Integrated Urban Water Cycle Management: moving towards systems understanding

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Abstract

The urban water cycle is currently managed as separate centralized water supply, wastewater and stormwater disposal processes that have endured for over 100 years. The infrastructure costs, water quality and environmental concerns associated with continuing with the current urban water cycle paradigm are increasing to unsustainable levels. It is argued that a systems approach is required to understand and hence find optimum solutions for urban water cycle management that includes decentralized approaches used to supplement to current centralized management methods.

1.0 Introduction

This paper discusses the urban water cycle, the way we currently manage it and the way it should be managed in the future. Figure 1 presents a schematic of the urban water cycle. The urban water cycle begins with water extracted from streams and aquifers, usually stored in reservoirs and then processed to potable quality via filtration and chlorination processes before delivery through an extensive pipe system to residential, commercial and industrial developments. The treated water is also used for recreational purposes including irrigation of parks and gardens. Some of this water is then used to transport wastes through a network of sewers to treatment plants which discharge effluent into receiving waters such as rivers, lakes and oceans. Rainfall falling on the consumer's allotment contributes to the urban catchment's stormwater that is collected by an extensive drainage system for disposal into receiving waters.

Although the treatment technologies for water and wastewater have improved,

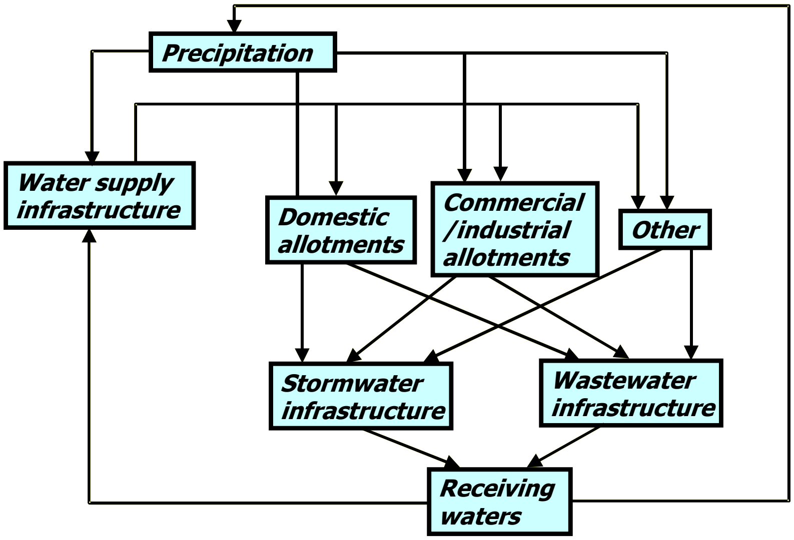

Figure 1. Schematic of urban water cycle.

approaches to supply of water, and wastewater and stormwater disposal have remained largely unchanged over the last 120 years [Troy, 2001]. We are of the view that the Australian paradigm for urban water cycle management has compartmentalised the cycle into the provision of water supply, wastewater and stormwater services. The paradigm is deeply embedded in our thinking. We teach it to our students, we document it in our textbooks and codes of practice, we live it professionally, we institutionalise it. This does not mean that everyone conforms to the paradigm. It suffices that the paradigm is promoted by influential leaders and institutions. One can argue that there are good reasons to manage the urban water cycle as three "separate" systems. Each system is complex and intrinsically different. This provides a convenient model to map out institutional boundaries.

It is our contention, however, that the current urban water cycle paradigm has resulted in sub-optimal outcomes for both the community and the environment. In this paper we document evidence of how the paradigm has failed us. We demonstrate that outcomes currently provided by the water industry in major urban areas can be unambiguously improved upon. We argue that it is not technology that restrains us but rather our perception of system boundaries and constraints that clouds our vision of what is possible. Ultimately the adoption of integrated urban water cycle management approaches will allow provision of sustainable water services to the community.

2.0 Consequences of the Current Urban Water Cycle Paradigms

There are only limited opportunities remaining to further exploit surface water and ground water resources in regions nearby our cities. The extraction of increasing volumes of water from river systems and aquifers, and the construction of additional dams in river systems to supply water to our growing urban areas is likely to place considerable stress on the ecosystems within river systems.

