The local influence of residential infill on the urban water flows: a multi-city analysis

M. Moravej[a, b], **S. Kenway**[a, b], **M. Renouf**[a, b], **C. Urich**[c, b], **O. Sainsbury**[b, d], **N. Bertram**[b, d] **and G. London**[b, e]

[a] *Australian Centre for Water and Environmental Biotechnology (formerly AWMC), the University of Queensland, St. Lucia, QLD,* [b] *CRC for Water Sensitive Cities, Monash University, Clayton, VIC,* [c] *Civil Engineering Department, Monash University, VIC,* [d] *Monash Art Design and Architecture, Monash University,* [e] *Design School, University of Western Australia*
Email: m.moravej@uq.edu.au

Abstract: Infill development is an unprecedented opportunity to reshape cities incorporating innovative design to address urban water challenges such as pluvial flooding, water insecurity, and degraded receiving water bodies. This study aims to address the influence of architectural design (before and after infill) on the urban water flows by studying the water performance of 28 design typologies in three cities of Adelaide, Brisbane, and Melbourne.

Design typologies were categorised based on the scale of infill (e.g. Small Infill vs apartments) and infill typologies: representing before infill or existing case (EX) and two categories for after infill namely business-as-usual (BAU) demonstrating developments under current planning policies and building design codes and Alternative (ALT) designs following Water Sensitive Urban Design principles. We used Site-scale Urban Water Mass Balance Assessment (SUWMBA) tool to estimate urban flows into and out of development sites to quantify the local influence on the urban water cycle.

The results showed design typologies exhibit a varying performance in different cities, calling for city-specific rather than generic designs. BAU infill, in particular, demonstrates the most disruption to the natural hydrology by increasing stormwater discharge up to 442% and decreasing evapotranspiration and infiltration down to 31% and 36% of the flows in the natural landscape. The implication of this disruption on stormwater management (i.e. urban drainage), risk of pluvial flooding, and urban heat was discussed. ALT designs show a lower degree of disruption of natural hydrology while providing more densification compared to BAU. Despite this relative success, all designs failed to restore natural hydrology fully. We argue that improvements in architectural designs combined with Water Sensitive Urban Design technologies (e.g. local harvest of rain and stormwater) to a varying degree are needed to achieve net-zero water impact.

Keywords: *Integrated modelling, water sensitive urban design (WSUD), low-impact development (LID), densification, urban hydrology*

1. INTRODUCTION

Infill development involves the redevelopment of under-used parcels or the development of vacant lands within existing urban areas. It has become the most common type of urban growth in Australia with capital cities having infill targets of 50-90% (Newton et al., 2012). Currently, the design of infill developments is driven by the need for densification to meet housing targets while maintaining characters of low-density housing. This has led to significant growth of impervious areas (e.g. roof, car parks), loss of green space/urban forest, and also loss of soil moisture storage in many urban areas. Therefore, the benefits of green spaces in terms of hydrology (Renouf et al., 2019) is being lost.

Previous research has linked infill development with a significant loss in urban vegetation (Brunner and Cozens, 2013). There are a few strategies suggested by the literature for greening infill, however, the loss of green space is continuing in Australian cities (Newton et al., 2020).

Alternative architectural design following Water Sensitive Urban Design (WSUD) principles aim to improve infill design by providing densification while maintaining green spaces, among other objectives (London et al., 2020; Murray et al., 2011). They can potentially avoid the negative consequences in relation to hydrology and restore multiple benefits. However, although many alternative architectural designs for infill have been proposed, their water performance and their local influence on the urban water flows have not been quantified.

Therefore, this study aims to characterise the water performance of residential land parcels before infill, denoted as existing or EX, and after infill. We considered two variations of infill development, one representing business-as-usual (BAU) infill occurring under planning policies and building codes; and a set of alternatives (ALT) proposed by architects (London et al., 2020; Murray et al., 2011). We aim to understand the local influence of design typologies (e.g. EX vs BAU) on the urban water flows in three cities of Adelaide, Brisbane, and Melbourne to test if they perform the designs perform the same in different cities. ALT designs aim for higher residential densities compared to BAU and EX, but maintaining outdoor spaces on the site. They provide more capacity plan and incorporate water sensitive design solutions by consolidating lots rather than sub-dividing.

