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E-PROCEEDING OF

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"Sustaining the
Resilient, Beautiful and Safe Cities
for a Better Quality of Life"

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“Sustaining the Resilient, Beautiful and Safe Cities for a Better Quality of Life”

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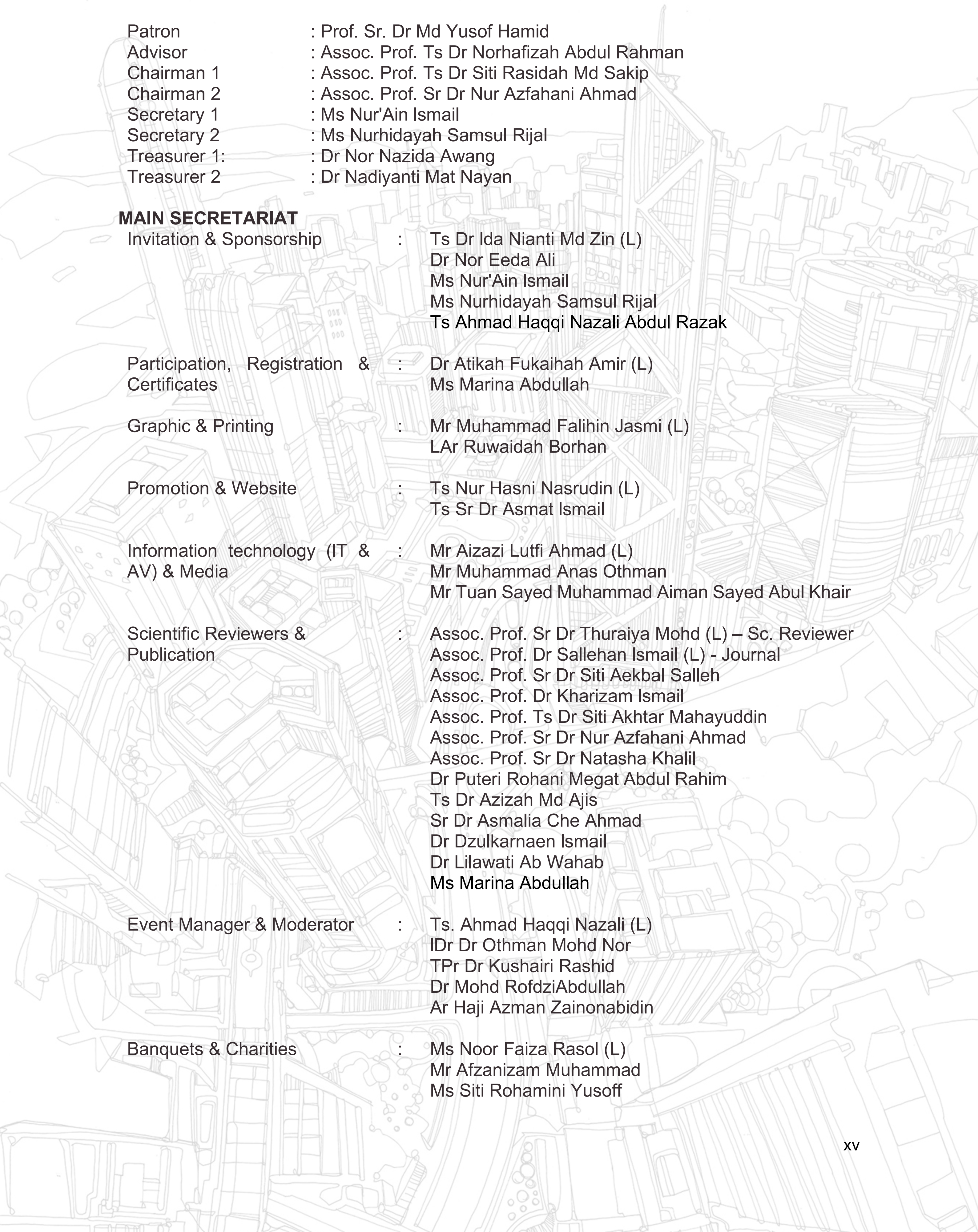

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DESIGN TYPOLOGICAL ANALYSIS FOR URBAN WATER MANAGEMENT: WHY QUANTIFICATION IS NEEDED AND HOW IT CAN BE DONE?

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Abstract

This paper describes urban design typological analysis for water management, an emerging multidisciplinary design method involving urban planning, architecture, urban water engineering, hydrology, and sustainability fields. The challenge in multidisciplinary design is that it often results in 'too many' options, therefore, consistently and systematically comparing and evaluating interdisciplinary alternatives is difficult. We addressed this gap by reviewing evaluation frameworks, water performance quantifications methods and water indicators to identify their strength and weaknesses for design typological analysis. We first reviewed urban water management goals and conducted a review-of-reviews to identify suitable methods and indicators that can link design typological analysis to urban water management objectives. The results identified analysis was most often underpinned by urban water metabolism, economic evaluation, life cycle assessment, and water neutrality. Their function for exploring trade-offs, ranking options, and informing the decision-making process were discussed and a generalised synthesis of principles for design typological analysis is presented. The literature review also identified three main categories of models suitable for water performance quantifications, namely urban drainage, urban water mass balance, and integrated urban water system models. We suggest that urban water mass balance is used for design typological analysis due to its flexibility regarding the issue of scale (site, precinct, city, etc.) and comprehensive accounting of urban water flows. The results have great implications for sustainable urban water management in relation to the risks associated with pluvial flooding and water insecurity. They also highlight the underutilised role of architects and urban planners to address urban water issues.

