Analysing water sensitive urban design options

Using water mass balance to analyse hydrological performance of water sensitive urban design options in infill development

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ABSTRACT

Planning for 'water-sensitive' infill development has become a priority for sustainable urban development in Australia. With city growth, infill development in vacant or under-used land parcels is becoming a dominant mode of development. However, the current 'knock-down-rebuild' approach to such development will undermine resource efficiency, liveability and urban amenity, particularly for natural water systems. There is a need to identify development options that are more water sensitive. To better analyse water efficiency and hydrological performance of Water Sensitive Urban Design (WSUD) options, we use a water mass balance evaluation framework to demonstrate the 'whole of water cycle' approach. The new insights gained were the extent to which the proposed WSUD options impact the water metabolism performance of the urban area through modelling the water mass balance of eight selected WSUD options within different scenarios, involving pre-development (1825), current (2016), before and after water-sensitive options in 2031. The novel contribution is the development of one new hydrological performance indicator, open space ratio and redeveloped other four water metabolism indicators to assess water performance in infill development. Results show that urbanisation dramatically altered the water flows, like stormwater runoff. Also, road space plays an important role in future solutions.

Keywords: hydrological performance, water mass balance, urban metabolism evaluation framework for water, water sensitive urban design, infill development, water sensitive city

INTRODUCTION

Growing population and urbanisation change water flows due to the creation of impervious hard surfaces, removal of endemic plants, changes in land use, alteration of water use and introduction of water-based recreation (Cosgrove & Rijsberman, 2014; Loucks & Beek, 2017). These activities lead to a massive and comprehensive change of the hydrological system across a range of spatial scales. For example, in most of the watershed studies, stormwater runoff and sedimentation rapidly increase with urbanisation (Meyer & Turner, 1992; Booth & Jackson, 2007; Novotny, et al., 2010). Increased stormwater runoff has direct effect on a range of issues, such as a crisis of water quality (Astaraie-Imani, et al., 2012), sedimentation and erosion issues (Nie, et al., 2011), risk of flooding (Wahl & Plant, 2015; Raadgever & Hegger, 2018), waterborne diseases (Hunter, et al., 2001), pollution of underground water (Lenny, et al., 2011), aquatic species issues (Quattro, et al., 2002) and acidification of water bodies (Grunewald & Schoenheinz, 2014).

To alleviate the pressures from these 'business-as-usual' (BAU) developments, in many existing urban areas, particularly those where rainfall is extremely uneven, development with water sensitive urban planning and resources management has been introduced (Queensland Government, 2017). In fact, developing water-sensitive designs for infill development is an 'urgent task' for South East Queensland (SEQ) as larger numbers of redevelopment projects are currently using a 'knock-down-rebuild' approach (Queensland Government, 2017). To better manage WSUD options, we look forward to a new

'whole of water cycle' approach to assess the hydrological performance of infill development in the case study area, Norman Creek catchment. This new way for water evaluation may assist stormwater management approaches in Australia, and particularly Brisbane.

Water sensitive urban design (WSUD)

WSUD options include sustainable technologies in water management; new technologies in the anthropogenic hydrological flow recycling; new architectural designs in land use; and new designs in natural hydrological flow harvesting (Payne, et al., 2015). Rainwater collection and reuse is recognised as one of the most effective ways to reduce stormwater runoff and pollution at an affordable cost (Imteaz, et al., 2011). Similarly, wastewater recycling is another pathway to reduce the wastewater discharge. Additionally, with the development of new sustainable technologies, many WSUD projects can be applied in city development to alter the impervious fraction through new architectural designs, such as green roofs, green fences, horticulture gardens, shared gardens and linear parks (Engelman, 2013; Payne, et al., 2015).

Overall, these WSUD applications can: reduce the volume and peak flow; increase evapotranspiration and infiltration; decrease imperviousness ratio; improve stormwater runoff quality; convert some pollutants into inert substances; add to neighbourhood aesthetics; improve land value; recover biodiversity; and supply an alternative and local water source (Payne, et al., 2015). This paper will examine eight different WSUD options in a semi-hypothetical catchment-scale urban area – Norman Creek, Brisbane.

Urban mass balance and UMEF4Water

An urban water mass balance is a comprehensive account involving all water inputs, outputs, and storages, such as precipitation, centralised supply, evapotranspiration, stormwater runoff, wastewater discharge, groundwater infiltration and storage (Kenway, et al., 2011). Moreover, Kenway, et al. (2011) pioneered the use of urban water mass balance for metabolism evaluation by using it to evaluate a city's water characteristics. Researchers have since applied this innovative approach in other case studies (Marteleira, et al., 2014; Farooqui, et al., 2016).

In fact, there are two different opinions in the water mass balance establishment; the first approach can be applied to water supply infrastructure to inform design so that supply matches demand (Bach, et al., 2014). The second concentrates on hydrological catchments to understand the influence of urbanisation on natural hydrological flow

(Haase, 2009). Based on these two opinions, Kenway, et al. (2011) developed the urban metabolism system to study 'anthropogenic' hydrological and 'natural' flows at the same time, and also highlighted that water resources management needs to treat 'cities as catchments'.

Additionally, Urban Metabolism Evaluation Framework for Water (UMEF4Water) is a new framework system to assess hydrological performance in an urban area as a whole, rather than individual components of the water budget within an urban area. Generally, there are four steps in this evaluation framework, involving: defining the urban boundary; collecting data about water inflows and outflows; generating a water mass balance; and assessing water metabolic performance of an urban area through indicators (Renouf, et al., 2016).

METHOD

To test the utility of the urban water metabolism evaluation framework in the infill development, in this paper we will: 1) model water performance (water mass balance) with different WSUD scenarios; and 2) assess the hydrological performance of each option and analyse how they mitigate high volume runoff and spatial variation. This will involve:

- Defining WSUD scenarios (Table 1).
- Generating a water mass balance.
- Assessing water metabolic performance through indicators.

We selected Norman Creek catchment (South East Queensland, Australia) as the study area. The catchment was surveyed and named by Edmond Lockyer in 1825, and at that time was almost impenetrable (BCC, 2010a). This catchment has an area of about 3,038ha, runs through 23 suburbs and contains 90,000 residents (BCC, 2010b). Urbanisation has reshaped the land use and the relationship between residents and the local waterways, causing high pollutant runoff, overland flow flooding, water shortages and reduced liveability.