2. METHODS

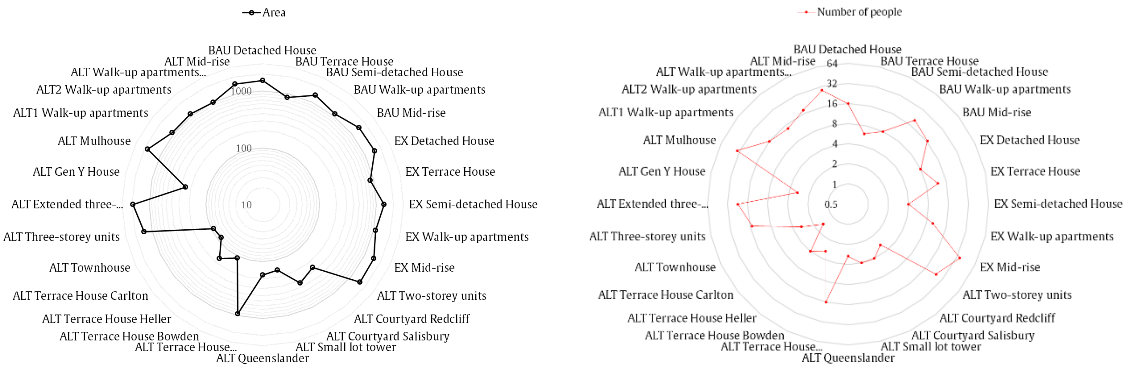
A total of 28 design typologies were sourced from London et al. (2020) and presented in Table 1. Following London et al. (2020) we categorised the topologies as the scale of infill development: i. Small Infill, ii. stacked or clustered units, iii. walk-up apartments, and iv. mid-rise apartments. The typologies were also categorised depending on the conditions they are representing: i. existing case (EX) or before infill, ii. Business-as-usual (BAU) infill, and alternative (ALT) infill. More information can be found in London et al. (2020). The site area of the selected design typologies and population provided is presented in Figure 1.

Table 1. Selected 28 Architectural designs, based on London et al. (2020)

Small infill	Stacked, clustered	Walk-up apartments	Mid-rise apartments
EX Detached house EX Terrace House	EX Semi-detached	EX	EX
BAU Detached house BAU Terrace House	BAU Semi-detached	BAU	BAU
ALT Two-storey units ALT Terrace House Salisbury ALT Terrace House Bowden ALT Terrace House Heller ALT Terrace House Carlton ALT Townhouse ALT Courtyard Redcliffe ALT Courtyard Salisbury ALT Small Lot Tower ALT Queenslander	ALT Three-storey units ALT Extended three-storey units ALT Gen Y House ALT Mulhouse	ALT1 ALT2 ALT Redcliffe	ALT

Urban water flows in and out of the development sites for each 28 design typologies were estimated using the Site-scale Urban Water Mass Balance Assessment (Moravej et al., 2021) tool (SUWMBA). The tool calculates an urban water mass balance for a 3-dimensional system boundary over the development site (i.e. lot scale) horizontally extending from the development boundary and vertically from treetops/rooftops to the root zone (i.e. one meter below the surface). All inflows and outflows, which are precipitation (P), imported water (W), evapotranspiration (ET), stormwater discharge (SW), infiltration (I), and wastewater discharge (WW) are calculated using the tool. SUWMBA performs the calculations on daily basis, integrating an urban hydrology model and a water demand module. For details refer to Moravej et al. (2021).

The design typologies were modelled under environmental conditions (e.g. climate, soil) of Adelaide, Brisbane, and Melbourne. The hydrological parameters representing soil and hydrological characteristics of the three cities were obtained from guidelines and local reports compiled in the tool (Moravej et al., 2020). Precipitation and reference evapotranspiration were obtained from the Bureau of Meteorology for the period of 1/1/2005 to 31/12/2018. The annual average of the water flows from the daily output of SUWMBA was calculated and reported.



(a) (b)

Figure 1. Site area in m^2 (a) and the number of people (b) for the selected architectural designs. Note the axis are in logarithmic scales.

3. RESULTS

First, the flows in the natural landscape are presented as a point of reference in three cities of Adelaide, Brisbane, and Melbourne. This contextual information is important to understand the water performance of architectural designs in different cities given their climate differences. Then, urban water flows, both hydrological and anthropogenic, are presented for each city.

