Transitioning Drainage into Urban Water Cycle Management

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Abstract

There is a need to expand the stormwater elements of Australian Rainfall and Runoff to accommodate contemporary and integrated approaches to urban water cycle management, starting with integration of land and water planning across time horizons and spatial scales. This guidance should encompass advances in urban water cycle management, and must be cognisant of the likely advances in science and professional practice over the next 30 years. An appropriate policy framework is also required that integrates land and water management with design processes at all spatial scales from local to regional, which also applies to urban renewal and asset renewal or replacement. Appropriate design methods for integrated solutions are likely to include the variability of real rainfall events by using continuous simulation, Monte Carlo frameworks and techniques that consider complete storms, frequency of rainfall volumes and spatial variability of events.

1. INTRODUCTION

Urban stormwater management is described in Australian Rainfall and Runoff (ARR) as the hydraulic design of urban drainage. The current approach to urban drainage is based on conveyance of stormwater runoff to meet minor and major design objectives to mitigate nuisance, and to avoid damage to property and loss of life. There have been many changes in our approach to urban water management in Australia since the establishment of the centralised and separate water supply, stormwater and wastewater paradigm in the late 1800s. Urban water management has especially evolved over the last two decades to include protection of waterways, mitigation of stormwater quality, Water Sensitive Urban Design (WSUD) and Integrated Water Cycle Management (IWCM) approaches. Although these approaches are relatively new, they have wide adoption and support in legislation and policies for water management throughout Australia. This paper discusses the integration of contemporary approaches to urban water cycle management into urban stormwater approaches (e.g. Chapter 14 or Book IIIV) of ARR (IEAust., 1987).

2. THE JOURNEY FROM 1987 TO 2015

There has considerable improvement in urban water management since the late 1800s, supported and underpinned more recently by publications such as ARR (PMSEIC, 2007). Stormwater drainage in Australia evolved from combined sewers that rapidly discharged the accumulated rubbish, sewage, sullage and stormwater from streets to waterways (Armstrong, 1967; Lloyd et al., 1992). The impacts on waterways and amenity of urban settlements drove the separation of sewage and stormwater infrastructure. The filling of swamps and urban development of contributing catchments to accommodate population growth resulted in frequent flooding of early settlements, as well as stagnant water and adverse health impacts. Drainage solutions emerged as a response to these issues. Nation building works-programs during economic depressions (for example in 1890 and 1920) and following wars provided large scale drainage infrastructure throughout Australia.

The first edition of ARR was published in 1958 (IEAust, 1958) as a standard for stormwater management and subsequent major revisions were provided in 1977 (IEAust, 1977) and 1987 (IEAust, 1987). These publications successfully supported the engineering profession and made a significant contribution to Australian hydrological practice. The 1977 edition contains a clarification that the guidance on hydrological analysis and design was not intended to be a generalised or prescriptive code of practice. The third edition of Australian Rainfall and Runoff was published in 1987 as a textbook to provide guidance for designers rather than mandate prescriptive techniques (IEAust., 1987). However, Chapter 14 of this edition was concerned with urban stormwater drainage which at the time was described as:

- Roof and property drainage;
- Street drainage including piped and surface flows;
- Trunk drainage in larger conduits and open channels, and
- Receiving waters.

This guideline focussed on the collection and conveyance of peak stormwater flows in drainage networks. Advice on hydrologic and hydraulic analysis was consistent with the emerging computer age and therefore hand calculations, programmable calculators and computer methods were discussed. The increasing complexity of the different methods and an associated requirement for use of personal desktop computers was highlighted. The use of statistical design rainfall bursts was recommended to calculate inflows to drainage networks and the Rational Method was described as the best known method for estimation of urban stormwater runoff. The major objective of urban drainage at the time was to convey stormwater from streets and adjoining properties without nuisance for minor rain events, and to avoid flooding of property and associated damage from major rain events (the minor/major design approach). In contrast to the introductory comments of the 1987 version of ARR, urban drainage was presented as a prescriptive approach using pipes to convey minor flows and transfer of major flows using streets, open space and trunk drains. Trunk drainage was described to include designs for open channels, detention and retention basins, and bridges. Whilst urban stormwater management was presented and interpreted as a drainage approach, Chapter 14 also highlighted that urban drainage solutions should also:

- Limit pollutants entering receiving waters;
- Consider water conservation;
- Integrate into overall planning schemes;
- Be based on measured or observed real system behaviour;
- Be viewed in relation to the total urban system; and
- Maximise benefits to society.