Keywords: *Water Sensitive Urban Design, Infill development, Design typology, Water management, Performance quantification.*

INTRODUCTION

Major urban water management objectives are providing safe drinking water, handling wastewater for public health, and protecting residents against flooding (Larsen et al. 2016). Meeting these objectives is becoming increasingly challenging with urban population growth and erratic climate change on the horizon. There is a growing body of evidence that urban water management services can be sustainably met through a mix of centralised and decentralised water systems (Eggimann et al. 2015, Hoffmann et al. 2020, Kavvada et al. 2016) and innovative urban design (Moravej et al. 2022a, Sochacka et al. 2021a), the process of designing and shaping the physical features of cities and regional spaces. Thus, decisions related to the design of dwellings and public open spaces are increasingly recognised as important to the sustainability of urban areas.

A recent study showed that the role of innovative urban design solutions to impact urban water flows is up to 3 times larger than decentralised water servicing technologies (Moravej et al. 2022a). However, architects, urban designers, and urban planners currently are not systematically involved in decision-making around water issues. To enable collaborative or participatory urban design, where urban planning, design and water professionals can work together, it is pivotal to provide tools that (i) allow to diagnose the effects of urban design and planning on water systems in different environmental and social contexts, and (ii) support decision making where multiple assessment criteria need to be weighed against each other.

Design typological analysis, which focuses on groups of residential buildings with similar design characteristics (e.g. detached houses), answers the first challenge. It is an emerging interdisciplinary method that allows the impact assessment of architectural, planning, and design decisions on the environment. It focuses on defining integrated design typologies (London et al. 2020b, Moravej et al. 2022b), as a proxy of urban design heterogeneity across a number of water-relevant parameters, to inform urban water performance (Renouf et al. 2019) and heat performance (Nice 2021) analysis. Design typologies represent a combination of building types (e.g. detached house), suited for a specific planning area (e.g. low-density residential), and a range of centralised and decentralised water servicing options, framed in environmental conditions (e.g. climate and soil) and social acceptability (Iftekhar et al. 2022). Thus, opposed to e.g. land use classifications, also used in water modelling, design typologies capture social preferences and norms of housing choice (Iftekhar et al. 2022) and local level of acceptance for particular water servicing technology - e.g. rainwater tanks (Domènech and Saurí 2010, Rauch et al. 2017).

Collaborative or participatory urban design is needed to involve architects, residents, and planners in solving urban water issues (Renouf et al. 2019, van de Ven et al. 2016). This collaboration though, often results in ‘too many’ options. Therefore, the challenge in design typological analysis becomes how systematically compare and evaluate interdisciplinary options consistently, given that they might refer to different total areas, land cover characteristics, technologies, and number of residents. The use of evaluation frameworks (Puchol-Salort et al. 2022, Renouf et al. 2020a), underpinned by quantitative models (Moravej et al. 2021, Renouf and Kenway 2017) and water performance indicators (Kakwani and Kalbar 2022, Renouf et al. 2017, Rogers et al. 2020, van Leeuwen et al. 2012), presents an opportunity to make design typological analysis useful to decision-making in settings with multidisciplinary expertise (McEvoy et al. 2018, McEvoy et al. 2019). However, there is a gap in understanding strengths and weaknesses of different evaluation frameworks, quantitative models, and water performance indicators for design typological studies. Therefore, it is difficult for practitioners to select an appropriate method to understand the current water sensitive performance of urban areas in relation to water management objectives, set appropriate water performance targets, and test the extent to which various interventions can influence that performance.

Consequently, this paper explores the applicability of frameworks, assessment methods, and water performance indicators, and their strengths and weaknesses for design typological analysis. Based on the review of current literature, we synthesised approaches that inform performance reporting suitable for design typological analysis to achieve sustainable urban design, contributing to solve urban water management issues.

METHODOLOGY

The review was conducted through a systematic review-of-reviews (Ekeland et al. 2010) by searching peer-reviewed articles in Web of Science and Scopus databases. Search keywords were “urban water”, “review”, “state-of-the-art”, “water sensitive”, “water wise”, “low impact”, “development”, “modelling”, “indicators”, “urban design”, “framework”, and "evaluation". We also conducted a citation analysis (Osareh 1996) for each selected paper to minimise the bias that keyword search might have imposed. Selected articles were Dietz (2007), Bach et al. (2014), Huang et al. (2015), Renouf and Kenway (2017), Peña-Guzmán et al. (2017), Kuller et al. (2017), Hoekstra et al. (2018), Sochacka et al. (2021b), Moravej (2022), Meng (2022), and Sochacka et al. (2022). The criteria for selecting review papers were consideration of urban water flows and inclusion of architectural design variables. Therefore, reviews solely focusing on imperviousness, e.g. Shuster et al. (2005) and Jacobson (2011), and other siloed approaches were excluded.

