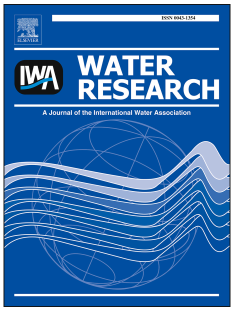

A metabolism perspective on alternative urban water servicing options using water mass balance

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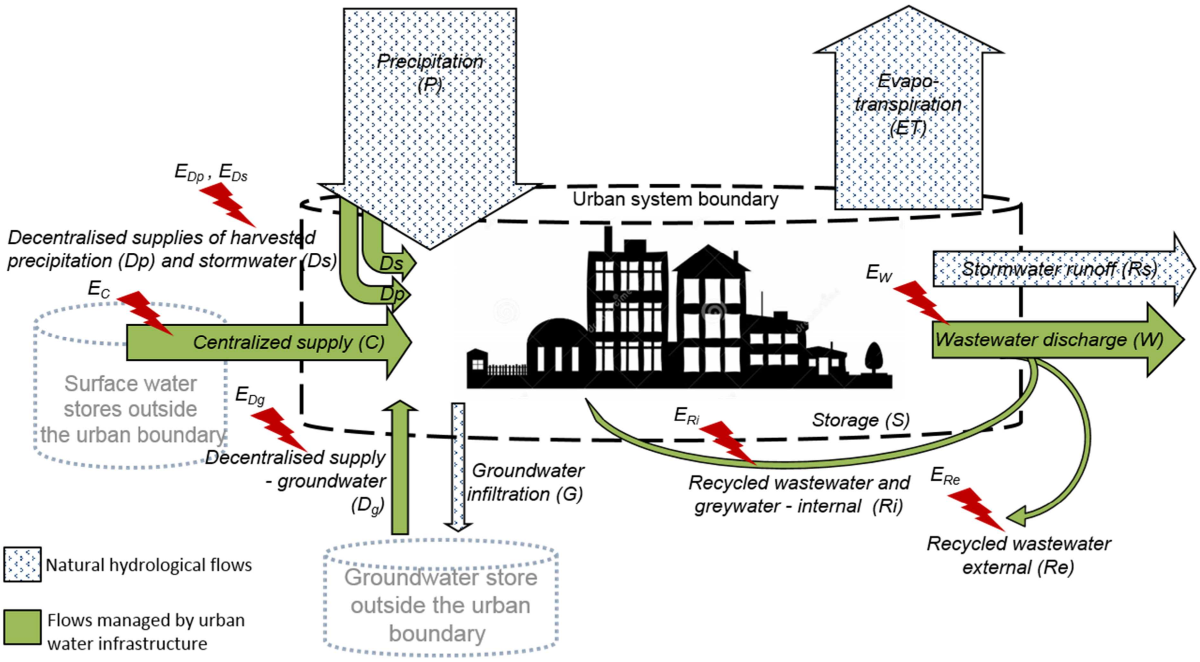
Precipitation (P)
Evapo-transpiration (ET)
E_{Dp}, E_{Ds}
Urban system boundary
Decentralised supplies of harvested precipitation (Dp) and stormwater (Ds)
Ds
Dp
E_C
Centralized supply (C)
Surface water stores outside the urban boundary
E_W
Stormwater runoff (Rs)
Wastewater discharge (W)
E_{Dg}
Decentralised supply - groundwater (D_g)
Groundwater infiltration (G)
E_{Ri}
Storage (S)
Recycled wastewater and greywater - internal (Ri)
E_{Re}
Recycled wastewater external (Re)
Groundwater store outside the urban boundary
Natural hydrological flows
Flows managed by urban water infrastructure

A metabolism perspective on alternative urban water servicing options using water mass balance

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KEYWORDS

urban hydrology; water mass balance; water efficiency; water-related energy; wastewater recycling; stormwater

ABSTRACT

Urban areas will need to pursue new water servicing options to ensure local supply security. Decisions about how best to employ them are not straightforward due to multiple considerations and the potential for problem shifting among them. We hypothesise that urban water metabolism evaluation based a water mass balance can contribute to this, and explore the utility of this perspective and the new insights it provides about water servicing options. Using a water mass balance evaluation framework, which considers direct urban water flows (both ‘natural’ hydrological and ‘anthropogenic’ flows), as well as water-related energy, we evaluated how use of alternative water sources (stormwater / rainwater harvesting, wastewater / greywater recycling) at different scales influences the ‘local water metabolism’ of a case study urban development. New indicators were devised to represent the water-related ‘resource efficiency’ and ‘hydrological performance’ of the urban area. The new insights gained were the extent to which alternative water supplies influence the water efficiency and hydrological performance of the urban area, and the potential energy trade-offs. The novel contribution is the development of new indicators of urban water resource performance that bring together considerations of both the ‘anthropogenic’ and ‘natural’ water cycles, and the interactions between them. These are used for the first time to test alternative water servicing scenarios, and to provide a new perspective to complement broader sustainability assessments of urban water.

1. INTRODUCTION

An increasingly large proportion of the world’s growing population will reside in urban areas, especially cities (UN 2014). The resulting growth in demand for water coupled with climate change constraining supply or making it more erratic, means that large cities are increasingly prone to water shortages (Jenerette et al. 2006). Around a quarter of urban water supplies are estimated to be stressed, and if surface flows needed to maintain ecosystem service are considered, this would increase to a third (McDonald et al. 2014). Competition for supply with other water users, such as agriculture and environmental flows, is also expected to intensify as cities expand (OECD 2015). This means that urban areas, particularly those whose supplies are already stretched, will need to pursue efficiency measures and alternative water servicing options, such as utilising available water within the urban area (rainwater and stormwater) and recycling wastewaters (IWA 2010).

Making decisions about alternative water servicing options involves numerous considerations (Xue et al. 2015). For water cycle managers these include supply security, long-term costs, public health, allocating water to competing demands, and increasingly, the environmental externalities of energy use, greenhouse gases emissions (Behzadian and Kapelan 2015, Kenway et al. 2011b, Makropoulos and Butler 2010), and water quality (Walker et al. 2012). For urban and regional planners and managers, considerations also include the management of flooding, urban streams degradation from increased surface water runoff, and protecting the ecological and cultural values of water. In dealing with such multiple objectives, which can be at odds with each other, it becomes important to look at urban water systems holistically (Huang et al. 2013), to avoid problem shifting and to optimize the overall outcome (Xue et al. 2015). For example, what is the best configuration for decentralized rainwater, stormwater and recycled wastewater in order to make optimal use of limited supplies, maintain / restore pre-urbanized hydrological flows, with least energy cost?

A number of authors have explored the multiple objectives of water servicing options at small and intermediate urban scales (households / suburbs) (Makropoulos and Butler 2010, Makropoulos et al. 2008, Matos et al. 2014, Sharma et al. 2008), and at larger city scale (Behzadian and Kapelan 2015, Venkatesh et al. 2014, Xue et al. 2015). Criteria considered include supply reliability, water savings, water-related energy use and greenhouse gas emissions, runoff quantity and quality, costs and human health.

This past work has tended to focus on those water flows managed by the urban water infrastructure, rather than all flows of water (natural and anthropogenic) in an urban area . So it is currently not clear how to employ water servicing options to deliver desired outcomes for the ‘whole urban water system’, capturing issues of importance for both the managed and natural water cycles. In this work we account for both ‘natural’ hydrological flows (evapotranspiration, stormwater flows and groundwater infiltration) and ‘anthropogenic’ flows managed by urban infrastructure (piped water flows), together within a metabolism framework to consider the ‘whole urban water system’.

We hypothesise that the urban metabolism concept based on water mass balance offers a perspective that can complement decision making about urban water servicing. At its broadest, metabolism is a framework for conceptualising resource flows through urban systems as you might observe it in eco-systems or organisms (Decker et al. 2000, Fischer-Kowalski 1998, Newman 1999, Pincetl et al. 2012, Wolman 1965), with an inferred intent of emulating the higher resource efficiencies of natural systems. As an evaluation approach it has been used to quantify a range of resource flows into, out of, and through urban areas, most commonly energy, materials, greenhouse gases, nutrients, etc. (Daniels and Moore 2001, Kennedy et al. 2007, Wolman 1965). We focus on the less-explored water-related resource flows, employing the mass-balance technique to account for direct urban water flows, as well as water-related energy.

Some researchers apply a broad interpretation of urban metabolism, considering both the direct and indirect metabolism of resources (Daniels 2002, Pincetl et al. 2012). In the case of water, this means direct (real) flows of water from surrounding regions (‘local metabolism’), but also to indirect (virtual) water embodied in the goods and services produced using water from elsewhere (‘global metabolism’) (Huang et al. 2013). We apply a tighter interpretation of urban metabolism, after Baynes and Weidmann (2012), which focuses on direct resource exchanges. So we consider only direct water-related flows from surrounding supporting region, and define urban water metabolism evaluation as the quantification of water exchanges between an urban entity and its supporting region, both natural and managed, to generate indicators of metabolic performance (Renouf and Kenway 2016).

Based on this interpretation, urban water metabolism is a component within the broader (and extremely widely defined) topic of ‘urban water sustainability’. Other frameworks consider the broader economic, social and environmental sustainability dimensions (Behzadian and Kapelan 2015, Venkatesh et al. 2014) or the life cycle environmental impacts of urban water systems (Fagan et al. 2010, Lane et al. 2015). Urban water metabolism evaluation, based on water mass balance of all direct flows can complement and link to broader sustainability assessment, and these links are described by Renouf and Kenway (2016).