In this project, the hydrological flows in the Norman Creek catchment under different scenarios were calculated based on the rainfall-runoff modelling algorithm of MUSIC (Model for Urban Stormwater Improvement Conceptualisation) (Water by Design, 2010; CRCWSC, 2018), which is a model commonly used for stormwater infrastructure design (Elliott & Trowsdale, 2007). Cadastral and land use information about the Norman Creek catchment was collected from the previous research including thirteen subsystems and roof,

car park, driveway, amenity area, open space, and road for four selected subsystems (Appendix A and B). We hypothesised that WSUD projects may influence the hydrological performance of the whole catchment due to change of imperviousness for each subsystem.

Defining WSUD scenarios

The Norman Creek catchment has high volume runoff and spatial variation. In response to these issues, this catchment requires appropriate water-sensitive designs to restore water flows. This will involve an assessment of:

1. Planning guidelines: Both state planning policies (Shaping SEQ Strategy) and Brisbane City Council (BCC) planning scheme support the application of water sensitive approaches to future infill development, Brisbane City Sharp 2026 (2006) highlighted that green

roofs, shared and community gardens, wastewater recycling, stormwater collection from the road will be encouraged to be implemented (Queensland Government, 2017).

2. Technical evaluation: An evaluation of design options to determine a solution that will increase evapotranspiration and groundwater infiltration; decrease stormwater runoff; and reduce the potable water demand in the city (Engelman, 2013; Payne, et al., 2015).

3. Past examples of WSUD cases in Australia: Horticulture and shared gardens applied in Brisbane (Guitart, et al., 2014); green roof cases implemented in Melbourne and Adelaide (Victorian Government, 2014); grasscrete has been applied in Brisbane and many areas in Australia (BCC, 2006).
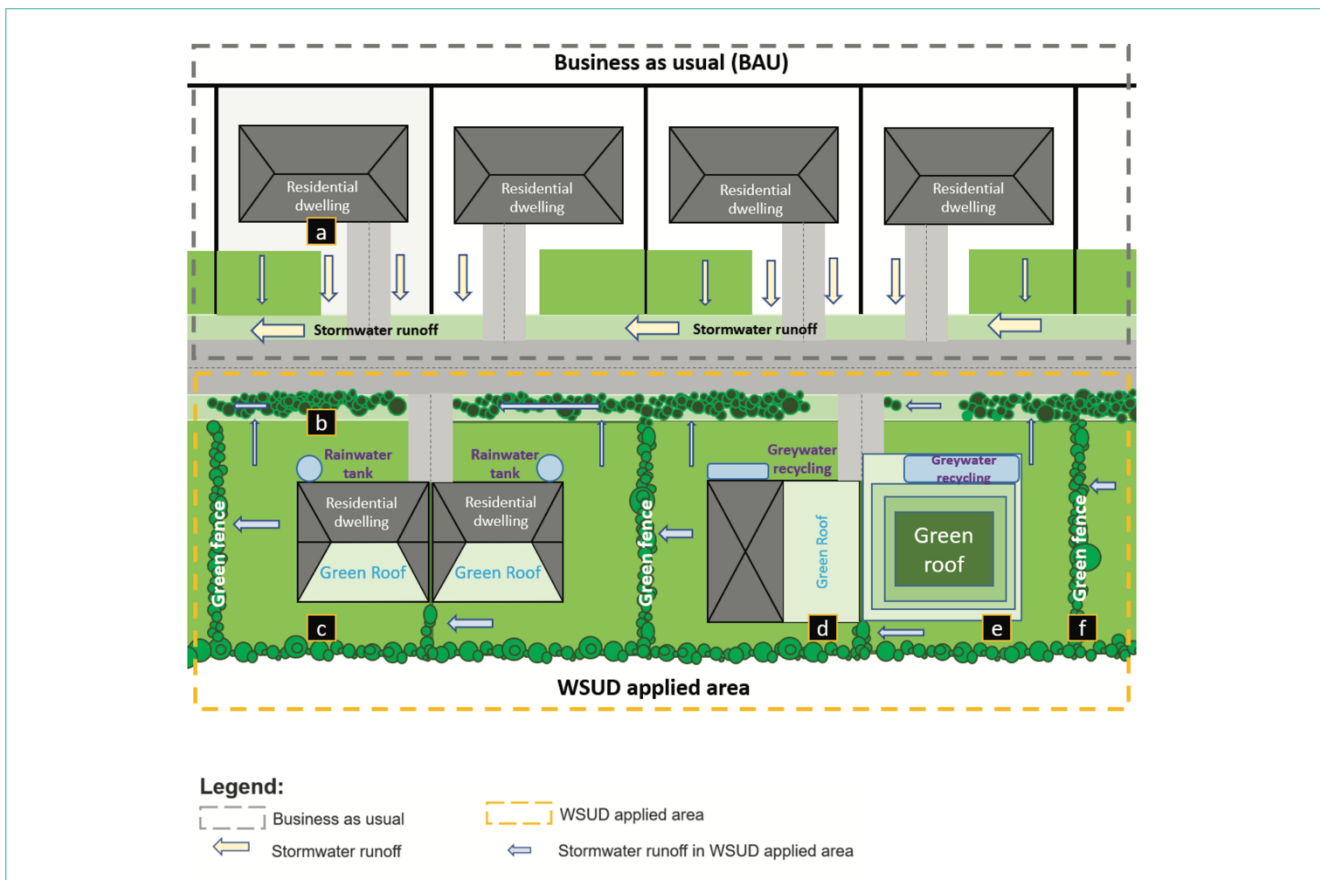

Figure 1: (a) traditional residential dwelling, (b) linear park/garden with WSUD functions, (c) New residential dwelling with green roof, (d) new apartment with green roof, (e) new commercial building with green roof (grass roof), (f) green fence.

Assumptions of WSUD options

For this study, we have adopted two WSUD scenarios, a conservative implementation and a maximised implementation case as well as the business as usual (BAU) scenario (Figure 1). The details are set out in Table 1.