Drainage solutions were solely focused on the developed catchment and were mostly designed by engineers. The simplicity of the methods for estimating stormwater runoff implied accuracy and certainty of design performance to many users. Urban water management further evolved in the mid 1990's to include protection of waterways[1], mitigation of urban stormwater quality, WSUD (Whelans et al.,1994) and IWCM approaches (Coombes, 2002). Although these approaches are relatively new, they have subsequently gained widespread adoption and support throughout Australia. To support this evolution, Engineers Australia published "Australian Runoff Quality – a guide to water sensitive urban design" in 2006 (EA, 2006). The acceptance of WSUD, IWCM and related approaches has been manifested in three significant ways – (i) the development of benchmark projects [e.g; Lynbrook Estate (Lloyd et al., 2002), New Brompton Estate (Argue and Barton, 2006) and Fig Tree Place (Coombes et al., 2000)] that provided evidence that these new approaches were successful, (ii) the creation of local policies and plans for integrated water management and, in recent times, (iii) the adoption of policies for sustainable water management by State and Federal governments. Recent droughts also triggered many other changes in the urban water sector, largely associated with water conservation, harvesting, recycling and reuse (Aishett & Steinhauser, 2011).

The integrated nature of contemporary water management approaches is different to the objectives and design solutions envisaged in 1987. Urban water management is now required to consider multiple objectives (e.g. resilience, liveability, sustainability and affordability) and the perspective of many disciplines. Advances in computing power, more available data and associated research also allows the analysis of increasingly complex systems to understand the trade-offs between multiple objectives (Coombes & Barry, 2014). Design of urban water management seeks to integrate land and water planning with ecological sustainability. Use of more comprehensive datasets also revealed a greater range of potential outcomes which need to be properly understood to develop integrated solutions. The urban designer now aims to manage the impacts of urban stormwater runoff 'at source' (Argue, 2004) and at multiple scales by retaining stormwater in landscapes and soil profiles, rainwater harvesting and disconnecting impervious surfaces from drainage networks (Poelsma et al., 2014).

[1] Increases flow volumes and rates from urban areas (flow regimes) contributes to degradation of riparian ecosystems and promotes geomorphological changes within stream beds.

Consistent with the philosophy of source control and systems analysis, stormwater runoff is now seen as an opportunity and is valued as a resource (Clarke, 1990; Mitchell et al., 2003; McAlister et al., 2004). Modern design criteria may include analysis of the volumes, timing and frequency of stormwater runoff to determine peak flow rates, water quality and requirements to mimic natural flow regimes to protect waterway health (Walsh, 2004).

3. THE OPPORTUNITIES AND CHALLENGES OF 2015 ONWARDS

Urbanisation generates dramatic changes to the natural water cycle. Impervious surfaces and directly connected drainage infrastructure decrease evapotranspiration and infiltration to soil profiles resulting in reduced baseflows in waterways. This increases the volume and frequency of stormwater runoff and reduces baseflows, which in-turn can create flooding and affect waterway health. Drainage strategies that are reliant on conveyance can transfer additional stormwater runoff and pollutant loads from urban areas to other locations. The different regional scale responses within a river basin and a linked urban catchment are presented in Figure 1. The accumulation of stormwater flows within urban catchments is highlighted by the red hydrographs. The first response at A is the (undisturbed) ecosystem upstream from urban impacts, the second response at B includes the impact of water extraction to supply the urban area (changed flow regime in rivers created by water supply) and the third response at C includes water discharges from the urban catchment (changed flow and water quality regime from both stormwater runoff and wastewater discharges) into the river basin.