Applications of urban water metabolism evaluation to date have mostly examined and compared potable water use among cities and over time (Kennedy et al. 2007, Kennedy et al. 2015), to highlight the underutilization of available water sources (Kenway et al. 2011a), or quantify the degree to which urbanisation influences natural hydrological flows (Haase 2009). We extend its use to evaluating water servicing options.

Urban water mass balance has been identified as a preferred approach for evaluating local urban water metabolism (Renouf and Kenway 2016), because it forces a comprehensive account of all water flows and fluxes (natural and anthropogenic) needed to assess an urban area as a whole. Traditional evaluation frameworks have largely focused only on centralized potable water and wastewater systems, with the intent of matching supply to demand. More recent frameworks have enabled the integrated assessment of diversified (rainwater, stormwater, recycled wastewater) and centralized supplies (Bach et al. 2014), but still focus on water systems within an urban area, rather than the urban area as a whole. The framework proposed and tested here is a next step towards holistic evaluation because it considers the urban area as a whole, accounting for all water flows and fluxes, and also considers water-related energy implications (Renouf et al. 2016).

In this way, planning can optimise outcomes for the urban area as a whole, and avoid unintended problem shifting.

We test our hypothesis by applying an *urban water metabolism evaluation framework* to a semi-hypothetical large-scale urban development, and ask 1) what new insights about water servicing options does urban water metabolism evaluation provide, and 2) what is its utility in this context? The original concept for the framework (Renouf et al. 2016) aims to generate information for informing strategic urban and regional planning. In this work it is operationalized for the first time, with specific application to water servicing options. The main contribution is a demonstration of a holistic approach for evaluating water management in urban areas, with indicators of interest to water managers and urban planners.

2. MATERIAL AND METHODS

The water metabolism evaluation framework (Figure 1) developed for this work has at its core an urban water mass balance, based on a method described by Kenway et al (2011a). The water mass balance quantifies all natural and anthropogenic flows and fluxes of water through a defined urban area. The original method of Kenway et al. was extended to enable evaluation of alternative water sources by accounting for decentralized and recycled water supplies (described in 2.3). The second component is the quantification of energy use associated with water flows to estimate the water-related energy of the system (described in 2.4). The third component is the set of indicators derived from the water flow and energy use data to describe the water metabolism performance (described in 2.5). The novel features are its perspective on the urban system as a whole (rather than the water systems within the urban system), the detailed evaluation of all urban water flows in conjunction with the water-related energy implications, and new indicators that reflect the water resource management performance of the urban area. .

To test the utility of the framework water metabolism indicators were generated for a case study urban development in South East Queensland (SEQ) Australia (described in 2.1), for a set of water servicing scenarios (described in 2.2):

- the development base case as described in the planning scheme, with a traditional, centralized water supply strategy; and
- six alternative water servicing strategies, incorporating internal supplies of rainwater, stormwater and recycled wastewater.

The derived indicators for the alternative strategies were compared with those for the base case to see what changes could be discerned, and what new insights the information provided.

The analysis focused on exploring the utility of the framework, rather than drawing conclusions about the water servicing strategies, as the latter would require consideration of parameters beyond the resource management aspects considered here (such as life cycle costs and public health consideration). It used readily available data for a semi-hypothetical case study and water servicing scenarios, considered representative enough for the intended purpose of informing its further development.

2.1 Case Study Urban Development

The case study is the Ripley Valley Development Area (Figure 2), a proposed new urban development on the fringe of the high-growth, sub-tropical region of South East Queensland, Australia, designed to accommodate 120,000 people / 50,000 dwellings by 2030 (ULDA 2011). It was selected because i) being a new urban area, both the pre- and post-development states could be assessed, ii) prior hydrological modelling had been undertaken, providing some of the required data (McIntosh et al. 2013), and iii) alternative water servicing options had been scoped (CRC WSC 2015). It presented an opportunity to evaluate innovative solutions for securing water supply in a region predicted to experience water stress with climate change (Gooda and Voogt 2012), but which also improve its natural environment and enhance livability for its residents. The urban boundary was defined as the outer edge of the built-up areas (Figure 2), with an area of 3,002 ha. Surrounding nature reserves (1,678 ha) were excluded. Vertically, the boundary extends from rooftop and tree tops, to the root zones of trees (assumed to be 1 meter below ground). The timeframe for the analysis was based on future land development, so the most recent data was obtained wherever possible.

2.2 Water servicing scenarios

Six water servicing scenarios were developed based on various modes of fit-for-purpose water supply (rainwater / stormwater harvesting, and wastewater / greywater recycling) at different urban scales (whole urban area, household, appliance) (Table 2). Harvesting of precipitation was considered at the large urban scale (harvesting stormwater for use across the whole urban area) as well as at the household scale (harvesting rainwater for use in residential and commercial premises). Recycling of wastewater was considered at the large urban scale via centralized reuse within or outside the urban area, at the household scale via decentralized use of greywater, as well as the small scale via reuse within an appliance (recirculating showers). Different extents of implementation (conservative and maximized) were also considered, where relevant. Conservative implementation was based on the scale typically being implemented in Australia at present. Maximized implementation assumes maximum practical utilization, including using more water than otherwise for maintaining green open space and vegetation for enhancing amenity.

2.3 Estimation of water flows / fluxes as an urban water mass balance

The water mass balance method is a refinement on one originally described by Kenway et al (2011a), and is represented by the following equation (Figure 1):

$$Input\ (Qi) \qquad = \qquad Output\ (Qo) + \Delta S$$

$$(P' + C + D + Ri) \qquad = \qquad (ET + Rs + W + G + Ri + Re) + \Delta S \qquad (1)$$

Where:

P' = unharvested precipitation falling in the urban boundary, i.e. total precipitation (P) less any rainwater or stormwater harvested within the urban boundary

C = centralized water supplies sourced from outside the urban boundary, which could include surface waters and groundwater

D = decentralized water supplies harvested inside the urban boundary, including rainwater and stormwater and groundwater

ET = evapotranspiration from the urban boundary

Rs = stormwater run-off discharged from the urban boundary (not including that which is harvested within the urban boundary)

W = wastewater discharged from the urban boundary (total wastewater generated less that which is recycled internally or externally)

G = groundwater infiltration

Ri = reuse / recycling of wastewater internally within the urban boundary

Re = reuse / recycling of wastewater externally, in this case to agriculture in an adjoining valley

ΔS = change in the stored water volume within the defined boundary

Decentralized supplies (D) can include stormwater and rainwater harvesting, local groundwater extraction (bores) and wastewater recycling (Sharma et al. 2013). In this work we mainly refer to D as stormwater and rainwater harvested within the urban boundary, and consider wastewater recycling separately.

$$D = Dp + Ds + Dg \qquad (2)$$

Where:

Dp = rainwater harvesting

Ds = stormwater harvesting

Dg = groundwater extraction

Internally recycling of wastewaters can be via centralized collection by the sewerage system or decentralized collection of greywater at the household or appliance scale.

$$Ri = Rw + Rg + Rh \qquad (3)$$

Where:

Rw = wastewater reused / recycled to the centralized water supply system

Rg = greywater reuse / recycled to the household

Rh = greywater reuse / recycled within an appliance, in this case a recirculating shower

Changes in storage (ΔS) within the urban system were considered to achieve the mass balance, but were assumed to be minimal under normal circumstance, so any change in storage (ΔS) can be attributed to computation errors.

Refinements made to the original Kenway et al. (2011a) equation addressed some limitations in how it accounts for wastewater reuse / recycling, and rainwater / stormwater harvesting. The first was in relation to how it accounts for water reuse /recycling. The original equation only accounted for inputs and outputs across the urban boundary, and not water recirculated within the urban boundary. The refined equation represents reused / recycled volumes as first flowing out of the urban boundary then re-entering as an input. This means that Ri is included in both sides of the equation, keeping the mass balance intact while making these flows obvious in the mass balance. The second refinement was to deduct harvested rainwater (Dp) and stormwater flows

(Ds) from the amount of precipitation (P), so that P now represents unharvested precipitation available to hydrological processes. Finally, the original equation assumed that total volumes of rainwater and stormwater runoff could be harvested, which in practice overestimates Dp and Ds. The refined equation instead adopts maximum harvestable volumes of Dp and Ds, after McIntosh et al. (2013), which is the difference between post-development and pre-development stormwater runoff (Fletcher et al. 2007). This ensures that stormwater runoff exiting the system does not fall below the natural runoff in the pre-development scenario, thus avoiding overharvesting and the negative effects on soil moisture and downstream ecology.

Other studies have used water mass balance equations similar to the one developed here, (Barron et al. 2013, Bhaskar and Welty 2012, Haase 2009, Kennedy 2012) except that some flows have been included, excluded or itemised separately depending on the context or objective of the study, such as groundwater exchanges, leakages from and infiltration into piped water supplies, lawn and garden irrigation and decentralized supplies.

The values derived for populating the water mass balance were based on estimates and assumptions defined in Appendix A. Values for flows managed by the urban water infrastructure (C, D, W, R) were derived from published data or estimated from first principles. Values for the natural hydrological flows / fluxes (P, Rs, G and ET) were derived using a hydrological model - Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (http://ewater.org.au/products/music).

