal of Water Research, 40(6):1326-1332	The use of harvested rainwater in domestic hot water systems can result in optimised environmental and economic benefits to urban water cycle management, however, the water quality and health risks of such a scenario have not been adequately investigated. Thermal inactivation analyses were carried out on eight species of non-spore-forming bacteria in a water medium at temperatures relevant to domestic hot water systems (55–65 1C), and susceptibilities to heat stress were compared using D-values. The D-value was defined as the time required to reduce a bacterial population by 90% or 1 log reduction. The results found that both tested strains of Enterococcus faecalis were the most heat resistant of the bacteria studied, followed by the pathogens Shigella sonnei biotype A and Escherichia coli O157:H7, and the non-pathogenic E. coli O3:H6. Pseudomonas aeruginosa was found to be less resistant to heat, while Salmonella typhimurium, Serratia marcescens, Klebsiella pneumoniae and Aeromonas hydrophila displayed minimal heat resistance capacities. At 65 1C, little thermal resistance was demonstrated by any species, with log reductions in concentration occurring within seconds. The results of this study suggested that the temperature range from 55 to 65 1C was critical for effective elimination of enteric/ pathogenic bacterial components and supported the thesis that hot water systems should operate at a minimum of 60 1C.
13	Spinks, A. T., R. H. Dunstan, P. Coombes, G. Kuczera, 2006, Bacterial Water Quality of Rainwater Fed Domestic Hotwater Systems, Water & Environmental Management Series, IWA Publishing, WEMS No.10	Rainwater harvesting within the urban environment is being increasingly recognised for its important role in reducing pressures on mains water supply and reducing stormwater runoff. The extent to which rainwater tanks can improve our management of the urban water cycle depends on the level of usage of the rain-harvested water. By incorporating the hotwater service into the suite of uses of harvested rainwater, substantial systemic benefits can be realised. This paper discusses some of the water quality implications of using harvested rainwater through hotwater systems. Field sampling of hot and cold water taps supplied by rainwater tanks was conducted over a 12 month period, together with laboratory conducted thermal destruction experiments on enriched rainwater samples. The field results showed substantial reductions (85-100%) of E. coli, total coliform, Pseudomonas, and Heterotrophic Plate Count concentrations in harvested rainwater passing through hotwater systems maintained between 50-70°C. The results of the laboratory thermal destruction experiments indicated that the time required to reduce a heterogeneous bacterial population at

		55°C over each of the first three log reductions were 10, 190, and 400 seconds, respectively. The lengthening of times required for inactivation demonstrated a pronounced shift in population. The hygienic quality of harvested rainwater was greatly improved after passing through hotwater systems maintained at adequately high temperatures.
14	Spinks, A. T., R. H. Dunstan, P. Coombes & G. Kuczera, 2006, Urban Rainwater Harvesting: A Comparative Review of Source Water Quality, Water Intelligence Online, IWA Publishing, Vol. 5 (Feb)	The arbitrarily defined origin, or source , of water supplies used for human consumption indicates a great deal about the nature of its past interactions with the physical environment and its vulnerability to contamination. This interaction with the physical environment largely determines what is known as its source water quality. Water used for municipal supplies is generally sourced from either (or a combination of) river water, groundwater, or reservoir water. These water sources may be vulnerable to a number of microbial contamination sources, including human, animal, bird, and environmental, each with their own diverse range of microbial pathogens. Rainwater harvested from house roofs within the urban environment is vulnerable to far fewer potential routes of pathogen transmission than that of water sourced from most municipal supplies. Despite the widespread use of untreated rainwater, the total number of reported cases of illness attributed to rainwater tanks is significantly lower than that of single outbreaks from centralised water supplies. Consequently, harvested rainwater provides arguably the highest quality source water available. This paper does not discuss finished drinking water qualities, but proposes an argument for the further and fuller utilisation of a freely available and relatively high quality source water.
15	Spinks, A. T., Dunstan, R.H., Coombes, P. & Kuczera, G., 2005, Tank Sludge as a Sink for Bacterial and Heavy Metal Contaminants and its Capacity for Settlement, Re-suspension and Flocculation Enhancement, 12th International Rainwater Catchment Systems Conference, Delhi, India, 15th-18th November 2005	Temporal changes in water quality as well as variations in water quality at points along rainwater harvesting systems have revealed the existence of a number of incidental water treatment mechanisms, termed here the 'treatment train'. Analysis of sludge samples from six rainwater tanks located in urban areas on the Australian East Coast found extremely high concentrations of a number of key contaminants, identifying tank sludge as an important sink for contaminants and a key aspect of the water quality treatment train. The potential for resuspension of the sludge during rain events could result in an extreme compromise of tank water quality. Lead levels in the sludge from the six tanks varied in concentration between 520 – 7070 ppm, representing a magnification of 34 000 – 360 000 times that detected in the respective water columns. Elevated bacterial concentrations and a number of macroinvertebrate species were observed within the sludges. The distribution of sludge in each tank was quantified and analysed with the results indicating that while the quantity of sludge in different areas of the tanks varied significantly, the elemental and bacterial composition did not. Experiments to determine rates of settlement and flocculation capacity were carried out on two different tank sludges, representing two common types of tank sludge. Rates of settlement differed remarkably between the two sludges as measured by total bacterial counts and spectrophotometrically. The most common type of sludge, 'type A', required only 30 minutes before complete re-settling had occurred, whereas 'type B' sludge required 7 days. Sampling of the water column in the five tanks in the days following rain events showed that water quality decreased immediately after a rain event and improved over the subsequent seven days.
