Blue-Green Systems

Blue-Green Systems Vol 4 No 1, 58 doi: 10.2166/bgs.2022.008

Multi-scale stormwater harvesting to enhance urban resilience to climate change impacts and natural disasters

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ABSTRACT

Stormwater harvesting systems are a viable option to adapt cities to cope with climate change and reduce pressure on water supply services. This is particularly crucial in the event of natural disasters (e.g., earthquakes, floods), where large parts of cities may become disconnected from a secure water supply for prolonged time periods. We demonstrate how optimum location, density and storage size can be determined using UrbanBEATS, a spatial planning-support system for planning and design of sustainable Blue-Green Infrastructure strategies. We investigate the Ōtākaro/Avon River catchment, Christchurch, New Zealand for the time periods 2011–2020, 2041–2050 and 2091–2100 (for the RCP 8.5 climate change scenario). For targets of 30% of potable water substitution and 70% storage volumetric reliability, we found that stormwater harvesting systems in all climate scenarios required a larger capacity compared to the baseline. Most storages achieved their set targets and were larger than the municipality's recommended 9 m^3 for flood inundation, indicating that the identified storages would also reduce minor flooding while ensuring water savings. A shift in the spatial layout of modelled systems from highly distributed to more centralised, however, raises a potential conflict with disaster resilience where more local solutions would be preferable.

Key words: Blue-Green Infrastructure, climate change impacts, natural disasters, rainwater harvesting, UrbanBEATS, water supply security

HIGHLIGHTS

- We investigate spatial solutions to stormwater harvesting in the Ōtākaro/Avon River catchment.
- Choice of lot-scale and larger storages is heavily influenced by urban form, density and location.
- Modelled systems show the potential to also mitigate floods according to council recommendations.
- Future climate influence on location/viability of stormwater harvesting is more complex than just rainfall volume.
- Potential conflict was observed between spatial approaches of climate change adaptation and disaster resilience.

1. INTRODUCTION

Combined effects of urbanisation, climate change and natural disasters significantly increase pressure on urban water supply services (Aboelnga *et al.* 2019). As the world's population continues to grow, urban expansion and density threaten natural processes, resource availability and environmental quality (McGrane 2016). Climate extremes, such as droughts, floods and heatwaves, along with industrial intensification, affect urban water quantity and quality (Georgi *et al.* 2016). Disruptions of water systems by these natural hazards and disasters increasingly challenge communities in accessing adequate water services (Balaei *et al.* 2021). At present, many cities around the world do not have sufficient system redundancy to cope with such pressures and shocks (Leal Filho *et al.* 2019).

Blue-Green Infrastructures (BGI) are scalable nature-based solutions that provide a range of stormwater management functions and other ecosystem services (Maksimovic *et al.* 2017; Oral *et al.* 2020) – the practice is also commonly referred to, among other terms, as Water Sensitive Urban Design (WSUD) (Fletcher *et al.* 2015). They are regarded as key to achieving urban resilience to climate change (Almaaitah *et al.* 2021) and encompass a variety of large- and small-scale systems. From the stormwater management perspective, BGIs remove or reduce surface water or stormwater at the source and transport it away from the vulnerable urban system (McGrane 2016). As large 'grey' infrastructure is expensive and disruptive, major infrastructure upgrades are less preferred in capturing stormwater runoff compared to potential BGIs (Houston *et al.* 2011). BGI's multi-scalar response ranges from individual buildings or new development complexes to regional systems which help reduce runoff volumes by incorporating local stormwater management techniques cumulatively and at-source, removing water from the broader urban catchment cycle, and 'translate water from being viewed as a risk into a resource' (McGrane 2016).

Distributed stormwater harvesting systems (SWHS) commonly incorporate BGI elements (Wong *et al.* 2013) and have been adopted by governments and water management authorities as they reduce the pressure on potable water supplies (especially for outdoor uses), therefore reducing extraction from reservoirs, rivers, aquifers, seas and oceans (Imteaz & Moniruzzaman 2020). Additionally, they contribute to flood mitigation caused by frequent, short rainfall events (Jamali *et al.* 2020), stormwater pollution management (Zhang *et al.* 2020) and energy saving for water extraction, processing, transportation and pumping (Imteaz & Moniruzzaman 2020). These benefits contribute to overall water sustainability in urban environments. As cities have full access to stormwater, SWHS can help meet water demand and avoid over-extraction from surface and groundwater sources (Stockholm Environment Institute 2009). Increasing the water provisioning capacity for cities can reduce the burdens imposed on the natural ecosystem and contribute to human well-being (Semeraro *et al.* 2021). Cities can be considered as 'artificial ecosystems', where controlled flows of water and energy provide a habitat for the urban population (Stockholm Environment Institute 2009). Storm flows, incidences of flooding and peak flows can hence be reduced/regulated by stormwater harvesting interventions (Nkirote 2020), which, in turn, provide valuable ecosystem services.