MUSIC is an urban hydrological model that simulates the characteristics of stormwater runoff (flows, duration, frequency, quality) based on rainfall data, land characteristic and imperviousness factors, and used most commonly to design stormwater infrastructure (Elliott and Trowsdale 2007). Here we have used it to estimate the magnitudes of the annual natural hydrological flows from the defined urban system boundary. Rainfall data available within the model was for Brisbane, the major city adjacent to the case study development and within a similar climatic region.. Data for the period 1 July 2000 to 15 June 2010 was used. This was considered to be a reasonable representation of the case study area for the purposes of our study. Evapotranspiration data for Ripley Valley was obtained from the Bureau of Meteorology (BOM 2006). Soil characteristics required by the model to estimate infiltration were taken from the Gold Coast City Council's guidelines (GCCC 2006).

For the pre-development landscape, the imperviousness factor was set to 10%, giving an annual volumetric runoff coefficient (AVRC) of 0.15 (GCCC 2006). For the post-development scenarios, imperviousness factors were generated using the regression equation (5) developed by McIntosh et al. (2013), which is based on dwelling density. This generated overall AVRC values which compared favorably with generic values reported in GCCC (2006) (0.38 to 0.40).

$$\text{Total imperviousness} = 0.0649 \times \ln(\text{housing density}) + 0.1822 \qquad (5)$$

For the post development scenarios, flows / fluxes resulting from irrigation and pipe leakages were added to the groundwater infiltration (G) and evapotranspiration (ET) values based on a partitioning to ET and G of 75% and 25% respectively, after Chrysoulakis et al. (2015). Pipe leakage rates from the centralized supply main were assumed to be 8% of C (BOM 2015) and leakages at the user were assumed to be 7% of demand (Beal et al. 2012).

2.4 Estimation of water-related energy

Energy of the water supply system was calculated according to the following equation, using estimates and assumptions defined in Appendix A:

$$E_{tot} = E_C + (E_{Dp} + E_{Ds} + E_{Dg}) + (E_{Ri} + E_{Re}) + E_W + \Delta E_U \quad (4)$$

Where:

E_{tot} = total energy used by the water system

E_C = energy used for treating and supplying centralized water

E_{Dp} = energy used for treating and supplying harvested rainwater

E_{Ds} = energy used for treating and supplying harvested stormwater

E_{Dg} = energy used for extracting, treating and supplying groundwater

E_{Ri} = energy used for treating and supplying wastewater recycled internally

E_{Re} = energy used for treating and supplying wastewater recycled externally

E_W = energy used for treating and discharging wastewater

ΔE_U = change in household energy use

Energy use associated with water treatment, distribution, wastewater treatment (secondary treatment), and operation of rainwater tanks, was based on water-related energy use for South East Queensland reported by Kenway et al.(2015). Energy use in rainwater tank operation was further validated against Cook et al. (2012). In the absence of energy use data for household greywater recycling in Australia, data related to UK households (Memon et al. 2015) was used. In the absence of data on energy use for stormwater treatment, it was estimated assuming a pressure sand filtration and chlorine disinfection. Energy for pumping was estimated from first principles, based on assumed delivery heads, because as the development was not yet in place it was not possible to source real data (see Appendix A).. For greywater recycling within the appliance (recirculating shower), changes in water-related energy in the use phase was also considered, to account for the water heating avoided due to the recovery of heat energy as well as water. For the other scenarios there were no changes to water-related energy in the use phase.

2.5 Indicators of local water metabolism

There is no agreed set of indicators for representing the performance of urban water systems. Indicators currently reported in literature represent a diverse range of water system characteristics depending on the study's objective (for example, level of service, reliability, system yield, resilience, system leakages, water management policies, social acceptance, pollutant loads and environmental impacts, etc.) (ADB 2013, Behzadian and Kapelan 2015, EIU 2011, Mirza et al. 2013, van Leeuwen et al. 2012, Venkatesh et al. 2014).

Indicators of local water metabolism specifically focus on water resource management, in terms of how well water (and water-related resources) are utilized in urban areas, with the aim of guiding decisions towards more metabolically-efficient urban areas. They can be a sub-set of, or complement, broader sustainability indicators reported by other evaluation frameworks, which for example often include social and economic performance indicators (Behzadian and Kapelan 2015). Some studies report indicators that we'd suggest are related to water metabolism, such as water self-sufficiency and the scale on centralized or externally-sourced water input (Kennedy et al. 2014, Makropoulos and Butler 2010, van Leeuwen et al. 2012), but the development of water metabolism indicators is in its infancy.

The elements of metabolic-efficiency we considered were i) reducing demand for water extracted from external sources by harvesting water within the urban area and recycling wastewaters, ii) avoiding unintended consequences of energy use, and iii) maintaining or restoring pre-development hydrological conditions (Table 2). The first two have been captured in a set of water-related resource efficiency indicators and the third in a set of hydrological performance indicators. There are other elements of water metabolic efficiency, such as nutrient conservation, or the drain of urban areas on their supplying region, but we have not explored these at this stage.

The indicators of water-related resource efficiency tell us the extent to which resources are consumed for the provision of urban water, in this case water extracted from external sources and energy (both per person per year). They also tell us the extent of internal harvesting and recycling in place to affect the resource efficiency. The internal harvesting and recycling ratios represent the proportion of urban water demand that is met by fresh water (rainwater and stormwater) harvested and wastewaters recycled within the urban area, respectively.

The indicators of hydrological performance tell us about the degree of departure from pre-development hydrological flows, in terms of the magnitude of annual flows. It is the ratio of post- to pre-development flows, for stormwater runoff, total stream discharge, evapotranspiration and infiltration to groundwater. A ratio > 1 means that the magnitude of the annual flow/flux is larger than pre-developed landscape, and a ratio <1 means it is smaller. The rationale for these indicators is that the changed hydrology brought about by urbanization affects environmental qualities that urban planners endeavor to manage. Increased stormwater flows and stream discharges degrade the health, ecology and water quality of urban streams and receiving water bodies (Walsh et al. 2005), reduced evapotranspiration contributes to urban heat island effect (Coutts et al. 2014), and reduced infiltration inhibits natural groundwater recharge.

In relation to stormwater runoff, we recognize that frequency, duration and intensity of flows are important considerations for harvesting potential and for urban stream health (Ashbolt et al. 2013, Fletcher et al. 2007). However, the framework currently uses the magnitude of stormwater flow as a proxy for stormwater flows.

3. RESULTS AND DISCUSSION

The estimated annual water flows / fluxes contributing to the water mass balance of the Ripley Valley for each scenario are reported in Table 3. These are also depicted in Sankey diagrams (Figure 3) to visually show how the different water servicing options affect the water balance. It was possible to achieve a water mass balance for the system ($Q_i = Q_o + \Delta S$) (see right hand columns in Table 3). The water-related energy estimates are reported in Table 4. This data was used to derive the water metabolism indicators (Figures 4a and b) for each scenario.

3.1 Water metabolism of the urban development base case

Here we discuss the water metabolism of the pre-development and post-development base case scenarios, against which the performances of the alternative water servicing options were evaluated.

In the pre-development case, the only inflow of water into the system is precipitation (P), 70% of which subsequently flows out of the system as evapotranspiration (ET), 16% as stormwater runoff (Rs), and 14% as groundwater infiltration (G) (Figure 3a). The pre-development Rs, estimated using the MUSIC model (3.7 GL/yr), corresponds well with the annual average harvestable volumes estimated for Ripley by McIntosh et al (2013) using the ArcHydro model (1.3 – 3.1 GL/yr depending on dry/wet year, degree of dwelling density). There were no prior estimations of ET and G to compare our estimates with.

Urbanization of the Ripley Valley in the development base case (as per the planning scheme) introduces an additional inflow of centralized water supply (C) and outflow of wastewater (W), of a scale equivalent to around half the annual precipitation (Figure 3b). The increased imperviousness was estimated to increase Rs by around 2.5-fold, which is consistent with other modelling studies for similar climatic regions (Ashbolt et al. 2013, Fletcher et al. 2007, McIntosh et al. 2013). Total stream discharge, which is the combined outflows of Rs and W to receiving waters, would increase by 5-fold. Evapotranspiration and infiltration are expected to decrease by 17%, and 27% respectively. The base case development has no internal harvesting or recycling, with all water supply sourced externally at a rate of ~95 kL/p/yr and with water-related energy use of 115 kWh/p/yr.

3.2 Water metabolism of the development with alternative water servicing options

Here we discuss how the alternative water supply options influence the water metabolism of the urban development. The volumes of rainwater, stormwater and wastewater potentially available for use in the urban development, could individually supply a significant proportion of the development's water demand in theory (50%, 50%, and 80% respectively), if water quality constraints were not considered. More realistically, if only non-potable uses were considered, this would reduce to 21%, 21% and 34% respectively. Therefore there is considerable capacity for internal supply in theory, as previously recognized by Kenway et al. (2011a) for Australian cities.

Rainwater and stormwater scenarios

If rainwater or stormwater were harvested (Dp and Ds) and used to a conservative extent (garden irrigation and toilet flushing) a modest reduction in the stormwater runoff ratio (post development flows relative to pre-development flows) would be expected, reducing it from 2.5-fold to 2.0/2.3-fold respectively. This is consistent with the findings of Ashbolt et al (2013) for a similar scenario. If Ds use was maximized (all legal sub-potable uses), stormwater flows could potentially be restored to near pre-development flows (Figure 3c and 4b). However similar modelling for nearby Brisbane by Fletcher et al (2007) found that this would be difficult in practice because the greater rainfall intensities in this sub-tropical climate leads to overflowing of stormwater collection ponds. So considering the magnitude of total annual flows alone does not necessarily give a realistic representation of the hydrological restoration potential. Total stream discharge will remain high since externally sourced water (C) will continue to be discharged as wastewater (Figure 4b).

