Alternative water supply systems to achieve the net zero water use goal in high-density mixed-use buildings

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Abstract

The water crisis in urban areas has manifested concerns for sustainable water supply practices in buildings. Although efforts have been taken to reduce freshwater consumption through demand management techniques and alternative supply strategies to some extent, when it comes to a more sophisticated concept like net zero water (NZW) use, practically implemented cases are rare. Due to building characteristics, geographical location, and uncertainties in the decision-making process, the feasibility of the NZW target needs to be explored. This research used a framework with a case study in Melbourne, Australia, to evaluate alternative water supply scenarios that may have the potential to approach this target in mixed-use buildings. Alongside their technical performance in reducing mains water consumption, wastewater discharge, and stormwater runoff, alternative systems were analyzed against environmental, economic and social aspects of sustainability. For each sustainability criterion, an indicator was selected. Through the proposed scenarios, the goal of NZW use was not fully achieved. However, the three performance indicators exhibited considerable reductions in net water flows. Supposing that the three sustainability aspects are equally valued, a hybrid utilization of rainwater and treated greywater may be the preferred option for mixed-use buildings in a temperate climate.

Keywords: Alternative water supply systems; mixed-use buildings; net zero water; mains water consumption; sustainability criteria

1. Introduction

Buildings are one of the highest consumers of fresh potable water around the globe (Mannan and Al-Ghamdi, 2020). With the population growth and rapid urbanization, more buildings are expected to be developed over the next decades. Consequently, in regions where unsustainable use of water sources or poor supply system's performance is prevalent, the urban development results in a water shortage (Jussah et al., 2020). This crisis has urged water authorities around the world to be more concerned about sustainable water supply systems in buildings.

The United Nations General Assembly launched the Water Action Decade in 2018, setting a number of targets to be achieved by 2030. Target 6.3 of their Sustainable Development Goals (SDG) expects improving water quality, halving the proportion of untreated wastewater, and substantially increasing recycling and safe water reuse globally by 2030 (UN, 2020). Towards this objective, governments are currently encouraging developers to apply environmentally sustainable design methods, following the concept of Water Sensitive Urban Design (WSUD) in Australia, Low Impact Development (LID) in North America, and Sustainable Urban Drainage System (SUDS) in the UK (Fletcher et al., 2015). As a result, the national green building certification systems such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) have emerged (Awadh, 2017). These tools consider a range of criteria, including rainwater management, outdoor and indoor water use reduction, water quality, water recycling, and surface water runoff. In Australia, the Green Star Rating issued by the Green Building Council of Australia has listed potable water and stormwater within its assessment criteria.

Utilizing water demand management techniques, such as low-flow showerheads, dual flush toilets, low-pressure supply connections, and pressure-reducing valves (Dziegielewski, 2003) is a solution to improve water supply at the building scale. These techniques may decrease the amount of water required to accomplish a task, reduce losses in water transfer, and improve the system's functionality during drought (Brooks, 2006). Another solution to reduce potable water consumption is to apply "alternative water supply systems".

Alternative supply solutions reduce the pressure on traditional water resources and potentially improve the system's resilience. Apart from their environmental benefits, decentralized alternatives can effectively reduce water and sewage fees where drinking water quality is not required (Pagano et al., 2021). However, the cost-effectiveness of decentralized systems has been debated at different scales and in various locations over recent years (Amos et al., 2018). Decentralized solutions, including rainwater harvesting system (RWHS) and greywater reuse, can be operated at the onsite scale, cluster scale, or distribution systems (Sharma et al., 2013). Net zero water building (NZWB) is an example at the on-site scale, which was introduced by the International Living Future Institute in 2012 (International Living Future Institute, 2014). In a net NZWB, the total annual water usage is equal to the sum of the annual alternative water usage and the total annual water returned to the original water source, i.e. surface water or groundwater sources within an aquifer or watershed similar to that of the building's supply system (Rasekh and McCarthy, 2016; U.S. Department of Energy, 2015).

Several researchers have carried out case-specific research to investigate the performance of alternative supply systems in single housings (Stec et al., 2017; Słyś and Stec, 2020), commercial developments, public buildings, and sport facilities (Chen et al., 2021; Burszta-Adamiak and Spychalski, 2021; da Silva et al., 2019; Ghisi et al., 2014), and residential developments (Kolavani and Kolavani, 2020; Zhang et al., 2010). It is demonstrated that greywater reuse is economically attractive as an alternative water supply system for single housing, where the region is water-stressed, and the cost of water is high (Juan et al., 2016). Nevertheless, comparing the two systems in a commercial building, RWHS can be more effective in terms of mains water consumption and may include lower related costs (Stec et al., 2017; da Silva et al., 2019). This may not be true if irregular rainfall patterns reducing system reliability and the emphasis on the need for backup is ignored. Former studies revealed that building's typology and the factor of geographical location are deterministic factors in alternative systems' performance. Similar results may not necessarily be achieved in other types of buildings or a region with different water consumption habits, climates, and cultures.

The economic feasibility of such systems also cannot be generalized to other cases (Lam et al., 2017). However, the outcomes of such studies give a good understanding of the available water-saving scenarios, their fundamental principles, factors to be considered in their evaluation, and their performance in similar circumstances.

Water-saving scenarios have been widely analyzed in previous studies against different sustainability criteria and across various geographical locations. However, these studies mainly focused on single-use buildings. Particularly, special attention has been given to full-residential developments. This is while the world is moving towards increasing urbanization combined with inefficient territorial expansion. The sustainable future of high-density urban regions is coupled with the development of dense multi-functional buildings that replace precise zoning. They integrate commercial, recreational, and residential uses and allow for efficient land use and better living standards (Generalova and Generalov, 2020). In countries such as Nigeria, China, Canada, and the United States, the mixed-use development concept is already a necessary feature of future urban planning schemes (Salami et al., 2021; Moos et al., 2018). Such developments soon will be one of the main building typologies in urban settings. However, there is still little information is available on their capability to comply with water conservation targets, in particular, considering that those buildings have different water consumption patterns, include a wider range of stakeholders, and have less empty space available.

