Utilising integrated urban water management to assess the viability of decentralised water solutions
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ABSTRACT
Cities worldwide are challenged by a number of urban water issues associated with climate change, population growth and the associated water scarcity, wastewater flows and stormwater run-off. To address these problems decentralised solutions are increasingly being considered by water authorities, and integrated urban water management (IUWM) has emerged as a potential solution to most of these urban water challenges, and as the key to providing solutions incorporating decentralised concepts at a city wide scale. To incorporate decentralised options, there is a need to understand their performance and their impact on a city’s total water cycle under alternative water and land management options. This includes changes to flow, nutrient and sediment regimes, energy use, greenhouse gas emissions, and the impacts on rivers, aquifers and estuaries. Application of the IUWM approach to large cities demands revisiting the fundamental role of water system design in sustainable city development. This paper uses the extended urban metabolism model (EUMM) to expand a logical definition for the aims of IUWM, and discusses the role of decentralised systems in IUWM and how IUWM principles can be incorporated into urban water planning.

Key words | alternative solutions, decentralisation, EUMM, IUWM, metabolic models, total water cycle

INTRODUCTION
Nearly 50% of the world’s population currently lives in cities and it is expected that this will increase to about 70% by 2050 (United Nations 2009). Population growth is a key driver that influences demand for water in all cities around the world, with climate change exacerbating this effect in some cities. This has led to water shortages significantly earlier than those predicted by water balance studies. For example, in Australia the impact of these two factors, especially in the southern states has led to water scarcity, which has meant Australian cities have faced a number of urban water challenges to supply potable water (WSAA 2010).

Integrated urban water management (IUWM) has emerged as a potential solution to most of these urban water challenges (Maheepala & Blackmore 2008). It is an approach that allows urban water utilities to plan and manage water supply, wastewater and stormwater systems to minimise their impact on the natural environment, to maximise their contribution to social and economic vitality and to engender overall community improvement (Maheepala et al. 2010a). Adopting an IUWM approach for large cities requires revisiting the role of water system design in sustainable city development and especially the role of decentralisation, which conceptually has the potential to bring key innovative elements of the IUWM approach to traditional urban water management.

Although most of the challenges for supplying future water services for cities will be common, they will vary depending on geographical location, prevailing climate and the needs of the local community. Variability in climate, topography and demographics must therefore be considered when deciding whether to adopt the IUWM approach. A key component of this consideration involves understanding the total water cycle under alternative water and land management options, in terms of changes to flow, nutrient and sediment regimes, energy use, greenhouse gas emissions and the impact on natural streams, aquifers and estuaries. This paper describes the aims of IUWM, the role of decentralised systems in IUWM and
how IUWM principles can be incorporated into urban water planning.

THE AIM AND PRINCIPLES OF IUWM

The overall aim of IUWM is to provide socially acceptable, economically viable and environmentally sustainable water supply, wastewater and stormwater services in urban areas by considering interdependencies between water/wastewater/stormwater, energy, urban design and the surrounding environment. IUWM has the potential to achieve a sustainable environment in an urban area from a water perspective, which is the general vision encapsulated in the concept of a ‘water sensitive city’ (Skinner & Young 2010).

The concept of a water sensitive city including its principles is discussed by Wong & Brown (2009), whilst the key features of IUWM are discussed by Mitchell (2006). While both studies discuss principles and key features, they fail to describe a valid basis for choosing the key features of IUWM that make up the water sensitive city concept. In this paper, the extended urban metabolism model (EUMM) (Newman 1999) is used as a basis for deriving the principles of IUWM that can be used in the water sensitive city concept, as shown in Figure 1. The EUMM is based on the human body’s metabolic processes and has been used to define the goals of sustainable urban settlements (Arief 1998; Newman 1999; Newton & Bai 2008; Novotny et al. 2010).