Selecting the optimum size of SWHS can help to ensure that this water supply provides for the expected domestic uses (Haque *et al.* 2016) and, concurrently, adequate storage buffer during large rain events (Jamali *et al.* 2020). Choosing sizes that are either larger than what can be used efficiently or too small to meet demands can lead to a waste of energy, time, available urban space and resources. Another consideration in designing SWHS for water resource planning and management is the potential impact of climate change, especially changes in rainfall amount and temporal distribution, as it is the main variable that will affect SWHS (Aurib *et al.* 2017). Understanding the performance of SWHS under different climate conditions will increase the certainty and robustness of designs and support decision-making regarding alternative water sources (Zhang *et al.* 2019a; Imteaz & Moniruzzaman 2020).

Due to the complex interactions between natural, social and built environments (e.g., urban drainage systems, quantity of available measures and significant investments needed to implement climate change adaptation measures), it is challenging to select the most suitable options for a given city (Jha *et al.* 2012; Simonović 2012). Appropriate planning-support systems can help by processing significant volumes of quantitative and qualitative information required in the planning and design process. However, many frequently focus on either suitable locations or suitable system types and fall short of integrating all aspects. Some examples of planning-support systems include the Storm Water Management Model (SWMM) (Rossman 2015), the Adaptation Support Tool (AST) (Voskamp & Van de Ven 2015), Preparing for Extreme and Rare Events in Coastal Regions (PEARL) intelligent knowledge-base (PEARL KB) (Karavokiros *et al.* 2016), System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) (Lee *et al.* 2012), Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Hamel *et al.* 2021) and the Urban Biophysical Environments and Technologies Simulator (UrbanBEATS) (Bach *et al.* 2018, 2020). As an open-source software, SWMM is the most frequently used tool in catchment and BGI planning, able to estimate the effects of different interventions on the hydrologic cycle (Kim *et al.* 2015; Joshi *et al.* 2021; Jiang *et al.* 2022), but relies heavily on users to provide pre-defined infrastructure plans for evaluation. AST provides planning practitioners a range of preferred measures based on local environmental characteristics, characteristics of the urban built form, spatial scale, position of adaptation measures in the watershed, combinations of BGI measures and using multiple ecosystem functions (Voskamp & Van de Ven 2015). PEARL KB was developed based on previous projects and tools to select suitable measures to adapt and mitigate the impacts of hazards and risks resulting from extreme hydro-meteorological events (Karavokiros *et al.* 2016). In order to meet water quality and quantity goals, SUSTAIN supports watershed practitioners in evaluating stormwater management options based on their optimal location, type and cost (Lee *et al.* 2012). InVEST (Hamel *et al.* 2021) adopts a broader ecosystem services perspective and helps identify priority locations in cities for nature-based interventions. Most of these models either have a weak link between urban planning and BGI or do not consider multiple aspects of BGI planning, multiple system types and scales, as well as multiple purposes. UrbanBEATS, in particular, supports the design and planning of BGI opportunities at multiple spatial scales and for different water management objectives (Bach *et al.* 2018, 2020), integrating both location choice and BGI system selection and sizing (i.e., storage volumes in the case of SWHS) based on scale, urban form and demographic characteristics. As such, it provides a suitable basis for exploring the multiple benefits that BGI can provide.

In this study, specifically, we used the UrbanBEATS planning-support system to assess the suitability and robustness of SWHS to improve urban stormwater management and safeguard urban areas from the impacts of climate change and their potential benefits in making cities more resilient to natural disasters. Specifically, we focus on the following objectives:

- to understand how SWHS vary across a disaster-prone city,
- to explore how climate change might impact SWHS planning outcomes (i.e., system capacity, scale, and location), and
- to discuss the implications of multi-functionality of SWHS in infrastructure planning practice.

Our findings provide water authorities, policy makers, and the public with a better insight into how strategic use of SWHS can reduce the impacts of climate change and disaster risks.