The current study aims to answer three main research questions. First, what is the potential of multi-storey mixed-use buildings in urban areas to comply with the green rating system, and to what extent the concept of NZW buildings (NZWBs) is approachable through alternative water supply systems? In this research, we hypothesized that by substituting traditional water supply systems with decentralized solutions, we may approach the concept of NZWBs. This is a scenario that is considered ideal from an environmental perspective in sustainable urban planning; however, it requires technical and financial justification from the developers' viewpoint. Although the economic feasibility of NZW management is case-specific and depends upon the scale of the project, those strategies are often costly and energy-intensive (Guo et al., 2016; Chhipi-Shrestha et al., 2018). One of the limitations of net NZWBs is the investment cost (Rasekh and McCarthy, 2016). Many countries have developed strategies to decrease water consumption and increase water saving; nevertheless, real net NZWB cases are rare (Asadi et al., 2020). Hence, economic feasibility may be a great concern in the development of sustainable supply solutions at an onsite scale. The next question this study aims to answer is that what are the advantages and disadvantages of alternative water supply systems in such buildings? Finally, what are the effects of context-specific features on alternative water supply projects?

2. Methodology

This research proposed a comprehensive framework (Fig.1) to assess available water-saving solutions against sustainability criteria at the building scale.

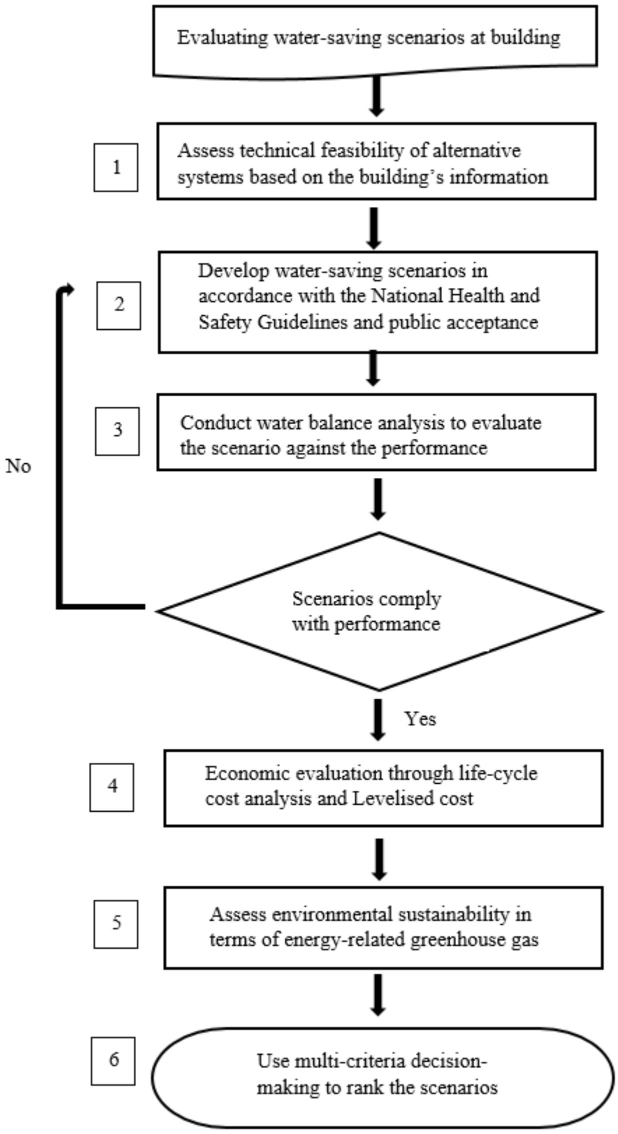


Fig. 1. Water-saving solutions assessment methodology

A brief description of the steps involved in the proposed methodology is provided in the following:

Step 1: Collect data and assess the technical feasibility of the alternative supply systems- There are generally four alternative supply options available to mains water in a building or urban development: rainwater, stormwater, greywater, i.e. the portion of wastewater that is collected from bathtubs, showers, hand-basins, and clothes washers, and contains no faecal contaminations, and blackwater, which is collected from local sewers. Utilization of all these supply sources is not technically feasible nor necessarily advisable in every development. Deciding which option to be considered for further evaluation requires detailed information on the potable and non-potable water demand of the building, the available land space, and complexities in construction.

Step 2: Develop potable water-saving scenarios based on the National Health and Safety Guideline and the community perceptions- These two factors determine the appropriate end-use of each alternative water source. In this study, we applied government guidelines on health and safety and adopted social considerations from the literature studies.

Step3: Conduct water-balance analysis- This step involves the estimation of water flow performance measures, including mains water consumption, wastewater discharge, and stormwater runoff. Scenarios that are able to make any effects on those indicators will proceed to the next step.

Step 4: Economic evaluation- It comprises the estimation of the systems' economic indicators, i.e. the life-cycle cost and accordingly the levelized cost. The major financial components, including system cost, energy cost, replacement cost, and maintenance costs, will be compared among the proposed scenarios.

Step 5: Assess environmental sustainability through estimation of Greenhouse Gas (GHG) emission- GHG emission is an indicator of the United Nations SDG (Dong and Hauschild, 2017) and a measure of environmental sustainability. Calculation of energy-related GHG emissions was conducted in this study, according to the operational energy of pumps and the treatment process.

Step 6: Multi-criteria decision-making- To identify the most suitable scenario, the outcomes of the previous steps, i.e. water-balance analysis, economic evaluation, environmental sustainability, and social constraints, should be precisely considered. We applied a multi-criteria decision-making approach to rank the proposed scenarios.

3. Case study description and climate data

3.1. Case study site specifications

In this study, a conceptual mixed-use building located in Melbourne, the second most populated metropolitan region in Australia, was used to define and present water-saving solutions on a prototypical basis. The concept of the proposed case study was taken from an existing building, Library at The Dock, which is lying at the latitude of 37° 82’ South and the longitude of 144° 94’ East in Melbourne, Victoria. It is one of the four community hubs in the city, and Australia’s most sustainable community building, which currently holds a green six-star rating under the public buildings rating tool from the Green Building Council of Australia. The hub currently has a rainwater harvesting system that collects water from the roof (roof area 974 m^2) and discharges it to a 55 kL tank in the nearby Victoria Green park for reuse within the building (City of Melbourne, 2021). The building originally comprises three institutional levels. The total area of the land is 7,138 m^2, including 947 m^2 of building surface area, 4,181 m^2 of open spaces for public usage, and 1,545 m^2 of the paved area. A model programmer for public libraries has estimated 100,000 annual visits for the Library at The Dock (The Agency for Culture and Palaces, 2017). Assuming that the daily potable water demand for each person is 30 L, and the non-potable demand of the library includes toilet flushing for 27 toilet bowls with dual flush system and 5 L water consumption per flush (as suggested by the City of Melbourne), and considering each visitor uses the toilet on average two times per visit, the total yearly water demand was estimated approximately 4,000 kL.