Table 1: **WSUD scenarios in 2031**

Alternative infill development options applied separately in Norman Creek (2031)	Conservative implementation (C)	Maximised implementation (M) (In addition to the conservative implementation)
1. Rainwater reuse	C1. Assumed to install 6,107 new rainwater tanks, over half will be plumbed into dwellings to replace centralised water.	M1. Assumed to install 12,214 new rainwater tanks.
2. Greywater recycling	C2. Assumed 70% of wastewater is greywater, and its quality will be improved by water treatment technology (Beal, et al., 2012). 10% of the total generated greywater is recycled and used for sub-potable demand in residential and warehouse dwellings.	M2. Assumed 30% of the total generated greywater is recycled for non-potable demand in residential and warehouse dwellings.
3. Green roof (grass roof)	C3. Assumed 10% of single residential, medium residential and warehouse dwellings will install a green roof, and in a single building, 30% of the roof will be replaced by a green roof.	M3. Assumed 30% of residential and commercial dwellings will install a green roof.
4. Green fence to replace the traditional solid fence	C4. Assumed 10% of single residential, medium residential and warehouse dwellings will install a green fence, and 100% of fence replaced by the green fence in a single building.	M4. Assumed 30% of single residential, medium residential and warehouse dwellings will install a green fence.
5. Horticulture garden	C5. Assumed 20% of single residential dwellings will keep single car park and driveway, and 50% of the car park and driveway area in one dwelling will be replaced by horticulture gardens or suitable WSUD applications, such as bio-filtration system in the single residential dwelling area.	M5. Assumed 50% of single residential dwellings will change the current car park and driveway use.

6. Shared garden	C6. Assumed 20% of medium residential and warehouse dwellings will build shared gardens in the previous car park area, and 50% of car park and driveway will be replaced by the shared gardens in one dwelling.	M6. Assumed 50% of warehouse and medium residential dwellings will install permeable pavement.
7. Grasscrete in amenity area	C7. Assumed 20% of single residential dwellings will install permeable pavement with vegetation in the amenity area, and 100% of amenity area will be replaced by grasscrete.	M7. Assumed 50% of single residential dwelling will apply grasscrete to replace traditional material.
8. Linear park in the road and intersection area	C8. Assumed 10% of road and intersection area will build the linear park, such as subtropical boulevards and neighbourhood shadeways (Engelman, 2013).	M8. Assumed 30% of road and intersection will be replaced by a new linear park.

Generate water mass balance

After having selected the design scenarios, the second step is to generate a water mass balance for each scenario, the pre-development year 1825[1], the current year 2016[2], future year (BAU) 2031[3], and hypothetical water sensitive interventions in 2031. Water mass balance is an equation used to describe the water flows into and out of the system. From a hydrological perspective, it represents the sum of water inflows equalling water outflows and the change in storage. To address limitations in the traditional balance equation, there are some new water flows to be identified, such as water from recycling and precipitation harvesting.

The water metabolism evaluation framework (Figure 2) is developed from the water mass balance, treating an urban area as a whole (Kenway, et al., 2011). The water system developed for this work quantified 'anthropogenic' fluxes, including decentralised supplies of harvested precipitation (D), centralised supply (C), wastewater discharge (W), greywater recycling (R) and 'natural' flows, involving precipitation (P), groundwater infiltration (GI), evapotranspiration (ET) and stormwater runoff (Rs) (refer to Equation 1).

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[1] Pre-development: Edmond Lockyer had first time marked and named Norman Creek in 1825, at that time Norman Creek was almost impenetrable.
[2] Current: approximation of current conditions based on 2016 data, with rainwater tank data from 2013.

[3] Future: The information about the future is based on Brisbane, including Clean, Green, Sustainable 2017-2031, Norman Creek Master Plan 2012-2031, and population and dwellings data from BCC.
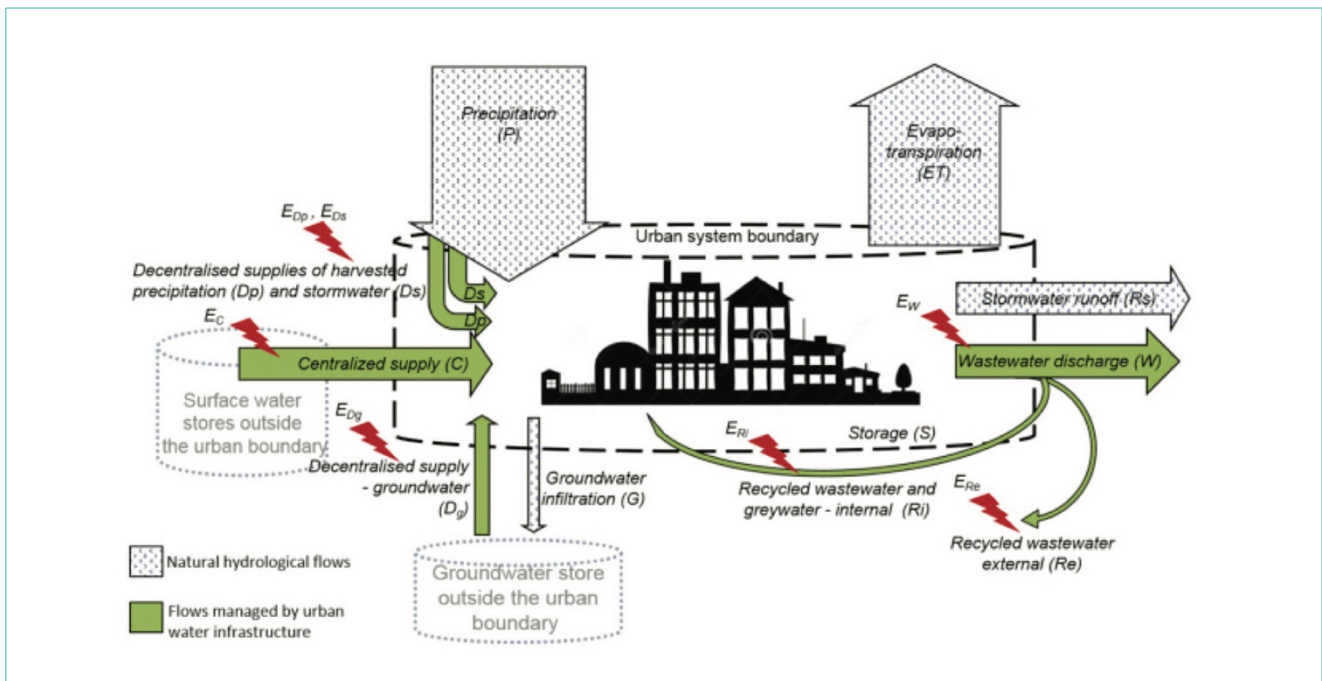
Figure 2: Urban water metabolism evaluation framework (Renouf, et al., 2016). The framework is a refinement of the urban water mass balance described in Kenway et al. (2011)