2. MATERIALS & METHODS

2.1. Case study description

The case study catchment is the Ōtākaro/Avon River catchment, located in Christchurch, the largest city on the South Island and the second-largest city in New Zealand (see Figure 1(a)). Christchurch's population in 2018 was 380,400 and it is expected to grow to 463,500 by 2048 (Stats NZ 2021a, 2021b). Data for 2018 show higher density (persons/ha) in the central and southern parts (Stats NZ 2019). The population trend (Figure 1(b)) shows the continued increase of residents from 1996, except for a strong decline due to the major earthquake sequence during 2010/2011. The average daily residential water consumption is 0.252 m^3/person/day (R. Will, personal communication, May 27, 2021). Whilst residents have paid for water indirectly through rates, as of July 2022, a water bill will be introduced if the usage limit is exceeded (per 1,000 L of excess water supplied) (Christchurch City Council 2021). The Christchurch City Council (CCC) has included stormwater tanks as one of the solutions to attenuate runoff from residential intensification within the Ōtākaro/Avon River catchment (Christchurch City Council 2015). A minimum 9 m^3 tank size was recommended for this purpose (Christchurch City Council 2004).

Identifying measures to achieve water security is of great importance as the city is likely to face water-related challenges in the future because of potential water shortage due to increased population, climate change and natural disasters caused by weather extremes. In the past, due to the movement and liquefaction caused by the 2010–2011 Canterbury Earthquake sequence (shown in dark red in Figure 1(c)), much of the underground infrastructure (pipes, wells and reservoirs) was damaged and potentially contaminated, necessitating the application of chlorine to some of the supply until late 2011 (Potter *et al.* 2015). Furthermore, seven of the eight main reservoirs were damaged and/or emptied during the incident (Marsollier *et al.* 2015). As a result, no main water supply was available for more than 100 days after the earthquakes in some communities (Dearnaley 2011). Widespread flooding of properties in river suburbs occurred following several intense rain events in March 2014, June 2016, July 2017 and December 2021. High flood hazard areas (blue colour in Figure 1(c)) have been identified in areas such as the Cranford Basin or most of the Ōtākaro/Avon River Corridor with flood depths greater than 1 m. Likewise, potential tsunami inundation (cyan colour in Figure 1(c)) plagues coastal regions and has led to clear identification of permitted and/or restricted/controlled/prohibited activities in the Christchurch district plan (Christchurch City Council 2019). Apart from earthquakes and floods, water restrictions (i.e., cutting back on outdoor water use) were enforced by the CCC, for example, in the summers of 2019, 2020 and 2021 when air temperatures and demand for water were high, further pressuring the city's water supply network (Christchurch City Council 2020). With this knowledge, it is of interest in this study to understand not only the potential water supply security benefits that SWHS can provide but also how these strategies may vary across different disaster-prone regions.