Whilst the advent of centralised water supply and wastewater disposal processes in the nineteenth century saved many lives, in recent times, there have also been notable failures of mains water supplies resulting in public health epidemics caused by discharge of sewage or chemicals to water supply catchments (including a viral outbreak originating from sewage contamination that affected thousands of people in Sunbury in Victoria and the Milwaukee *Cryptosporidium* outbreak in the USA that affected 400,000 people) [Maher et al., 1997]. Failures of centralised water supply systems can result in widespread public health epidemics.

The replacement value of Australia's urban water cycle infrastructure is of the order of $50 billion [Johnson and Rix, 1993]. A large proportion of this infrastructure is dedicated to transporting water and wastes across large distances. These systems are mostly old and overloaded. Unless alternative urban water management approaches are sought these systems will ultimately require replacement at considerable national expense. In addition population growth will cause our cities to expand at the fringes requiring additional reticulation networks that span considerable areas and import water from increasingly remote locations.

Unfortunately most centralised water supplies rely on lengthy pipe networks to distribute water to households. The amount of disinfectant added to the water supply is dependant on the length of the pipe system. Disinfection residual must be maintained throughout the distribution system to ensure that pathogens are eliminated. The internal surfaces of the pipe systems are usually colonised by layers of micro-organisms known as biofilms. In pipe distribution systems biofilms can neutralise the effect of disinfection, revive bacteria that have been injured by disinfection and with the assistance of the flow rate in a pipe release bacteria into the water supply. Bacteria in biofilms are highly resistant to disinfection residuals. In aging pipe distribution systems that contain established biofilms large doses of disinfectants are required to maintain water quality but disinfection by-products in combination with organic materials are potentially carcinogenic [Morris and Naumova, 2000] and may cause birth defects [Bove, 2000]. Current centralised disinfection practices are not suited to mains water distribution systems.

The traditional urban drainage paradigm involving use of more and bigger capacity pipes to discharge stormwater runoff as quickly as possible mitigates risk of localised nuisance flooding but also results in costly solutions and adverse environmental impacts [Andoh and Declerk, 1999]. The hydraulic capacity of stormwater drainage systems also decrease as the systems age resulting in increased flooding.

Rainwater falling on urban areas is regarded as a problem that should be discharged rapidly via extensive “big pipes” systems to waterways. Although rainwater is relatively clean when it falls on roofs its potential value in replacing water imported via expensive reticulation networks from remote river systems that are subject to environmental stress is largely ignored. Stormwater runoff from urban areas including roofs is arguably the most significant source of pollution of waterways surrounding and within cities. An excuse often given for discharging roof water directly to street gutters is that it is relatively clean. However, “clean” roof water discharged directly to the street gutter can acquire considerable kinetic energy and acts within the catchment to erode soils and carry contaminants to waterways [Coombes and Kuczera, 2001].

Sewage discharging from cities is, mostly, subject to limited treatment prior to discharge to rivers or oceans resulting in large and increasing point sources of pollution of waterways close to cities. During rain events sewage discharges increase by factors of 8 -12 above dry weather flows due to influx of stormwater into sewer system. This causes sewage overflows that cause environmental and human health impacts. The elimination of sewer overflows to comply with licence conditions using centralised approaches is expensive. Indeed over $550 million has been spent on this issue in Sydney over the last few years.

3.0 The Systems Approach

The urban water cycle is complex – it is physically complex but it is also complex because it involves conflicting social, economic and environmental objectives. The systems approach provides a decision-making philosophy for working with complex systems. One version of the systems approach is embodied in the multi-objective planning approach.

This approach is appropriate when there exist non-commensurable objectives such as when there are environmental objectives for which there is no agreed monetary valuation. The multi-objective systems approach is described by the following steps:

1) Identify system and its important linkages with subsystems.
2) Define objectives and how to measure performance.
3) Identify the feasible solution space.
4) Search for the Pareto optimal solutions.
5) Evaluate Pareto-optimal solutions to identify the preferred solution.
6) Can we do better? Review.

There is nothing very novel about the steps described above. All sectors of the water industry would implement these steps in one form or another. However, the “devil is in the detail". The success of the systems approach depends very much on how carefully each step of the process implemented.

4.0 Institutional Constraints

Our primary interest is on how the water industry implements the first and third steps of the systems approach, namely the identification of the system and the space of technically feasible solutions. We will consider in the context of the urban water cycle example presented in Figure 2.