In the EUMM, the system under consideration has physical and biological processes to convert resources into useful products and wastes, just like the human body’s metabolic processes. The inputs and outputs are based on the laws of thermodynamics, which say that anything which comes into a biological system must pass through and that the amount of waste is therefore, dependent on the amount of input resources and the efficiency of the metabolic system. Resource inputs include freshwater, physical and chemical materials, human, natural and built capital and energy. Climate change and population growth are exogenous or external factors of the system, but they have a great influence on the inputs and outputs. Resources are converted to products and wastes by the ‘systems and processes’ component of the EUMM, which includes planning and management, regulation, the governance processes of the urban water system, and technologies to support the efficient conversion of resource inputs to products and wastes. The products are liveability (i.e. the wellbeing of the urban community) and the wellbeing of the ecosystem or the surrounding environment.

The EUMM implies that wastes can be reduced by converting them to resources, which requires the input of additional energy. The level of waste depends on the levels of economically viable and socially acceptable energy. The system is thus in balance and will remain as such until it is possible to introduce more acceptable energy sources and/or appropriate technologies to generate energy and/or use the available energy more efficiently, which will allow the
system to move to a new state of balance. In this concept IUWM can be viewed as a process to identify opportunities to use fewer resource inputs and convert them efficiently into human and ecosystem wellbeing, whilst producing a minimum amount of waste. The EUMM concept can thus be used to derive a revised definition for the IUWM approach:

‘IUWM is an approach to plan and manage urban water systems (i.e. water supply, wastewater and stormwater systems) to minimise their impact on the natural environment, and to maximise their contribution to economic vitality and overall community improvement using less resources and producing less wastes and harmful emissions’.

THE ROLE OF DECENTRALISATION IN IUWM

Historically ‘decentralised systems’ were associated with household on-site wastewater systems (septic tanks) and rainwater tanks. Now, it refers to a range of advanced water, wastewater and stormwater treatment systems at an allotment or cluster (neighbourhood) scale of development (Crites & Tchobanoglous 1998).

Classically, the main application of decentralised systems was for servicing residential areas that are difficult to serve with centralised systems due to topographic and/or economic reasons. In the current environment of water scarcity and interest in maintaining ecosystem health, decentralised systems are viewed as systems with the potential to reduce demand for drinking water from centralised systems, as well as deliver wastewater services near to the point of generation, thereby eliminating the need for expansion of existing infrastructure. The former is achieved by optimising water reuse within the neighbourhood through recycling of wastewater, harvesting of rainwater and stormwater. Decentralised systems also need to enable improvements in ecosystem health by attenuating peak flows and reducing pollutant loads discharging to urban waterways. If the decentralised systems can achieve such environmental benefits whilst also improving liveability in a sustainable manner, decentralised systems can undoubtedly meet the major objectives of IUWM.

Adopting decentralised solutions, however; is not a trivial task because the designing, maintaining and implementation of decentralised solutions needs to consider such factors as type and scale of development, proximity to existing centralised services, the sensitivity of the surrounding environment, topography, climate, customer acceptance for recycling, local water sources and the allocation of financial resources (Sharma et al. 2008). In addition, the optimal portfolio of options for providing water supply, wastewater and stormwater services in a given city must consider the optimal spread of decentralised systems across the city by considering interactions between decentralised options and traditional urban water systems. In this context the challenge is how to design, operate and maintain decentralised systems, which embrace IUWM concepts and provide acceptable service now and into the future in such a way that the overall outcome is more sustainable than the current urban water system (Moglia et al. 2010, 2011).

At present, there are no available studies examining the optimal implementation of decentralised systems at a whole of system scale, but there are many studies that examine urban water servicing options at a development scale in terms of triple bottom line objectives and community acceptability. These studies include those of Diaper & Maheepala (2005); Mitchell et al. (2005); Grant et al. (2006); Maheepala et al. (2006); Sharma et al. (2007, 2008, 2009, 2010); Barton et al. (2009); Nancarrow et al. (2010) and Narangala et al. (2010). These studies which considered approaches such as local recycling of wastewater, rainwater tanks, greywater use and local stormwater harvesting are in line with the generic objectives of IUWM as discussed in this paper. A development scale study is briefly described below to demonstrate how decentralised systems can achieve IUWM objectives.