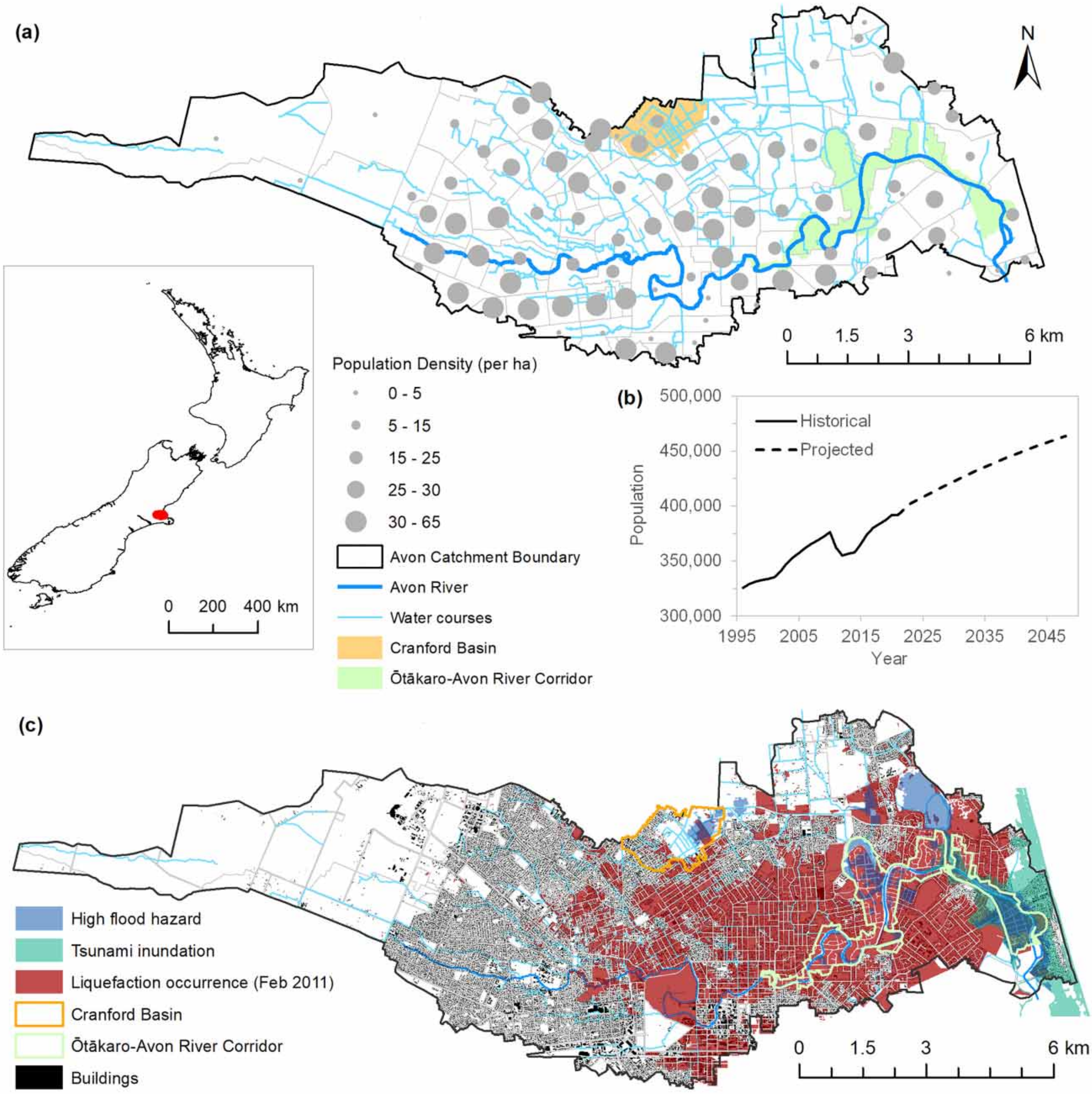

Figure 1 | Overview of the Ōtākaro/Avon River catchment case study showing (a) boundary (black line) and population density (persons/ha) in 2018 in each statistical area defined by Stats NZ (2019) and water courses, (b) historical and projected population in Christchurch City until 2048 (Stats NZ 2021a, 2021b) and (c) areas susceptible to major disasters including the 2011 earthquake (data source: CCC).

2.2. Overview of the UrbanBEATS model

UrbanBEATS is a planning-support system that integrates BGI technologies for stormwater management with urban planning (Bach *et al.* 2018, 2020). It processes detailed information of the simulation case study including land use, soil type, topography and population density, to a coarse uniform grid of cells known as 'blocks' (Bach *et al.* 2018), delineates sub-catchments (SC) through flow-path delineation and characteristics of the urban form using statutory planning regulations as input parameters (Bach *et al.* 2018). The spatial representation in the model uses a coarse spatial grid, each block therein containing a geodatabase of local information. Using this, UrbanBEATS then generates spatially explicit BGI layouts to fulfil stormwater quantity, quality and/or potable water substitution objectives (Bach *et al.* 2018).

To create spatial layouts for stormwater harvesting, UrbanBEATS first estimates water demands across the spatial region on a block-by-block basis (Bach *et al.* 2020) based on end-use analysis (Mitchell *et al.* 2001). The generation of BGI options then follows several steps including (1) an 'optioneering step', where all possible locations and scales (i.e., lot and neighbourhood/catchment scales) in the map are identified and potential technological designs are created (here we focus only on storage volumes of SWHS through the use of rain/stormwater tanks), (2) a Monte Carlo algorithm that generates thousands of layouts by randomly selecting sets of locations and appropriate designs across the map and combining them (Bach *et al.* 2013, 2020) and (3) a filter and evaluation step where suitable layouts are identified that align closest with stormwater management objectives and stakeholder preferences (the latter of which are not considered here). SWHS are designed based on 'storage-behaviour analysis' (Mitchell *et al.* 2008) at a daily time step using the water demand information in UrbanBEATS and rainfall and potential evapotranspiration (PET) data as input. Volumes of SWHS are optimised to the desired, user-defined volumetric reliability, (defined as the total volume of water supplied from SWHS divided by the total demand required (Imteaz *et al.* 2011a)). To coordinate the spatial allocation of harvesting systems in the model, catchment information and water flow-paths are explicitly considered. We opted for a 'harvest from upstream catchment to supply both upstream and downstream areas' strategy. A more detailed description of the model and its alternative options for SWHS can be found in Bach *et al.* (2018, 2020). Although UrbanBEATS can design treatment systems as part of SWHS options, they are currently limited to Australian standards and therefore limited in application internationally. Our primary focus is on identifying suitable storage capacities of SWHS, which are readily adaptable to an international context and future climate data.