3.1. Natural hydrology

The water flows in the natural landscape and the hydrological partitioning factor (i.e. percentage of precipitation to *SW*, *ET*, and *I*) are presented in Table 2.

Brisbane has the highest precipitation followed by Melbourne and Adelaide, leading to more stormwater, evapotranspiration and infiltration compared to the other two cities. For example, the stormwater discharge in Brisbane is 146% higher than in Melbourne.

The majority of precipitation received on the sites' areas is removed through evapotranspiration in the natural landscape. Adelaide has the highest evapotranspiration fraction (75%) followed by Melbourne (72%) and Brisbane (68%). A larger fraction of precipitation converts to stormwater discharge in Brisbane (22%) compared to Melbourne (17%) and Adelaide (14%). Infiltration shows the smallest fraction of precipitation and it is constant across the cities (11%). We use these comparisons as a point of reference to understand how architectural designs alter natural hydrology in later sections.

The calculated flows in the natural hydrology were validated against those of AWRA-L V5 (Frost et al., 2015; Viney et al., 2015) model on annual basis and presented in Figure 2. High correlation coefficient, generally above 0.72, shows good alignment between two models. Therefore, we inferior that SUWMBA has successfully modelled the flows in the natural hydrology.

Table 2. Annual average (2005-2018) of water flows in the natural landscape (natural hydrology) in mm/yr and the percentage of water flows to precipitation (i.e. hydrological partitioning fractions) in parenthesis

City	Precipitation (*P*)	Stormwater discharge (*SW*)	Evapotranspiration (*ET*)	Infiltration (*I*)
Adelaide	465.3	63.8 (14%)	350.2 (75%)	52.8 (11%)
Brisbane	1086.7	239.6 (22%)	734.4 (68%)	115.8 (11%)
Melbourne	565.0	97.9 (17%)	408.6 (72%)	59.5 (11%)

3.2. Adelaide

The local influence of architectural designs on the urban water flows in Adelaide is presented in Figure 3, showing a wide range of impacts between different scales of development (e.g. small infill vs. apartments) and infill typologies (e.g. EX vs. BAU).

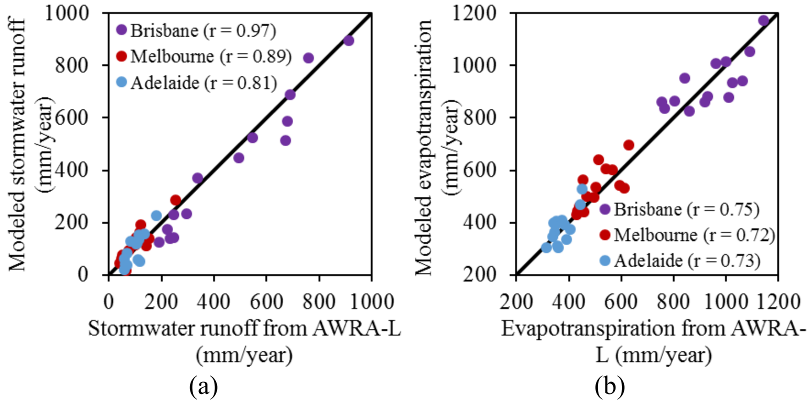


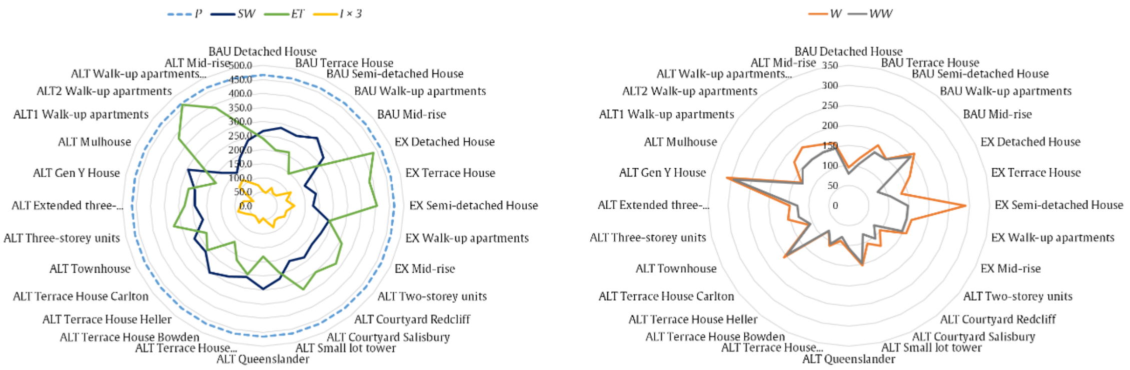
Figure 2. Modelled (a) stormwater runoff and (b) evapotranspiration using SUWMBA versus those from AWRA-L (Viney et al., 2015) for the studied period (2005-2018), r = correlation coefficient.