Using rainwater and stormwater to enhance green space and vegetation use was found to have little restorative effects on evapotranspiration (ET) and groundwater infiltration (G), even when maximized (Figure 4b). The fraction of harvested water assumed to be directed to irrigation and subsequently becoming ET and G, is very small compared with the total ET and G fluxes of the urban area, and so the relative changes to ET and G are minor. We suspect the scale of vegetation and irrigation would need to be much larger than modelled here to bring about any significant restoration of ET and G, but this was not explored.

In relation to resource efficiency, an internal harvesting ratio of up to 45% could be achieve through rainwater or stormwater use, although in practice around 20% is more likely based on conservative practices. External water extraction would decrease from 95 kL/p/yr to around 60 kL/p/yr when maximised, and to 82-92 for conservative use (Figure 4a). There would be an overall energy cost for rainwater use of 15-35 kWh/p/yr (Figure 4a), because household rainwater pumps were assumed to be relatively energy inefficient, and would offset the energy savings from displacing centralized water supply (Table 4). For stormwater utilization, there could be a slight energy saving of 12 kWh/p/yr if use is maximized (Figure 4a) because pumping at this larger scale can be more energy-efficient, whereas conservative use gives a similar overall energy use to the base case (Table 4).

Wastewater recycling scenarios at different scales

The influence that wastewater recycling has on the metabolism of the urban area was found to depend on the scale. For centralized wastewater recycling, the resource efficiency benefits are similar to the stormwater scenario, increasing the internal recycling ratio, displacing demand for external water supplies, and reducing energy intensity (Figure 4a). Decentralized greywater recycling at the household scale also reduces demand for external water supplies, but comes at a considerable energy cost of between 43-80 kWh/p/yr (Figure 4a). This is because, the on-site treatment (sand filtration and UV disinfection) and pumping are relatively energy inefficient. Greywater recycling within the appliance (recirculating showers) offers significant overall energy use reductions due to the heat recovery that occurs within the appliance (Figure 4a). The short timeframe of the recycling enables heat energy as well as water to be recovered. Since energy for water heating in the use phase is far much more significant than energy use for supplying water (Kenway et al. 2011b), influencing this component of the water cycle can be very significant. The recycling scenarios do not offer any restorative effects on Rs, ET and G, but total stream discharge is decreased because less wastewater is discharged (Figure 4b), which occurs downstream of the development. Recycling wastewater to agricultural areas outside the urban development does not provide any metabolism benefits to the urban development itself. The benefits would accrue to the agricultural activities by way of displaced freshwater extraction, and possibly displaced fertilizer input if the nutrient content of the wastewater is utilized. Due to the urban-centric nature of the evaluation framework, this external benefits are not considered.

3.3 What new insights does the urban metabolism perspective provide about water servicing options?

The insights in relation to resource efficiency are as follows:

- The harvesting and use of rainwater / stormwater and the recycling of wastewaters offers noticeable improvement to water efficiency only when utilization is maximized, i.e. reducing per person extraction of external water by 37% (from 96 kL/p/yr to 56-63 kL/p/yr). In contrast conservative use only improves it by only 4-18% (from 96 kL/p/yr to 80-92 kL/p/yr).
- Energy considerations can be important. The water efficiency benefits of utilizing rainwater and greywater at the household-scale can have energy trade-offs (for pumping), increasing water-related energy use by up to 31% and 67% respectively. Whereas the higher pumping efficiency of stormwater and wastewater utilization at larger scales can reduce overall water-

related energy use by up to 10%. However, when heat energy is recovered through greywater recycling within the appliance (recirculating shower) the energy savings can be considerable.

The insights in relation to hydrological performance are as follows:

- When the use of harvested rainwater and stormwater is maximized it can potentially reduce the scale of annually-averaged stormwater runoff to near pre-development levels, whereas conservative use has only moderate influence.
- Utilizing internal water sources for irrigation may have little effect on restoring evapotranspiration (ET) and groundwater infiltration (G) toward pre-development levels, even when maximized. For ET, any increases from irrigation of green space are too small to offset the large decrease from the vegetation loss of urbanization. This has implications for the role of irrigation to mitigate urban heat island effects (Coutts et al. 2014). The scale of rainwater/ stormwater / wastewater use for vegetation irrigation may need to be very large to have to effect a discernable restoration of ET. For G, opportunities for improving infiltration become scarcer with increasing dwelling density, unless irrigation occurring in the urban periphery within the defined urban boundary is considered.

Overall, the analysis suggests that use of harvested rainwater / stormwater may offer more metabolism benefits than wastewater recycling. This is because harnessing precipitation falling on the urban area improves both resource efficiency and restores hydrological flows (of stormwater), also been noted by Fletcher et al. (2007). In comparison, while wastewater recycling offers similar water efficiency benefits, it does less to restore hydrological flows. However, the analysis did not consider potential nutrient recovery benefits of wastewater recycling, which may alter the relative benefits.

These insights about water servicing options are from a local resource management perspective, i.e. they are ‘urban centric’. Other studies that have taken different perspectives to evaluate water servicing options have come to different conclusions. For example, Sharma et al (2009) assessed a similar suite of urban water servicing options to those assessed here using environmental life cycle assessment (LCA). They concluded that stormwater harvesting may not be preferred, due to the indirect environmental impacts embodied in the establishment of water storage and third-pipe distribution infrastructure. This flags that both the direct and indirect implications of urban water management need to inform decision making.

3.4 What is the utility of a metabolism evaluation framework?

The value of the metabolism perspective was to understand the attributes of water servicing options from the perspective of both resource efficiency and restoring hydrological performance. The water mass balance that underpins the evaluation accounted for all anthropogenic and natural flows through urban areas, so that the multiple aspects of local water resource efficiency were considered in a consistent framework. In particular evapotranspiration and groundwater infiltration, which are not commonly considered in water cycle studies, can be considered as well as stormwater runoff. Also, observations about the scale of implementation were possible within this consistent context.

The resource efficiency indicators are useful for quantifying and comparing the degree to which urban areas are moving towards reduced reliance on external, centralized supplies. The hydrological performance indicators help us understand the extent of intervention needed to maintain or restore pre-development hydrological conditions. It brings together consideration of both the ‘anthropogenic’ and ‘natural’ water cycles, and the interactions between them, and considers the urban area as a whole rather than just the water systems within the urban area.

The following limitations were revealed which should be addressed in future iterations of the framework:

- The selection of a greenfield development made it straightforward to examine hydrological flows relative to the pre-development conditions, but this would be more difficult when evaluating existing or in-fill urban developments, and would require definition of the pre-urbanized reference landscape.
- Setting the urban boundary tightly around the built-up urban footprint means that the benefits when urban waters are utilized outside the urban area are not evident, and may require reconsideration of how the urban boundary is set.
- There are limitations to using only the annual magnitude of stormwater flows, as flow frequency and intensity strongly influence harvest potential and urban stream impacts.
- A resource efficiency consideration missing from this current analysis is that of nutrients. Decisions about alternative water servicing options would be further enhanced by also considering nutrient metabolism, both in terms of their mobilization by stormwater and wastewaters, and their conservation and beneficial utilization in wastewater.
- Metabolism evaluation which focuses on the direct implications of urban water management should be considered along with the indirect implications as assessed by life cycle assessment.

4. CONCLUSIONS

This work demonstrated how a “water mass balance” metabolism perspective can be used to generate indicators of urban water-related resource efficiency and hydrological performance, from a local resource management perspective. The novel contribution is the development of new indicators that bring together consideration of both the ‘anthropogenic’ and ‘natural’ water cycles and the interactions between them, on the basis of the whole urban area rather than just the water system within the urban area.

Scenario analysis was used to show how this can be used to assess alternative urban water servicing options. The new insights this provided, which are different from other perspectives, relate to the extent to which alternative water supplies can influence the water efficiency and hydrological performance of the urban area:

i) The harvesting of precipitation falling on the urban area (rainwater, stormwater) can positively influence both the water efficiency and the restoration of natural hydrological flows (especially runoff), whereas wastewater recycling only influences water efficiency;

ii) The extent to which alternative water sources are used needs to be maximized to give noticeable benefits;

iii) While the runoff can be reduced through the harvesting rainfall and runoff, it will be more difficult to influence restoration of evapotranspiration and groundwater infiltration;

iv) Scale of implementation influences water-related energy efficiency. Rainwater/graywater use at household scale can have an energy cost, but stormwater / wastewater use at larger scales can be an energy saver. Water recycling at the appliance scale (eg. recirculating showers) can be a very large energy saver due to the heat recovered.

The indicators are a step forward in representing local urban water performance and can guide us toward more resource-efficient urban water systems. However, there remains considerable scope to further optimise the framework in future iterations by extending scope of metabolism indicators, in particular water-related nutrient efficiency.

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Table and figure captions

Table 1 – Scenarios

Table 2 – Indicators of urban water metabolism

Table 3 – Water mass balance, before and after development, and for water servicing alternatives

Table 4 – Water-related energy use, before and after development, and for water servicing alternatives

Figure 1 Urban water metabolism evaluation framework.

The framework is a refinement of the urban water mass balance described in Kenway et al. (2011a), to enable evaluation of alternative water sources and water-related energy use.

Figure 2 Structure plan and location of the case study Ripley Valley Urban Development Area.