To keep our example manageable we start with the premise that the community requires the provision of urban water cycle services to a certain standard. For example, the urban community may require that water supply services are secure during all but the severest drought and provide potable water at an acceptable pressure. The community may require that stormwater be managed so that frequent nuisance flooding is avoided and damage in major flood events is mitigated. There are many ways that water cycle services can be provided at the required level of service. To rationally choose between competing options, the community may decide that these services be provided in a way that trades-off two objectives, minimise community lifecycle costs and maximise the sustainability of the ecosystems that underpin the water cycle services.

The light grey region in Figure 2 represents the performance outcomes of all technically feasible solutions that provide water cycle services to a certain standard. The Pareto frontier describes the solutions that the community should carefully examine in order to arrive at a preferred solution. Solutions that do not lie on the Pareto Frontier are unambiguously inferior. For example, solution A has lower lifecycle costs and better sustainability than solution B. No rational person would prefer B to A unless there are other objectives not articulated in the analysis. On the other hand, one cannot argue that solution A is better than solution C. Although A has lower lifecycle costs than C it has worse environmental performance. The community must examine the trade-off between A and C and in doing so implicitly value sustainability in monetary terms.

The darker grey region in Figure 2 represents a constrained technically feasible solution space which is a subset of the technically feasible solution space. The constrained space may arise because of institutional constraints that limit or prohibit implementation of alternative feasible solutions (such as rainwater tanks) or may arise because it is believed that the alternative solutions are not feasible.

The price paid for artificially constraining the solution space can be considerable. In Figure 2 the constrained Pareto Frontier is unambiguously inferior to some solutions on the unconstrained Pareto Frontier. For example, solution C produces lower lifecycle costs and a more sustainable outcome than any solution in the constrained space. Removing the "artificial" constraints on solutions will produce a more beneficial outcome for the community.

5.0 Source Control – a missed opportunity?

Figure 1 showed that at the allotment all three components of the urban water cycle meet. Mains water is consumed, wastewater is produced, and stormwater runoff is generated. The management of water at the allotment scale is referred to as source control. The philosophy of source control is to minimize cost-effectively the consumption of mains water and the production of storm and wastewater. Source control can be implemented through retention of roof rainwater (rainwater tanks), stormwater detention, on-site treatment of greywater (laundry, bathroom and kitchen) and blackwater (toilet), use of water efficient appliances and practices, on-site infiltration and aquifer recharge/recovery.

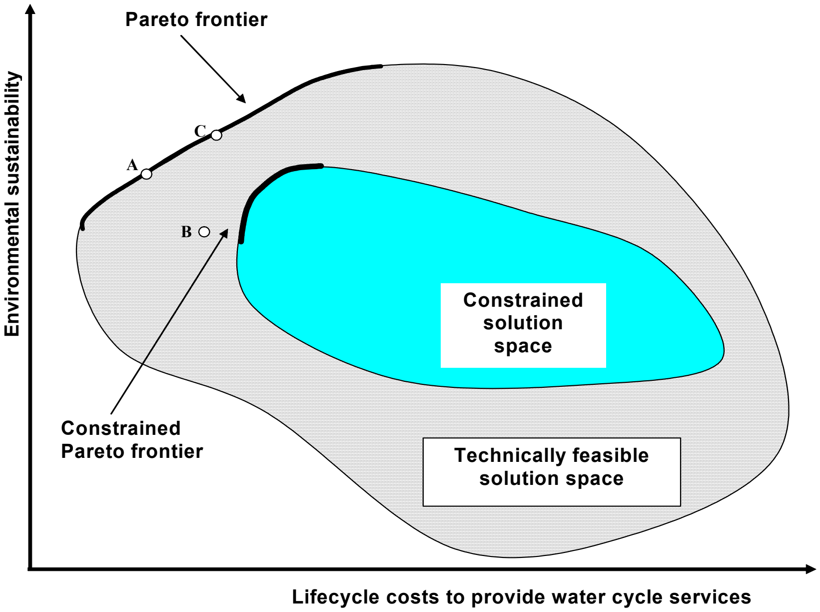

Figure 2. Conceptualisation of the constrained Pareto Frontier.