Equation 1: Input and output about water account

Input (Qi) = Output (Qo) + ΔS

Input (Qi) = (P' + C + D + R) and Output (Qo) + ΔS = (ET + Rs + W+ GI + R) + ΔS

Where:

P=precipitation falling (P' = unharvested precipitation)

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

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

ET=evapotranspiration from the study site boundary

Rs=stormwater run-off discharged from the study area 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)

GI=groundwater infiltration

R=reuse/recycling of wastewater within the urban boundary

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

In this research paper, the after-development introduces two water flows to the pre-development water system, including centralised water supply (C) and wastewater discharge (W). After that, there are two new flows that are added to the refined model. One is rainwater harvesting (D) from WSUD Option 1 rainwater reuse; precipitation (P) in this study is separated into unharvested precipitation (P') and rainwater harvesting (D). The other flow is greywater recycling (W) from WSUD Option 2 greywater recycling, which is flowing out of the system and re-entering after treatment as a new input. Around 70% of wastewater is greywater (Farooqui, et al., 2016).

Assess water metabolic performance

The last step of water evaluation framework in infill development is to assess the water metabolism performance through UMEF4Water indicators. Based on the previous water metabolism studies from Renouf et al. (2016), we had developed a total of eight water metabolism indicators to assess the hydrological performance of infill development options at the study site. In Table 2, these indicators are categorised into two groups: resource efficiency and hydrological performance.

Indicators of resource efficiency

Water extracted is an existing UMEF4Water indicator, concerning water efficiency which is used to assess water usage before and after water-sensitive options. Some researchers define the water efficiency to include both direct and indirect use, where direct use considers the local environment only, while indirect use involves global supplies (Huang, et al., 2013). In this study, water efficiency focuses on direct water used locally and uses indicator 'water extracted' to represent the overall efficiency of water. The second and third indicators from UMEF4Water are used to evaluate harvested stormwater and recycled wastewater in this work. They are internal harvesting ratio and internal recycling ratio respectively.

WSUD indicators of hydrological performance

The last is a set of five indicators, four of them are redeveloped from previous UMEF4Water research, including stormwater runoff, total stream discharge, infiltration, and evapotranspiration ratio (Farooqui, et al., 2016). The fifth is a new indicator, 'open space ratio'. These five indicators for the first time are used to assess infill development projects for water resources protection and hydrological flows restoration (Table 2). Moreover, the open space ratio is a practicable indicator introduced to assess water restoring in infill development, because it is readily available with access to data concerning open space.

Table 2: Infill development indicators and equations developed by Kenway, et al. (2011), Renouf, et al. (2016), and Farooqui, et al. (2016)

Water metabolism indicators	Description	Equation	Performance target
I. Indicators of resource efficiency			
Water extracted	$\dfrac{\text{Volume of water extracted from external sources}}{\text{Population of the urban area}}$	$\dfrac{C}{\text{Population}}$	Smaller is better
Internal harvesting ratio	$\dfrac{\text{Volume of freshwater harvested internally}}{\text{Total volume of water supplied to meet demand}}$	$\dfrac{D}{C + D + R}$	Higher is better
Internal recycling ratio	$\dfrac{\text{Volume of water recycled internally}}{\text{Total volume of water supplied to meet demand}}$	$\dfrac{R}{C + D + R}$	Higher is better

II. WSUD Indicators of hydrological performance[4]

Stormwater runoff ratio	$\dfrac{\text{WSUD case stormwater runoff}}{\text{Base case stormwater runoff}}$	$\dfrac{\text{Rsx}}{\text{Rs0}}$	Depends on the base case, if the base case is pre-development, higher is better; if the base year is BAU, lower is better.
Total stream discharge ratio	$\dfrac{\text{WSUD case total stream discharge}}{\text{Base case total stream discharge}}$	$\dfrac{(\text{Rs} + \text{W})\text{x}}{(\text{RS} + \text{W})0}$	
Infiltration ratio	$\dfrac{\text{WSUD case groundwater infiltration}}{\text{Base case groundwater infiltration}}$	$\dfrac{\text{GIx}}{\text{GI0}}$	Higher is better
Evapotranspiration ratio	$\dfrac{\text{WSUD case evapotranspiration}}{\text{Base case evapotranspiration}}$	$\dfrac{\text{ETx}}{\text{ET0}}$	Higher is better
Open space ratio	$\dfrac{\text{WSUD case open space}}{\text{Base case open space}}$	$\dfrac{\text{OSx}}{\text{OS0}}$	Higher is better

C: centralised water supply, D: decentralised water supply, R: reuse of wastewater, Rs: stormwater runoff

RESULTS AND DISCUSSION

The results from the following Table 3 and two figures (Figure 3 and 4) show that BAU will maintain the study site as a 'typical' infill development scenario, with higher imperviousness, more runoff, less evapotranspiration and less infiltration, compared to current hydrological performance in the Norman Creek. Moreover, the benefit is that the WSUD can help alleviate negative impacts of typical infill development, and especially demonstrate that:

- Hydrology and stormwater runoff can change due to development;
- Road space is a large part of the future solution; and
- How the 'whole of water cycle' method is applied in the infill development context.

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[4] WSUD case means the future case with WSUD options, the options can be the single, mixed or aggregated. Base case means the case without WSUD options, in this research paper, including year 1825 (pre-development) and 2031 BAU only.