The objective of this study was to add another three residential levels to create a mixed-use development and analyze the impacts of building size and typology. The first three levels remained unchanged, and it was assumed that the three upper levels involve 24 residential units: 12 one-bedroom apartments, 6 two-bedroom apartments, and 6 three-bedroom apartments with a total occupancy of 41. The occupancy of apartments was calculated using the information provided by the Australian Bureau of Statistics, which have estimated the housing utilisation based on the household size (Pink, 2012).

The building might be susceptible to water supply system upsizing and development for two reasons. First, it includes a large irrigation space with a relatively high irrigation water demand that develops the potential for water recycling and reuse within the complex. Second, the building currently has adequate space within its open spaces to upsize the alternative water supply system, and hence, the factor of land use may not be a deterrent against this development. The hypothesis was to upgrade the current water supply system of the building in a way that stormwater runoff, mains water consumption, and wastewater discharge can be minimized. Thus, the establishment of either the RWHS, submerged membrane bioreactor (MBR) technology for on-site greywater treatment, untreated greywater subsurface irrigation conduit, or combinations of these systems were suggested.

3.2. Climate data

The State of Victoria is the second most pluvial state in Australia, with a mean maximum temperature of 19.9 °C and annual mean rainfall of 534.9 mm (Bureau of Meteorology, 2021). To conduct water balance analysis, any length of meteorological data can be used, providing that adequate data is available for the three parameters of daily precipitation, potential evaporation, and average temperature. Stations that measure evaporation in Victoria are more limited in number, and generally, are relatively newer than the ones used for precipitation measurements. These stations provide evaporation data since 2009. In this study, the daily meteorological data collected in the closest weather station to the building, being Melbourne Olympic Park, over ten years from 2011 to 2020, was used. The annual average precipitation, potential evaporation and number of rainy days are displayed in Table 1. This information formed the basis of the water balance analysis undertaken in this research.

Table 1. Average climate statistics per areal depth (mm)

	Average	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Precipitation	557	731	483	605	432	439	600	602	514	374	787
Potential Evaporation	1,212	1,260	1,361	1,406	1,169	1,173	1,149	1,149	1,179	1,203	1,073
Rain days (number)	141	141	146	136	132	127	177	139	126	135	146

4. Water-saving scenarios

Two main factors were considered for proposing water-saving scenarios: 1) health and safety guidelines, 2) social acceptance. Both of these factors were analyzed in the local context, according to the place of study. In terms of health and safety, the end-uses of the alternative water sources were identified in accordance with the following guidelines:

1. Rainwater will not require treatment or disinfection for any usage other than drinking or food preparation when recommended preventive measures explained in Section 6 are taken to manage the collected rainwater quality, and the system is undergone regular maintenance (Environment Protection Authority Victoria [EPA Victoria], 2007; National Water Quality Management Strategy, 2009),
2. Only reticulated drinking water should be used for drinking and food preparation (Department of Sustainability and Environment, 2006; Patrick Dupont, 2013; Department of Health, 2013),
3. For garden watering purposes, greywater subsurface irrigation can be used with little or no treatment (Simon Fane, 2013; EPA Victoria, 2020a),
4. Greywater cannot be used for laundry and toilet flushing without proper treatment (EPA Victoria, 2020a),
5. Greywater should be of secondary quality for surface irrigation use (EPA Victoria, 2020b),
6. Advanced secondary treatment should be applied for greywater reuse in the toilet, washing machine, and surface and underground irrigation (EPA Victoria, 2020b).

The success of a sustainable water supply project highly depends on the perception of users, even when it complies with local health and safety regulations. Resistance to water reuse is normally psychological rather than technical (Callaghan et al., 2012); thereby it is associated with several psychological predictors, including health risk perceptions, social norms, environmental concern, prior experience, and pricing concern (Fielding et al., 2019; Campisano et al., 2017). Recycled water may be of greater social acceptance when it does not have humans contact (Fielding et al., 2019). The most common type of stormwater and rainwater residential end-use in Australia is garden irrigation followed by toilet flushing and other outdoor uses, including domestic car washing (Hatt et al., 2006; Inamdar et al., 2018; Department of Environment and Conservation, 2006). Therefore, although it is not against the health and safety regulations, this study ignores considering rainwater for reuse purposes in kitchens, laundry, and bathrooms due to negative social perceptions. Compared to the rainwater, the greywater reuse is more subject to uncertainty due to the associated health risks (Lemée et al., 2018). The social acceptance of greywater recycling techniques differs worldwide and depends on the degree of the treatment. In Australia, more than 70% of people agree to use recycled water for toilet flushing, irrigation, and car washing (Pham et al., 2011). Even 60% of respondents are willing to use recycled water for clothes washing in the presence of a systematic treatment. This study, however, follows EPA guidelines for greywater reuse and on-site greywater treatment, which automatically avoid recycled water for domestic consumptions other than subsurface irrigation and toilet flushing.

According to the discussion above, several water-saving scenarios were developed:

- Base scenario: Mains water for the total demand of the building,
- Scenario 1: Rainwater harvesting for toilet flushing and irrigation,
- Scenario 2: Untreated greywater for subsurface irrigation,
- Scenario 3: On-site greywater treatment for toilet flushing and irrigation,

- Scenario 4: Rainwater harvesting for toilet flushing and untreated greywater for subsurface irrigation, and
- Scenario 5: Rainwater harvesting for toilet flushing and on-site greywater treatment for irrigation.

Table 2 and Table 3 show the required level of treatment for each particular supply system, and the end-use water supply of the building in Litres/person/day (LPD), respectively.

Table 2. Required level of treatment for the designed alternative water supply solutions

Supply system	End use	Level of treatment	On-site treatment system	Treatment technologies
Mains Water	All purposes	Class A⁽¹⁾	Not required	NA
Rainwater harvesting	Toilet flushing-irrigation	Class A	Not required	Preventive measures
Greywater subsurface irrigation	Irrigation	Class A	Not required	Preventive measures
Greywater treatment system	Toilet flushing-irrigation	Class A	Advanced secondary	Pre-treatment, aeration, clarification, disinfection

(1) Class A refers to the level of treatment required for the wastewater collected from sewerage systems to be reused for high-exposure applications in residential developments, including toilet and garden use.

Table 3. End-use water supply for different parts of the mixed-use building

Part of the building	End-use	Water demand,
Residential levels⁽¹⁾	Kitchen	39 LPD
	Bathroom	53 LPD
	Toilet	28 LPD
	Laundry	42 LPD
	Total	162 LPD
Institutional levels⁽²⁾	Potable	8,220 L/day

	Non-potable	2,740 L/day
	Total	10,960 L/day
Open spaces$^{(3)}$	Irrigation	7,906 L/day

(1) Adopted from McGee (2013).