Some of these source control technologies have seen wide adoption, for example, the use of water efficient appliances and the growing requirement for stormwater detention in new urban development and redevelopment of existing areas. However, other source control technologies such as use of rainwater tanks and on-site infiltration have seen limited usage particularly in the major urban centres on the east coast. Figure 3 offers a revealing perspective on source control at the allotment scale. It shows the boundaries of the sub-systems responsible for water supply, stormwater and wastewater. Interestingly, all three sub-systems intersect at the allotment. In such a case implementation of source control solutions may require the involvement of two or more sectors of the water industry with different perspectives and priorities. The prospect for missed opportunities is apparent.

6.0 Integrated Urban Water Cycle Management Opportunities

The goal of water sensitive urban design is to optimize and integrate urban planning and the management of the urban water cycle [Mouritz, 1996]. This can be achieved by the integration of urban planning and design for the provision of water, wastewater and stormwater services at a range of cascading scales from region to allotment [Coombes, 2002]. In particular the strategic use of rainwater and wastewater at source can supplement the performance of conventional centralized systems to provide more sustainable outcomes.

6.1 Rainwater tanks

There are many misconceptions about the quality of water from rainwater tanks. The early debate about the quality of water from domestic rainwater storages was propagated for economic reasons. Troy [2001], Armstrong [1967] and Lloyd et al. [1992] explain that early water authorities were in debt. Acts of Parliament were created in the 1800s requiring the occupiers of all properties to pay for mains water supply even if they did not use it to ensure that government debt was repaid. The reluctance of the community to part with their rainwater storages had threatened the economic viability of the new centralised water supply paradigm. The legislated mandatory fixed charges ensured that citizens used mains water in preference to household rainwater tanks.

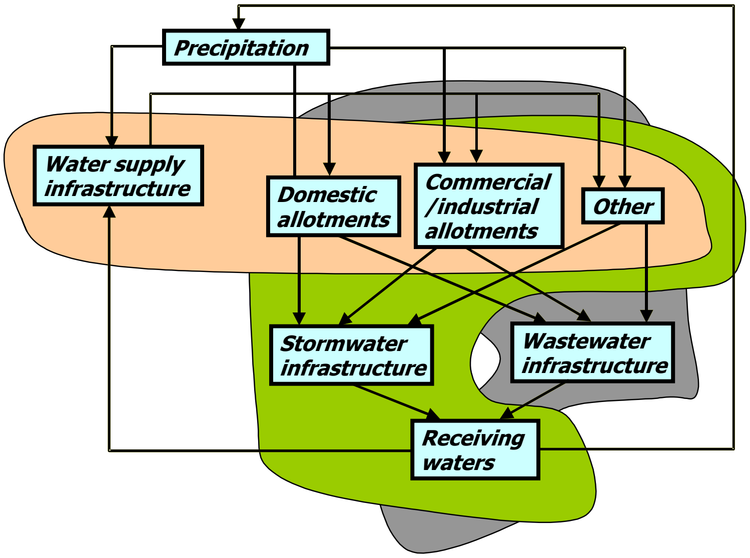

Figure 3: Schematic of urban water cycle depicting sub-system spheres of influences

The arguments predominately used to discourage the use of rainwater are public health concerns although very few published studies or data are in existence to justify this position. Indeed over 3 Million Australians currently use rainwater from tanks for drinking [Coombes and Kuczera, 2001] in urban and rural regions with no reported epidemics or wide spread adverse health effects. Fuller et al., [1981] and Mobbs et al., [1998] found that the quality of tank water was often adequate for potable uses. Coombes et al., [2000; 2000a; 2002] reported that that rainwater collected from roofs in an inner city industrial area and stored in tanks was of acceptable quality for hot water, toilet and outdoor uses. Although roof runoff and the surface of stored water was sometimes found to be contaminated, the quality of water at the point of supply in rainwater tanks was significantly improved. The Namoi Valley Public Health Unit [Bell G., personal communication, 1999] and The Newcastle Public Health Unit [James J., personal communication, 1999] also reported that the quality of rainwater improved in rainwater tanks. Rainwater used in storage hot water systems (temperature settings: 50ºC to 65ºC) and instantaneous hot water systems (temperature setting: 55ºC) was found to be compliant with Australian Drinking Water Guidelines [Coombes et al., 2000a; 2002].

