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Baseflow Contribution from Water Sensitive Urban Design

Restoring baseflow to desirable ecological limits using water sensitive urban design

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ABSTRACT

Urbanisation has altered streamflow and severely degraded our natural aquatic ecosystems. It is vital that we look beyond studies of water quality and hydrogeomorphology and into natural baseflow regimes and whether restoration is possible to within the ecological limits. This review paper examines empirical studies of water sensitive urban design (WSUD) projects which report improvements to baseflow. It is apparent that baseflow is critical to stream health; however, it is inconclusive that current WSUD practices can systematically restore baseflow to within the natural ecological limits. Fortunately, a solution could exist by increasing infiltration within allotments and by expanding WSUD objectives.

Keywords: baseflow; water sensitive urban design; WSUD; allotment scale; infiltration; rainwater tanks

INTRODUCTION

Rapid urbanisation is occurring in Australia, and globally with damaging consequences to biodiversity (Williams 2012). Development of peri-urban areas to cope with this growth is compounding the problem (Maheshwari & Connellan 2015). Urban environments introduce large impervious areas and drainage structures which may significantly alter the natural flow of stormwater to the point of creating destructive consequences (Hall 2018). Hydrogeomorphic episodes of erosion and deposition obviously degrade ecosystems physically (Steiger et al. 2005). The urban sprawl is also diminishing occurance, scale and quality of natural freshwater ecosystems which are already stressed by the impacts of climate change (Kingsford 2011), but other subtle changes can be equally destructive.

Baseflow is vital to sustain stream ecosystems through dry periods without significant rain events (Murphy et al. 2009). It is the minimum flow provision for a stream when rainfall is absent, often unseen but when inadequate streams dry out, reliant biota can perish or be forced to become transient. Impacts to aquatic ecosystems from baseflow decline have been recently reported by Choi, Kang and Lee (2018) who found that restored baseflow was beneficial to aquatic fish species. Aesthetics and increased property values of an area have been linked to the quality of urban streams (Nicholls & Crompton 2017).

Where a stream intersects the groundwater table, water can move freely into a stream to create baseflow, as groundwater discharges (Arnold et al. 2000). Changes in groundwater often lead to reduced baseflow (Rassam et al. 2017). Urban development often restricts area for rainfall to infiltrate into the soil and recharge groundwater (McGrane 2016). In severe cases, an absence of prolonged infiltration occurring with insufficient groundwater tables creates a hydrological drought which inhibits seepage into streams and significantly alters baseflow characteristics (Van Loon 2015).

Baseflow rates are highly variable and influenced by seasonal changes in evapotranspiration rates (Morton & McKelvey 1971). With passing time, baseflow declines as ground stores are diminished during dry periods until a significant rainfall event occurs (Brodie & Hostetler 2005). Baseflow variability is becoming more extreme (Li et al. 2018), with climate change being reported as a cause of decline (Zhang et al. 2010), together with combinations of natural processes and anthropogenic activities (Arciniega-Esparza et al. 2017; Orimoloye et al. 2018). Of most concern are the numerous reports that baseflow decline is directly attributed to anthropogenic activities (Dudgeon et al. 2006; Mondal et al. 2017; Romanowski 2013; Tooth 2018). Concerns are however forgotten when rainfall returns (Preston 2008), and with drought policy having a poor track record the goal must be to ensure failures are not repeated (Kiem 2013).

The location of infiltration areas within catchments are a crucial factor in recharging groundwater systems (Moore et al. 2013). Anthropogenic alterations to the landscape like house footings, impervious pavements, and underground drainage systems have altered groundwater paths to streams (Bonneau et al. 2019). If well-sited though, there is a high potential for infiltration basins to improve baseflow. Infiltration basins efficiencies reported for attenuating stormwater runoff are up to 100% and averaging 64% (Natarajan & Davis 2016), which indicates significant volumes available for baseflow.

In Australia, the solution to anthropogenic disturbance of natural stream flow is often by implementing Water Sensitive Urban Design (WSUD). WSUD is a philosophical concept based on scientific research to create sustainable communities that mitigate impacts to the natural environment by incorporating all sources of water into the design of their urban environment (Hunt, Ocampo & Oldham 2017).