(2) See Section 3.1 for more information.

(3) Modeled in UVQ. Please refer to Section5.1 for more information.

5. Analytical methods

A three-step analytical method was adopted to evaluate proposed water supply scenarios against sustainability criteria.

5.1. Water balance analysis

Water balance analysis was conducted using the Urban Volume and Quality (UVQ) model (Mitchell and Diaper, 2005) to measure how successful the supply solutions can be in reducing mains water consumption, wastewater discharge, and stormwater runoff. The UVQ model is a conceptual daily urban water and conteminant assessment tool. It represents water and conteminent flows through the water supply, wastewater and stormwater systems from source to disposal point. UVQ can model options for potable water supply; rainwater supply; graywater irrigation; on-site treated wastewater; groundwater bore supply; aquifer storage and recovery; and sizing of allotement scale rainwater tanks; cluster scale stormwater and wastewater storage; and catchment scale stormwater and wastewater storage. It carries out a comprehensive evaluation of water movement, and models water transfers as depths on a daily basis, through the concept of an urban volume. In this concept, the model is considered as a cube that consists of a horizontal surface and a height that extends from above the roof to below the groundwater table. Equation (1) represents the principle of the water balance analysis that UVQ conducts for stormwater and wastewater stores.

$$S_t = S_{t-1} + In - ff - C - O - E_p + P \qquad (1)$$

Where S_t is the storage volume at the end of the current time step; S_{t-1} is the initial storage volume; In is the inflow of stormwater or wastewater runoff; ff is the first flush volume (not applicable to the wastewater store); C is the volume of water consumed from the store; O is the overflow; E_p is the evaporation from the store; and P is the precipitation entering the store. To carry out the water balance analysis using UVQ, the following input parameters were adopted:

1) Physical characteristics of the land block, including divisions of the land area (Section 3.1), percentage of garden irrigated (assumed 100%), indoor water usage (162 litres per person per day, 33% shower, 17% toilet, 26% laundry) (McGee, 2013), imported supply leakage and wastewater exfiltration that were assumed 5% and 0.03, respectively. It should be noted that the imported supply leakage and the wastewater exfiltration are not site-specific parameters, and were decided based on the available literature. Water leakage in water distribution systems varies between 5% and 55% (Macías Ávila et al., 2021). Since this study comprises a green-rated building in Australia, a country that is moving toward lowering this rate to below 6% (WSAA, 2019), the minimum leakage rate has been assumed. Moreover, wastewater exfiltration may vary from 0.01 to 0.05, i.e. 1% to 5% of wastewater generated (Rutsch et al., 2006). This value has been debated over several studies and a value of 0.03 was selected in this study as an average reliable value aligned with the literature;

2) Climate data (as detailed in Section 3.2);

3) Calibration variables were derived from a iterative trial and error process to make the model match with the expected stormwater, wastewater, and imported water flow within the study area. The model was cross-validated with the hand-calculated data from the site. Parameters used in hand calculation included roof runoff coefficient of 0.85 (Van der Sterren et al., 2012), and the assumption of 6 hours storm with Annual Exceedance Probability of 50%;

4) The partial area approach was assumed in this analysis since case study area Docklands' soil consists of alluvial flats, mudflats, and estuarine deposits including silt, clay and aquatic

animals' detritus. This approach is appropriate for less permeable soils such as silty clay, and where the soil depths vary within the pervious area (Wolf et al., 2007). By inserting the required inputs, each scenario was set up and analyzed through the UVQ model.

5.2. Life-cycle costing

To analyze the economic sustainability of the proposed scenarios, we employed the concept of levelized cost for various analysis periods, from 20 to 50 years, i.e. the dominant lifespan of a building is 50 years and is rarely considered below 20 years (Marsh, 2017), to reflect the variation in levelized cost due to different analysis periods. The levelized cost is the ratio between total life-cycle cost and the present value (PV) of total usage of reclaimed water over its lifetime (Hall et al., 2015), and can be determined using Equation 2. We adopted a 4% discount rate from Economic Evaluation for Business Cases Technical Guidelines issued in August 2013 by the Department of Treasury and Finance, under the authorization of the Victorian Government.

$$\mathrm{LC} = \frac{\mathrm{LCC}}{\mathrm{PV}(\mathrm{i},\ \mathrm{N},\ \Delta\mathrm{IW})} \tag{2}$$

Where LC is the levelized cost (AUD); LCC is the life-cycle cost (AUD), N is the intended analysis period (years); ΔIW is the annual imported water saving or the amount of annual alternative water used (kL); and i is the discount rate.

Bills of quantities (BOQ) was the method used to estimate the total life-cycle cost of each scenario. For this purpose, a list of systems' components, their materials, characteristics, and unit prices were developed. The BOQ comprised the initial cost, i.e. plumbing, materials, preliminaries, the operational cost, i.e. energy, replacement, and the maintenance cost. The present cost of energy and replacement was estimated through Equations 3 and 4, respectively, considering a 0.8% inflation rate in accordance with the Reverse Bank of Australia.

$$\mathrm{EC} = \mathrm{PV}(\mathrm{i},\ \mathrm{N},\ \mathrm{UEC}) \tag{3}$$

$$\mathrm{RC} = \mathrm{UC}\left(\frac{1}{(1+\mathrm{i})^{\mathrm{n}}}\right) \tag{4}$$

where EC is the energy cost (AUD); UEC is the unit cost of energy (AUD); RC is the net present value (PV) of the system replacement cost (AUD) after its useful life; n is the life-cycle analysis period of component (years); and UC is the unit cost of component (AUD). Apart from counting for the inflation rate, the effort was taken to apply real updated costing information in the Australian context into the investigation. Rawlinsons Construction Cost Guide (Rawlinsons, 2019) and the supplier's quote were the two references of unit costs in this analysis. It was assumed that the system will be recycled for the same purpose or other applications at the end of life-cycle period so that end of Life (EOL) cost was ignored in this analysis being comparatively small.