Reproduced with the permissions of Ipswich City Council (ICC 2009). Ripley Valley is located in South East Queensland, approximately 40km south-west of Brisbane.

Figure 3–Urban water mass balances (maximized scenarios only)

The width of the lines represents the magnitude of the annual flows / fluxes of water (GL/yr) flowing into, out of, and through the urban boundary of the proposed Ripley Valley urban development, (a) before development, (b) after development (b), and (c-f) under alternative water servicing alternatives. Only the maximized scenarios are depicted. In the case of (c) and (e), two separate scenarios are shown in the one diagram, in which case, the two values refer to each scenarios respectively.

a) Pre-development
b) Development base case
c) Rainwater harvesting (in households) / stormwater harvesting (in the urban area)
d) Wastewater recycling (in urban area)
e) Greywater recycling (in household) / Greywater recycling (in appliance)
f) Wastewater recycling (outside urban area)

Figure 4– Indicators of water metabolism

For stormwater and total stream discharge, urbanisation generates flows that are higher than pre-development (>1), so initiatives that reduce the relative flows down towards 1 are preferred. For evapotranspiration and infiltration, urbanisation generates flows that are lower than pre-development (<1), so initiatives that increase the relative flow up towards 1 are preferred.

a) Indicators of resource efficiency

b) indicators of hydrological performance (relative to pre-development state)

Appendix A: Analysis parameters and data sources

Parameter	Unit	Assumed values	Source and comments
Proposed urban development in Ripley Valley			
Total area	ha	4,680	Ripley Valley Development Scheme (ULDA 2011) - Includes urban area and nature reserve.
Total urban development area	ha	3002	(ULDA 2011)
Population	people	120,000	(ULDA 2011) - projection as at 2030.
Dwellings	-	50,000	(ULDA 2011) - projection as at 2030.
Land use types			
Urban core	ha	289.72	(ULDA 2011) - 55 households/ha
Secondary urban core (west)	ha	304.83	(ULDA 2011) -35 households/ha
Secondary urban core (east)	ha	250.48	(ULDA 2011) - 20 households/ha
Neighborhoods	ha	1,156.56	(ULDA 2011) - 15 households/ha
Villages and constrained residential areas	ha	988.29	(ULDA 2011) - 10 households/ha
Rural residential	ha	11.93	(ULDA 2011) - 3 households/ha
Parameters applied in MUSIC to model natural hydrological flows (P, Rs, G and ET)			
Rainfall	mm	1021.6	Time series rainfall data for Brisbane for the period 1 July 2000 to 15 June 2010 was used in the model, based on 6 min intervals. This data was pre-loaded in the MUSIC model, but originated from the Australian Bureau of Meteorology (www.BOM.gov.au). The value provided here is the mean annual rainfall for Brisbane.
Evapotranspiration	mm	66.7	Monthly average evapotranspiration data for Brisbane for the period 1 July 2000 to 15 June 2010 was used in the model, derived from BOM (2006). The value provided here is the annual average.
Soil characteristics			As per Gold Coast City Council's guidelines (GCCC 2006).
Imperviousness factors	%		For the pre-development case, the imperviousness factor was set to 10% giving an annual volumetric runoff coefficient (AVRC) of 0.15 (pers. Com. Tony Weber, May 2015).
• Pre-development		10	
• Urban core		44	
• Secondary urban core west		41	
• Secondary urban core east		38	For post development scenarios, the imperviousness factors from McIntosh et al. (2013) were adopted.
• Neighborhoods		36	
• Villages and constrained residential areas		33	
• Rural residential		24	
Applied irrigation directed to G	%	25	Derived from Chrysoulakis et al. (2015)
Applied irrigation directed to ET	%	75	
Parameters applied to estimate flows managed by the centralized urban water system (C and W)			
Residential water demand	L/p/day	200	Derived from SKM (2013).
Portion of residential water demand that is for conservative sub-potable uses	%	22	Percentage of total demand used for irrigation, toilet flushing and washing machine, based on Beal et al. (2012).
Portion of residential water demand that is for maximised sub-potable uses	%	43	Derived from Beal et al. (2012)
Commercial water demand	kL/ m^2 /yr	3.34	Average annual demand as per the Department of Environment and Heritage (2006) guidelines for mixed office and commercial area.
Total commercial area	ha	34	ICC 2009
Portion of commercial water demand that is for conservative sub-potable uses	%	50	Estimated percentage based on total demand, in the absence of reliable data.
Open space / green area	ha	304.5	(ICC 2009) (this is doubled for maximized case)

Parameter	**Unit**	**Assumed values**	**Source and comments**
Open space water demand	ML/ha/yr	1.8	Open space water use for SEQ estimated by Mitchell et al. (2008).
Water supply leakage rate	%	10	Derived from BOM (2015).
Wastewater generated as a percentage of water use	%	80	The ratio can be 50 - 90% depending upon leakage, lawn irrigation and stormwater infiltration. It was assumed to be 80% as lawn irrigation is modest and being a new planned development, stormwater infiltration is expected to be minor.
Parameters applied to estimate decentralized inflows (D)			
Groundwater withdrawal		0	No groundwater withdrawal.
Roof area for rainwater harvesting – residential	m^2	150	Assumed roof area per residential dwelling.
Roof area for rainwater harvesting – commercial	%	60	Percentage commercial roof area (34 ha) available for harvesting
Maximum roof runoff generated	GL/yr	5.96	Calculated from above values
Volumetric reliability of rainwater tanks	%	29	Umapathi et al. (2012)
Parameters applied to estimate recycled flows (R)			
Greywater generation – residential	%	71	Percent of residential demand (based on Beal et al. (2012) – Bath 31%, Taps 19%, clothes washer 21%)
Greywater generation – commercial	%	25	Assumed, based on minimal bath or clothes washing facilities in commercial buildings.
Maximum greywater generated	GL/yr	6.46	Calculated from above values.
Residential water use for showers	L/p/day	59	Derived from Beal et al. (2012).
Reduction in shower water use with recirculating showers	%	70	Cintep (2012).
Area of irrigated urban agriculture	ha	1,000	Derived from assumed vegetable demand of 375 gm/person as per NHMRC (2013) recommendation, and vegetable production of 15.8 tonnes/ha/yr for SEQ region.
Irrigation water demand for urban agriculture	ML/ha/yr	3.75	Based on water demand for vegetable irrigation in peri-urban areas around Brisbane (Lockyer Valley)
Parameters applied to estimate water-related energy (E)			
Supply of water from Mt Crosby water treatment plant to Ripley Valley	kWh/ML	102	Estimated based on a delivery head presure of 40m, (assuming head loss from 22 km pipeline through hilly terrain, and residual head of 10 m to deliver to local storage tanks), and a pump efficiency of 70%.
Supply of harvested rainwater and recycled wastewater to local users	kWh/ML	68	Estimated based on a delivery head pressure of 30m (transmission pipe losses and residual pressure of 10 m at the farthest property), and a pump efficiency of 70%.
Supply of recycled wastewater to nearby agricultural areas	kWh/ML	85	Estimated based on a delivery head pressure of 35m (same as local supply plus additional loss of 5m due to 4-8km transmission pipeline to agricultural areas).
Stormwater treatment	kWh/ML	78	Based on a pressure sand filtration with pumping head of 20 m, and a pump efficiency of 70%.
Energy consumption in water treatment at Mt Crosby WTP	kWh/ML	301	Kenway et al. (2015)
Retail water distribution	kWh/ML	78	Kenway et al. (2015)
Wastewater treatment to secondary level fit for stream discharge, irrigation and sub-potable use	kWh/ML	587	Kenway et al. (2015)
Greywater treatment and supply at individual household level	kWh/ML	3,512	Memon et al. (2015)
Rainwater supply from storage tanks at	kWh/ML	1,509	Kenway et al. (2015)