2.3. Input data

To set up UrbanBEATS for the Ōtākaro/Avon River catchment, a spatial data set comprising four basic input maps and one calibration map was prepared (see Figure 2). Urban land use was reclassified from the district plan map (provided by CCC) into nine of UrbanBEATS' 16 land-use classes (Table S1 in Supplementary Information – SI). A digital elevation model (Land Information New Zealand 2019) at 10 m resolution was prepared. Soil classification was obtained from S-map soils (Landcare Research New Zealand 2020) and reclassified into UrbanBEATS' four categories ranging from sandy to clay soils (SI Table S2). Missing soil information around the airport and the estuary was infilled through spatial interpolation of nearest neighbour categories. The

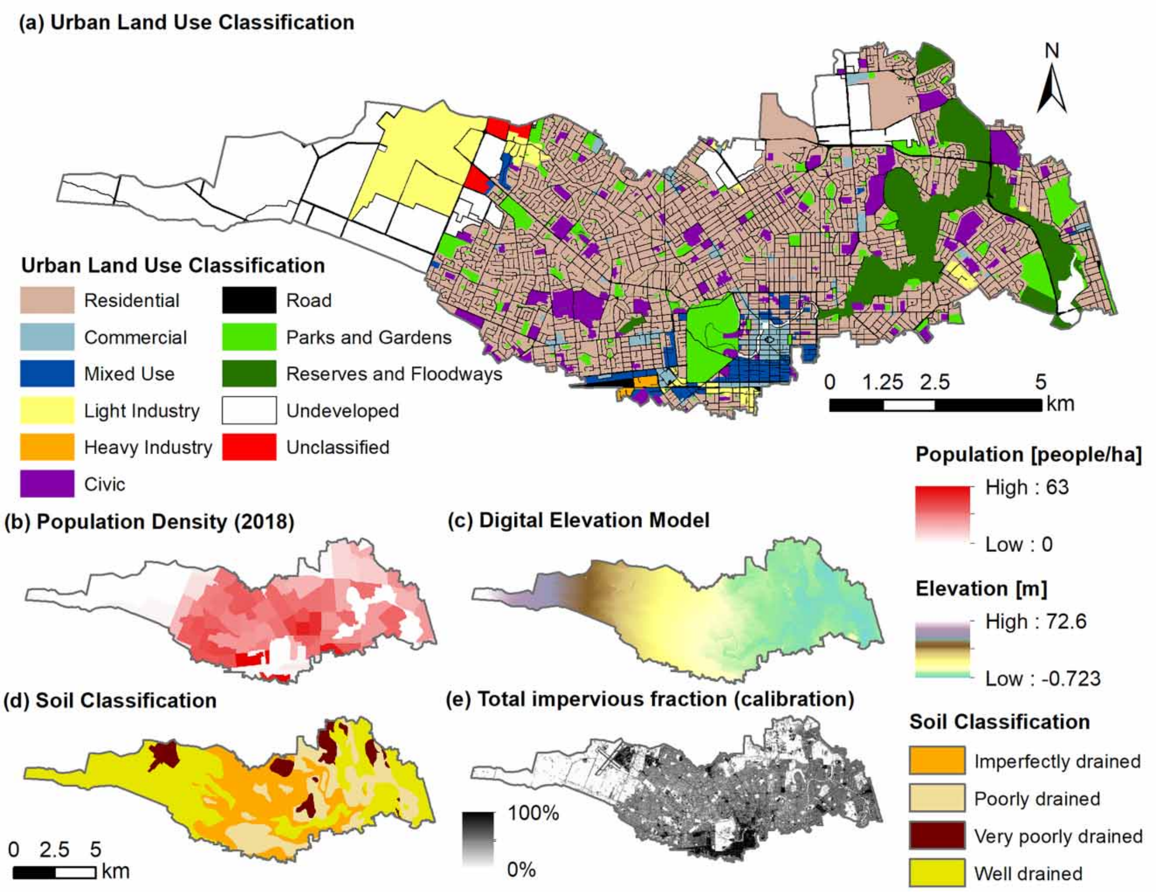

Figure 2 | Overview of land use characteristics and other spatial input data for the Ōtākaro/Avon River catchment.

population density was based on the 2018 Census (Stats NZ 2019). Finally, the total impervious fraction map for Christchurch (Pairman *et al.* 2013) was employed for calibrating the model's urban form characteristics.