Collection of roofwater in rainwater tanks for domestic use can provide substantial cost savings for the construction of stormwater infrastructure in new developments. The Figtree Place development provided a 1% cost saving ($960 per dwelling) in stormwater infrastructure [Coombes et al., 2000]. Kuczera and Coombes [2001] found that roofwater reuse in a new development would reduce the need for stormwater pipes and end of pipe water quality devices resulting in a 3% cost saving (including the cost to install rainwater tanks). The use of rainwater tanks can also have significant impact on the provision of water supply headworks and distribution infrastructure. Research shows that the introduction of rainwater tanks to supply domestic toilet, hot water and outdoor uses will significantly defer (38 – 100 years) the need to construct new dams in the Sydney, Lower Hunter and Central Coast regions of NSW [Coombes et al., 2002a]. It was also found that the use of rainwater tanks with mains water trickle top can reduce annual maximum daily peak demands by up 40% for domestic dwellings. This can reduce the cost of water distribution (pipes) infrastructure [Coombes et al., 2002 and 2002a; Burn et al., 2002].

Evaluating the impact of rainwater tanks on the urban water cycle is an extremely complex task. Yet the historical evaluation of such impacts has been dominated by ‘back of the envelope’ calculations, the use of untested assumptions and institutional constraint. There are many ‘classic’ untested assumptions about the use roofwater. A common argument used to claim that rainwater tanks do not provide stormwater management benefits is that the tank will have no storage available prior to a storm event. Monitoring and analysis by the University of Newcastle finds this assumption to be incorrect. Coombes et al., [2002c] found that rainwater tanks used to supply toilet, hot water and outdoor uses will have 42% of their capacity available for roofwater retention prior to a 100 year ARI storm and will reduce peak stormwater discharges by about 80% for the one year ARI storm event in the Parramatta region of NSW. The use of rainwater tanks to supplement the existing water supply paradigm can also reduce localized urban flooding, improve stormwater quality and minimize the influx of stormwater into the sewer system.

6.2 Wastewater reuse

The rapid development of small scale wastewater treatment plants is improving the viability of decentralized treatment of wastewater for reuse at the allotment and cluster scale. Improved treatment techniques (including biological and electro-flocculation applications) and filtration methods ensure that recycled water can be of acceptable quality.

Many authors including Mitchell et al. [1997] and Troy [2001] find that the use of treated wastewater for outdoor and toilet flushing uses can significantly reduce water demand and sewer discharges. The use of decentralized wastewater treatment and reuse approaches to supplement the existing centralized wastewater disposal paradigm will significantly reduce infrastructure costs for replacement and upgrade of treatment works and trunk mains as well as reducing the pumping capacity and energy costs of servicing cities.

7.0 Models

Unfortunately the infrastructure cost savings and environmental benefits of decentralized approaches can only be realised if approval authorities accept that these methods provide urban water cycle management benefits thereby reducing the requirement for centralised infrastructure. The current genre of models and design methods that have centralized supply and discharge philosophies rather than decentralized philosophies that include storages cannot provide reliable guidance for approval authorities [Kuczera and Coombes, 2002]. Fortunately new models and design methods for urban water cycle management are being developed by the Australian research industry. For example the Aquacycle model [Mitchell et al., 1997] allows the designer to understand daily water balances. The PURRS model [Coombes, 2002] operates at small time steps allowing understanding of the impact of decentralized approaches on the provision of urban water cycle infrastructure.

8.0 Conclusions

It is clear that Australia cities cannot continue to harvest increasing volumes of water from river systems whilst ignoring the resource potential of the rain that falls on those cities by discharging it to the environment as stormwater. Similarly we cannot continue to discharge increasing volumes of wastewater to the environment without attempting to ultilise this resource. The infrastructure costs and water quality concerns associated with continuing with the current urban water cycle paradigms are increasing to unsustainable levels. Decentralised approaches to urban water cycle management are required to improve the performance of currently accepted centralized approaches by reducing the volume of water imported into cities, and decreasing volumes of wastewater and stormwater discharged to the environment.

This paper advocates the use of a systems approach to the evaluation of the costs, benefits and design of integrated urban water cycle management. Only then will the full range of opportunities of alternatives that can supplement the existing water supply, wastewater and stormwater paradigms be understood allowing implementation of optimum solutions for management of the urban water cycle.

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