WSUD is not a deterministic science (Department of Planning and Local Government 2010). WSUD systems must be tailored to local situations as there are often site-specific factors that need to be identified and clearly considered (City of Gold Coast 2007). Factors should include soil structures (Soil Science Society of America 2018); soil profiles and infiltration rates (Melbourne Water 2013); groundwater tables (Hunt, Ocampo & Oldham 2017); flood clearance and groundwater waterlogging (Radcliffe 2018); urban structures (Meng & Kenway 2018); and many others. Incorporating these factors leads to more appropriate design of WSUD systems that effectively treat and convey stormwater for environmental betterment.

WSUD also includes the creation of living landscapes comprising wetlands, bioretention beds, grass swales and other elements that survive on sources of urban water, attenuate water flows and improve the quality of water leaving the catchment. In combination, these elements remove gross pollutants and managing phosphorus, nitrogen and suspended solids to target percentages of reduction (Hatt, Fletcher & Deletic 2009). Experiencing living environments can often influence people to change their attitudes and prioritise environmental conservation (Price-Mitchell 2014). These spaces additionally entice people to enjoy their living landscape and interact with each other (Zelenski & Nisbet 2014), while protecting urban aquatic systems from any further degradation (Lloyd, Wong & Chesterfield 2002).

WSUD is a globally significant field known by various terminologies. Fletcher et al. (2015) attribute the first known reference of WSUD to a report made by Mouritz in 1992. The terminology is entrenched in Australian literature relating to sustainable development. The United Kingdom prefers the terminology Sustainable Urban Drainage Systems, while the United States opts for Best Management Practices or Low Impact Development (Fletcher et al. 2015). Regardless of the terminology, broadly the same focus exists, namely sustainability in stormwater management in and from urban communities.

WSUD also has the potential to provide direct environmental benefits, particularly in projects incorporating the infiltration of stormwater into groundwater systems (Jolly, McEwan & Holland 2008). Many WSUD treatment elements rely on water infiltrating the underlying strata to reduce the volume treated by subsequent elements in the treatment train and to reduce the surface runoff discharged from a whole system. WSUD elements that incorporate infiltration include grass swales, rain gardens, bioretention basins, tree pits, porous pavers, and wetlands, but many other varieties are also in use (City of Melbourne 2019). A continuous infiltration system is an approach which mimics the natural infiltration processes on undeveloped catchments. Supplementing baseflow is a desirable outcome from WSUD (Prosser, Morison & Coleman 2015). Urban allotments can make a significant contribution to stormwater infiltration and to reverse baseflow decline (Burns et al. 2015). In many medium and high-density urban areas, a significant proportion of the urban permeable catchment and groundwater recharge areas are within the individual allotments and thus remains inaccessible for retrofitting street and estate-scale WSUD systems (Ossola & Burns 2016). Controlled discharges from rainwater tanks can offer an allotment-scale low-cost method to improve infiltration and potentially return urban baseflow to within natural ecological limits (Taylor, 2012).

Betterment of urban baseflow through WSUD systems including rainwater harvesting is the focus of this review. The paper identifies conflicting reports in the literature, differentiates claims of WSUD improvements to baseflow, presents some detrimental impacts of WSUD, explores the allotment-scale approach to WSUD, and offers a view of improving WSUD for the future.

METHODOLOGY

WSUD improvements to baseflow reported in the literature were differentiated by how authors' claims were substantiated. The trichotomic approach adopted classified papers as either baseflow being restored to a benchmark derived from natural flow characteristics, baseflow partially restored but without explicit benchmarking, or only a possibility of some indirect benefit to baseflow.

A database search was made using the keywords of 'baseflow', 'WSUD', 'groundwater' and combinations of these terms with replenish, restoration, recharge, supplement, assessment, analysis, and model. Disregarded were any unpublished, unauthored, or undated work. Specific journal searches included *Water*, *Water Science and Technology*, *Journal of Water Resources Planning and Management*, *Journal of Hydrology* and *Water Resources Research*. Specific conference proceedings searches included Ozwater, WSUD and Novatech. Australian government reports and water research institutes, such as Goyder, were also searched. The review focused on Australian literature predominantly with some international comparisons where appropriate. A complicated interface exists between WSUD systems and stream baseflow which necessitates analysis of the phenomenon by empirical research. A significant body of knowledge based on the modelling and simulation of WSUD systems was therefore primarily excluded.

CONFLICTING LITERATURE

Despite extensive reports that urbanisation has decreased groundwater and baseflow, recent literature claims increases to baseflow by a combination of two main factors could occur from urbanisation: increased stormwater infiltration sites and decreased evapotranspiration rates due to the clearing of deep-rooted vegetation (Barron, Barr & Donn 2013; Locatelli et al. 2017). An extreme case in India suggested that infiltration was increased by more than ten times the pre-urbanisation conditions (Wakode et al. 2018). While anthropogenic disturbance may create new recharge points, it is hard to fathom that the areal infiltration rate would increase significantly with the introduction of large impervious surfaces which prohibit direct infiltration. The current empirical data on urbanisation improving groundwater recharge is too limited to make a conclusive argument (Hall 2018).