The systematic review-of-reviews also included high-level urban water management goals often set out in policy and water planning documents. These included the International Water Association's Cities for Future or Water Wise Cities (International Water Association 2016), Water Sensitive Cities (Wong and Brown 2009), and the Integrated Urban Water Management concept (Maheepala et al. 2010) promoted by the United Nations Environment Programme and the Global Water Partnership. The key urban water management goals identified were (i) access to water, (ii) supply security, (iii) environmental protection, (iv) functionality, (v) risk management, and (vi) institutional efficiency.

Following Renouf et al. (2017) and Renouf and Kenway (2017), the urban water management goals were then mapped against evaluation methods and water performance indicators resulted from the systematic review-of-reviews. We also mapped the contributions of design typology, analysis to achieving the urban water management goals. This enabled us to have in-depth discussions on (i) how design typology analysis contributes to urban water management goals, (ii) what are the suitable methods for the evaluation, and (iii) how quantifications can inform better design using water performance indicators. Water performance quantifications here refer to quantifying volume of water passing through urban landscape and urban water infrastructure.

Water performance analysis was conducted for a case study in Greenslopes, Brisbane, following the steps outlined in Moravej et al. (2022a) described below.

First, satellite images, Geoscape (Geoscape 2021), were used to characterise recent redevelopment trends in the case study and the resulted land cover changes. This was essential to define design typologies. Second, three scenarios regarding on-site water servicing technologies were defined, namely Efficient appliances and fixtures (EA), Rainwater tanks (RT), and a combination of EA and RT, or 'max scenario'. Third, the environmental conditions in Brisbane (climate and soil) were sourced from BOM (2019) and Moravej et al. (2021) for an average year between 2000 to 2015.

The fourth step was to populate inputs into Site-scale Urban Water Mass Balance Assessment (SUWMBA) model (Moravej et al. 2021) and calculate urban water flows and water performance indicators. The model contains algorithms for hydrological and water demand modelling that are calibrated for Australian major cities; it also has libraries for precipitation, potential evapotranspiration, and hydrological parameters for major Australian cities to minimize the need for users to prepare and input required data. It is useful to (i) understand water-related impacts of urban development and possible variations in different parts of Australia, (ii) understand the role of alternative water servicing options to improve water performance, (iii) identify key variables for guiding design in different Australian contexts, (iv) inform setting and screening water performance targets for site-scale developments, and (v) identify good examples of design typologies.

Three indicators were considered: water use intensity (I), supply internalisation degree (S), and stormwater neutrality index (N), calculated using equations (1) to (3).

$$I = \frac{\text{water sourced from bio-regions}}{\text{number of people}} \tag{1}$$

$$S = \frac{\text{water sourced from within the development site}}{\text{total water demand}} \tag{2}$$

$$N = \frac{\text{stormwater runoff after development (i.e. subdivision)}}{\text{stormwater runoff in the existing case}} \tag{3}$$

RESULTS

Design typological analysis

The general impacts of imperviousness on stormwater discharge (Schueler 1994), and urban heat (Stone et al. 2010) are well documented: increased volume and velocity, and decreased time of concentration and water quality of surface runoff (Kuichling 1889). However, emerging concepts in urban water management, including decentralised systems, local harvest and reuse of water, and integrated urban water management, are changing this linear impact (i.e. more imperviousness more runoff) to form complex, non-linear systems, with some examples provided at building scale (Agudelo-Vera et al. 2013, Trowsdale et al. 2007a, Trowsdale et al. 2007b), precinct scale (Farooqui et al. 2016), and city-region scale (Renouf et al. 2018). The typological analysis aims to decrease the development impacts upstream (e.g. water supply catchment) and downstream (e.g. receiving water bodies) by identifying better design typologies and on-site interventions (e.g. storage)

Recent years have seen an increasing interest in design typological analysis by developing frameworks to justify its need and importance, and to define practical steps addressing its complex and multi-disciplinary nature. The review discussed in this paper identifies four major evaluation frameworks: urban water metabolism (Chrysoulakis et al. 2013, Renouf et al. 2020a), economic evaluation (Iftekhar et al. 2019, Iftekhar and Pannell 2022, Puchol-Salort et al. 2021), life cycle assessment (Hu 2019), and water neutrality (Puchol-Salort et al. 2022). The identified design typology analysis often follows four steps shown in Figure 1.