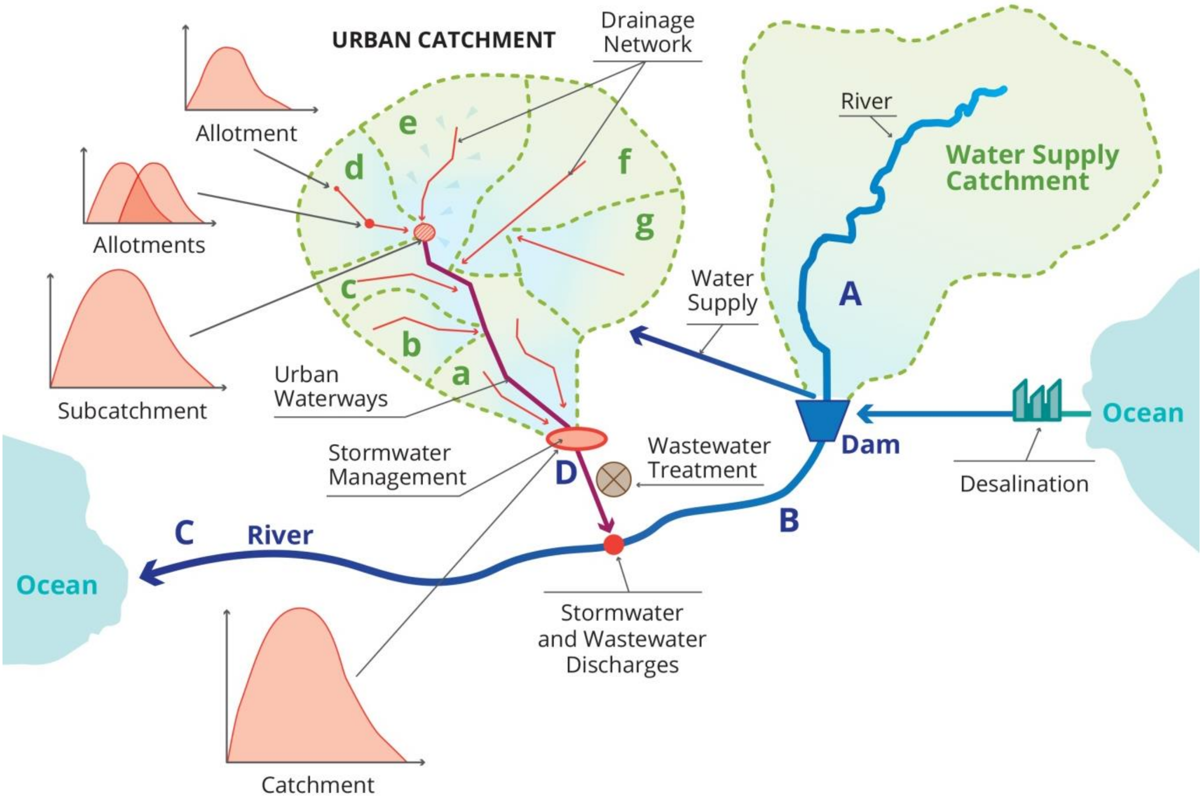

Figure 1 Traditional urban catchments and cumulative stormwater runoff processes

Figure 1 demonstrates that analysis and solutions at point D at the bottom of urban catchments can exclude understanding of impacts within the urban catchment (sub-catchments a-h) and external impacts to the river basin at B and C. Traditional analysis of urban catchments is from the perspective of rapid discharge and accumulation of stormwater in drainage networks (in sub-catchments a-h) with management of flows and water quality at the bottom of the urban catchment (D) using retarding basins, constructed wetlands and stormwater harvesting. However, the benefits for flood protection, improved stormwater quality and protection of the health of waterways from this approach do not occur within the urban catchment upstream of point D. Figure 1 also highlights that distributed land uses (allotments or properties) produce hydrographs of stormwater runoff into the street drainage system. The street drainage system accumulates stormwater runoff from multiple inputs that creates progressively larger volumes of stormwater runoff that ultimately flows into urban waterways or adjoining catchments (Pezzaniti et al., 2002). This process results in dramatic changes in the volume and timing of stormwater discharging to downstream environments. There is an evolving realisation that this issue can be solved by viewing urban stormwater as an opportunity to supplement urban water supplies and to enhance the amenity of urban areas (Mitchell et al., 2003; Coombes & Barry., 2006; Wong, 2006).[2] Urban catchments with impervious surfaces are substantially more efficient than conventional water supply catchments in translating rainfall into surface runoff. Rainwater and stormwater harvesting can extend supplies from regional reservoirs and restore environmental flows in rivers used for water supply (Coombes, 2007). Reducing urban stormwater runoff volumes via harvesting and retention in upstream catchments can also decrease stormwater driven peak discharges and surcharges in wastewater infrastructure (Coombes & Barry, 2014).