5.3. Energy-related GHG emission

This study focused on greenhouse gas (GHG) emissions as indicative of environmental sustainability. The GHG emission in alternative water supply systems is predominantly energy-related (Chong et al., 2013; Sharma et al., 2010; Sharma et al., 2009), and it is mainly associated with the energy used for pumping (Inamdar et al., 2018) and the treatment process. Knowing the Victorian GHG emission factor of 1.09 kg CO_2-e/kWh (DISER, 2020) and the energy consumption of the pumps, GHG emission was calculated in tones CO_2-emission. It should be noted that in addition to the pumping energy, the CO_2 emission of greywater treatment systems (GWTSs) corresponds to the energy consumed at each stage of the treatment. This energy is relatively higher than RWHSs and can be calculated using Equations 5 and 6 (DISER, 2020):

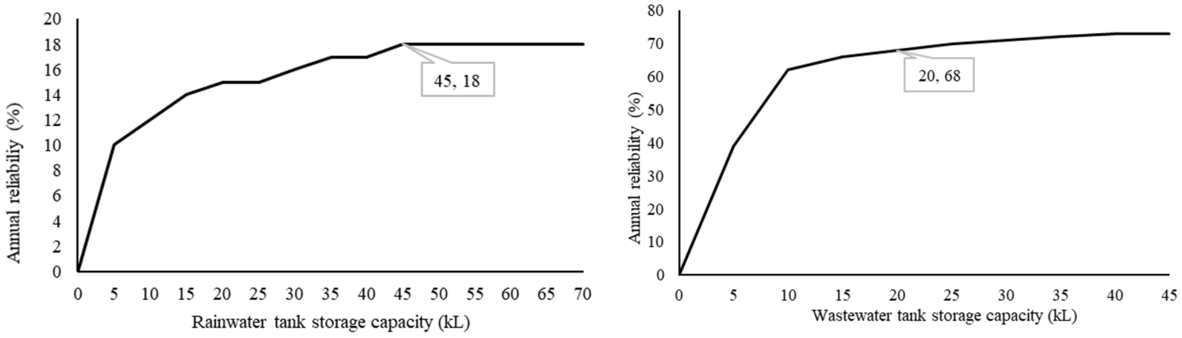
$$\mathrm{CO_2 - e = (COD \times (1 - F_{sl}) - COD_{eff}) \times MCF_{ww} \times EF_w} \tag{5}$$

$$\mathrm{COD = Population \times DC_w} \tag{6}$$

Where $\mathrm{F_{sl}}$ is the default fraction of chemical oxygen demand (COD) removed as sludge; $\mathrm{COD_{eff}}$ is the quantity of COD in wastewater discharged in the effluent from the treatment plant (tone); $\mathrm{EF_w}$ is the default methane emission factor for wastewater (CO_2-e/tone COD); $\mathrm{MCF_{ww}}$ is the fraction of COD anaerobically treated in wastewater; and $\mathrm{DC_w}$ is the COD per capita per year of wastewater (kg). The National Greenhouse Accounts Factors (2020) from the department of industry, science, energy, and resources (DISER, 2020) have been used as the reference for calculation, indicating $F_{sl} = 0.15$, $COD_{eff} = 90\%$ COD removal, $EF_w = 7$, $MCF_{ww} = 0.8$, $DC_w = 0.0585$.

6. Conceptual design of infrastructure for service provision

Before carrying out the analyses, conceptual designs of rainwater and recycled water systems were conducted in accordance with selection guidelines and AS-NZS 3500: Plumbing and drainage standard. The rainwater and greywater storage tank sizes were optimized through an iterative method using UVQ model outputs and each tank was considered individually. To estimate optimal size of the tank, the UVQ model was simulated for various tank sizes in incremental order for estimating rainwater usage for water demand on rainwater tanks. The analysis started with the base scenario, and the size of the tank was increased in 5 kL increments. After running the model each time, the output of the analysis for the annual volumeteric reliability and the tank's water usage was recorded. The annual volumetric reliability is the ratio of rainwater supplied from the raintank over the water demand on raintanks for intended usage per year. Finally, the charts (Fig. 2) were plotted between annual volumetric reliability and tanks sizes were selectedaccordingly. The optimum capacity of the storage tank is the point where increase in tank size only marginally increases the tank water usage or the annual volumetric reliability, as demonstrated in Fig. 2. Storage tanks may be located close to the building, at the Eastern side on the ground level, albeit ignoring aesthetic purposes.



(a) (b)

Fig. 2. Optimal capacity of (a) the rainwater and (b) the greywater storage tanks based on annual volumetric reliability.

A summary of design components is listed in Table 4. Also, Fig. 3 provides a comprehensive view of the building's supply system from the Eastern side of the building studied in this research. It should be noted that the greywater irrigation conduit is not shown in the figure since the pipes and pumps are similar to the ones designed for the GWTS. The only difference is that in greywater conduit, greywater tank and treatment system are substituted by a greywater diverter and a subsurface drip irrigation system.

Table 4. The design components of rainwater harvesting and greywater recycling systems

Storage tanks						
Storage tank	Collection method	Volume	Location	Dimension	Empty tank management	Overflow management
Rainwater	Siphonic drainage	45 kL	Ground level-East	4.6m × 3.4m	Backup by mains water	Directed to stormwater drain
Greywater	Gravity	20 kL	Ground level-East	3.45m × 2.9m	Backup by rainwater tank	Directed to sewer
Pipes						
Pipe No.	Origin		Destination		Length (m) (1)	Size (mm)
1	Roof siphonic outlet		Rainwater tank		48.3	80

2	Canopy gutter	Rainwater tank	45.0	65
3	Household	Greywater primary tank	24.4	25
4	Mains	Library and residential units	92.0	50
5	Rainwater tank	Residential units	30.0	25
6	Greywater storage tank	Green open space	87.0	25

Pumps

Pump No.	Supply system	Required head (m)	Pump model	Required flow rate (L/min)	Pump series
1	Mains	35	Domestic pressure system	85.08	CAM 120/35
2	Rainwater	63	Vertical inline pump	14.64	1SV:11stage
3	Greywater	16.5	Submersible pump	11.64	DN120

(1) This length is the distance between the farthest point of collection and the tank, or the distance between the source and the farthest supply point.