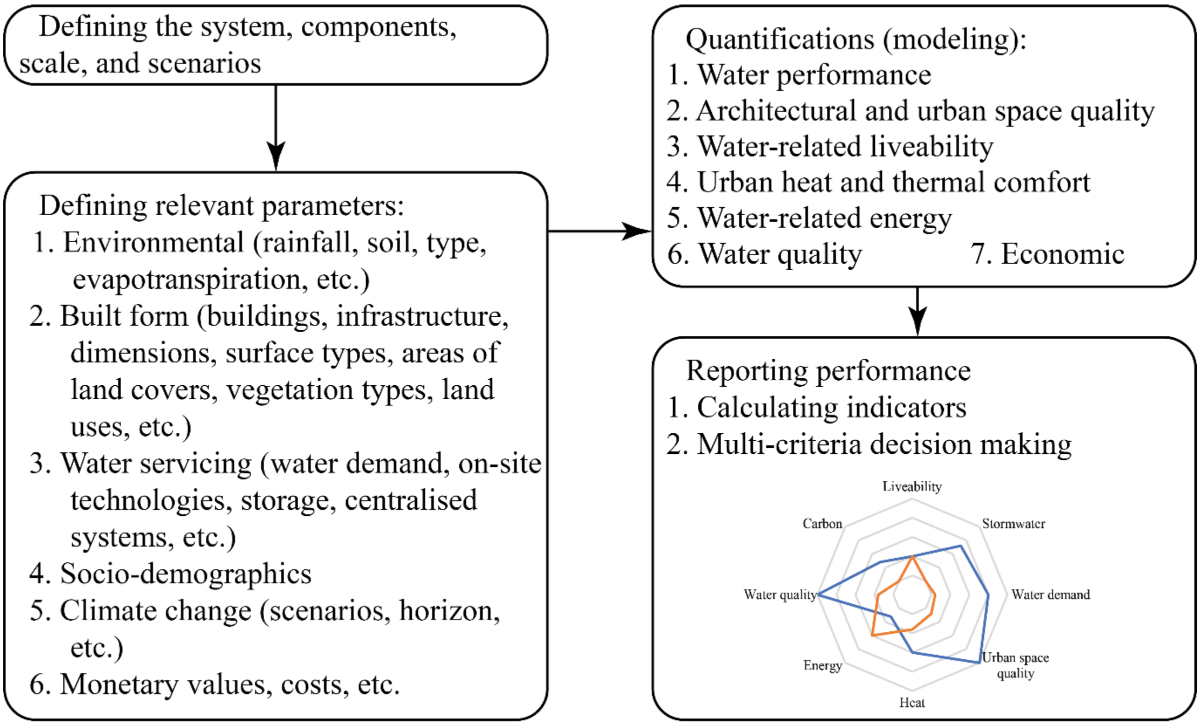
Urban water metabolism

The first urban water metabolism-based design typological analysis and related planning decisions was The BRIDGE project (Chrysoulakis et al. 2013), where water, energy, carbon, and pollutant planning alternatives were quantified. The study showcased how quantifying the multidimensions of performance can inform urban design and urban planning decisions in a variety of projected scenarios where, for example, dependence of climate change, energy, economy, and development are explicitly explored. The benefits of quantifying design typologies were not only future-proofing cities but also allowing stockholders to gain an understanding of the underlying process and the relative importance of set objectives (Chrysoulakis et al. 2013). In addition, the quantitative performance analysis was useful for exploring trade-offs in the water-energy-carbon-pollutant nexus (Lam et al. 2017, Lam et al. 2016, Moravej et al. 2021) and ranking planning alternatives (Chrysoulakis et al. 2013).

The second urban water metabolism-based design typological analysis is the Infill Evaluation Framework (Renouf et al. 2020a), where the water-heat-liveability aspects of design typologies are analysed for exploring trade-offs and ranking options, and informing the decision making process (Sochacka et al. 2021a). This framework is applied to two Australian real-world case studies (London et al. 2020a, Renouf et al. 2020b). It functions at the infill redevelopment scale and in addition to design attributes, and considers water servicing technologies at the site- and precinct-scales. It helps inform governance mechanisms that drive urban development and residential design, including development approval processes, planning policies, building rating and certification schemes, and guidelines and codes (Renouf et al. 2020a). In addition to the outcomes mentioned, it influences the processes in which urban design takes place by improving awareness of designers, architects, planners, and developers about water sensitivity of design typologies.

Figure 1

Generalised principles of design typological analysis for urban water management



Economic evaluation

The second group of design typological analysis is based on economic evaluations, for example, the Investment Framework for the Economics of Water Sensitive cities (Iftekhar et al. 2019, Iftekhar and Pannell 2022). The main aim of this group of frameworks is to use performance quantifications to build a business case considering primary and secondary benefits of water-sensitive urban design (Iftekhar and Pannell 2022). Therefore, in this category, the design typological analysis is formulated under a multicriteria analysis, often cost-benefit analysis, by monetising multifunctional benefits. It facilitates a transition from a cost-effectiveness approach to a net-benefit alternative for decision-making and for identifying best-performing design typologies. The advantage of economic evaluation is the incorporation of intangible benefits (i.e. non-market benefits) and a clear demonstration of full values of water-sensitive projects, which, in turn, could increase the likelihood of adoption in the future.

Life cycle assessment

Life cycle assessment is commonly used to understand the environmental impacts of design typologies across the life cycle, from extraction of material to end of life (International Organization for Standardization 2006a, b). The advantage of this type of analysis is that it provides a clear picture about the choice of material and construction processes, in relation to building design characteristics. However, most life cycle assessment studies are conducted for a “exemplary building” (i.e. buildings designed for good performance) rather than “traditional buildings” mostly found in cities (Cabeza et al. 2014).

Water neutrality

The water neutrality framework enables design typological analysis based on the idea of no change to the existing impact on the environment (Puchol-Salort et al. 2022). It aims to guide new development to have zero additional impacts by minimising the impacts on urban water security and offset remaining stresses by retrofitting existing housing stock. Therefore, it is useful to identify sustainable design typologies and water servicing interventions to tackle issues such as water insecurity, risks of flooding, and river water pollution. The framework can theoretically be used to allow for reduction of impacts, but such applications are not found in the literature. The key assumption is that increasing population, either through densifying urban areas or horizontal growth, has a negative impact on the environment, which can be reduced using planning interventions (e.g. mandating on-site water servicing technologies) in new developments and retrofit existing housing stock. An example was provided for London, showing the implementation of an array of blue-green infrastructures in all new developments plus 432,000 existing houses that are required to achieve water neutrality for the projected population in 2041.