The literature is also conflicted over tree abundance and impacts to baseflows. Price (2011) noted several studies of watersheds accrediting tree abundance with decreased baseflows because of increased evapotranspiration rates (Hicks, Beschta & Harr 1991). However, there are also reports that baseflow increased with tree abundance because of increased infiltration sites (Brown et al. 2005). Maintaining desirable evapotranspiration rates is a critical factor in maintaining the philosophy of WSUD, yet evidence of attainment is inconclusive and limited.

The traditional form of urban rainwater tanks, being only to supplement municipal water supply, is argued to serve no benefit to restoring baseflow (Poelsma, Fletcher & Burns 2013). However, rainwater tanks are being recognised for their potential to supplement baseflow among many other outcomes such as flood mitigation (Gee & Hunt 2016). Recent claims have reported, albeit through modelling, that there is significant potential for achieving environmental benefits through urban rainwater harvesting (Xu et al. (2018). In some cases, a minimal 10% reduction in household water supply might facilitate significant improvements for the environment from a system purposefully designed for these dual duties (Taylor & Brodie 2016). It is apparent that we have not yet fully accepted and exploited the environmental benefits of rainwater harvesting.

WSUD LINKS TO BASEFLOW IMPROVEMENTS

Baseflow restored to a desirable level

Evidence of achieving full baseflow restoration came from only one source. Poelsma, Fletcher and Burns (2013) found that a 100m² infiltration system with runoff from a 9800m² catchment in Victoria was able to restore baseflow. Data was collected using ultrasonic level sensors at both the inlet and outlet of the system and analysed for a suite of various flow metrics including baseflow rate.

Baseflow potentially improved

Evidence of partially restored baseflow came from one authorship group, Hunt, Ocampo and Oldham (2017) based on four projects in Victoria including living streams, rain gardens, and infiltration basins. Studies were made using electrical conductivity tracers and readings, plus equations of inflows minus outflows to calculate the water balance.

Possible indirect improvement to baseflow

A possible contribution from 54 literary sources showed that supplementing baseflow is possible but is often not a focus in this field. Infiltration basins, wetlands, trenches, swales, living streams, rain gardens, direct recharge, and injection projects were all represented in this group (Dillon, et al. 2009; Hamilton 2018; Mitchell et al. 2007; Tjandraatmadja et al. 2014; Walsh et al. 2015). This field contains a select group of Australian literature. Later publications include comprehensive authorship.

Despite ephemeral streams existing throughout the world, no international water sensitive projects reported desirable baseflow improvements or similar. International projects were all thereby categorised as having possible indirect contributions. This omission suggests that baseflow improvements may not currently be a priority internationally. Instead, the focus is on direct aquifer recharge where water is forcibly introduced into the ground (Gibson, Campana & Nazy 2018). In most cases, this water is not directly intended to be a part of the groundwater table. The importance of aquifers to baseflow is that aquifers will generally seep to groundwater. In Australia, it is evident that bio-systems are designed to direct stormwater runoff to groundwater which is a process that is more likely to improve baseflow.

EVIDENCE WSUD COULD BE DETRIMENTAL

Some WSUD elements, if designed incorrectly, can reduce groundwater levels and hence decline baseflow. Bullock and Acreman (2003) completed a comprehensive literature study dating from 1930 to 2002 exploring the role that wetlands play in the hydrological cycle and found that studies were divided on the benefits (Fig.1).