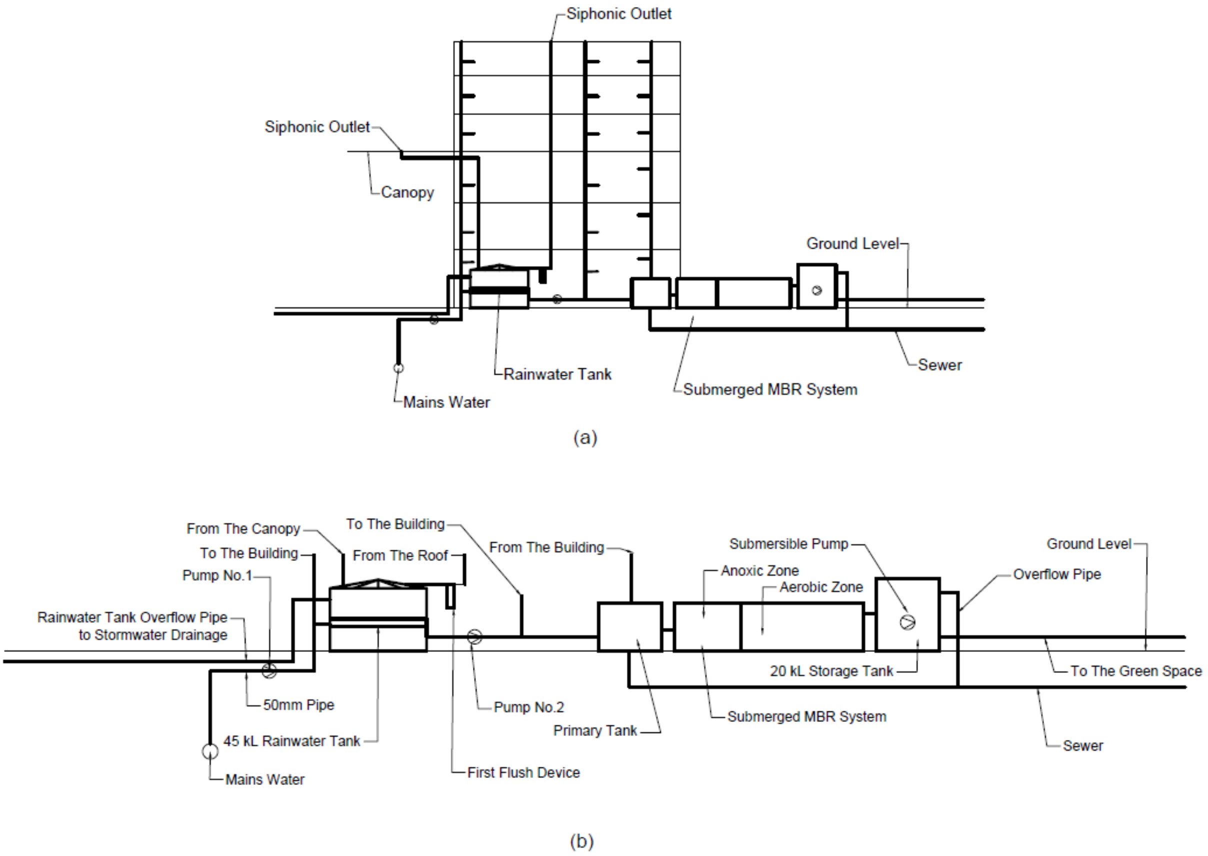


Fig. 3. Conceptual plan of the proposed upgraded water supply system from (a) the building view (b) detailed view of the rainwater and GWTS.

The conceptual design of the upgraded supply system was associated with some details to simplify assumptions made throughout the analysis. One of the design highlights was the use of siphonic drainage to collect rainwater from the roof, which operates passively without using any pump or electric system. It was also assumed that the quality of the collected rainwater is managed through the provision of a plastic leaf guard, leaf strainer and first flush device (EPA Victoria, 2007). Another feature of the design was the management of the empty rainwater and greywater tanks, using a rain aid float valve.

7. Results

7.1. Effects of proposed water-saving scenarios on water balance parameters

Through water-balance analysis using the UVQ model, the average water demand of the building for different in-house and outdoor purposes was determined. The total daily water usage of the site was 25.475 kL, 17.569 kL within the building and 7.906 kL for irrigation. Scenarios listed in Section 4 were examined against water-balance parameters and the results are presented in Table 5.

Table 5. Water balance parameters for each scenario per annum

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Alternative water use (kL)	684	1,853	2,686	2,518	2,714
Rainwater	684	0	0	665	665
Untreated greywater	0	1,853	0	1,853	0
Treated greywater	0	0	2,686	0	2,049
Wastewater discharge reduction(%)	0	28.90	41.86	28.90	31.88
Stormwater runoff reduction(%)	26.18	4.97	7.33	30.63	31.15

Although all scenarios were able to provide an alternative to mains water, the amount of water supplied by each scenario varied. Considering single systems, the annual alternative water use of RWHS was 684 kL, and this amount for the greywater subsurface irrigation and the GWTS was 1,853 kL and 2,686 kL, respectively. While wastewater discharge was unchanged with RWHS, local GWTS decreased wastewater discharge by 42%. Compared to subsurface irrigation, this high rate was due to the treatment process, which prepared water to be reused within the building rather than for irrigation alone. The advantage of RWHS over the other two systems was the potential of reducing stormwater runoff (26.2%). It should be noted that there are still slight reductions in stormwater runoff in the absence of the RWHS. This is because imported water supply leakage and wastewater exfiltration were assumed as non-zero parameters. When a lower amount of mains water is consumed, the supply leakage and consequently stormwater runoff automatically make some reductions.

Integrating RWHS with the other two systems improved the system's performance. It also increased the volumetric reliability of the rainwater tank from 18% to 63% as presented in Table 6. In this case, the rainwater demand is only for toilet supply. Scenario 5, as a combination of RWHS and GWTS, was the most efficient system in terms of mains water consumption and stormwater reduction, with 72% of on-site greywater treatment reliability.

Table 6. Average annual reliability of the alternative supply systems in percent

Alternative supply system	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Rainwater tank	18	NA	NA	63	63
Sub-surface greywater	NA	64	NA	64	NA
On-site greywater treatment	NA	NA	68	NA	72

7.2. Economic implications of water-saving scenarios

Table 7 displays how much each proposed scenario costs initially and during its operation phase. It can be concluded that scenario 2 is the most cost-effective solution due to the following reasons: 1) The system is technically less complex and low-cost at the development stage; 2) It does not supply water to the building so that pumping water to the open space requires a lower amount of energy; 3) Due to the simplicity of the system, the replacement cost is considerably lower. Thus, in scenario 2, it costs AUD 0.75 per kiloliters of untreated greywater over a 45-years analysis period, which has the lowest cost among all solutions, considering the amount of water it supplies. Scenario 4 is the second economic solution due to the presence of the greywater conduit (AUD 1.99 per kL in 45 years). Both RWHS and GWTS and their integration, i.e. scenarios 1, 3, and 5, involved high initial, operational and maintenance costs. However, scenario 1 did not offer any cost advantages, considering its water supply potential. Suppling the whole demand of the building from the mains costs an average of AUD 3.00 per kiloliter (City West Water, 2020), while it costs around AUD 6.00 for each kiloliter of water supplied by RWHS.