Changes in land uses, climate change, increased density of urban areas or decline in the hydraulic capacity of aging drainage networks can also result in local flooding and damage to property. Climate change is expected to reduce annual rainfall volumes and generate more intense rainfall events in a warming climate (PMSEIC, 2006). This will exacerbate the challenges of providing secure water supplies and mitigating risks of urban stormwater runoff. There may also be a need to replace stormwater networks installed during post-war urban redevelopment that are nearing the end of their useful life. In this situation, the capacity of aging drainage networks or increased runoff from increasing density of development can be supplemented by source control measures and integrated solutions (Barton et al., 2007). Integrated solutions and flexible approaches to design can avoid costly replacement of existing infrastructure. Flood management issues for many urban areas are driven by runoff discharging towards waterways (pluvial flooding) rather than from flood flows originating from waterways (fluvial flooding). There is a need to consider a more extensive range of stormwater runoff events from the frequent to the extreme and the associated impacts on urban environments (Weinmann, 2007, Van Der Sterren, 2012). Management of these flood related impacts requires integrated water management of the full spectrum of flood events (Figure 2).

Figure 2 highlights the evolving analysis methods, including continuous simulation and Monte Carlo simulation of full storm volumes that are likely to be required throughout the spectrum of rainfall events as defined by Annual Exceedance Probability (AEP). The definition of rain events is currently a mix of assumptions about frequency and magnitude that requires clarification to allow more effective advice on design of stormwater management schemes.