Kalkallo residential development, Melbourne, Victoria, Australia

Kalkallo is a residential development proposed for a population of 80,000 on 3062 hectares. A decentralised water and wastewater systems is proposed for this development. The objectives of the Kalkallo decentralised system are to:

(a) minimise fresh water resource use,
(b) minimise contaminant discharges to receiving waters, and
(c) minimise the community cost.

Three alternative servicing options have been considered and compared with the conventional approach as detailed in Table 1 and discussed in Sharma et al. (2009).

It can be seen that the self sustained option (option D), which utilises rainwater and greywater for internal and external use, has the highest potential to minimise the use of imported fresh water resources. However, a water balance analysis showed that this option was only able to achieve 90% reliability in terms of water supply provision...
and thus this option was not considered suitable for implementation. The preferred option was the wastewater reuse option (i.e. option B), which has the potential to reduce the load on imported water by 43%, reduce wastewater flows to the receiving environment by 50%, with total nitrogen flows reduced by 35% and total phosphorus by 32% compared with option A. Conceptual infrastructure designs also revealed that option B would allow infrastructure pipe sizes to be reduced when compared with option A. Using lifecycle cost analysis based on Nett Present Value (NPV) analysis and encompassing the environmental costs of nitrogen discharge to the environment and fresh water extractions; the community cost for option B was 20% less than the centralised approach of option A, as shown in Figure 2.

### IMPLEMENTATION OF IUWM AT A CITY SCALE

Although the principles of IUWM can be applied at any scale (household, cluster and city scales), the decentralised system described above represents an example of an ad-hoc household/cluster scale application, which does not significantly improve the sustainability of the city-wide system. To achieve a sustainable urban water system which embraces EUMM principles, the IUWM approach must be implemented at a city or whole-of-urban water system scale, which requires identifying the optimal distribution of decentralised systems across the city, acknowledging the fact that there are a number of ways to provide decentralised systems (e.g. household rainwater tanks, wastewater recycling, stormwater harvesting or different combinations of these individual systems).

If we wish to apply IUWM planning strategies at large spatial scales (e.g. a city or a region), the next logical questions to ask are: what is the sensible starting point for implementing IUWM? How do we incorporate IUWM into current urban water management practice, and what is an appropriate process? Maheepala et al. (2010a, b) argued that as IUWM, as discussed in this paper is a new approach, the obvious starting point is at the strategic planning phase, in which long-term goals are set, the best strategy to achieve those goals is identified, and resources (e.g. capital, equipment and people) are allocated to implement the chosen strategy. They also developed a process for adopting IUWM for urban water planning as shown in Figure 3.

This IUWM implementation process consists of three phases and five key activities, organised as a spiral to indicate that the five key activities have to be repeated with an increased depth of analysis as we move from Phase 1 to Phase 3. The aim of the Phase 1 analysis is setting the strategic direction. For example, in Phase 1, use of stormwater can be chosen as a possible way to reduce fresh water usage based on a high level feasibility analysis (e.g. annual water balance analysis at whole of system scale), but Phase 1 analysis does not define locations of stormwater harvesting schemes and the technologies to be used. The
The aim of Phase 2 is to identify a feasible set of options in line with the strategic direction set in Phase 1. The aim of Phase 3 is to define an IUWM plan, which describes how the water supply, wastewater and stormwater services will be provided, the extent to which the services meet IUWM principles, the analysis undertaken to inform the IUWM plan and the action required to implement the IUWM plan. An overview of each activity is given below. The depth of analysis and the details of tasks undertaken in each activity increase from Phase 1 to Phase 3.

**Activity 1: engaging with key stakeholders**

Unlike traditional urban water management, IUWM requires urban water planners to take a holistic view of the urban water system and to incorporate EUMM principles. Under IUWM, the urban water system is managed and planned as a single system without considering separate planning approaches for stormwater, wastewater and water supply. In Activity 1 it is essential to form a key stakeholder group (KSG), which has the overall responsibility for the effective delivery of the IUWM Plan and replaces individual strategic plans on stormwater, water supply and wastewater. In Activity 1 it is essential to form a key stakeholder group (KSG), which has the overall responsibility for the effective delivery of the IUWM Plan and replaces individual strategic plans on stormwater, water supply and wastewater. Although the process can be initiated by a single champion or organisation, effective planning requires committed participation from many organisations. Objectives are more likely to be achieved if key stakeholders are engaged early in the process, and if these critical players are involved in providing advice on strategic decisions. Once the IUWM plan is delivered, the KSG might also be responsible for ensuring that the plan is implemented and continues to meet agreed objectives throughout its life.