By increasing the analysis period, the initial cost remained unchanged, whereas the operation and maintenance cost, including the replacement cost of components after their useful life, increased. The levelized cost, however, varied in accordance with the amount of supplied water. In general, there was a downward trend in levelized cost with increasing the analysis period as shown in table 7.

Table 7. Costing components of the proposed water-saving scenarios

Analysis period	Scenario	Cost component, AUD			
		Initial	Operational and maintenance	Total life-cycle	Levelised per kL
20 years	1	23,301	43,471	66,772	6.81
	2	15,500	8,900	24,400	0.92
	3	43,723	50,287	94,010	2.45
	4	34,771	45,055	79,827	2.22
	5	58,243	65,154	123,397	3.18
25 years	1	23,301	47,989	71,290	6.33
	2	15,500	9,620	25,120	0.83
	3	43,723	73,959	117,682	2.66
	4	34,771	52,591	87,362	2.11
	5	58,243	92,028	150,271	3.37

30 years	1	23,301	55,463	78,764	6.32
	2	15,500	11,367	26,867	0.8
	3	43,723	82,249	125,973	2.58
	4	34,771	60,993	95,764	2.09
	5	58,243	104,003	162,247	3.29
35 years	1	23,301	59,639	82,940	6.16
	2	15,500	14,122	29,622	0.81
	3	43,723	88,831	132,555	2.51
	4	34,771	67,483	102,254	2.07
	5	58,243	111,879	170,122	3.19
40 years	1	23,301	63,875	87,176	6.11
	2	15,500	14,522	30,022	0.78
	3	43,723	94,241	137,965	2.47
	4	34,771	71,756	106,527	2.03
	5	58,243	119,156	177,400	3.14
45 years	1	23,301	66,696	89,997	6.02
	2	15,500	14,850	30,350	0.75
	3	43,723	98,688	142,411	2.43
	4	34,771	74,608	109,379	1.99
	5	58,243	130,834	189,077	3.2
50 years	1	23,301	69,517	92,818	5.99
	2	15,500	16,380	31,880	0.76
	3	43,723	108,699	152,423	2.51
	4	34,771	78,714	113,485	1.99
	5	58,243	135,709	193,952	3.16

7.3. Environmental sustainability in terms of the energy-related GHG emission

The CO_2 emission of the intended scenarios was analyzed following the approach explained in Section 5.3 Depending on the energy used for pumping and the requirement of treatment, scenarios differed in energy-related GHG emission. When reclaimed water was only supplied to the open space (scenario 2), the pumping energy was 1,369 kWh/ year, producing 1.49 tons of CO_2 yearly. Pumping water to both the building and the open space consumed 6,187 kWh/

year (scenarios 1,3,4, and 5) and comprised a higher amount of yearly CO_2 production (6.74 tones). Finally, the treatment process (scenarios 3 and 5) involved the highest yearly CO_2 emission (26.88 tones). As indicated in Fig. 4, scenario 2 had the lowest GHG emission in absence of the treatment system and with the minimum pumping requirement. As both scenarios 3 and 5 required treatment, they included the highest amount of CO_2 emission (33.5 tones yearly). Noting that GWTSs are also associated with non-energy related emissions of nitrous oxide (N_2O) and methane (CH_4), namely fugitive emissions (Sharma et al., 2012), the actual GHG production of the scenarios with the treatment system is higher than the amount calculated here.

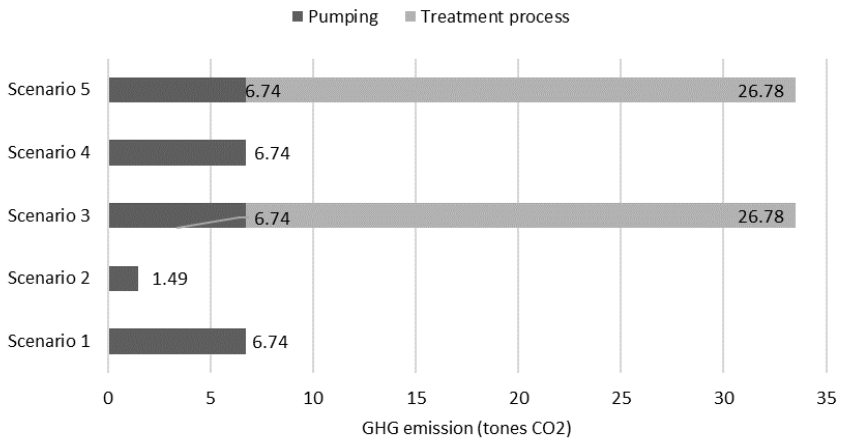


Fig. 4. Annual CO_2 emission of the proposed water supply scenarios

8. Discussion

8.1. Alternative supply solutions for large mixed-use developments: single or hybrid?

This study provided an opportunity to investigate the effects of size and typology on water green-rated buildings. The question was whether the building can comply with the green rating system after upsizing and transformation to the mixed-use development.

In response to this, it should be noted that the green star is a credit-based rating system, focusing specifically on potable water consumption as a sustainability criterion; it, however, is not limited to the application of alternative supply systems and considers a wider range of solutions, including demand management techniques. It cannot confidently be claimed that the building does or does not fulfil the rating system's requirements after the modifications being applied. Nevertheless, the potable water saving will be undoubtedly lower if solely the existing alternative supply solution, the 55 kL rain tank, is considered for the new development. The current rain tank can supply around an average of 700 kL each year (17.5%). Adding three residential levels to the building can decrease this amount to 7.4%. As upsizing the rain tank does not improve water usage any further (Fig. 2), it can be concluded that for large populated buildings where the irrigation space is sizeable, and commercial or institutional use is mixed with residential units, singular supply systems may not be sufficient. If adequate space is available, hybrid systems are recommended, such as the combination of RWHS and GWTS, or RWHS and greywater irrigation. Using hybrid systems, both wastewater discharge and stormwater runoff can be controlled simultaneously. It can also be ensured that non-potable water is supplied steadily over the year considering seasonal variations (Leong et al., 2017; Leong et al., 2018). Integrated systems can also be more economically advantageous due to their higher potable savings and lower pay-back periods (Coutinho Rosa and Ghisi, 2020).