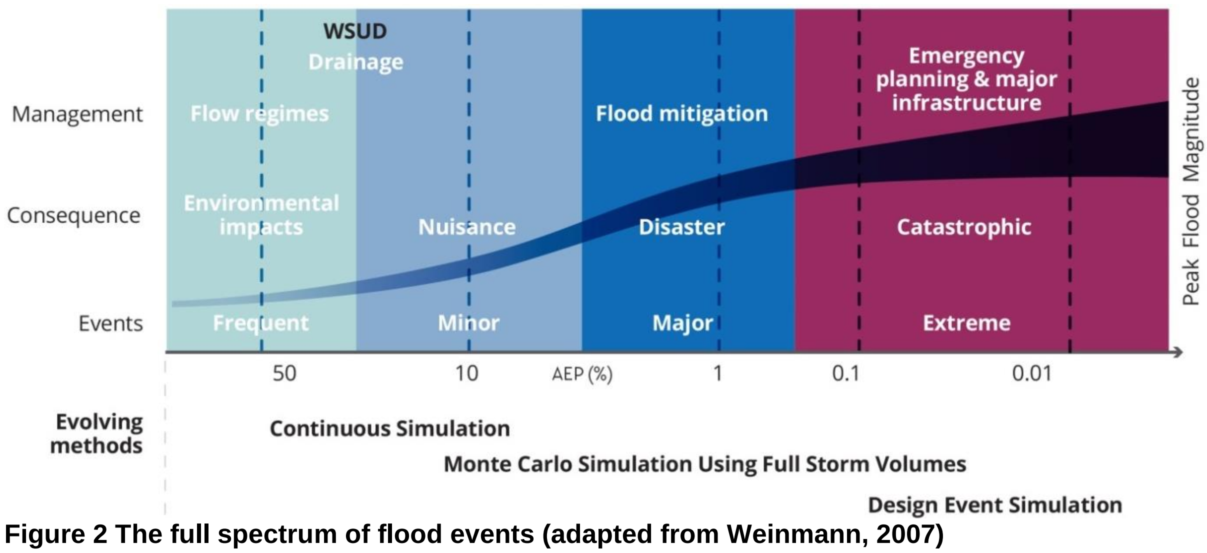

Figure 2 The full spectrum of flood events (adapted from Weinmann, 2007)

The strategic use of water efficiency, rainwater, stormwater and wastewater at multiple scales can supplement the performance of centralised water supply systems to provide more sustainable and affordable outcomes (Victorian Government, 2012). These integrated strategies diminish the requirement to transport water, stormwater and wastewater across regions with associated reductions in the costs of extension, renewal and operation of infrastructure (Coombes & Barry, 2014). This leads

[2] Including development of green infrastructure and microclimates with reduction of urban heat island effects

to decreased requirement to augment regional water supplies and long run economic benefits. Strategies that focus on restoring more natural flow regimes in waterways will be beneficial in reducing remedial works in waterways and provide a reduction in the size or footprint of quality treatment measures (Poelsma et al., 2013). Current approaches to stormwater management include separate design processes and infrastructure for flooding, drainage and water quality. Jurisdictional and institutional boundary conditions are often imposed on analysis (Brown and Farrelly, 2007; Daniell et al., 2014). Integrated design includes solutions that meet multiple objectives, includes the catchment boundaries of each element and aims to avoid redundant infrastructure. Realisation of these benefits is dependent on integrated design approaches that account for changes in the timing and volumes of stormwater runoff, and respond to multiple objectives. Analysis of the economic benefits of integrated designs and drainage networks should be evaluated across an entire system from the perspective of whole of society. The methods and objectives for estimating urban stormwater runoff and the design of pipe drainage networks from 1987 do not include these additional considerations. A challenge to integrated solutions is presented by engineering and economic methods of estimating performance that are reliant on average assumptions and judgements as inputs to empirical methods of estimating performance. As a consequence, optimum design based on average assumptions and model approximations may not represent the actual integrated response of a project.

Educated empirical input assumptions and estimation processes can reasonably be approximated as generic processes for known historical and static problems (Kuczera et al., 2006; Weinmann, 2007). However, these processes may not replicate performance of multiple solutions within a system (for example with respect to intersection of local water cycle solutions with town planning processes and regional infrastructure) and, therefore, cannot understand or value a system that changes runoff behaviour from the smallest distributed scales (from the ‘bottom up’) (Argue, 2004; Coombes & Barry, 2014). For example, cumulative actions at the smallest scale, such as retaining stormwater in the soil profile (e.g. within sub-catchment g) can produce significant responses throughout urban systems as shown in Figure 3. These measures at the allotment and precinct scale can accumulate through the system to the reduce hydrograph peak at the sub-catchment and catchment outlets.