Table 3: Norman Creek catchment water mass balance and metabolism indicators within separated WSUD options in the average year (base year - 2031)[5] relative to the base case for the 17 scenarios

Separated WSUD options within different scale implementation: Conservative (C); Maximised (M):		Imperviousness (%)	Water Mass balance											
			Qi (GL/yr)			Qo (GL/yr)				R	ΔS	Qi	Qo+ ΔS
			P'	D	C	ET	Rs	GI	W				
Base case (BAU) 2031		67.3	34.8	0.4	8.8	9.5	23.8	1.2	9.5	0	0	44.0	44.0
1.Rainwater reuse	C1	67.3	34.4	0.8	8.4	9.5	23.4	1.2	9.5	0	0	43.6	43.6
	M1	67.3	34.0	1.2	8.0	9.5	23.0	1.2	9.5	0	0	43.2	43.2
2.Greywater recycling	C2	67.3	34.8	0.4	8.1	9.5	23.8	1.2	8.8	0.7	0	43.3	43.3
	M2	67.3	34.8	0.4	6.7	9.5	23.8	1.2	7.4	2.1	0	41.9	41.9
3.Green roof (grass roof)	C3	66.6	34.8	0.4	8.8	9.6	23.6	1.2	9.5	0	0	44.0	44.0
	M3	65.7	34.8	0.4	8.8	9.9	23.4	1.2	9.5	0	0	44.0	44.0
4.Green fence	C4	67.1	34.8	0.4	8.8	9.6	23.7	1.2	9.5	0	0	44.0	44.0
	M4	66.6	34.8	0.4	8.8	9.6	23.6	1.2	9.5	0	0	44.0	44.0
5.Horticulture garden	C5	67.3	34.8	0.4	8.8	9.5	23.8	1.2	9.5	0	0	44.0	44.0
	M5	66.2	34.8	0.4	8.8	9.7	23.5	1.3	9.5	0	0	44.0	44.0
6. Shared garden	C6	66.6	34.8	0.4	8.8	9.6	23.6	1.2	9.5	0	0	44.0	44.0
	M6	65.1	34.8	0.4	8.8	10.0	23.2	1.3	9.5	0	0	44.0	44.0
7.Grasscrete (s/dwelling)	C7	66.6	34.8	0.4	8.8	9.6	23.6	1.2	9.5	0	0	44.0	44.0
	M7	65.8	34.8	0.4	8.8	9.8	23.4	1.3	9.5	0	0	44.0	44.0
8.Linear park	C8	65.5	34.8	0.4	8.8	9.9	23.3	1.3	9.5	0	0	44.0	44.0
	M8	61.4	34.8	0.4	8.8	10.8	22.3	1.4	9.5	0	0	44.0	44.0

Separated WSUD options within different scale implementation: Conservative (C); Maximised (M):		Water metabolism indicators							
		I. Resource efficiency			II. Protecting water resources and hydrological flows				
		I/harvesting	I/recycling	W/extracted	Rs ratio	TSD ratio	GI ratio	ET ratio	OS ratio
Base case (BAU) 2031		4%	0%	84	100%	100%	100%	100%	100%
1.Rainwater reuse	C1	8%	0%	81	98%	99%	100%	100%	100%
	M1	13%	0%	77	97%	98%	100%	100%	100%
2.Greywater recycling	C2	4%	7%	78	100%	97%	100%	100%	100%
	M2	4%	22%	65	100%	93%	100%	100%	100%
3.Green roof (grass roof)	C3	4%	0%	84	99%	99%	101%	102%	103%
	M3	4%	0%	84	98%	98%	103%	105%	110%
4.Green fence	C4	4%	0%	84	99%	99%	100%	101%	101%
	M4	4%	0%	84	99%	99%	102%	102%	103%
5.Horticulture garden	C5	4%	0%	84	99%	99%	101%	100%	106%
	M5	4%	0%	84	98%	99%	104%	102%	114%
6. Shared garden	C6	4%	0%	84	99%	99%	103%	102%	102%
	M6	4%	0%	84	98%	98%	107%	105%	105%
7.Grasscrete (s/dwelling)	C7	4%	0%	84	99%	99%	103%	102%	105%
	M7	4%	0%	84	98%	98%	105%	104%	112%
8.Linear park	C8	4%	0%	84	98%	98%	106%	104%	110%
	M8	4%	0%	84	93%	95%	119%	114%	130%

[5] In this table, base case is BAU in 2031. Acronyms for water flows and indicators: P': unharvested precipitation, D: decentralised water supply, C: centralised water supply, ET: evapotranspiration, Rs: stormwater runoff, GI: groundwater infiltration, W: wastewater discharge, R: recycled greywater, ΔS: storage water, I/harvesting: internal harvesting, I/recycling: internal recycling, W/extracted: water extracted (KL/p/yr), TSD: total stream discharge, OS: open space.

Table 4: Norman Creek catchment water mass balance and metabolism indicators before and after aggregated WSUD options (base year - 1825) [6]

Norman Creek Catchment BAU; Conservative (C) or Maximised (M) implementation (ten-year average rainfall 1,159mm/y)		I (%)	Mass balance							R	ΔS	Qi	Qo+ ΔS
			Qi(GL/yr)			Qo(GL/yr)							
			P'	D	C	ET	Rs	GI	W				
Base case pre-development (1825)		0	35.2	0	0	25.1	6.2	3.9	0	0	0	35.2	35.2
Current case (2016)		67.2	34.8	0.4	7.5	9.6	23.7	1.2	8.2	0	0	42.7	42.7
Business-As-Usual (2031)		67.3	34.8	0.4	8.8	9.5	23.8	1.2	9.5	0	0	44.0	44.0
Aggregated of all options (2031):	C	62.5	34.4	0.8	7.7	10.8	22.2	1.5	8.4	0.7	0	42.9	42.9
	M	53.9	34.0	1.2	5.8	12.9	19.5	2.1	6.5	2.1	0	41.0	41.0

Norman Creek Catchment BAU; Conservative (C) or Maximised (M) implementation (ten-year average rainfall 1,159mm/y)		Water metabolism indicators							
		I. Resource efficiency			II. Protecting water resources and hydrological flows				
		I/harvesting	I/recycling	W/extracted	Rs ratio	TSD ratio	GI ratio	ET ratio	OS ratio
Base case pre-development (1825)		0	0	0	100%	100%	100%	100%	100%
Current case (2016)		5%	0%	84	384%	497%	31%	38%	27%
Business-As-Usual (2031)		4%	0%	84	384%	537%	31%	37%	27%
Aggregated of all options (2031):	C	8%	8%	74	358%	494%	40%	43%	30%
	M	14%	23%	56	314%	420%	55%	51%	43%