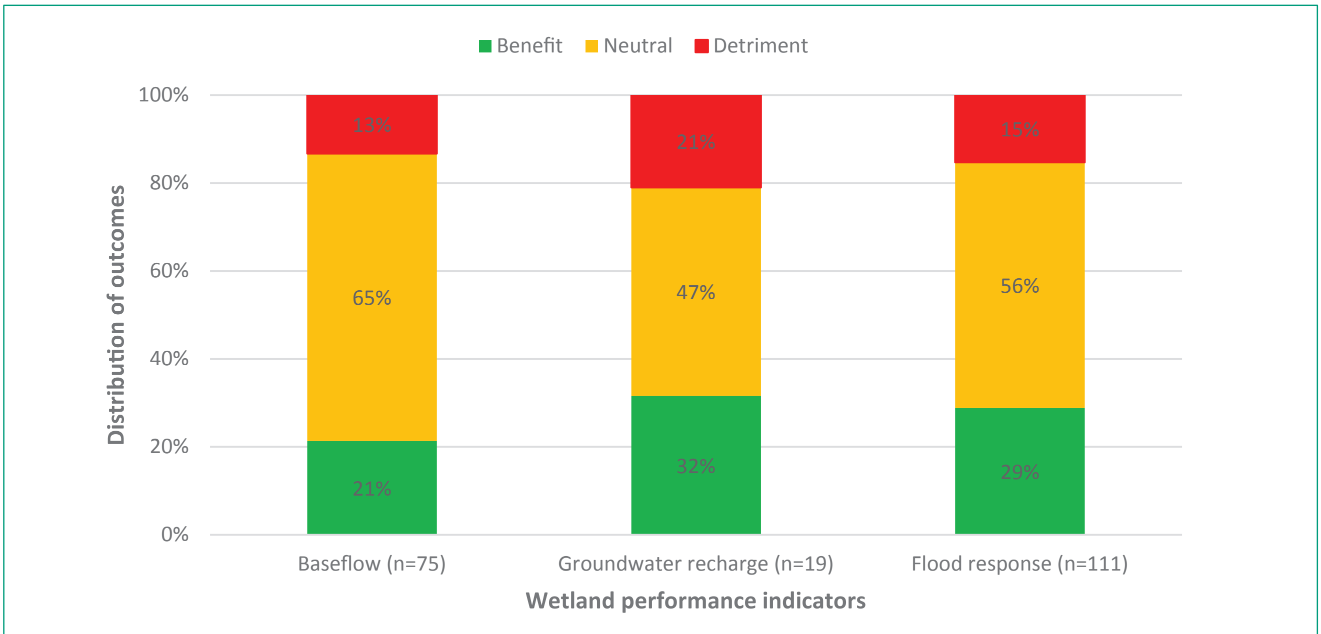

Figure 1: Review of wetland performance indicators adapted from: (Bullock & Acreman 2003)

Wetlands can facilitate groundwater recharge or discharge depending on their location. Open wetlands expose water to the atmosphere increasing evaporative losses. Evaporative rates from wetlands are disguised by water table recharge and other feed sources (Acreman et al. 2003). Also, tree canopies can markedly reduce evaporation (Mohamed et al. 2012). Therefore, it is possible for a catchment to dewater through evaporative losses from wetlands.

AN ALLOTMENT-SCALE APPROACH TO WSUD

Drought around Australia has led to increased installations of rainwater tanks (Fletcher et al. 2012). In urban communities, rainwater harvesting involves minimising runoff from rooves entering drainage systems by capturing and using the water in and around the home (Aswathanarayana 2001).

Seqwater's (2017) strategic management plan for 2016 to 2021 aims at addressing unpredictable rainfall by including rainwater tanks at urban sites as an essential part of planning. Research by Knights, Hanley and McAuley (2012) found that rainwater tanks can contribute to WSUD, both to supplement household water use and reduce impacts on the environment. The benefits increase when water use is high, such as regular irrigation of open spaces.

The extent of open space which remains in urban catchments varies significantly and, in some cities, might be insufficient to facilitate adequate retrofitting of WSUD systems on land controlled by the local government (Fig.2). Suitable permeable space remains within individual allotments providing many potential infiltration sites plus potentially allowing urban communities to contribute to the restoration of baseflow in their catchment.