**Activity 2: developing objectives and assessment measures**

The process of agreeing on objectives starts with recognition of the problem. The problem is likely to be the driver for considering IUWM (e.g. water scarcity). The problem is then generalised, to add context, which assists in recognising the full benefits of IUWM, and allows a wide range of solutions to be identified. Upon agreeing on objectives, measures are defined to determine the extent of achievement of each objective. At present, there is no agreed set of measures for IUWM. Commonly used measures are given in Table 2.

**Activity 3: understanding the current system**

The purpose of this activity is to understand the current system in sufficient detail to enable the identification of potential opportunities in line with IUWM principles. An essential part of this activity is defining the system boundaries. The IUWM approach requires consideration of the
whole urban water system including social, economic, regulatory, institutional and legislative structures that affect the performance of the urban water system. The physical system boundaries encompass the urbanised area and include system components that lie outside the urban area such as sources, discharge points and receiving waters. The non-physical system boundaries relate to social and economic activities of communities served by the urban water system, and regulatory, legislative and institutional structures currently in place.

Activity 4: assessing the system performance

The purpose of this activity is to formulate possible options and evaluate them in terms of the measures identified as part of Activity 2. The knowledge acquired as part of Activity 3 (i.e. understanding the current system) enables identification of issues in the current system and formulation of options that have the potential to address the respective issues. The purpose of evaluating options is to identify options that are effective in meeting the IUWM objectives.

Figure 4 shows linkages between this activity and activities 2 and 3. Assessment of options may involve, but is not exclusive to, processes such as integrated systems analysis in time and space, involving analysis of the physical, environmental, economic and social domains, followed by multi-objective,

| Commonly used measures for assessing objectives in IUWM context |
|-------------------|---------------------------------------------------------------|
| Measures           |                                                                 |
| Economic           | Net present value; annualised value of capital; operating, maintenance and replacement of infrastructure; costs and benefits to the community, which include externalities, regional economic growth and return on investment |
| Environmental      | Environmental flows in waterways and rivers in urban areas; quantity of pollutants in waterways and rivers in urban areas; changes to habitats and biodiversity of the surrounding environment; energy usage; greenhouse gas emissions |
| Social             | Drinking water quality; degree of flood protection and mitigation; sanitation; supply reliability, affordability and equity; wastewater and stormwater service provision; amenity and recreation aspects of waterways and green spaces; home gardening; degree of public participation in decision-making |

Figure 4 | Links between Activity 2, Activity 3 and Activity 4 (Maheepala et al. 2010a).
or multi-criteria decision analysis (MCDA). Techniques such as Bayesian networks are emerging as a means for considering uncertainty and defining risk associated with each of the domains. Studies informing both of these areas include those of Brans et al. (1986); Massam (1988); Colson & Debruyne (1989); Munda et al. (1994); Guitouni & Martel (1998); Crosby (1999); Bertrand-Krajewski et al. (2000); Wiboonsak-Watthayu (2004); Proctor & Drechsler (2006); Kain et al. (2007); Assaf & Saadeh (2008); Makropoulos et al. (2008) and Moglia et al. (2012).

Activity 5: implementation planning

Once the systems analysis has been completed, the findings, which include a comparison of alternatives against measures; and a ranking of alternatives, are presented and discussed with the decision makers (DMs). Implementation requires that the DMs reach agreement on the outputs of each Phase, as shown in Figure 3. For example MCDA methods may be used in a workshop setting to reach an agreement. The agreed outputs in each of the Phases are generally set out as a list of actions or a plan to follow in the next Phase. The output of Phase 3 is called the IUWM plan, which will include the preferred water management options defined in detail and the actions required to implement it. An important part of this activity is communicating the output of each Phase to relevant stakeholders, which include city councils, utilities, householders, industry and other bodies as appropriate.