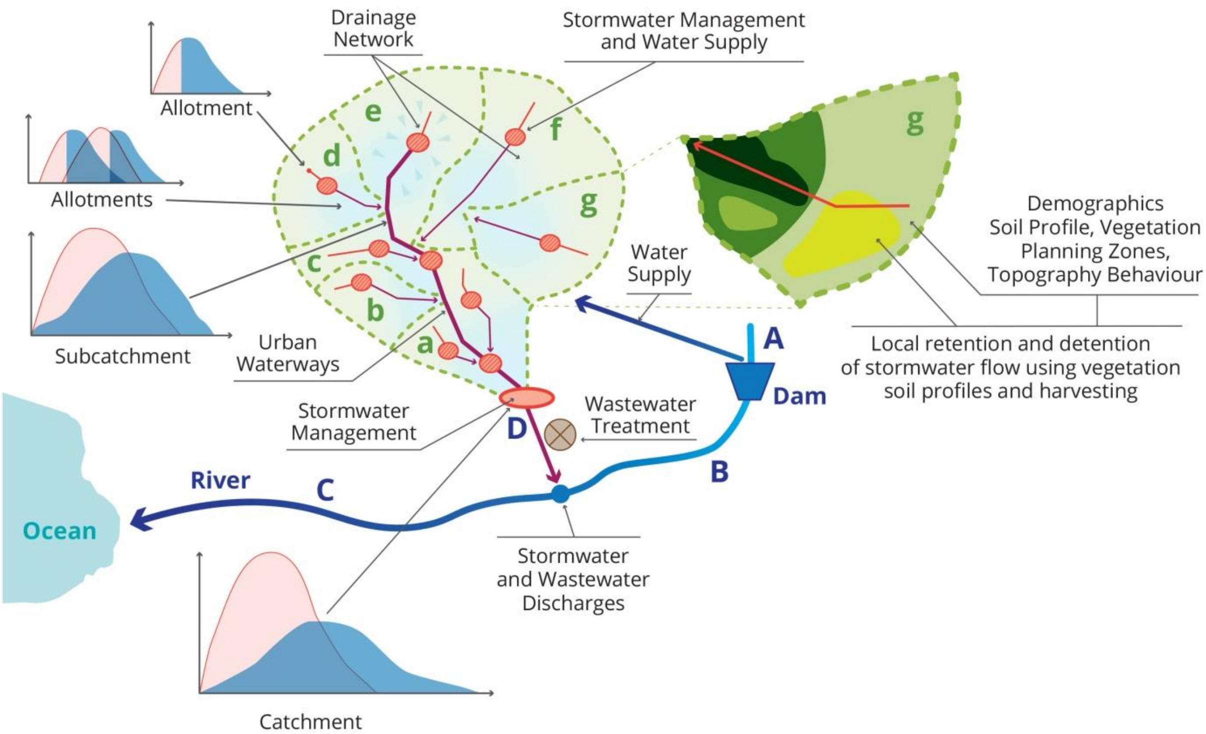

Figure 3 Cumulative impacts of distributed retention measures

It also follows that historical ‘top down’ design processes cannot evaluate distributed processes because a small proportion of the available data may be simplified as whole of system average or fixed inputs (such as a runoff coefficient and rainfall intensity). Thus the signals of linked distributed performance in a system are smoothed or completely lost by partial use of data as averages and by the scale of analysis. As a consequence, there is no direct mechanism to capture cascading changes in behaviors throughout a system.[3] For a simple example, consider the connectivity of traditional water cycle networks presented in Figure 4.