The highest and the lowest stormwater discharge is 309 mm/yr (BAU Walk-up apartments) and 151 (ALT2 Walk-up apartments). Comparing this range with EX Walk-up apartments (239 mm/yr) reveals that depending on the design, stormwater discharge can increase by 30% or decreases up to 37%. This reduction for ALT2 Walk-up apartments becomes more important when accounting for the higher number of people that it accommodates (see Figure 1.b). ALT design does not always reduce stormwater discharge in other scales of infill developments. For example, ALT Two-storey units (222 mm/yr) shows an increase by 35% compared to EX Detached House (164 mm/yr). On average, stormwater discharge of EX, BAU, and ALT designs is 200, 282, and 244 mm/yr which is 43%, 61%, and 52% of precipitation respectively. Comparing this with stormwater discharge in the natural landscape in Adelaide (see Table 2), this is 3.0, 4.3, and 3.7 times disruption (increase) to the natural hydrology.

Evapotranspiration ranges from 145 to 459 mm/yr, with the lowest and highest numbers being associated with BAU Walk-up apartments and ALT2 Walk-up apartments. Comparing this with stormwater discharge results indicates that increasing evapotranspiration by enabling more green spaces and irrigation, and decreasing building footprints and impervious surfaces is an effective measure to reduce stormwater discharge. Evapotranspiration of EX, BAU, and ALT designs, on average, is 355, 204, and 244 mm/yr, which exhibits a considerable reduction linked to BAU designs. Comparing the numbers with the evapotranspiration in the natural landscape (350 mm/yr) indicates a 2% increase for EX designs and reductions of 42%, and 20% for BAU, and ALT designs. The reason for the slight increase is irrigated greenspaces. Although the areas for greenspaces is reduced compared to the natural landscape, the irrigation enables a higher rate of evapotranspiration, especially during dry periods.

Similar to evapotranspiration the highest infiltration is observed for ALT2 Walk-up apartments (39 mm/yr) while the lowest is associated with ALT Mulhouse (13 mm/yr). On average, the infiltration for EX, BAU, and ALT is 32, 19, and 23 mm/yr or 7%, 4%, and 5% of precipitation. Comparing this with infiltration in the natural landscape (11%) this is a 38%, 63%, and 54% reduction for EX, BAU, and ALT designs.

Architectural designs are an important factor influencing imported water and wastewater discharge by determining the number of people residing on the site, occupancy rate, land cover areas (e.g. roof areas) and hydrological connectivity (e.g. passive irrigation of green spaces). The highest imported water is observed for designs with the lowest occupancy rate and large green spaces (e.g. EX Semi-detached House) being 311 l/person/day. On average, the imported water of EX, BAU, and ALT designs is 182, 148, and 146 l/person/day, indicating low water use efficiency associated with EX designs.



(a) (b)

Figure 3. Hydrological (a) and anthropogenic in (b) flows of 28 architectural designs in Adelaide in mm/yr and l/person/day. Note infiltration values are multiplied by 3 to have the same scale as other flows in (a).