‘

Parameter	Unit	Assumed values	Source and comments
individual household level			

Table 1 – Scenarios

Reference cases			
Pre-development	Agricultural landscape with limited paved surfaces and roads, as modelled by McIntosh et al. (2013).		
Developed base case	An urbanised landscape as per the Ripley Valley Development Scheme (ULDA 2011) at 2030 (see Table 2). All water is supplied via the centralized system which supplies treated water from Wivenhoe Dam, 300km NW, via Mt Crosby Water Treatment Plant, outside the urban boundary. There is no supplementary supply of rainwater / stormwater, or recycling of wastewater / greywater. Wastewater generated from all dwellings is treated at a local wastewater treatment plant (WWTP) to secondary level conforming to surface water discharge standards and discharged to the nearby Bundamba Creek.		
Alternative water servicing options	**Urban scale of implementation**	**Conservative implementation**	**Maximised implementation**
Stormwater use	In urban area	Stormwater runoff is harvested from all hard surfaces (roofs, roads, carparks) within the urban boundary. Volume harvested is assumed to be limited by the maximum harvestable volume.[1] Stormwater is treated by sand filtration, and supplied for irrigation within the urban boundary. **10% of maximum harvestable volume** is used to irrigate 304.5 ha designated as **open space** in the planning scheme (parks, sports fields, green corridors, street landscaping etc.).	As per conservative implementation, except that: **97% of maximum harvestable volume** is used to irrigate **open space** within the urban boundary (*304.5 ha*), plus **natural areas** (*300 ha – 10% of total area*) to enhance vegetation, plus **all legal sub-potable demand** in residential and commercial dwellings (garden irrigation, toilet flushing, clothes washing) by ‘third pipe’ supply.
Rainwater use	In household	Rainwater is harvested from the roofs of residential and commercial dwellings in individual tanks. Volume harvested is assumed to be limited by the maximum harvestable volume[1] and the volumetric reliability of the tanks.[2] Water supplied untreated to same property. 100% of harvested volume is used for **some sub-potable demand** (garden irrigation and toilet flushing)	As per conservative implementation, except that: The **volumetric reliability of the tanks[2] is assumed to be large enough to supply maximised sub-potable demand.** 100% of harvested volume is used for **all legal sub-potable demand** in (garden irrigation, toilet flushing, clothes washing)
Wastewater recycling	In urban area	Wastewater from all residential and commercial dwellings (80% of water supply) is treated at a local wastewater treatment plant to secondary level with disinfection suitable for irrigation, stream discharge and sub-potable use. 5% of treated effluent is recycled for irrigation within the urban boundary, in the same way as the conservative stormwater use scenario.	As per conservative implementation, except that: 59% of the treated effluent is used for irrigation, in the same way as the maximised stormwater use scenario.
	Outside urban area	As per wastewater recycling within the urban area, except that treated wastewater is supplied to an adjacent agricultural area, 4-8km W, outside the urban boundary. Used for irrigation of vegetable crops. Volume used is based on that required to grow crops to meet local demand only.	Not applicable
Greywater recycling	In household	Greywater (bathroom wastewater) from residential and commercial dwellings (approximately 70% of total wastewater after Beal et al. (2012) is collected in individual tanks. It is treated using sand filtration and UV disinfection at the property and supplied back to the same property. 34% of total 6.46 GL/yr of generated greywater is used for **some sub-potable demand** in residential and commercial dwellings within the urban boundary (garden irrigation and toilet flushing).	As per conservative implementation, except that: 62% of generated greywater is used for **all legal sub-potable demand** in residential and commercial dwellings within the urban boundary (lawn irrigation and toilet flushing, clothes washing)
	In appliance	Recirculating showers are installed in all residential dwelling to recycle shower water. Water, and electricity for water heating are assumed to be reduced by 70%.	Not applicable

Notes:

1. Maximum harvestable volume is the difference between post-development and pre-development stormwater runoff, to ensure that stormwater runoff exiting the system does not fall below the natural runoff in the pre-development scenario, thus minimizing negative effects of over-harvesting on soil moisture, downstream hydrology / ecology (Fletcher et al. 2007, McIntosh et al. 2013).
2. Volumetric reliability is the ratio of rainwater available from the rainwater tank to the total household water demand (Umapathi et al. 2013)

Table 2 – Indicators of urban water metabolism

	Unit	Description	Equation
Indicators of resource efficiency			
Internal harvesting ratio	-	$\frac{\text{Volume of freshwater harvested internally (within the urban area)}}{\text{Total volume of water supplied to meet demand}}$	$\frac{D}{(\mathrm{C}+\mathrm{D}+\mathrm{Ri})}$
Internal recycling ratio	-	$\frac{\text{Volume of water recycled internally (within the urban area)}}{\text{Total volume of water supplied to meet demand}}$	$\frac{\mathrm{Ri}}{(\mathrm{C}+\mathrm{D}+\mathrm{Ri})}$
Water extracted	kL/person/yr	$\frac{\text{Volume of water extracted from external sources}}{\text{Population of the urban area}}$	$\frac{\mathrm{C}}{\text{Population}}$
Energy used	kWh/person/yr	$\frac{\text{Total water} - \text{related energy use}}{\text{Population of the urban area}}$	$\frac{E_{\mathrm{Tot}}}{\text{Population}}$
Indicators of hydrological performance			
Stormwater runoff ratio	-	$\frac{\text{Post} - \text{development stormwater runoff}}{\text{Pre} - \text{development stormwater runoff}}$	$\frac{\mathrm{Rs}_{\mathrm{x}}}{\mathrm{Rs}_0}$
Total stream discharge ratio	-	$\frac{\text{Post} - \text{development discharge}}{\text{Pre} - \text{development discharge}}$	$\frac{(\mathrm{Rs}+\mathrm{W})_{\mathrm{x}}}{(\mathrm{Rs}+\mathrm{W})_o}$
Infiltration ratio	-	$\frac{\text{Post} - \text{development groundwater infiltrate}}{\text{Pre} - \text{development groundwater infiltrate}}$	$\frac{G_{\mathrm{x}}}{G_{\mathrm{o}}}$
Evapotranspiration ratio	-	$\frac{\text{Post} - \text{development evapotranspiration}}{\text{Pre} - \text{development evapotranspiration}}$	$\frac{\mathrm{ET}_{\mathrm{x}}}{\mathrm{ET}_0}$

Notations: See Section for 2.1 for definitions of acronyms. x = value for post-development scenario, o = value for pre-development

Table 3 – Water mass balance, before and after development, and for water servicing alternatives

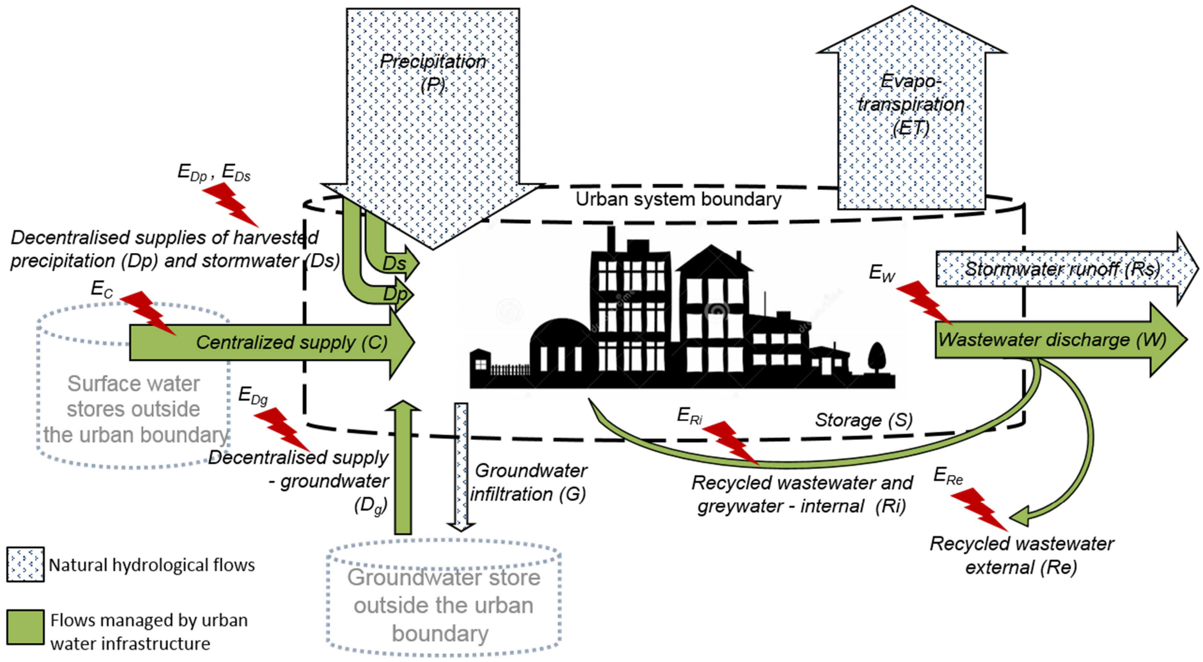
Scenario		**Qi (GL/yr)**			**Qo (GL/yr)**					**Ri**	**ΔS**	**Mass Balance**	
		P'	C	D	ET	Rs	G	W	Re			Qi	Qo +ΔS
Pre-development		23.2	0.0	0.0	16.3	3.7	3.3	0.0	0.0	0.0	-0.1	23.2	23.2
Developed base case		23.2	11.5	0.0	13.6	9.3	2.4	9.2	0.0	0.0	0.2	34.7	34.7
Stormwater use	In urban area												
	Conservative	22.7	11.0	0.6	13.6	8.8	2.4	9.2	0.0	0.0	0.3	34.3	34.3
	Maximised	17.8	6.7	5.4	14.0	3.9	2.5	9.2	0.0	0.0	0.3	29.9	29.9
Rainwater use	In household												
	Conservative	21.5	9.8	1.7	13.6	7.6	2.4	9.2	0.0	0.0	0.2	33.0	33.0
	Maximised	18.9	7.2	4.3	13.6	5.0	2.4	9.2	0.0	0.0	0.2	30.4	30.4
Wastewater recycling	In urban area												
	Conservative	23.2	11.0	0.0	13.6	9.3	2.4	8.7	0.0	0.6	0.2	34.2	34.2
	Maximised	23.2	6.7	0.0	14.0	9.3	2.5	3.8	0.0	5.4	0.3	29.9	29.9
	Outside urban area	23.2	11.5	0.0	13.6	9.3	2.4	5.3	3.9	0.0	0.2	34.7	34.7
Greywater recycling	In household												
	Conservative	23.2	9.3	0.0	13.6	9.3	2.4	7.5	0.0	2.2	-0.3	32.5	32.5
	Maximised	23.2	7.5	0.0	13.6	9.3	2.4	6.0	0.0	4.0	-0.6	30.7	30.7
	In appliance	23.2	11.0	0.0	13.6	9.3	2.4	8.5	0.0	0.9	0.4	34.2	34.2