Water performance quantification methods

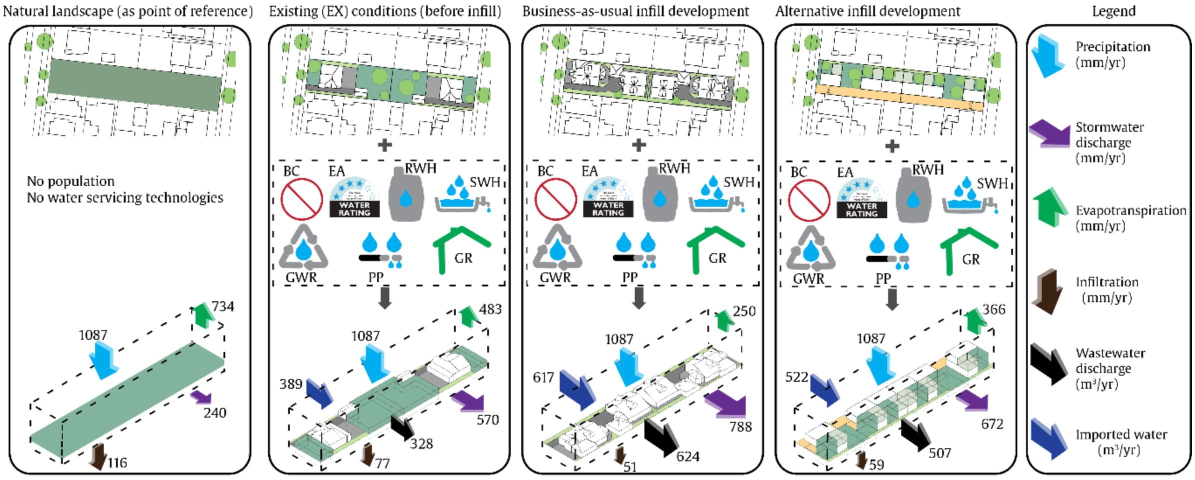
Urban water system models are widely used to understand different parts of urban water systems and have a great utility for water performance quantifications (Peña-Guzmán et al. 2017). A detailed review of urban water system models can be found in Kuller et al. (2017), Bach et al. (2014), Lerer et al. (2015), and Moravej et al. (2021). They can be further categorised into urban drainage models, urban water mass balance models, and integrated urban water system models (Moravej 2022).

Urban drainage models focus on rainfall-runoff and hydrodynamic processes concerning the production and the movement of stormwater in urban drainage pipes (1D modelling), landscape (2D modelling), or both (1D-2D integration). The most common urban drainage models are MIKE software (DHI 2017), Storm Water Management Model (SWMM) , TUFLOW (WBM 2016), Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (eWater 2011), and CityDrain3 (Burger et al. 2016). They have been used to locate, design, manage, and understand new and existing design typologies to minimise the risk of flooding (Tanner et al. 2021). The main drawback of models in this category is that they do not consider all urban water flows. This could potentially lead to identifying solutions that are optimised for one urban water flow (e.g. stormwater) but exacerbate other flows (e.g. potable water demand).

The second category, the urban water mass balance models, remove the limitation of urban drainage models. Notable models in this category are Aquacycle (Mitchell et al. 2001), City Water Balance (Last 2011), Urban Metabolism Framework for Water (Farooqui et al. 2016, Jeong and Park 2020, Kenway et al. 2011, Renouf et al. 2018), Site-scale Urban Water Mass Balance Assessment (SUWMBA) (Moravej et al. 2020, Moravej et al. 2021), and Conceptual Urban Water Balance (Zeisl et al. 2018). These models often function at large scales cover at precinct, or a city-region. The SUWMBA model is the only example of urban water mass balance models that functions at site-scale, which makes it suitable for design typological analysis. An example of water performance evaluations for a range of typologies is presented in Figure 2.

Figure 2

An example of water performance evaluations with SUWMBA for infill development, adapted from Moravej et al. (2022a)



BC = Base case, EA = Efficient Appliances, RWH = Rainwater Harvesting, SWH = Stormwater Harvesting, GWR = Greywater Reuse, PP = Permeable Pavement, GR = Green Roof

As integrated urban water system models combine different components of the water system with information from other disciplines, they are useful for interdisciplinary performance analysis. Notable models in this category are Dynamic Adaptation for eNabling City Evolution (DAnCE4Water) (Rauch et al. 2017), Dynamic Urban Water simulation (DUWSiM) (Willuweit and O'Sullivan 2013), Adaptation Planning Support Tool (van de Ven et al. 2016), and Scenario Tool (Urich et al. 2020). Examples of their use include integration with urban heat analysis (Moravej et al. 2022c) and urban form dynamics through the MOLAND model (Engelen et al. 2007). The MOLAND is a land use dynamic model. At the city-region scale it considers population projections and job market projections categorised by economic sectors. This information is translated to the number of land uses into 4 ha grids by running a cellular automata algorithm that stochastically identifies most probable development pattern in the region (Willuweit and O'Sullivan 2013)

Water performance indicators

The output of quantification methods is used to generate water performance indicators, gauging the contributions of design typologies to urban water management objectives. The list of indicators used in the literature is presented in Table 1. Indicators are collated from Nika et al. (2020), Renouf et al. (2017), Puchol-Salort et al. (2022), and Kakwani and Kalbar (2022). They cover different aspects of urban water management goals, including (i) contributions to resources efficiency, (ii) supply internalisation, (iii) protection and restoration of hydrological flows, and (iv) recognition of diverse functionality of water in the urban landscape and built environment.