3.1. Brisbane

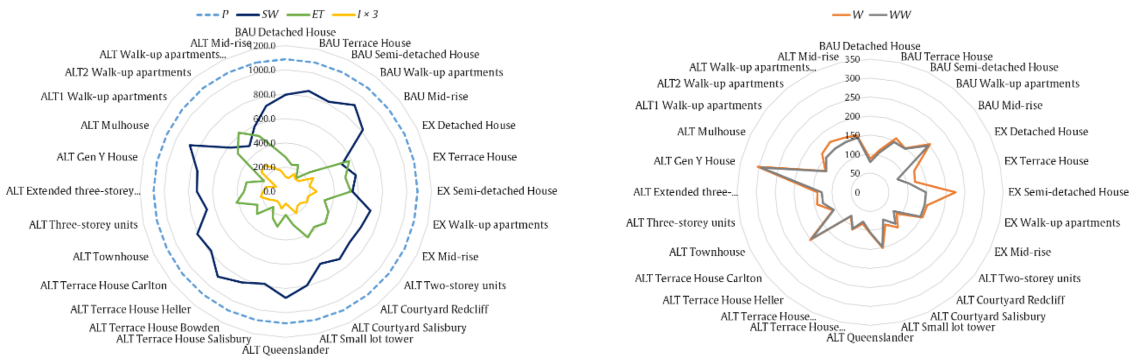
Figure 4 shows the local influence of the 28 architectural designs on the urban flows in Brisbane, showing a similar pattern to those observed in Adelaide with a different magnitude of impact.

Stormwater discharge varies between 479.5 (ALT2 Walk-up apartments) to 909.7 (BAU Walk-up apartments) mm/yr or 44% to 84% of precipitation. Comparing this to stormwater in the natural landscape (239.6 mm/yr or 22%) shows none of the architectural designs could mimic natural hydrology. Stormwater discharge for EX Walk-up apartments is 717, therefore, ALT design shows a 33% decrease, while BAU design increases the flow by 27%. On average, BAU exhibits the highest stormwater discharge (838 mm/yr) followed by ALT (733 mm/yr) and EX (603 mm/yr). The considerable increase caused by BAU designs negatively impacts urban drainage and downstream stream ecology.

Evapotranspiration variation is considerable among different design typologies having a minimum and maximum of 138.0 and 618.6 mm/yr or 13% and 57% of precipitation. Evapotranspiration of EX, BAU, and ALT designs, on average, is 469, 227, and 346 mm/yr, respectively. Comparing with the evapotranspiration in the natural landscape (734 mm/yr) shows a reduction of 36%, 69%, and 53% for BAU, and ALT designs. This result demonstrates that none of the architectural designs could achieve evapotranspiration to the natural level in Brisbane.

Infill development in the forms of BAU and ALT on average has infiltration of 44 and 54 mm/yr, a 40% and 25% reduction compared to EX designs (73 mm/yr). This is a 37%, 62%, and 53% reduction compared to the infiltration in the natural landscape (115.8 mm/yr) for EX, BAU, and ALT designs.

Imported water varies from 80.4 to 303.4 l/person/day with EX, BAU, and ALT designs having average values of 156, 142, and 139 l/person/day, respectively.



(a) (b)

Figure 4. Hydrological in (a) and anthropogenic in (b) flows of 28 architectural designs in Brisbane in mm/yr and l/person/day. Note infiltration values are multiplied by 3 to have the same scale as other flows in (a).

3.2. Melbourne

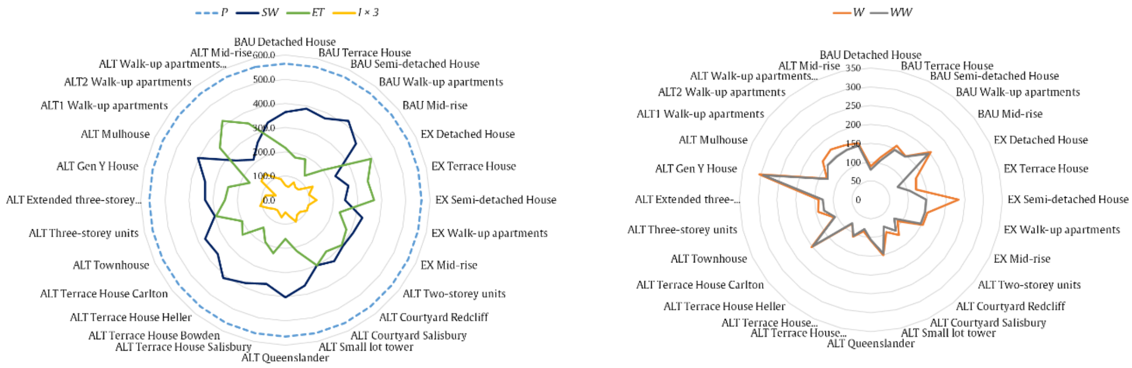
The estimated urban water flows for the 28 architectural designs are presented in Figure 5, revealing the local influence of design typologies on the urban water cycle in Melbourne.