IUWM LEARNINGS FOR THE IMPLEMENTATION OF DECENTRALISED SYSTEMS

The implementation of decentralised systems into Australia’s cities has to date been undertaken to address specific problems in isolated cases and no holistic strategy for their application across a city has been developed. The development of an IUWM strategy which can be applied at city scale (Maheeplea et al. 200a, b) now allows these studies to be undertaken in a cohesive manner; to demonstrate if decentralisation will provide a more sustainable solution to meet Australia’s growing water demands.

In a preliminary enabling study, Tjandraatmadja et al. (2008) evaluated the existing iconic water sensitive urban developments that have been implemented with IUWM and WSUD concepts. The study investigated the social, environmental, political, institutional and technological challenges faced in implementing water sensitive urban developments. It highlighted the need for a change to the current regulatory and legislative frameworks to enable a holistic approach for providing urban water services to residential developments. It also highlighted the need to consider key service requirements and externalities, as well as the need to engage and educate the community in order to develop acceptable management models for decentralised water systems, all critical components of an IUWM approach. As knowledge on the implementation, management and operation of decentralised systems in the government and water sectors is varied, a key component identified was skill development to enhance capacity building at all levels in these sectors.

Critical factors associated with the implementation of urban water services utilising decentralised systems are health, resilience, reliability and maintenance/monitoring. The community has valid concerns regarding the perceived health and safety risks of decentralised solutions, which is considered a barrier in the uptake of these systems. Research on this aspect is urgently needed before they can be widely applied, which is also true for their resilience, reliability and maintenance/monitoring needs.

One of the key issues in assessing the available systems is the lack of long-term data to enable valid decisions to be made on their performance and suitability for widespread application. Many of the current systems implemented are done in an ad-hoc manner by small communities and are in many cases poorly designed, ineffectively monitored and have the incorrect systems in place to allow them to be maintained or monitored by a water authority. Additionally many water authorities do not have the management systems to allow these smaller systems to be incorporated into their networks.

Adoption of an IUWM approach to the implementation of such systems will allow the necessary data gaps and application barriers to be identified, which will enable conventional systems designers and planners to adopt these systems for mainstream adoption across a city.

CONCLUSIONS

Integrated urban water management (IUWM) which embraces metabolic concepts, as discussed in this paper, has emerged as a potential solution for cities faced with the urban water challenges associated with population growth and climate change. It is an approach for water utilities to plan and manage water supply, wastewater and stormwater systems to minimise their impact on the natural
environment, to maximise their contribution to social and economic vitality and to engender overall community improvement. Adopting the IUWM approach for large cities requires revisiting the fundamental role of water system design and especially the role of decentralisation, which conceptually has the potential to bring key new elements to traditional urban water management.

To understand the impact of decentralisation, we have proposed a method based on IUWM principles, to analyze the total water cycle using a sequential three phase process which firstly sets a strategic direction, followed by feasible options and finally the definition of an IUWM plan. The IUWM plan defines the optimal distribution of decentralised systems, the characteristics of each decentralised system (e.g. sole use of rainwater tanks, sole use of local wastewater recycling or a mixture of different decentralised systems), how the decentralised options interact with centralised systems and the overall impact of the portfolio of options included in the IUWM plan in triple bottom line terms. This requires an understanding of the impact of decentralised options on aspects such as changes to flow, nutrient and sediment regimes, energy use, greenhouse gas emissions, and the impacts on rivers, aquifers and estuaries. Critically it requires data on how decentralised options perform and their impact on public health, resilience to different operating environments, reliability and maintenance/monitoring needs.

REFERENCES


Narangala, R., Pamminger, F. & Knight, K. 2010 Kinglake West decentralised urban water solution-Turning a wee problem into a solution, Ozwater Conference, Brisbane.


WSAA (Water Services Association of Australia) 2010 Implications of population growth in Australia on urban water resources, Occasional Paper No. 25, July 2010.

First received 5 October 2011; accepted in revised form 9 January 2012