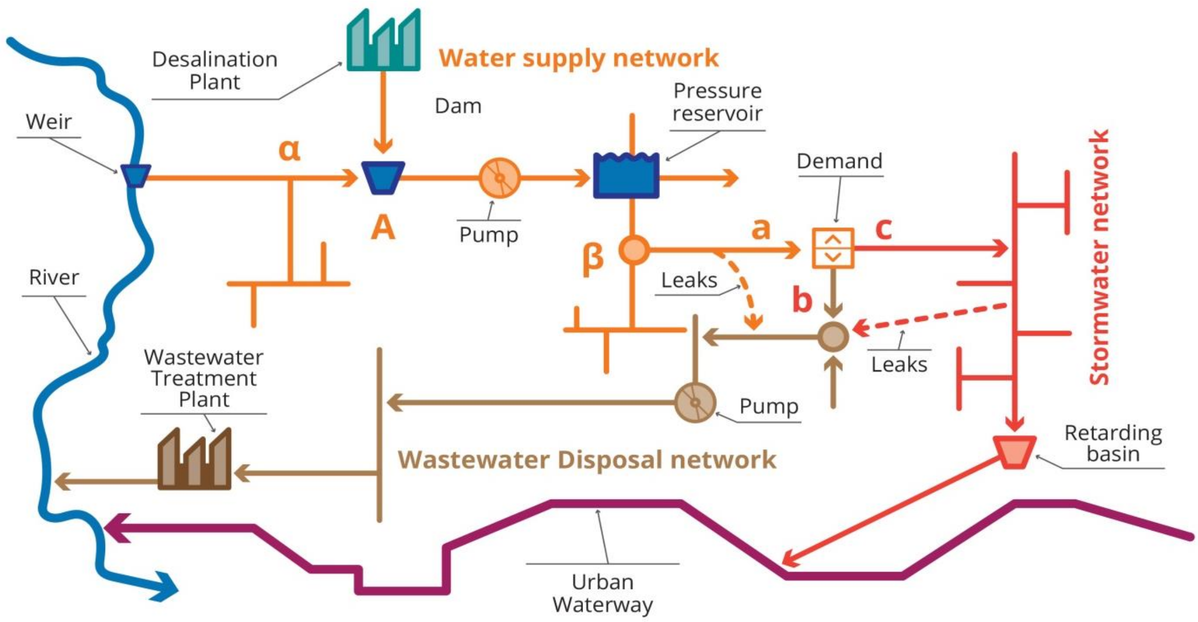

Figure 4 Schematic of the connectivity of urban water networks

Figure 4 shows that an input, or extraction at any point α or β, or an increase in water storage in a reservoir, say at A, will have some influence on flows and capacities at many other points in the system. These will, in turn, translate into changes in performance and costs across the linked networks of infrastructure. Similarly, changes in behaviour (demand) at any point in the system will generate different linked impacts a, b and c on water, wastewater and stormwater networks respectively. Analysis and design of integrated solutions needs to account for the linked dynamic nature of the urban water cycle. Inclusion of rainwater and stormwater harvesting, and wastewater reuse further increases the level of connectivity of urban water networks. The current practice for estimation of stormwater runoff rates and the design of drainage infrastructure is based on a methodology where all inputs, other than rainfall, are fixed variables. The fixed values of the inputs are selected to ensure that the exceedance probability of stormwater runoff is similar to that of the rainfall. However, catchments that contain cascading integrated solutions involving retention, slow drainage, harvesting of stormwater and disconnection of impervious surfaces require enhanced design methods (Kuczera et al., 2006; Wong et al., 2008, Coombes & Barry, 2008). These emerging methods for analysis and design of integrated solutions include the following considerations:

- Long sequences of rainfall that include full volumes of storm events are required to generate probabilistic designs of integrated solutions;
- Peak rainfall events may not generate peak stormwater runoff from projects with integrated solutions;
- The frequency of peak rainfall may not be equal to the frequency of peak stormwater runoff from integrated solutions;
- Stormwater runoff from urban catchments is influenced by land use planning, and the connectivity and sequencing of integrated solutions across scales;
- The probability distribution of the parameters that influence the performance of the integrated solutions (such as human behaviour, rainfall and soil processes) and the ultimate stormwater runoff behaviour are unknown for each project.
- Integrated solutions often meet multiple objectives (such as water supply, stormwater

[3] This can lead to competing objectives (e.g. local versus regional) and information disparity which can only be resolved through a broader analysis framework which recognises location based principles of proportionality and efficient intervention. For example, provision of a wetland and retarding basin downstream of an urban area when management is required within the urban area to protect urban amenity and avoid local flooding.

drainage, management of stormwater quality, provision of amenity and protection of waterways) and are dependent on linked interactions with surrounding infrastructure. We should be mindful that the limitations of design processes are not always apparent and diligence is required to ensure that substantial problems are avoided.