The lowest and highest estimated stormwater discharge is 213 (ALT2 Walk-up apartments) and 419 mm/yr (BAU Walk-up apartments) or 38% and 74% of precipitation. Comparing Figure 5 with Table 2 shows that none of the architectural designs could restore stormwater discharge in the natural landscape (97.9 mm/yr) in Melbourne. The flow for EX designs, on average, is 277 mm/yr, which can increase by 39% (385 mm/yr) for BAU and by 17% (to 334 mm/yr) for ALT designs.

Similar to stormwater discharge the evapotranspiration variation among design typologies is considerable, ranging from 128 to 418 mm/yr or 23% to 74% of precipitation. EX, BAU, and ALT designs show annual average evapotranspiration of 325, 182, and 254 mm/yr, respectively. Comparing with the flow in the natural landscape (408.6 mm/yr) shows none of the design typologies could restore natural hydrology. The natural evapotranspiration is reduced by 20%, 55%, and 38% for EX, BAU, and ALT designs.

Annual average infiltration for EX, BAU, and ALT designs are 37, 22, and 27 mm/yr, a 38%, 62%, and 54% reduction compared to the infiltration in the natural landscape (59.5 mm/yr).

Imported water varies from 81 to 304 l/person/day with EX, BAU, and ALT designs having average values of 160, 143, and 140 l/person/day, respectively.



(a) (b)

Figure 5. Hydrological in (a) and anthropogenic in (b) flows of 28 architectural designs in Melbourne in mm/yr and l/person/day. Note infiltration values are multiplied by 3 to have the same scale as other flows in (a).

4. DISCUSSION

The studied design typologies do not perform the same across different cities. For example, EX designs could improve natural evapotranspiration in Adelaide (i.e. 102%) while they only reach 64% and 80% of the natural levels in Brisbane and Melbourne. This difference in performance across cities strongly highlights the need for city-specific design typologies.

BAU designs show the most disruption in the hydrological flows by increasing stormwater discharge in a range of 350%-442%, decreasing evapotranspiration to 31%-58% and reducing infiltration to 36%-38% of the flows in the natural landscape. The considerable increase in stormwater discharge negatively affects urban drainage systems, increasing the risks for urban pluvial flooding. Reduced evapotranspiration is directly linked to increased urban heat (Renouf et al., 2020), therefore BAU designs pose higher risks of urban heat exposure compared to other design typologies. The decreased evapotranspiration also indicates less healthy green spaces and a potential loss of their associated benefits in terms of liveability (Sochacka et al., 2021) and human health.

Water Sensitive Urban Design (WSUD) technologies (e.g. local capture of rain and stormwater, on-site reuse, infiltration measures, green roofs, efficient appliances and fixtures, etc.) can potentially mitigate some of the impacts observed here for design typologies. However, extensive WSUD technologies would be needed for those designs with higher impacts. The question remains how to jointly optimise the architectural design and WSUD technologies for infill development with minimal local impact on the urban water cycle.

Future research could extend the result of our study for developing and testing city-specific design typologies and compare their performance with the benchmarks provided here. This can be further enhanced with the consideration of WSUD technologies to explore the joint impacts of design-technology configurations. We used data representing average precipitation and evapotranspiration for each city but the climate variabilities within cities need to be considered for future research.

5. CONCLUSIONS

Our study highlighted the potential of architectural design for influencing the urban water cycle in three cities of Adelaide, Brisbane, and Melbourne. The key messages are outlined below.

The design typologies show a noticeably varying performance in different cities when the performance is placed within their hydrological characteristics (i.e. compared to the natural hydrology). This is an important message because it flags the need for city-specific design typologies.

BAU infill has disruptive impacts on the urban water cycle by a considerable increase in stormwater discharge (up to 442% of the natural case) and a decrease in evapotranspiration (down to 31% of the natural case) and infiltration (down to 36% of the natural case).

ALT design shows a relative success compared to BAU by having a smaller impact on the urban water cycle and providing more population density capacity. However, it fails to restore natural hydrological flows. Further improvements in architectural designs combined with WSUD technologies might be needed.

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