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[6] I: imperviousness C: conservative, M: maximised.
Acronyms for water flows and indicators: Qi: input, Qo: output, ΔS: storage, P: precipitation, D: decentralised water supply, C: centralised water supply, ET: evapotranspiration, Rs: stormwater runoff, GI: groundwater infiltration, W: collected wastewater, R: recycled wastewater, I/harvesting: internal harvesting, I/recycling: internal recycling, W/extracted: water extracted (KL/p/yr), TSD: total stream discharge, OS: open space.
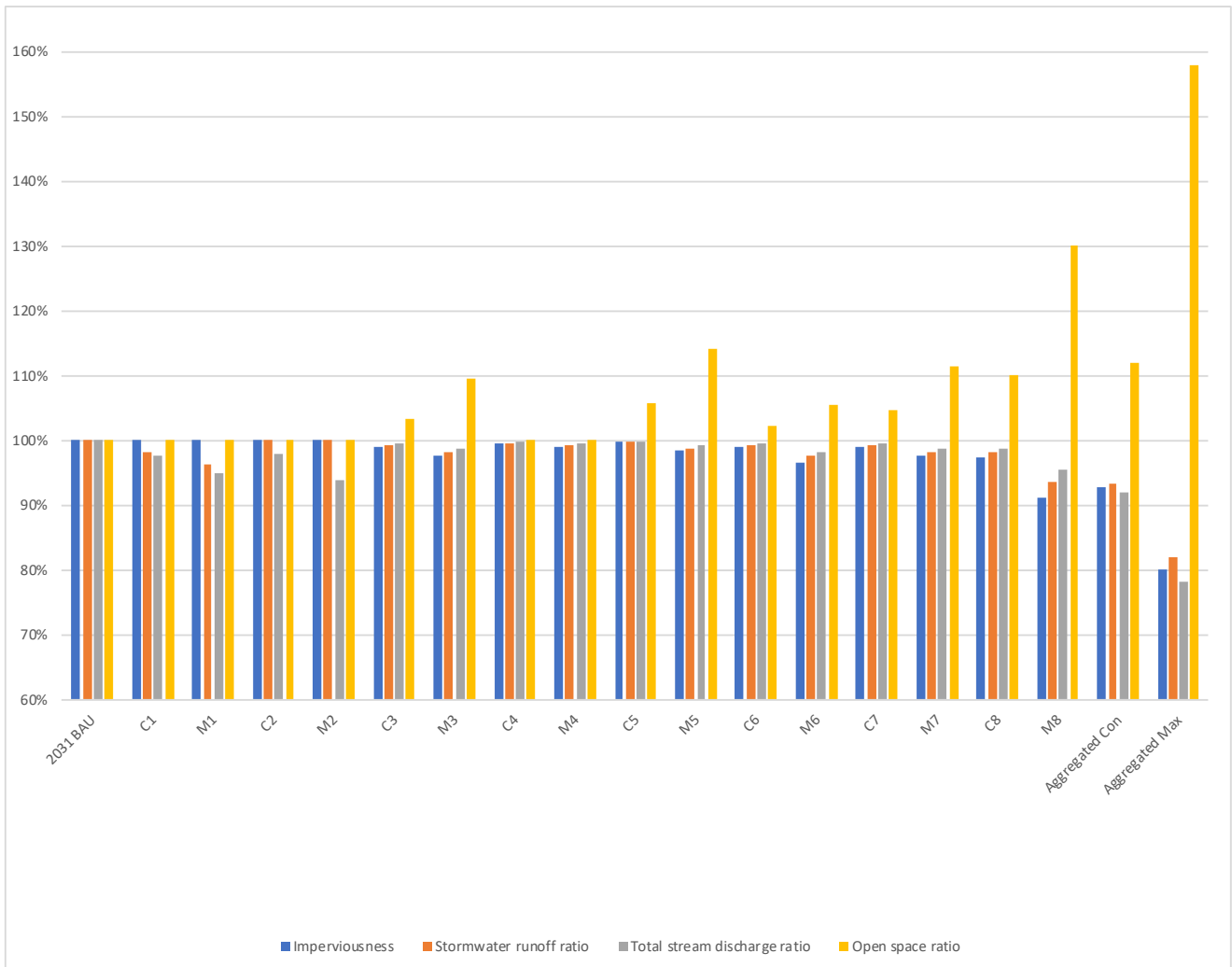
Figure 3: Imperviousness, stormwater runoff, total stream discharge, and open space performance, the base case is 2031 BAU[7]