2.4. Rainfall data and climate scenarios

Rainfall data were acquired from the Botanic Gardens rain gauge and climate data (temperature, solar radiation, wind speed, relative humidity and air pressure) from the Kyle Street climate station for a ten-year period (2011–2020) to represent the 'baseline' climate scenario. The locations of the two rain gauges are shown in Figure S1. Climate data were used to calculate PET using the Penman–Monteith approach (Allen *et al.* 1998). Climate change scenarios were prepared by feeding hourly climate data into SimCLIM, a modelling system designed to project climate changes (Warrick *et al.* 2012). For the purpose of researching the upper bounds of climate change impacts, this study focused on the potentially worst future climate change scenario (Representative Concentration Pathway – RCP 8.5). To reflect the range of uncertainty, out of the 46 regional climate model (RCM) simulations available in SimCLIM, two RCMs were selected as they produced the highest (GFDL-ESM2G) and lowest (GISS-E2-R-CC) average annual rainfall (SI Table S3). The future periods included 10 years during 2041–2050 and 2091–2100. Future PET was calculated by the Penman–Monteith approach.

Five climate scenarios were designed for this study: (1) the baseline 2011–2020 period ('Baseline'), (2) the RCP8.5 near future (2041–2050) maximum using GFDL-ESM2G simulation ('Near future max'), (3) the RCP8.5 near future (2041–2050) minimum using GISS-E2-R-CC GCM simulation ('Near future min'), (4) the RCP8.5 far future (2091–2100) maximum using GFDL-ESM2G simulation ('Far future max') and (5) the RCP8.5 far future (2091–2100) minimum using GISS-E2-R-CC simulation ('Far future min'). Based on these scenarios, we explore how stormwater harvesting schemes generated by UrbanBEATS will vary in terms of SWHS' sizes, densities and locations.

2.5. Model setup and calibration

UrbanBEATS was used to process input raster layers (10 m resolution) to an aggregated grid of 500 m discretisation of city 'Blocks'. To determine urban form characteristics, initial statutory planning parameters were derived from local regulations (Christchurch City Council 2019) and calibrated against the impervious fraction layer. To estimate water demands, we used an assumed two-star water efficiency rating based on the AS/NZ6400:2005 standards for the rating and labelling of products for water efficiency. Water demand for residential water use was estimated following Matthews & Dooney (2018): kitchen (1 time/day/person for 10 min), shower (1 time/day/person for 8 min), toilet (3 times/day/person) and laundry (4 times/week for a household with three members). Approximate annual irrigation volume for garden use was estimated as 1 ML/ha/year. For commercial and industrial water demand, the default of 40 ($\pm$10%) L/cap/day was used in this study. This information is employed for calculating water demand for a block and a whole catchment. SI Tables S4, S5 and S6 show detailed planning rules for land uses after calibration. UrbanBEATS was set to generate 1,000 different stormwater harvesting layouts (considering only rain/stormwater storage tanks) for each climate scenario and the 10 most suitable strategies were derived, which aligned closest with the following objectives:

- targeting 30% potable water substitution;
- all systems designed to achieve 70% volumetric reliability; and
- limiting the technological options to lot- and neighbourhood-scale SWHS (i.e., contained within their local 500 m 'Block').

Specifically, above-ground SWHS with a maximum depth of 2.0 m and 0.17 m of dead storage volume as required by Christchurch City Council (2004) were considered. Such SWHS are easier to implement post-development and are less prone to earthquake damage, which is relevant for a seismically active region. This also implies that UrbanBEATS will explicitly consider available land space to accommodate these systems. All output layouts were analysed collectively for each scenario to generalise and compare findings across the catchment.

3. RESULTS AND DISCUSSION

3.1. Catchment and urban form characteristics

At 500 m 'Block' size, the catchment was delineated into five SCs (see Figure 3). The largest SC by area is SC2 (in yellow) where most of the residential area was located. These delineated SCs can be related back to the overall

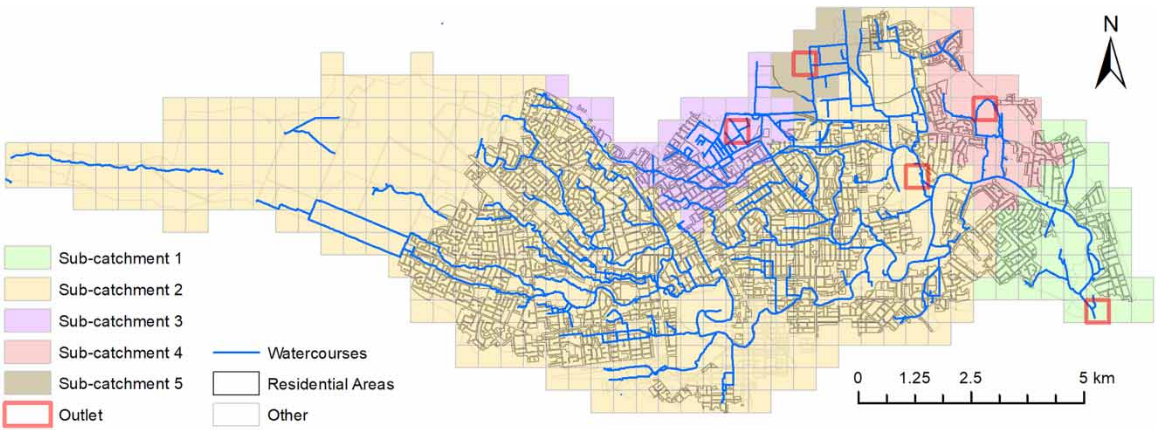

Figure 3 | Block and catchment delineation, together with residential areas and watercourses. Outlets in the map represent key locations in the region where major depressions, entry into significant water bodies or larger drainage infrastructures are often present.