8.2. Decision-making on the most applicable alternative

Deciding on alternative supply solutions at any development scale is always accompanied by a degree of subjectivity (Sapkota et al., 2018; Sharma et al., 2009). The final decision highly depends on multiple stakeholders' concerns, interests, and preferences, finally having greater attention. In mixed-use buildings, even the needs of residents and visitors may be differentiated. It is recommended that before making any decisions, case-oriented and context-specific surveys be carried out among different groups of stakeholders so that community perceptions can be incorporated into the decision-making process. Albeit, we may use a number of local presumptions to make general judgments. Considering the current research in the

Australian context, the findings of previous studies may be incorporated. Sapkota et al. (2018) highlighted that Australian water professionals weigh the three measures of mains water consumption, wastewater discharge, and stormwater runoff equally so that no priority exists among technical performance indicators.

On the other hand, the decision-making process is dealing with social concerns other than measurable indicators, i.e. technical performance, GHG emission, and cost, which might be evaluated through social surveys. In this study, the scenarios have been scored according to the fact that Australians are comfortable with rainwater more than any other alternative water source (Fielding et al., 2019).

Table 8 was developed based on the assumptions above and the parameters measured in Section 7. The evaluation suggested that the aspect at which each scenario excelled, may differ. Scenario 2 was superior in energy-related GHG emission and levelized cost, and scenario 1 best fitted the social criteria. However, the scoring system was a comparative process. Among all, scenario 5, with the highest reduction rates in mains water consumption and stormwater runoff, as well as the second-highest reduction in wastewater discharge, was scored the highest in technical performance (i.e. 5 out of 5). Since scenario 5 comprised a treatment process, similar to scenario 3, GHG emission was the highest, and the environmental score was the lowest (i.e. 1 out of 5). Due to the use of the rainwater and the treated wastewater, scenario 5 was the best community accepted alternative after scenario 1, so it was scored 4. Finally, scenario 5 had the highest levelized cost after scenario 1 and was scored 2. Therefore, considering that all performance indicators are valued equally, scenario 5 was the preferred option. This finding may comprise uncertainties and cannot be generalized to any other cases within Australia nor internationally, in particular, due to the subjective decision-making framework and the factors of location, site specifications, and social considerations. For instance, considering a similar case in a water-scarce region, water-saving benefits may outweigh environmental impacts (Hasik et al., 2017) so that the technical performance might be scored greater than that of the environmental aspect.

Despite uncertainties, the outcomes of this multi-criteria decision-making still emphasize the application of hybrid supply alternatives in high-density mixed-use buildings. It also rejects the single-use of RWHS for such buildings due to its low technical performance and high cost. To get the best results from water-saving projects, it may worth moving from conventional solutions to more advanced technologies in certain cases.

Table 8. Scoring scenarios against performance indicators

Performance aspect	Performance indicator	Scores				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Technical	Mains water consumption	1	2	4	3	5
	Wastewater discharge	1	3	5	3	4
	Stormwater runoff	3	1	2	4	5
Environmental	Energy-related GHG	3	5	1	3	1
Economic	Levelised cost	1	5	3	4	2
Social	Community comfort	5	3	1	2	4
Total score		14	19	16	19	21

Notes: each performance indicator is scored from 1: the lowest performance to 5 The highest performance, and the total score is the sum of all scores given to a scenario.

8.3. The potential of mixed-use buildings to achieve the goal of NZW use

According to the concept of NZW use and the performance of proposed alternative supply scenarios, it can be concluded that the building may not fully achieve NZW use through current measures. Whether the building can approach this goal further requires a higher level of investigation. In this study, scenarios that best-matched site specifications were proposed. The scenarios were technically and economically feasible and in accordance with the health and safety guidelines. They are expected to be socially accepted among residents and the community of visitors. Adding more options to the alternative supply systems, such as stormwater collection and treatment, groundwater usage, water sensitive urban design (WSUD) techniques, may imply better performance in reducing stormwater runoff and reticulated water consumption. However, it still may not replace the use of mains water.

The Department of Health and Human Services of the State Government of Victoria, Australia, suggests using mains water for potable purposes, where available (Health Victoria, 2020). Providing that the mains water was not available, the next best source of water, being rainwater, may be used with proper treatments. As the annual potable demand of the building is extremely higher than the annual rainfall, supplying potable water from RWHS may not be feasible. Moreover, as strict health and safety guidelines limit the use of reclaimed water for potable purposes, the concept of net NZWB may not be achievable for mixed-use buildings of high potable water consumption through alternative supply systems. A way to approach the goal of NZW use is the indoor or outdoor utilization of demand management scenarios (Olmos and Loge, 2013). Quantifying the performance of such scenarios was out of the scope of this study. However, it is recommended to be considered in future research. It should be noted that the projected changes in rainfall patterns and continuous global warming threaten the performance of alternative supply systems (Wijesiri et al., 2020). Hence, even if the goal of NZW use is achievable for a building at the time of construction, its sustainability should be assessed throughout the whole life-cycle period of the building.

9. Conclusion

There is an increasing trend across the globe in mixed-use developments in high density urban areas. This research aimed to investigate the potential of mixed-use buildings to approach NZW use through alternative water supply scenarios. The case study was located in the temperate oceanic climate of Australia and comprised a mixed institutional-residential use. Three singular and two hybrid scenarios were proposed based on the site characteristics and feasibility criteria.

For this study, the concept of NZW was not fully achieved through the proposed solutions. However, it was demonstrated that regardless of the geographical location, mixed-use buildings generally have high potable water demand and low potential for wastewater reuse as the health and safety regulations restrict the use of reclaimed water for purposes with close human contact. Therefore, they can only partially achieve water-saving targets through alternative supply systems, providing that they use hybrid solutions, which is, of course, costly and along with high consumption of energy and production of GHG emission.

Outcomes of this research cannot be generalized to all cases of mixed-use developments. Nevertheless, it can clarify the fact that in high-density populated urban areas, where multi-functional high-rise buildings are one of the essential elements of future urban planning, the use of conventional alternative solutions, which has been widely investigated through former studies, may not be adequate. This includes the use of large storage tanks and on-site treatment systems which may not always be technically nor architecturally feasible in dense land-sensitive urban environments. Reducing water demand at the building scale via community education and demand management techniques may further help to approach water-saving targets or the NZW use concept should be considered in future investigations. It is suggested that various types of mixed-use buildings being analyzed in different sizes and densities in future studies. It is also recommended that a wider range of water-saving scenarios being examined, along with conducting complete life-cycle impact assessments in other geographical locations so that the response of this building typology to water-saving strategies can be demonstrated globally. A detailed comparison between decentralized GWTSs and municipal sewage treatment plants in terms of energy-related GHG emissions is another prospect for future studies.

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