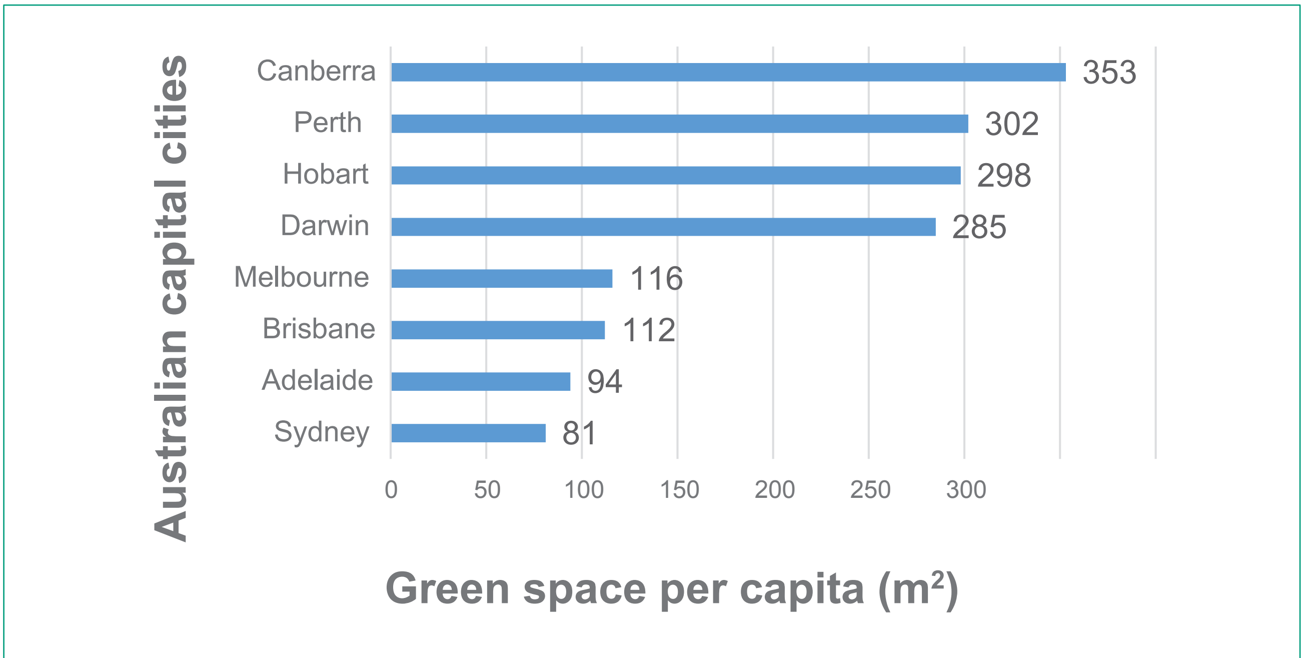

Figure 2: Permeable areas (open green space) per capita in urban catchments adapted from: (Commonwealth of Australia 2018)

Elements of pre-urbanised baseflow conditions can be achieved with rainwater tanks (Gee & Hunt 2016; Kinkade-Levario 2007) when their overflow systems redirect stormwater to a permeable surface, in dry periods, allowing drainage through soil substrate rather than to a drainage system for disposal. Those concepts that exist are Real-Time Control Technology for active releases (Xu et al. 2018) and passive release alternatives (Taylor 2013), also including the Dual Chambered Tank infiltration system (Raimondi & Becciu 2014).

The significance here is the potential to easily adapt in-situ rainwater tanks to create environmental betterment with little interruption to the water supplied to the household. Additionally, households without a rainwater tank could be encouraged to improve their urban environments and gain some water bill relief by installing a system.

Between 1994 and 2010, capital city households with a rainwater tank increased from 407,000 to 1,030,000 (Urban Water Security Research Alliance 2012). In 2013, 34% of households suited to having a rainwater tank had already installed a system, up from 24% in 2007 (Australian Bureau of Statistics 2013). 44% of regional and remote households have a rainwater tank compared to 28% in capital cities (Australian Bureau of Statistics 2013). For most, there is growth in the adoption of rainwater tanks (Fig.3), but recent data was not available for Hobart, and the report did not contain data for Darwin.