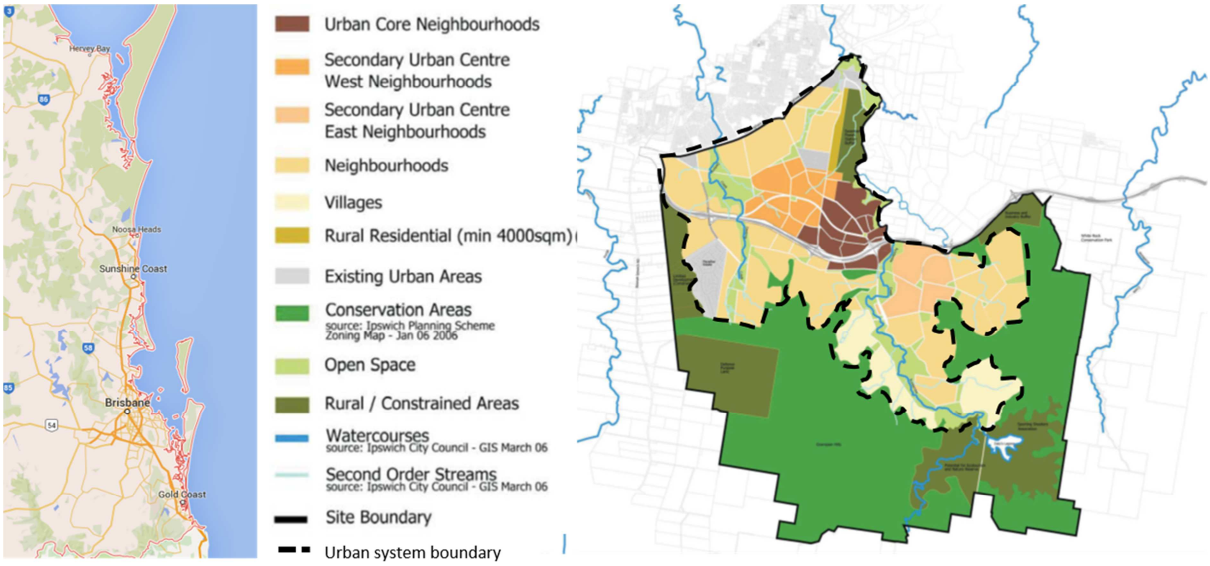
Notations: See Section for 2.1 for definitions of acronyms

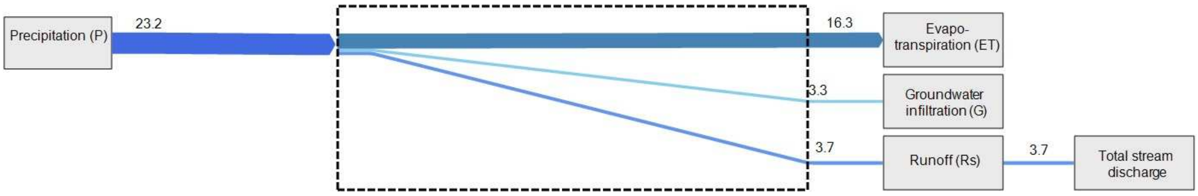
Table 4 – Water-related energy use, before and after development, and for water servicing alternatives

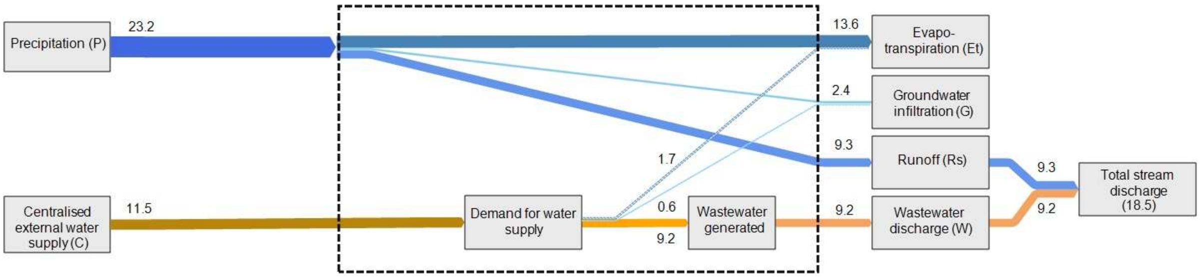
		Water-related energy use (GWh/yr)				
		Treating and supplying centralized water (E_C)	Treating and supplying decentralized and recycled water (E_D, E_R)	Treating and discharging wastewater (E_w)	Change to energy in use phase (ΔE_U)	Total (E_{Tot})
Developed base case		5.9	NA	7.9		13.8
Stormwater use	In urban area					
	Conservative	5.7	0.1	7.9		13.7
	Maximised	3.5	0.9	7.9		12.3
Rainwater use	In household					
	Conservative	5.1	2.6	7.9		15.6
	Maximised	3.7	6.5	7.9		18.1
Wastewater recycling	In urban area					
	Conservative	5.7	0.5	7.5		13.7
	Maximised	3.5	5.2	3.3		12.0
	Outside urban area	5.9	3.8	4.5		14.2
Greywater recycling	In household					
	Conservative	4.8	7.7	6.4		18.9
	Maximised	3.9	14.1	5.1		23.1
	In appliance	5.7	NA	7.3	-389	-376

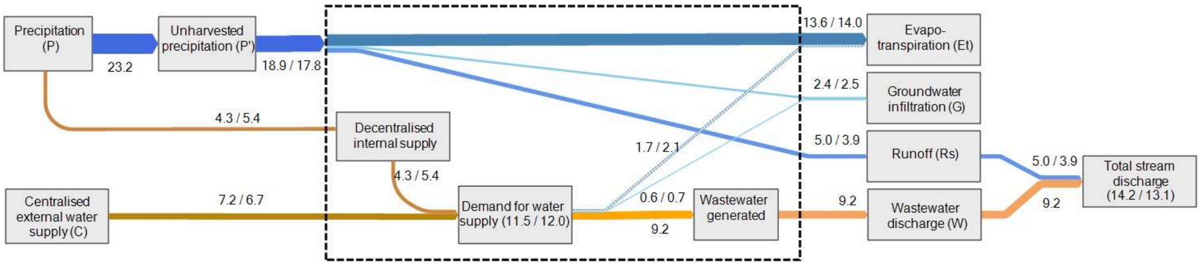
Notations: See Section for 2.1 for definitions of acronyms

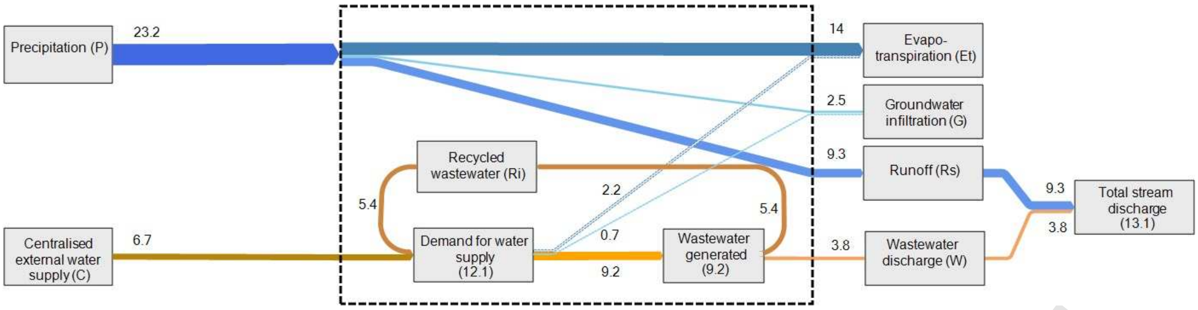

Precipitation (P)
Evapo-transpiration (ET)
E_{Dp}, E_{Ds}
Urban system boundary
Decentralised supplies of harvested precipitation (Dp) and stormwater (Ds)
Ds
Dp
E_C
Centralized supply (C)
Surface water stores outside the urban boundary
E_{Dg}
Decentralised supply - groundwater (D_g)
Groundwater infiltration (G)
Groundwater store outside the urban boundary
E_W
Stormwater runoff (Rs)
Wastewater discharge (W)
E_{Ri}
Storage (S)
Recycled wastewater and greywater - internal (Ri)
E_{Re}
Recycled wastewater external (Re)
Natural hydrological flows
Flows managed by urban water infrastructure

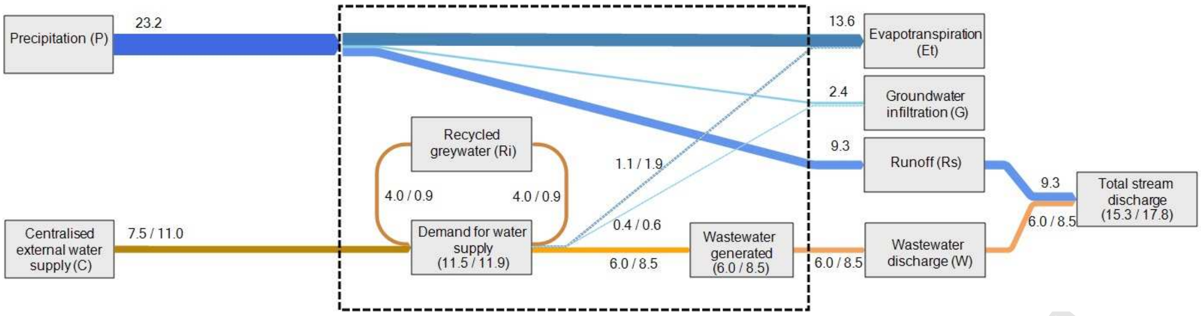

Hervey Bay
Noosa Heads
Sunshine Coast
Brisbane
Gold Coast
Urban Core Neighbourhoods
Secondary Urban Centre West Neighbourhoods
Secondary Urban Centre East Neighbourhoods
Neighbourhoods
Villages
Rural Residential (min 4000sqm)
Existing Urban Areas
Conservation Areas
source: Ipswich Planning Scheme Zoning Map - Jan 06 2006
Open Space
Rural / Constrained Areas
Watercourses
source: Ipswich City Council - GIS March 06
Second Order Streams
source: Ipswich City Council - GIS March 06
Site Boundary
Urban system boundary