16	Spinks, A. T., Dunstan, R.H., Coombes, P. & Kuczera, G., 2005, Balancing Microbial Quality and Corrosion Potential of Instantaneous, Solar, and Storage Hotwater Systems Supplied by Harvested Rainwater in the Urban Environment, 12th International Rainwater Catchment Systems Conference, Delhi, India, 15th-18th November 2005	The acceptability of the quality of hotwater supplied by harvested rainwater in the urban environment has been the subject of much debate in many developed countries as a result of attempts to maximise usage of harvested rainwater in order to improve city water-cycle management. Debate has centred around the issues of the microbiological quality of the heated rainwater, since many tank water samples fail drinking water guidelines due to the presence of Index Organisms, and the potential acceleration of hotwater system corrosion. The problem is complicated by the availability of a number of different types of hotwater systems including instantaneous, solar-powered, and conventional storage hotwater tanks. 27 rainwater tanks and associated hotwater systems from two major Australian cities were repeatedly tested over a period of 24 months for the index and indicator bacteria E. coli, total coliform, Heterotrophic Plate Counts and Pseudomonas, along with physicochemical parameters and a variety of heavy metals. The results showed that while temperature was a significant factor for determining the microbiological quality of heated rainwater, all hotwater systems achieved large reductions of E. coli (>98%) and HPC (62-99.99%). Lead and copper were found in increased concentrations in the hotwater of the solar powered systems. However, elements thought to be possibly associated

		with hotwater system corrosion, such as zinc and iron, were not found to be increasing
17	Spinks A.T., Coombes, P., Dunstan R.H., and Kuczera, G., 2003, Water Quality Treatment Processes in Domestic Rainwater Harvesting Systems, 10-13 November, 28th International Hydrology and Water Resources Symposium, Wollongong	Although the collection of rainwater for potable purposes is an ancient practice and is widespread in many parts of the world today, rainwater harvesting systems have largely been viewed as a black box. Research has neglected to investigate many important facets of rainwater harvesting including the critical area of process understanding with regard to water quality changes and treatment mechanisms. This paper overviews the possible treatment train and highlights gaps in our understanding. Exposure to UV, heat, and desiccation on the roof top destroy many bacteria. Within the tank, it is proposed that biofilms actively remove heavy metals and organics from the water, thus increasing the difficulty for planktonic organisms to survive. While many bacteria conglomerate in a micro-layer on the water surface, many of the heavy metals and other contaminants precipitate out of the water column and settle at the bottom of the tank. The precipitation of suspended solids and bacteria may also be possible during a rain event if re-suspension of the sediment occurs and acts as a coagulation-precipitation agent. Outlet taps on tanks are always located above the sediment layer, and in a trickle top up system the water surface layer is always above the outlet, effectively preventing these contaminants from being present in the available water supply. Tank water must also pass through a pump and possibly through a hotwater system, which impose sudden stresses on bacteria, disrupting cell structure and integrity. Hotwater systems maintained at 60°C in accordance with Australian Standards (AS3500.4.2) should not pose serious health risks as Legionella pneumophila, the main bacterial species of concern, are destroyed at temperatures above 50°C in water. Heat inactivation data are yet to be published for most other pathogenic species in a water medium. Rain harvesting in the urban environment produces valuable yields of water and research into treatment processes needs to be undertaken to ensure that in the future, this resource can be fully utilised.