The quantitative value of the majority of water performance indicators can be calculated with the outputs of urban water mass balance models (e.g. Aquacycle, SUWMBA), as both natural and anthropogenic water flows, and their complex interactions, are considered in urban water mass balance. Furthermore, in this category of models the urban landscape is considered as a whole, rather than focusing on its sub-systems, for example water infrastructure.

Resources efficiency indicators intend to decrease the required amount of water per unit of function, or, in other words, maximise the function per unit of water used. A simple example of this is the water used for flush toilets: less water per flush is considered more efficient. The same thinking can be applied to design typologies; i.e. less water sourced from the environment to keep the green spaces lush represents a more efficient use of water. This can occur with passive irrigation, the local harvest of water, cascading, and reuse. In the context of urban areas, defining the functions that water delivers is difficult and has been the focus of recent studies (Crosson et al. 2020, Sochacka et al. 2022).

Supply internalisation is the extent to which water demand is met by capturing and harvesting local resources (i.e. roof runoff). Its importance is two-fold: improving internalisation reduces not only the reliance on the centralised systems and bio-regions, but also downstream impacts such as flooding; therefore, it promotes sustainability and resilience at the same time.

Indicators regarding the protection and restoration of hydrological flows appear in a variety of forms and scales. Some indicators, such as the velocity of stormwater discharge and flood vulnerability, require detailed modelling in fine temporal resolutions, while others, for instance, naturalness deviation ratios, are less detailed. They could also be in the form of water quantity, quality, and in relation to carrying capacities (e.g. self-purification). Notable indicators in this category are naturalness deviation ratios, which represent the degree of deviation from pre-development hydrological flows; they can be defined for different urban water flows (e.g. stormwater, evapotranspiration) and different attributes of flows (e.g. velocity, peak, duration). The underlying principle is that design typologies with smaller deviations from the natural or pre-development state are more sustainable. This principle is also used to define the water neutrality index (Puchol-Salort et al. 2022) and to compare a wide variety of design-technology configurations (Moravej et al. 2022a).

Table 2
The list of performance indicators and suitable quantification methods drawn from the literature

Indicator	Example of suitable quantification method	Description
Benefit-cost ratio	The Investment Framework for the Economics of Water Sensitive cities	The sum of discounted benefits divided by the sum of discounted costs over the life span
Life cycle cost	Life cycle assessment	Benefits due to avoided environmental deterioration
Combined sewerage overflow (CSO)	Urban drainage models	Number and the volume of CSOs in a given period
Flood vulnerability	Urban drainage models	Number of nodes flooded
Flood frequency	Urban drainage models	Count of flooded nodes over a period of time
Flood hazard	Urban drainage models	overland flow depth multiplied by its velocity
Lower utility costs	SUWMBA	Savings due to reduction for water services due to offset locally
Water use intensity	SUWMBA	Total water use divided by number of people
Self-sufficiency	SUWMBA	Proportion of water demand met locally
Rainfall harvesting rate	SUWMBA	Percentage of rainfall falling onto the site that is captured and used
Turnover rate	SUWMBA	Inflows to the system divided by the storage
External harvesting ratio	Aquacycle	Proportion of external water demand met by internal harvest (i.e. contribution of the site to provide water resources outside the site boundary)
Water-related energy	Urban Metabolism Framework for Water	Energy used for providing water services
Stormwater naturalness	SUWMBA	Relative change in stormwater compared to natural hydrology

Evapotranspiration naturalness	SUWMBA	Relative change in Evapotranspiration compared to natural hydrology
Infiltration naturalness	SUWMBA	Relative change in Infiltration compared to natural hydrology
Demand minimisation index	SUWMBA, Aquacycle	Percentage of water demand reduced compared to a baseline
Productivity indicator	Aquacycle	Proportion of resources used from the total
Expected annual flood damage	DAnCE4Water	Monetary damage of flooding over a given period of time
Carbon, nitrogen, phosphorous fluxes in urban water flows	Integrated urban water system	Concentration of contaminants in urban water streams
Health of water emissions	Integrated urban water system	The ratio of actual amount of emissions to water bodies to self-purification capacities
Water circularity index	Aquacycle	Measures the restorative degree of water flows in the built form
Water neutrality index	Integrated urban water system	Relative difference between development impact with the existing performance

Design typological analysis for a subdivision site in Greenslopes, Brisbane

We used the generalised principles of design typological analysis provided in Figure 1 to give an example of how frameworks, quantification methods, and water performance indicators can be used together to inform design options in a subdivision site.