[7] 2031 BAU: Base case with BAU in 2031, C: conservative implementation, M: maximised implementation, 1: rainwater reuse, 2: graywater recycling, 3: grass roof, 4: green fence, 5: horticulture garden, 6: shared garden, 7: grasscrete in amenity area, 8: linear park.
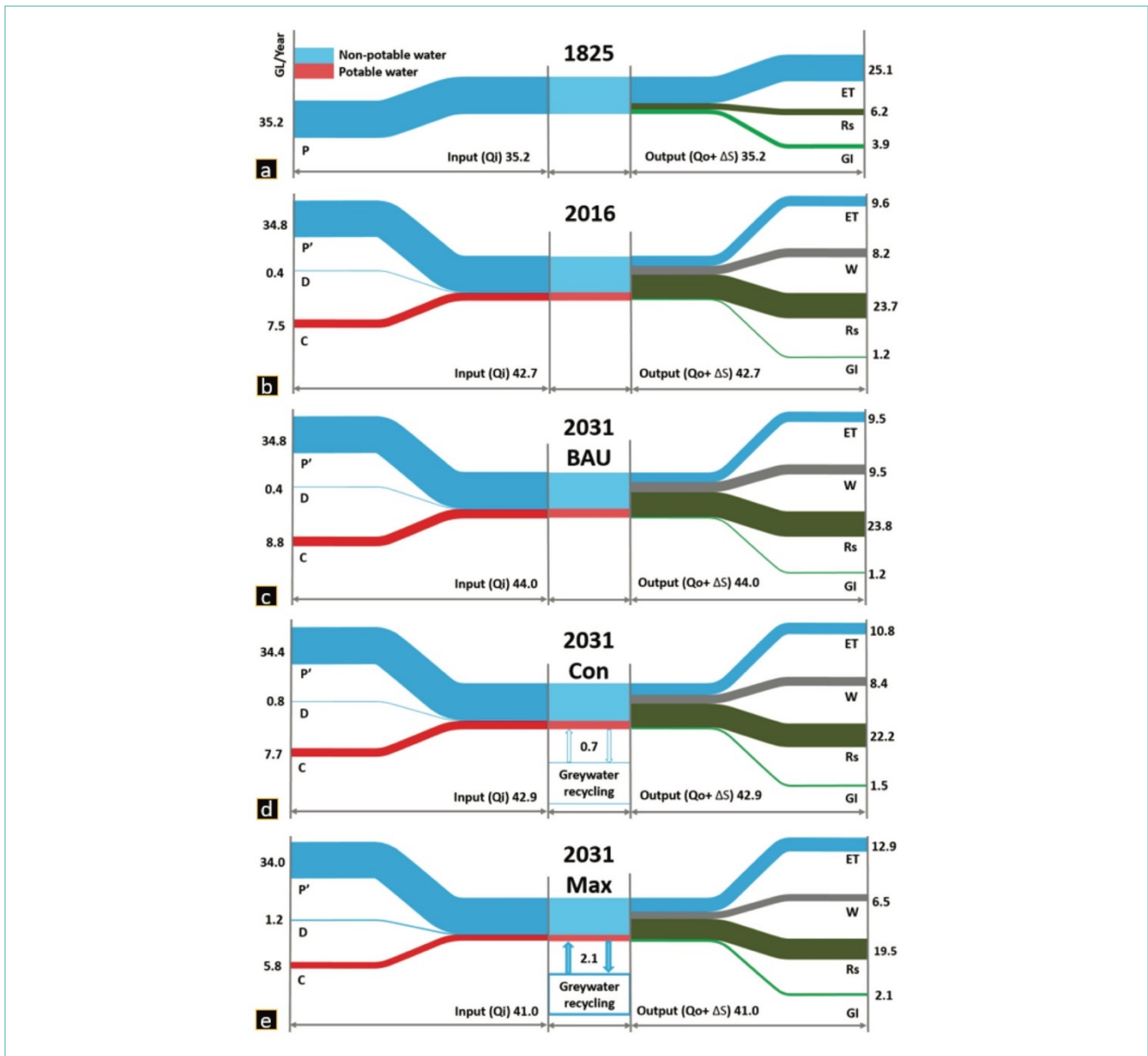
Figure 4: Water mass balances of: (a) Pre-development in 1825; (b) Current in 2016; (c) BAU in 2031; (d) WSUD with conservative implementation in 2031; (e) WSUD with maximised implementation in 2031. The width of the lines represents the magnitude of the annual flows/fluxes of water (GL/yr) flowing into, out of, and through the urban system boundary of the proposed Norman Creek catchment. P: precipitation, P': unharvested precipitation, D: rainwater reuse, C: centralised water supply, ET: evapotranspiration, W: collected wastewater, Rs: stormwater runoff, GI: groundwater infiltration.

3.1 Hydrology and stormwater runoff change due to development

Although multiple factors have a mixed effect on hydrological flows, the overall impact of urbanisation typically leads to hydrology change (Feng, et al., 2016). According to the results, stormwater runoff and total stream discharge are now 384% and 497% greater than the pre-development case (1825) (Table 4). Also, for an average rainfall year (2016), groundwater infiltration (GI), evapotranspiration (ET) and open space (OS) decreased by 31%, 38% and 27% respectively from pre-development (Figure 4), and a huge increase of stormwater runoff by 17.5GL/yr (from pre-development 6.2GL/yr to current 23.7GL/yr), which are similar to another case study in SEQ (McIntosh, et al., 2013).

Compared to the pre-development case (1825), the present (2016) total water input has increased by 7.5 GL/yr and will increase by further 1.3 GL/yr by 2031 (Table 4). This means that there will be more water demand in the future if there are no attempts to restore natural hydrology. It can also be noted that TSD will increase 537% compared to the pre-development case, which is 40% more than in 2016 (Table 4). There will be more stormwater runoff, less evapotranspiration and less groundwater infiltration for BAU in 2031 relative to pre-development in 1825.

To compare and assess hydrological performance about selected WSUD options, Table 3 details the water mass balance for each option, along with the water metabolism indicators quantified using the mass balance in 2031 and compares eight WSUD options in two different implementation scenarios (the base case 2031 BAU). The results clearly show that stormwater runoff increased over 282% in an average precipitation year due to the uneven rainfall and greater impervious surfaces after urban development. Figure 5 shows how the different individual WSUD options and how the aggregated options in the maximised case will influence runoff. The results show that:

- Urban development is dramatically changing the hydrology in the Norman Creek catchment.
- The aggregation of all WSUD options has the best water performance in all options.
- For all individual WSUD options, the option with the most potential to influence stormwater flows is the linear park.

Overall, the hydrological performance will deteriorate unless high imperviousness is mitigated, and pre-development hydrological conditions are restored. Compared to pre-development, this research paper predicted around 17.6 GL/yr stormwater runoff may run across the land after rain if it can not enter the stormwater drainage system in 2031 (Figure 5). To alleviate this, WSUD projects need to be introduced. Among all WSUD options in Table 3, the linear park from Option 8 with maximised implementation has the best performance to decrease stormwater runoff. The linear park also has the best hydrological performances on imperviousness, ET and GI.
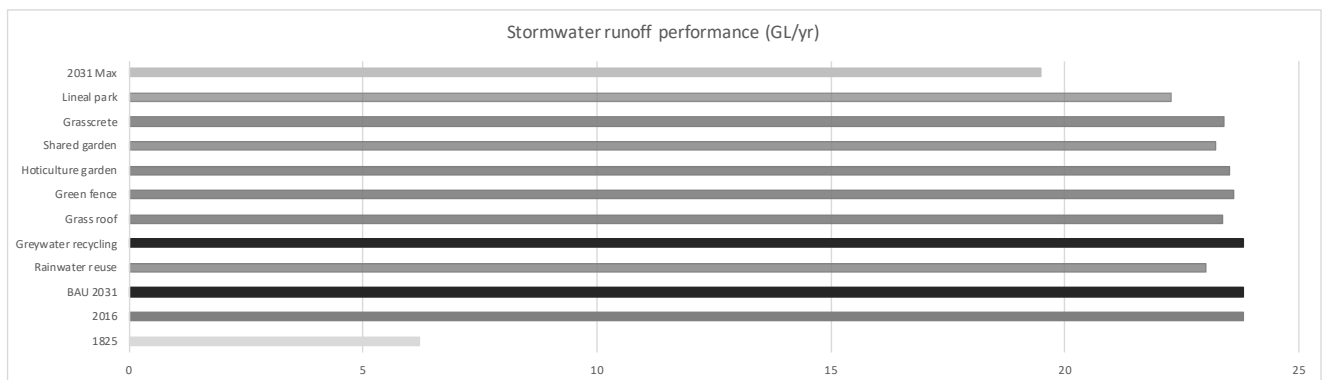