18	Spinks, A.T., Dunstan, R.H., Coombes, P., and Kuczera, G., 2003, Thermal Destruction Analyses of Water Related Pathogens at Domestic Hot Water System Temperatures, 28th International Hydrology and Water Resources Symposium, 10-13 November, Wollongong.	Rainwater tanks are fast becoming accepted as a best practice device in urban water cycle management due to their ability to reduce mains water demand and to reduce stormwater runoff. However, concerns over health issues and bacterial contamination of hotwater systems have thus far hindered widespread recommendation of rainwater use in hotwater systems when an alternative mains water supply exists. While extensive research has been undertaken to determine heat tolerance ranges for pathogens under pasteurisation conditions in perishable goods, little data exists for thermal resistance in a freshwater medium. Laboratory experiments were conducted using a variety of water related bacteria to determine D-values within a water medium. D-values are defined as the time required to reduce a bacterial population by 90% at a given temperature. The bacteria were exposed to temperatures of 65°C, 60°C, and 55°C for varying lengths of time. The results showed that water related bacteria rapidly die off in temperatures relevant for domestic hot water systems. The D-values at 65°C and 60°C for E. coli were 3secs and 62secs respectively, while at 55°C E. coli displayed a biphasic death curve, with an initial D-value of 21mins followed by 4mins. For Pseudomonas aeruginosa, the D-values at 65°C, 60°C, and 55°C were 5secs, 49secs, and 5mins, for Salmonella typhimurium, <2secs, 4secs, and 77secs, and for Klebsiella pneumoniae, <2secs, <2secs, and 35secs, respectively. The results indicate that after fifteen minutes at 60°C, E. coli concentrations will have been reduced by 15-log reductions, while the other pathogens experienced similar or even greater reductions. This is in agreement with water samples taken from domestic rainwater tanks and hot water systems which indicated almost complete kill off of bacteria through the hot water system. In view of Australian standards requiring temperature at or above 60°C to control L. pneumophila, these preliminary results suggest that it is highly improbable that human pathogens, if present in raintank water, will survive through a hot water system.
19	Kuczera, G., Coombes, P.J., Dunstan, H., Spinks, A., Holz, L. and Kalma, J., 2003, Integrated management of the urban water cycle from the allotment to the regional scale: Opportunities and benefits, in Watershed Management, eds. Singh, V.P. and Yadav, R.N., Proc. International Conference	The management of the urban water cycle is typically compartmentalized into water supply, wastewater and stormwater sub-systems. This institutional constraint has resulted in sub-optimal outcomes for both the community and the environment. At the allotment scale all three components of the urban water cycle meet with water consumed and stormwater and wastewater discharged. Management of the cycle at this scale offers the opportunity to provide very significant economic benefits to the community and to the ecosystems that provide water cycle services. To realize

	on Water and Environment (WE-2003), Allied publishers, New Delhi, 253-278.	these benefits it is necessary to imaginatively explore use of allotment-scale technologies. To evaluate these benefits requires a systems integration of the water cycle at all scales. This paper reports on a research program to realize and evaluate these benefits in the Australian urban context. Major urban areas in Australia experience a highly variable climate exhibiting long-term persistence in rainfall. This requires investment in massive water supply schemes to cope with long droughts and in drainage infrastructure to cope with heavy rainfall. It is shown that allotment–scale technologies can substantially reduce dependence on water supply and stormwater infrastructure and so reduce the urban ecological footprint. A case study involving the rainwater tank is presented. By conceptually subdividing the tank into three zones with the lowest zone topped up by mains water and by maximizing indoor and outdoor usage of stored rainwater it is shown the rainwater tank offers very substantial economic and environmental benefits without compromising public health when compared with traditional approaches. The evaluation of these benefits is a non trivial task requiring a systems approach coupled with the capability to perform continuous simulation of key processes at both the allotment and regional scale using long sequences of stochastically generated climate data.
20	Coombes, P.J., Holz, L. and Kuczera, G., 2003. The impact of supply and demand management approaches on the security of Sydney's water supply, Hydrology and Water Resources Symposium, Institution of Engineers, Australia, Wollongong.	The impact of supply and demand management approaches on the security of Sydney's water supply was evaluated using the non-parametric regional demand model [Coombes et al., 2002] and the WATHNET network linear headworks model [Kuczera, 1992]. The use of different pump marks for extractions from the Shoalhaven River, various frequencies of water restrictions, rainwater tanks and demand management measures has been investigated. An increase in acceptable frequency of water restriction to 5% and a pump mark of 70% will defer the requirement to augment the water supply headworks system by 26 years. The use of demand management measures only will not defer augmentation and installation of 5 kL rainwater tanks for hot water, toilet, laundry and outdoor uses can defer augmentation beyond 2090. A Pareto diagram is employed to determine optimum solutions.
21	Coombes P.J. and G. Kuczera. 2003. A Sensitivity Analysis of an Investment Model Used to Determine the Economic Benefits of Rainwater Tanks. 28th International Hydrology and Water Resources Symposium. Wollongong.	The community-based investment model created by Coombes et al. [2000a; 2002] that allows economic comparisons between a traditional base scenario for urban water cycle services and alternative scenarios that include rainwater tanks is examined. The economic benefits derived from the use of rainwater tanks vary with the price of mains water and the cost to augment mains water supply headworks systems. The magnitude of the economic benefits accruing to the community from widespread installation of rainwater tanks was dependent on real interest rates, the value of stormwater savings that result from the use of rainwater tanks and the installation costs of rainwater tank systems. Nonetheless it was shown that the use of rainwater tanks provided greater economic benefits to the community than the traditional water supply and stormwater management options in the majority of cases considered.