subdivision of key drainage corridors (SC1 representing the Ōtākaro/Avon Estuary, SC2 representing the main Ōtākaro/Avon River basin, SC3 representing Cranford basin, SC4 representing Travis Wetland and SC5 representing Marshland). Calibration of total impervious fractions was carried out based on Bach *et al.* (2018) and showed a good fit with observed data, a Nash–Sutcliffe efficiency (Nash & Sutcliffe 1970) of 0.73.

3.2. Baseline scenario

Simulation results across 10 modelled outputs for the baseline are shown in Figure 4 for the urban area including total spatial water demands (Figure 4(a)), location and density of lot-scale systems (Figure 4(b)) and, finally, the average proportions of water supplied by potable and alternative water sources (Figure 4(c)). The two disaster-prone locations Cranford Basin (yellow) and the Ōtākaro/Avon River Corridor (green) were investigated to see if specific opportunities for flood protection arise by installing SWHS. These results show that there are more opportunities to install larger-scale storages towards the edge of these two locations (where land has been cleared and future development is limited) compared to smaller-scale tanks. Apart from the two selected areas, there were few suggested SWHS in the areas of potential tsunami inundation (light blue in Figure 1(c)). Density of lot-scale storages positively correlates with population densities (Figures 1(a) and 2(b)). However, at higher densities, space becomes an issue. Logically, fewer systems were present in areas upstream of the residential land where less people live.

We selected the 10 modelled BGI system layouts from the 1,000 generated by UrbanBEATS that were closest to planning objectives. All layouts met the overall targets: substituting 30% of potable water demand at 70% volumetric reliability, but notably, these targets are achieved differently among the ten strategies analysed. The average performance shown in Figure 4(c) provides an indication of how stormwater harvesting opportunities will change across the catchment. At first glance, the substitution of potable supply is not uniform across the catchment and depends on several factors including types of water demands substituted, available space and the presence of lot-scale and neighbourhood-scale systems. Nevertheless, there is significant potential for alternative water sources to cover the entire demand in some city districts if a multi-scalar strategy is carefully planned. For example, in Figure 4(c), it can be seen in the central areas that there are frequently locations dominated by larger neighbourhood-scale systems, surrounded by sprawls of the residential area supported by lot-scale SWHS. City planners and councils could also use this information as guidance to relocate or prioritise how potable water supply services can be tailored in the event of emergencies in the locations where needed, by monitoring water levels with the support of internet-of-things (IoT) technology. IoT solutions applicable for this purpose have been reviewed recently by Jan *et al.* (2022).

Careful planning is needed to select appropriate systems. On the one hand, small-scale tanks on private land can be more easily managed than larger-scale storages in terms of cost, installation and maintenance (Abbott *et al.* 2011). On the other hand, decision makers and stakeholders need to carefully consider which areas need to be prioritised to install larger storages to achieve the desired water supply and the desired urban resilience to floods and/or disaster preparedness at the same time. Placing SWHS in disaster-prone areas can be