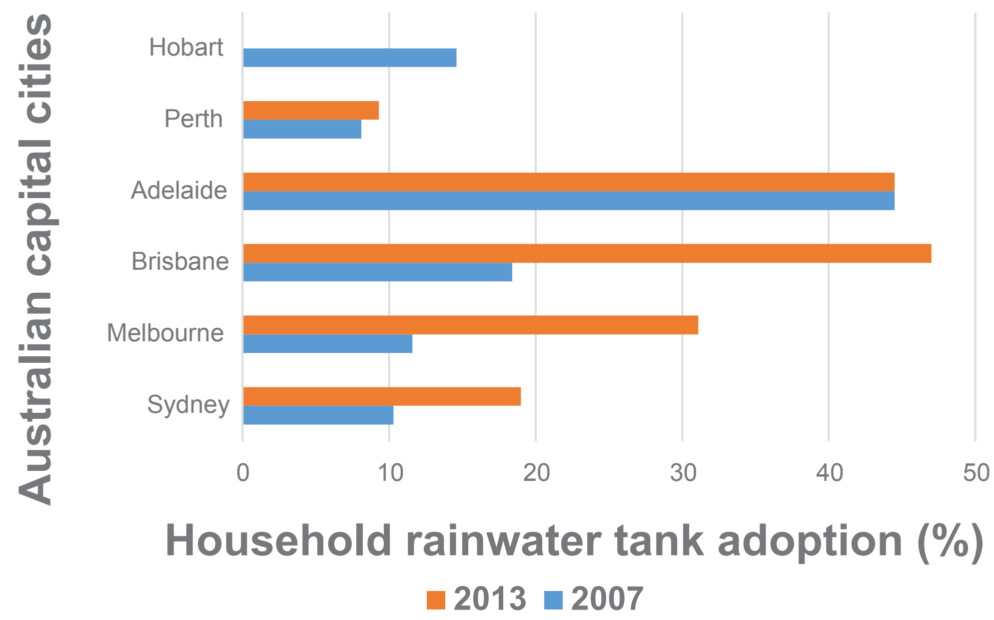

Figure 3: Percentage of households in Australian capital cities with a rainwater tank Source (Australian Bureau of Statistics 2013)

Brisbane is ahead of all capital cities in adopting rainwater tanks; conceivably influenced by economic incentives (Queensland Government 2008). The data reflects different public and regulatory attitudes to rainwater collection and usage.

Perth, with the least number of rainwater tanks, is located where more frequent and extreme dry spells are forecast (Government of Western Australia 2018). In the southern parts of Western Australia annual rainfall is predicted to drop by 40% over this century (Delworth & Zeng 2014). Furthermore, 2000 to 2014 data suggests that there is an immediate concern due to a 75% decline in water flowing into reservoirs in Perth (Brahic 2014). Notably, the area has a large freshwater aquifer supply supplemented by treated wastewater (Dillon, et al. 2018) and desalinated seawater (Engineering Heritage Western Australia 2012). Yet modest supply reliability can come from rainwater collection, with a minimal ecological footprint (Cook, Sharma & Gurung 2014). It is apparent that this region must embrace rainwater harvesting.

Melbourne and Sydney, although having a lot fewer rainwater tanks than Adelaide, have shown a much higher percentage growth rate in adoption. The 44% adoption rate achieved in 2007 in Adelaide may be plateaued ownership, suggesting this region might need more incentives for adoption.

WSUD FOR THE FUTURE

Common in the literature, as reported in Myers et al. (2014), is that WSUD provides benefits to an urban development like reduced mains water pressure and flood mitigation. WSUD is however meant to include the whole urban hydrological cycle and reports like this are focused on the aspects that are noticeable to the community while frequently neglecting the hidden aspects like baseflow.

There is evidence that misguided management occurs from simplifying complex aquatic systems to enable diagnostic analysis and to resolve management issues (Arthington et al. 2006). WSUD requires that all aspects of an urban hydrological cycle must not be oversimplified to exclude vital links. WSUD needs to focus on preparing a community for water demand issues including baseflow before an event occurs and not dealt with via reactive policies after an outcome (Wilhite, Sivakumar & Pulwarty 2014).

It is vital to replenish and maintain baseflow characteristics analogous with natural conditions (Bhaskar et al. 2016; Gleeson & Richter 2018; Wang & Cai 2010). The precautionary principle demands preventative action, especially where uncertainty exists (Kriebel et al. 2001). Establishment of comprehensive WSUD baseflow guidelines is another priority to enable sustainable development in cases where natural conditions are undetermined.

CONCLUSION

This review has discovered inconclusive evidence, yet significant potential that changes to current WSUD practices could restore baseflow to within the ecological limits of our natural ecosystems. By using existing space more effectively in an urban community at the allotment scale, we can improve WSUD techniques and outcomes.

Reconfiguring rainwater tanks to include a release mechanism, at as many premises as practicable, will increase infiltration in urban catchments, supplement groundwater systems, and potentially facilitate restoration of baseflow. Any additions to groundwater systems must be embraced to move towards sustainable urban living.

Rapid urbanisation can interrupt urban groundwater. Further research is needed to understand the circumstances in which urbanisation can increase water tables. Equally, confirmation of the role tree abundance and species has on baseflow in a variety of urban catchments should be undertaken.

Acknowledgment of Healthy Land and Water, New Water Ways, Water Sensitive SA, SEQ Healthy Waterways, CRC for Water Sensitive Cities, and others, to instigate change is deserved. Yet initiatives that specifically focus on improving baseflow are warranted. Baseflow is needed to maintain stream ecosystems which are the basis of many life forms and can add substantial value to our urban catchments.

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