Defining the system, scale and scenarios

Greenslopes (Figure 3) is selected for the case study because it is expected to experience significant urban redevelopment in the next two decades. Its current population of 9,679 is expected to increase to 16,256 by 2051, a 68% growth (Queensland Government 2019). This growth means that the 2016 population density of 33 person/ha will increase to 55 person/ha by 2051, imposing a substantial pressure for urban densification and new housing. The types of new development allowed in the case study area are determined by zoning and outlined in Figure 3. With limited allocated areas for high and medium residential, new infill is mostly constrained with "character infill" to preserve the low-density profile of the suburb. This means that the majority of new development will occur in the form of subdivisions (Sub).

We defined five scenarios outlined in Table 2. A typical existing residential lot in Greenslopes is a 20 × 40 m lot occupied by one detached house (Moravej et al. 2022b), underpinning the existing scenario (EX). This land often undergoes a longitudinal subdivision (i.e. Sub scenario). We compared the EX scenario with the Sub scenario, also considering various on-site water servicing technologies, as described in Table 2.

Figure 3

Overland flow and planning zones in Greenslopes (map produced by the authors using data from Brisbane City Council (2014))

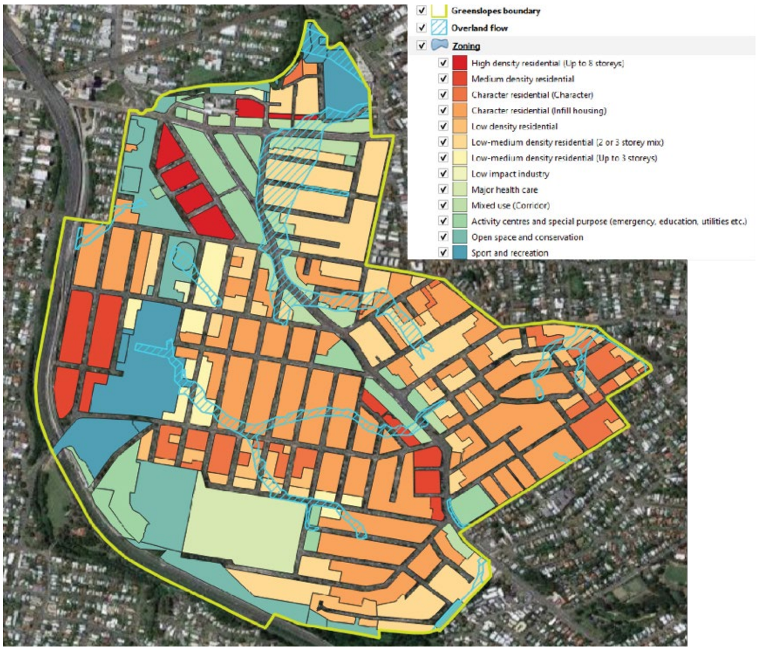


Table 3

Scenario definition

Scenarios	Design	On-site water technologies
Existing (EX)	Single detached house on a 20 × 40 m lot	None
Subdivision (Sub)	Two detached houses after subdivision, each occupying a 10 × 40 m lot	None
Sub-EA		Efficient appliances and water fixtures (EA) are fitted according to Water Efficiency Labelling and Standards scheme (Chong et al. 2008)
Sub-RT		Rainwater tanks (RT) are implemented in each house
Sub-max		The combination of EA and RT is considered

Defining parameters

The environmental conditions of Brisbane were sourced from Moravej et al. (2021), considering an average year for rainfall (2008 with 954 mm/yr) and potential evapotranspiration (1,474 mm/yr). The design parameters used for the calculation are provided in Table 3 and the parameters of on-site water servicing technologies are presented in Table 4.

Table 4
Design and socio-demographic parameters

	 As 15 October 2009 (source: Nearmap)	 As 13 July 2020 (source: Nearmap)
Site area	800 m^2	800 m^2
Number of dwellings	1	2
Number of people	4	8
Annual household income	$A70,000	$A70,000
Roof area of each dwelling (imperviousness = 1)	152 m^2 sloping tiles	465 m^2 sloping tiles
Pavement (imperviousness = 0.95)	60 m^2	120 m^2
Short vegetation (imperviousness = 0)	404 m^2	163 m^2
Tall vegetation (imperviousness = 0)	184 m^2	22 m^2
Pool	0 m^2	30 m^2

Water performance quantification and indicators

Water performance quantifications were made using the SUWMBA model (Moravej et al. 2020, Moravej et al. 2021). This is an Excel-based tool that can provide water performance analysis by quantifying the urban water mass balance of a three-dimensional system encapsulating the urban development. It provides an Australian-specific tool for analysing different site-scale architectural designs (e.g. detached houses, townhouses, walk-up apartments, green corridors, etc.) and water-sensitive urban design technologies (e.g. permeable pavement, efficient appliances and fixtures, purple pipe, rainwater harvesting systems, etc.) in different soil and climatic conditions.

Table 5
The parameters of on-site water servicing technologies

On-site water servicing technologies	Parameters
Efficient appliances and fixtures (EA)	5 star water efficient fixtures Front loader washing machine Half-flush toilet is usually used Eco dishwasher is used 50% of the times
Rainwater tanks (RT)	2 rainwater tanks for each dwelling Size = 2 m^3, half-full at t = 0. Roof coefficient = 0.9 Roof connection = 100%. Rainwater usage = washing machine, toilet flushing, irrigation. No first flush diverter
Combination of EA and RT	Joint consideration of EA and RT

Water performance reporting

The results of design typological analysis of the case study are presented in Table 5, showing the site has a water use intensity of 250 l/person/day, 100% supplied externally (i.e. internalisation is 0%). As subdivision increases the number of people, this indicator decreases to 158 l/person/day. Implementing scenario Sub-EA, Sub-RT, and a combination of the two (Sub-max) can decrease this indicator even further to 130, 113, and 96 l/person/day, respectively. However, increased imperviousness (see Table 3), led to a 265% rise in stormwater discharge from the site. Implementing rainwater tanks can alleviate this impact, achieving a stormwater neutrality of 215%.