Figure 5: Individual WSUD options and aggregated of all WSUD options in maximised implementation in the average precipitation year for runoff performance compared with pre-development (1825), the current (2016), and BAU (2031), 2031 Max: aggregated of all WSUD options in maximised case, dark colour means high runoff, light colour means low runoff.

Clarify how road space is a large part of the future solution

This project observed that WSUD options will impact the runoff through land use heterogeneity in the study area, due to:

- The higher road and intersection areas which form part of the overland flow system. This is around 22% (668 ha) of surface land in the study site used for transportation.
- The higher density of impervious land will cause more stormwater discharge to storm sewer systems (Gallo, et al., 2013).
- The high density of impervious channels will decrease the stream channel storage and at the same time, groundwater infiltration will decrease (Gallo, et al., 2013).

As shown in Table 3 and Table 5, urban planners and water resources managers can shift the overall impervious fraction in an urban subsystem (high imperviousness ratio) to a more water-sensitive urban area (low imperviousness ratio) through the WSUD options implementation. Especially, the linear park option in the maximised case can help the Norman Creek catchment shift the imperviousness ratio for the whole catchment by 5.8% (decrease from 67.2% to 61.4%), meaning over 200 ha road and intersection area (high impervious fraction) becomes linear park (low impervious fraction). In addition, the linear park option can decrease runoff by over 1.4GL/yr, compared to the current year (2016).

Obviously, it is an opportunity for city planners to add more water-sensitive designs, such as the linear park in new urban planning projects to improve hydrological performance through impervious fraction change.

Table 5: Stormwater runoff for the whole catchment before and after implementation of linear park option

Time	2016	2031	2031 linear park Conservative	2031 linear park Maximised
Road and intersection area (ha)	668	668	601	467
Imperviousness for road and intersection subsystem (%)	90	90	82	63
Imperviousness for whole catchment (%)	67.2	67.3	65.5	61.4
Runoff for whole catchment (GL/yr)	23.7	23.8	23.3	22.3

The utility of a 'whole of water cycle' method applied in the infill development context

This research paper is the first time to use the 'whole of water cycle' method in the infill development context, also the first time to test UMEF4Water evaluation framework within WSUD development, including to define WSUD scenarios, generate a water mass balance and assess hydrological performance.

To better assess water performance in UMEF4Water, we redevelop four water metabolism indicators (stormwater runoff ratio; total stream discharge ratio; infiltration ratio and evapotranspiration ratio) and introduce a new indicator (open space ratio) within the infill development context. In this case, there are eight different WSUD options to be selected to fit the different subsystems and we assume all subsystems can supply a maximum of land use transfers from high imperviousness towards natural land use status.

UMEF4Water can also be used to assess water sustainability, resources management and greater liveability in the urban environment. The next stage of the research needs to focus on how to develop more appropriate UMEF4Water indicators, particularly, to evaluate water, water-related energy, and material performance. The appropriate UMEF4Water indicators associated with water, energy and material can aid urban planners in evaluating metabolism performance with a broader view. Also, the completely established evaluation framework can support

the City Plan to assess infill development projects precisely and rapidly.

CONCLUSION

This research paper demonstrates how a 'water metabolism' perspective can be used to generate water efficiency and performance indicators to assist water resource management in the study area due to the high demand for WSUD. Based on results, WSUD options from this project such as linear parks should be applied to more infill development projects for better hydrological performance.

In this work, WSUD options have been analysed for future urban development. New insights include:

- Urban development has a dramatic alteration for the hydrological system of Norman Creek.
- The implementation of selected WSUD options has a benefit on both water efficiency and natural water flows restoration; they are proposed to mitigate stormwater runoff impacts. Of all the options evaluated, the linear park option has been shown to provide the greatest benefit of restoring natural hydrological flows.
- Introducing more UMEF4Water indicators for infill development.

Wider use of UMEF4Water system and indicators based on this work would help urban planners and water managers to identify more water-sensitive options for infill development. This would likely have an alternative systematic analysis effect on urban design and water management. It would also help quantify hydrologically efficient and water-sensitive performance in the future.

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Appendix A: Land use for 13 subsystems in Norman Creek catchment

Cluster	Land use	Area (ha)	Area (%)
1	Highway, rail and natural flooding area	127	4.2
2	Single residential dwelling	1,401	46.1
3	Shops and restaurant	41	1.3
4	Car parks	8	0.3
5	Warehouse/bulk store	28	0.9
6	Offices	34	1.1
7	Industries, motel, hotel	54	1.8
8	Library, clubs and sports clubs	44	1.4
9	Educational and retirement home	142	4.7
10	Medium residential dwelling	213	7.0
11	Parks and gardens	254	8.4
12	Road and intersections	668	22.0
13	Watercourse	24	0.8
Total		**3,038**	**100**

1 ha = 10,000 m^2

Appendix B: Land use areas for four subsystems in Norman Creek (single residential dwelling, warehouse bulk store, medium residential area, and road and intersection)

Four sub systems	Area (m^2)	Dwellings	Roof	Car park/ driveway/ road	Amenity area	Open space	Traffic area and sidewalk	Imperviousness
S/residential dwelling*	21696	41	38.8%	12.7%	10.3%	38.1%	n/a	65%
Warehouse bulk store	15169	5	59.5%	37.4%	n/a	3.1%	n/a	95%
M/residential area**	10799	13	42.3%	26.9%	n/a	30.8%	n/a	73%
Road and intersection	2303	n/a	n/a	n/a	n/a	5.5%	94.5%	90%

* S/residential dwelling: single residential dwelling. ** M/residential area: medium residential area

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