22	Coombes, P.J. and Kuczera, G., 2003.sis of the performance of rainwater tanks in Australian capital cities, Hydrology and Water Resources Symposium, Institution of Engineers, Australia, Wollongong.	The performance of 1kL to 10 kL rainwater tanks with mains water tickle topup used to supplement mains water supply for domestic toilet, laundry, hot water and outdoor uses was evaluated for Brisbane, Sydney, Melbourne and Adelaide. The PURRS (Probabilistic Urban Rainwater and wastewater Reuse Simulator) model developed by Coombes and Kuczera (2001) was employed to continuously simulate the performance of rainwater tanks using synthetic pluviograph rainfall generated by the DRIP (Disaggregated Rectangular Intensity Pulse) event based rainfall model by Heneker et al. (2001). Depending on roof area and number of occupants in a household, the use of rainwater tanks resulted in annual mains water savings ranging from 18 kL to 55 kL for 1 kL rainwater tanks to 25 kL to 144 kL for 10 kL rainwaters tanks. The average retention volumes available in rainwater tanks prior to storm events ranged from 0.26 m3 to 0.71 m3 for 1 kL tanks to 2.34 m3 to 8.4 m3 for 10 kL tanks.
23	Coombes P.J., M. Thyer, P. Kozarovski, A. Frost, G. Kuczera and I. Grimster, 2003.opment of Stochastic Multisite Rainfall and Urban Water Demand for the Central Coast Region of New South Wales. 28th International Hydrology and Water Resources Symposium. Wollongong.	A novel approach to the simulation of daily water demand and stream flow for use in water supply headworks models has been developed using the DRIP (Disaggregated Rectangular Intensity Pulse) rainfall model by Heneker et al. [2000] embedded in a multi-site daily rainfall framework. Rainfall series generated by the multi-site method are used in a non-parametric regional water demand model that incorporates water balances in households to estimate daily water demand in the Central Coast region of New South Wales. Multi-site production of synthetic daily rainfall using the DRIP model was able to simulate daily rainfall at multiple sites based on rainfall at a single site and reproduce the interannual

		and spatial persistence that exists within the Central Coast water supply catchments. In addition the method was able to capture the spatial variability of rainfall within the catchments. No metering data was available for this study other than daily water demand at the water treatment plants. Nonetheless the regional demand method was able to adequately estimate regional water demand including the day to day variation and strong seasonal trends of water demand in the Central Coast region.
24	Gardiner, A. 2003. The Values of Water, 28th International Hydrology and Water Resources Symposium. Wollongong.	The value of water has a component that is socially determined and does not necessarily correlate with cost or price. Romantic historical notions of water have been modified and new mythologies created. These incorporate some aspects of scientific reasoning but this stands alongside the effects of commercialisation, ethics and attitudes to pollution. A strong mythology of purity and cleanliness accentuates the difference between clean and dirty water. Water that is clear and moving as if in a 'natural' stream is regarded as a common resource. Concrete channels that have lost their natural connections are seen as gutters and contamination of gutters does not invoke the same moral indignation as contamination of a community stream. This paper addresses some of the mythologies of urban water in an attempt to inform management objectives. Suggestions will be developed as to how system design and community interfaces can be presented in a way that avoids, as far as possible, clashes with existing social and cultural expectations from water, and facilitate regard for the value of water.
25	Kuczera, G. 2008. Urban Water Supply Drought Security: A Comparative Analysis of Complimentary Centralised and Decentralised Storage Systems, Water Down Under, 30th Hydrology and Water Resources Symposium, Engineers Australia, Adelaide.	In Australian urban water supply, large reservoirs are traditionally used to ensure adequate drought security. In recent years there has been a trend towards decentralised storage in the form of rainwater tanks harvesting rainfall from small roof catchments. In the urban setting the rainwater tank is usually too small to provide high reliability of supply. Rather the tank is used to compliment mains water supply. This study asks the question, under what conditions do urban rainwater tanks make the most significant contribution to urban water supply drought security? To answer this question in a way that maximizes insight, a Monte Carlo study is conducted involving 2400 combinations of climate variability and physical configuration of large reservoirs and urban rainwater tanks. The results are summarised using non-dimensional variables. It was found that rainwater tanks make the greatest contribution to drought security when the centralised storage is stressed (i.e., it experiences a high level of regulation and/or high streamflow variability) and when per-capita domestic demand is minimised. Moreover, the contribution of rainwater tanks to system drought security is more robust in the presence of climate change with declining rainfall.