In this situation, continuous simulation using historical or synthetic sequences of rainfall in a Monte Carlo framework may be required to understand the probability of stormwater runoff and the design of infrastructure (Kuczera et al., 2006; Weinmann, 2007).[4] Assumptions and methods of analysis imposed by approval authorities in accordance with ARR can constrain the use of more appropriate analysis techniques required to better understand the behaviour of integrated solutions. Similarly, a default requirement by approval authorities for drainage networks that are designed using peak storm bursts alone can limit the adoption of innovative and integrated solutions. A combination of event based estimation techniques, either directly or indirectly, may not reliably produce probabilistic design of drainage, water quality, water or wastewater infrastructure within integrated strategies. Whilst use of best available event based design approximations are an accepted default or deemed-to-comply approach for design of infrastructure, there is a need to provide an authorizing guidance for more advanced methods for design of integrated solutions. The absence of an integrated approach to design and planning in stormwater catchments may also lead to missed opportunities and poor investment decisions that ultimately result in higher costs with diminished social and environmental benefits (Coombes, 2005). The guidance provided in ARR for estimation of stormwater runoff and design of drainage networks for mitigation of urban flooding needs to be enhanced to provide integration with water cycle management within a systems framework. It would also seem that the definition and purpose of the minor/major drainage system is unclear in the context of modern approaches to water cycle management. Replacement of the minor or major drainage description with a definition of managing nuisance or disaster would provide a clearer focus on the relative importance of both concepts. We may be too focused on a prescriptive drainage approach to the minor system to avoid nuisance. A well designed major system to avoid disaster is likely to allow more opportunity for integrated solutions that will also mitigate nuisance. We also need to be cognisant that water supply and stormwater quality options can also assist in avoiding disaster and mitigating nuisance.

4. CONTINOUS IMPROVEMENT

There is a need for continuous improvement in ARR to expand the stormwater components of ARR to accommodate contemporary and evolving integrated approaches to urban water cycle management, starting with the integration of land and water planning across time horizons and spatial scales. This continuous improvement in guidance should encompass advances in urban water cycle management, and must be cognisant for the likely advances in science and professional practice over the next 30 years. There is a need for an enabling framework of guidance in ARR that encourages and permits advances in analysis techniques and innovative designs. The guidance in ARR must not hold back advances in analysis of integrated solutions. In some jurisdictions there has been disproportionate focus on mitigating nuisance in the minor system at the expense of a proper analysis of the major system. Replacement of the minor or major drainage approach with the relativity of mitigating nuisance or disaster may be appropriate. Allowing space for a major system can help manage large events and provides flexibility for adapting stormwater management to incorporate integrated systems and better management of nuisance.

Continuous improvement in the new ARR should include an appropriate policy framework that integrates land and water management with design processes at all spatial scales, from local to regional, as well as to urban renewal and asset renewal or replacement choices. An evolution of design methods for integrated solutions are likely to include most of variability of real rainfall events by using continuous simulation, Monte Carlo frameworks and techniques that consider complete storms, frequency of rainfall volumes and the spatial variability of events. There is also a need to link ARR with Australian Runoff Quality (ARQ) and other quality guidelines so that urban drainage is an integrated part of the urban water cycle and so that duplication of infrastructure is avoided. An integrated approach to stormwater management should also avoid installation of infrastructure to meet separate objectives that, in combination, create unexpected diminished performance. The need to consider

[4] There are approximately 20,000 daily rainfall records with sufficient continuous rainfall records (more than 3,500) to allow continuous simulation using real or synthetic continuous rainfall records

integrated approaches for future urban water management means that our current approaches of separate analyses of water quantity, water quality, potable water and wastewater systems are no longer the best approach. Integrated systems have the capacity to produce solutions that respond to multiple objectives including economic, social and environmental criteria. ARR therefore needs to promote methods that bring these elements together in a combined analysis approach. This will require strong leadership from the water industry and a recognition of the need to collaborate across science, engineering, planning and sociological sectors in order to maximise the opportunities for implementing integrated solutions.

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