Table 6
Results of water performance quantifications

Water performance indicators	Scenarios				
	EX	Sub	Sub-EA	Sub-RT	Sub-max
Water use intensity (l/person/day)	250	158	130	113	96
Supply internalisation (%)	0	0	0	25	24
Stormwater neutrality (%)	100	265	265	215	225

The results (Table 5) show the impact of two alternative design and on-site water technologies on the urban water cycle, which has direct implication for water management. The increased stormwater discharge from the site increases the risk of urban drainage failure and pluvial flooding downstream. This, in turn, is a driver for investment in infrastructure upgrade/retrofits. Design typological analysis can help quantify the degree to which water managers need to respond to the change and identify alternatives that could increase housing stock whilst having a minimum impact.

DISCUSSION

The results have direct implications for (i) sustainable urban water management, (ii) urban design, and (iii), urban planning.

The design typological analysis shows the local influence of redevelopment on urban water management both upstream (i.e. water supply) and downstream (e.g. receiving water bodies). For example, vertical subdivision without implementation of on-site water servicing technologies has 265% more stormwater discharge compared to the existing case (EX). A wide-spread vertical subdivision across the city would increase the risk of overland flow and pluvial flooding. This information is critical for investments required in urban drainage systems to maintain reliability of urban water infrastructure.

The results of design typological analysis are immediately useful for urban design practices as they show the role of architects, urban designers, and developers in influencing urban water cycle. The quantifications can be used by practitioners to deliver liveable, compact redevelopment projects with minimal negative environmental impacts by comparing and benchmarking different design alternatives.

Finally, urban planning may benefit from a systematic method for setting water performance targets, which, in turn, can be incorporated into residential design codes to guide acceptable outcomes. It also encourages innovative measures to incentivise water sensitive design.

Limitations and future research needs

Limitations in current design typological analysis for water performance are (i) issue of scale and (ii) modelling resolution.

The first limitation is the issue of scale in evaluation frameworks. Water flows occur at multiple spatial scales, from property level up to city level. Each scale is associated with unique boundaries, activities, solutions, and potentials for improving water performance. There are multiple trade-offs across scales which evaluation frameworks need to consider in future studies.

The second limitation is temporal resolution of models, which is often daily. More explicit representation of resident's behaviour and design effects on water infrastructure requires increasing the temporal resolution from daily to sub-hourly. However, this also means that the model's complexity and computational cost increases. Solving these issues could be a direction for future research.

Designs analysed in this study are sourced from Greenslopes, Brisbane and are Australian-specific. However, design typologies chosen here (i.e. single detached house) and the process of subdivision is universal (Vanegas et al. 2012). For example, single detached houses (stand-alone building and relatively large private backyard) account for more than 60% and 50% of housing stock in the United State and Europe respectively (OECD 2019). However, we recognise that there are uncertainties associated with land covers in detached houses according to Moravej et al. (2022a) and Moravej et al. (2022b), which need to be considered in the future studies.

CONCLUSION

Our review showed there are four emerging frameworks, with great variability in structure and purpose, aiming to advance design typological analysis: urban water metabolism, economic evaluation, life cycle assessment, and water neutrality. This increased interest is driven by an improved understanding of the need to address multiple urban water management objectives with an interdisciplinary approach under a united framework. In this context, the role of architects, urban designers and planners in defining design typologies is key and yet often underutilised (Moravej et al. 2022a). We observed that, despite the great variability in design typological analysis, the frameworks essentially follow a few steps, which led us to propose a generalised framework; this is articulated into four steps defining (i) the system, (ii) parameters, (iii) quantification methods, and (iv) reporting water performance indicators.

Evidence of performance is needed to compare, rank, define, and choose sustainable options, which is enabled by urban water system models. However, these models vary markedly in purpose, spatial and temporal scale, and function, which highlighted they might be unevenly useful for design typology analysis. Our critical review shows urban water mass balance models have multiple advantages in this regard, which were discussed in detail in this paper. The choice of a specific model is often linked to costs as some of the models are too complex to be used outside the engineering community. Our review identified methods that can balance complexity and generalisation capacity of a model. For example, urban water mass balance models showed a promising capacity to quantify the majority of water performance indicators.

We then tested the proposed framework through application to a case study in Brisbane, which provided an example of design typological analysis to inform urban water management decisions in terms of stormwater management and water supply. The typological analysis showed the impact of redevelopment options in terms of stormwater discharge, and the potential benefits of technological solutions such as rainwater tanks and efficient appliances.

The importance of design typological analysis is two-fold. First, it encourages architects, urban designers, planners, and water engineers to create design alternatives to a subdivision scenario that demonstrate a lower impact on the urban water cycle. Second, it provides crucial information for water planning in order to predict upgrades and investments required to effectively supply water services to customers given the changes occurring due to urban redevelopment.

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