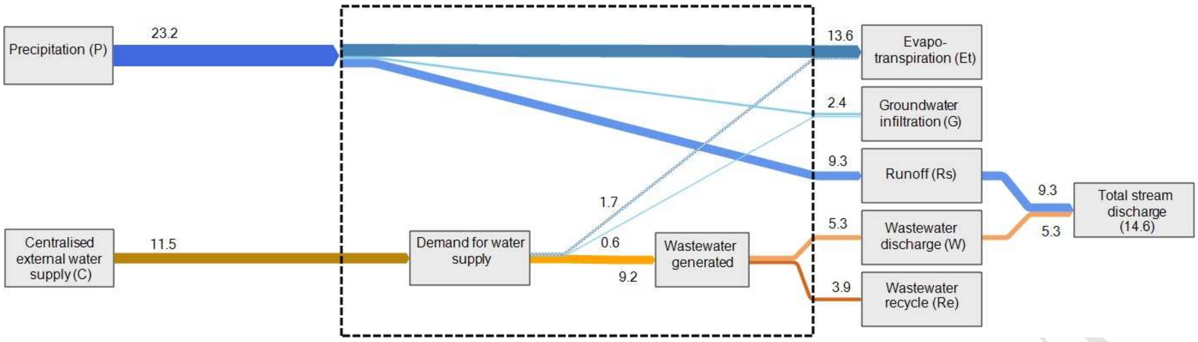

Precipitation (P)
23.2
16.3
Evapo-
transpiration (ET)
3.3
Groundwater
infiltration (G)
3.7
Runoff (Rs)
3.7
Total stream
discharge

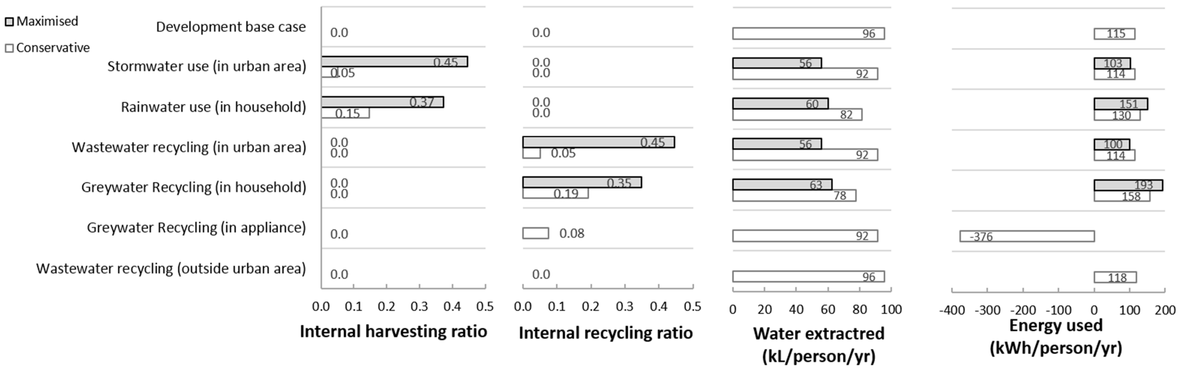

Precipitation (P)
23.2
Centralised external water supply (C)
11.5
Demand for water supply
1.7
0.6
9.2
Wastewater generated
13.6
Evapo-transpiration (Et)
2.4
Groundwater infiltration (G)
9.3
Runoff (Rs)
9.2
Wastewater discharge (W)
9.3
9.2
Total stream discharge (18.5)

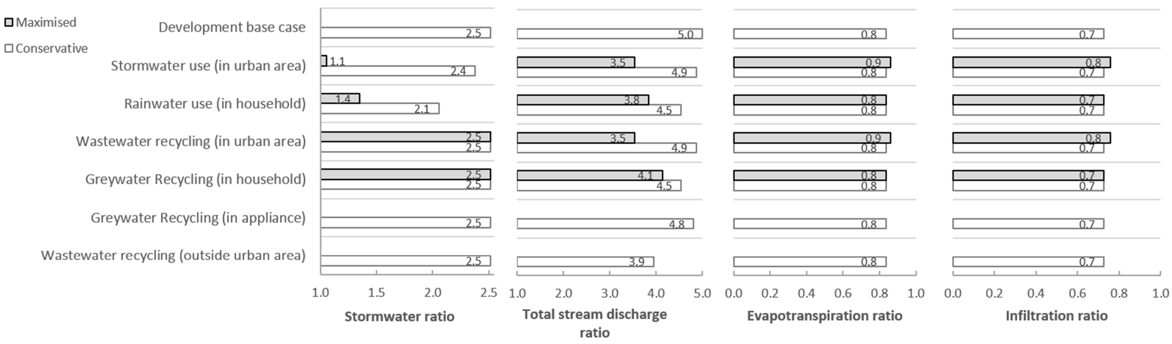

Precipitation (P)
23.2
Unharvested precipitation (P')
18.9 / 17.8
4.3 / 5.4
Decentralised internal supply
4.3 / 5.4
Centralised external water supply (C)
7.2 / 6.7
Demand for water supply (11.5 / 12.0)
1.7 / 2.1
0.6 / 0.7
9.2
Wastewater generated
13.6 / 14.0
Evapo-transpiration (Et)
2.4 / 2.5
Groundwater infiltration (G)
5.0 / 3.9
Runoff (Rs)
9.2
Wastewater discharge (W)
5.0 / 3.9
9.2
Total stream discharge (14.2 / 13.1)


Precipitation (P)
23.2
Centralised external water supply (C)
6.7
Recycled wastewater (Ri)
5.4
Demand for water supply (12.1)
2.2
0.7
9.2
Wastewater generated (9.2)
5.4
14
Evapo-transpiration (Et)
2.5
Groundwater infiltration (G)
9.3
Runoff (Rs)
3.8
Wastewater discharge (W)
9.3
3.8
Total stream discharge (13.1)


Precipitation (P)
23.2
Centralised external water supply (C)
7.5 / 11.0
Recycled greywater (Ri)
4.0 / 0.9
4.0 / 0.9
Demand for water supply (11.5 / 11.9)
1.1 / 1.9
0.4 / 0.6
6.0 / 8.5
Wastewater generated (6.0 / 8.5)
13.6
Evapotranspiration (Et)
2.4
Groundwater infiltration (G)
9.3
Runoff (Rs)
6.0 / 8.5
Wastewater discharge (W)
9.3
6.0 / 8.5
Total stream discharge (15.3 / 17.8)


Precipitation (P)
23.2
13.6
Evapo-transpiration (Et)
2.4
Groundwater infiltration (G)
9.3
Runoff (Rs)
9.3
Total stream discharge (14.6)
5.3
1.7
Centralised external water supply (C)
11.5
Demand for water supply
0.6
9.2
Wastewater generated
5.3
Wastewater discharge (W)
3.9
Wastewater recycle (Re)


Maximised
Conservative
Development base case
Stormwater use (in urban area)
Rainwater use (in household)
Wastewater recycling (in urban area)
Greywater Recycling (in household)
Greywater Recycling (in appliance)
Wastewater recycling (outside urban area)
0.0
0.45
0.05
0.37
0.15
0.0
0.0
0.0
0.0
0.0
0.0
0.0
0.0 0.1 0.2 0.3 0.4 0.5
Internal harvesting ratio
0.0
0.0
0.0
0.0
0.0
0.45
0.05
0.35
0.19
0.08
0.0
0.0 0.1 0.2 0.3 0.4 0.5
Internal recycling ratio
96
56
92
60
82
56
92
63
78
92
96
0 20 40 60 80 100
Water extractred (kL/person/yr)
115
103
114
151
130
100
114
193
158
-376
118
-400 -300 -200 -100 0 100 200
Energy used (kWh/person/yr)


Maximised
Conservative
Development base case
Stormwater use (in urban area)
Rainwater use (in household)
Wastewater recycling (in urban area)
Greywater Recycling (in household)
Greywater Recycling (in appliance)
Wastewater recycling (outside urban area)
2.5
1.1
2.4
1.4
2.1
2.5
2.5
2.5
2.5
2.5
2.5
1.0 1.5 2.0 2.5
Stormwater ratio
5.0
3.5
4.9
3.8
4.5
3.5
4.9
4.1
4.5
4.8
3.9
1.0 2.0 3.0 4.0 5.0
Total stream discharge ratio
0.8
0.9
0.8
0.8
0.8
0.9
0.8
0.8
0.8
0.8
0.8
0.0 0.2 0.4 0.6 0.8 1.0
Evapotranspiration ratio
0.7
0.8
0.7
0.7
0.7
0.8
0.7
0.7
0.7
0.7
0.7
0.0 0.2 0.4 0.6 0.8 1.0
Infiltration ratio

Highlights

A water mass balance that brings together both ‘natural’ and ‘anthropogenic’ urban water cycles

New ‘water metabolism’ indicators of ‘resource efficiency’ and ‘hydrological performance’

Insights about alternative water servicing options to support the holistic decision making