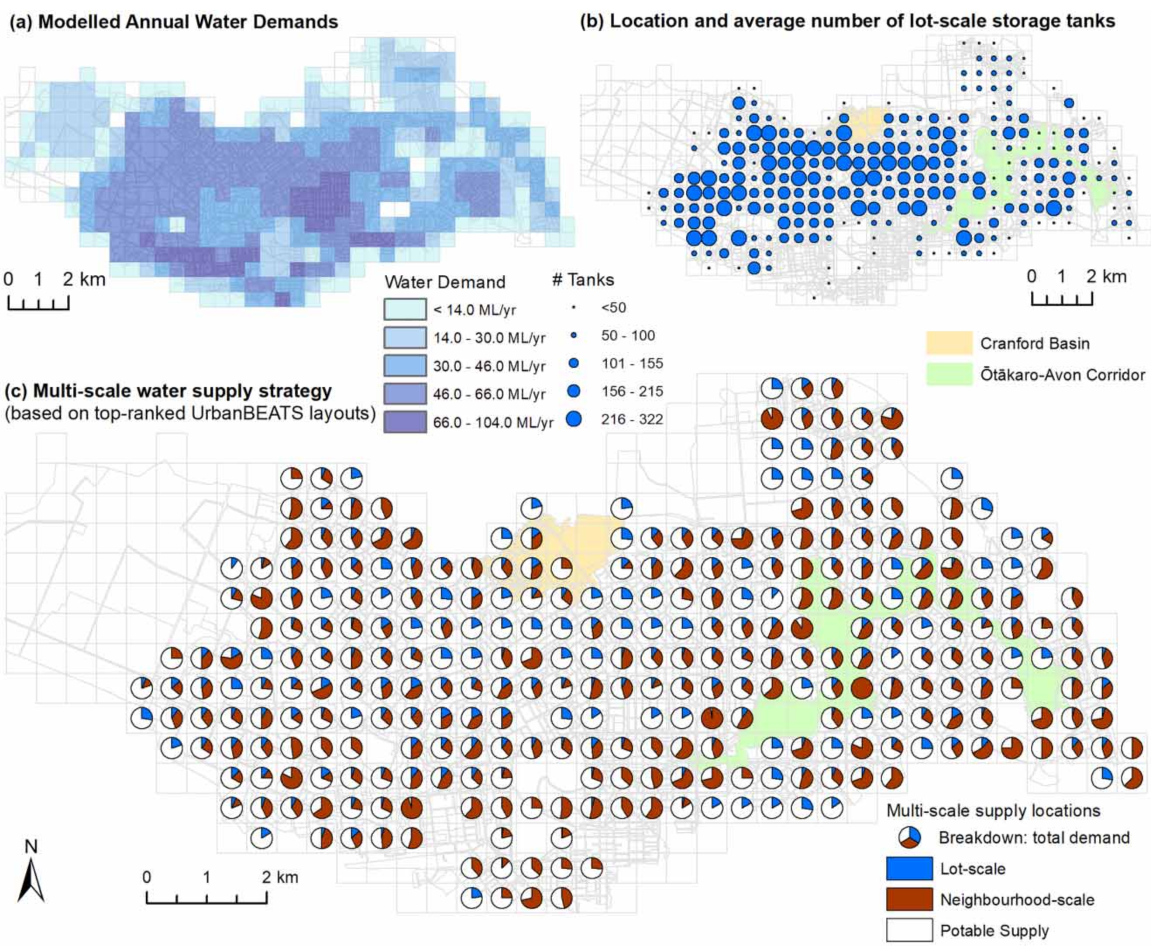

Figure 4 | Statistical evaluation of simulation results based on 10 modelled outputs, (a) modelled spatial annual water demands, (b) selected locations and average number of lot-scale stormwater tanks and (c) average breakdown of multi-scale water supply, showing proportions of total water demand supplied by lot-, neighbourhood-scale and potable water supply sources at suggested locations.

advantageous. These opportunities will reduce local flooding, as a percentage of stormwater during storm events will be stored in SWHS, thereby also reducing pressure on downstream areas, and sustaining one's own water supply for a significant time period until their local water supply is restored/available or safe to drink following an emergency. Larger storages, which are available in open green spaces such as the Ōtākaro/Avon River Corridor (with proposed areas for connecting and involving communities), can supply water for outdoor activities without drawing water from the mains water supply as well as sustain water for a larger number of people after an emergency. However, SWHS can only store a limited amount of stormwater. Reduced flooding could instead be achieved by combining SWHS with other flood mitigation measures, such as wetlands, and raingardens and allowing greater room within the floodplain. Other future options might consider the implementation of smart SWHS that automatically release stormwater prior to rainfall events to increase retention capacity at the household level (Olisa *et al.* 2021; Jan *et al.* 2022).

Figure 5(a) depicts stormwater storage volume per person in which the highest stormwater volume for one person was identified in SC2 and the lowest was found in SC5. The size was optimised based on the 10-year rainfall data and met 70% reliability and 30% potable water substitution. Stormwater storages at the neighbourhood scale ranged from 7 m^3 (min.) to 4,251 m^3 (max.) and their sizes varied from SC2 (largest volumes) to SC4 (lowest volume), except for SC5 (Figure 5(b)). Most storages (99%) exceeded 9 m^3, which was the minimum size proposed by CCC for flood attenuation in residential intensification. The average size of stormwater storages required at the neighbourhood scale for SC1 was 500 m^3, for SC2 was 800 m^3, for SC3 and SC5 was 600 m^3 and for SC4 was 300 m^3. Stormwater tanks for residential houses varied from 1 to 7.5 m^3, with most tank sizes falling in the category of 2 m^3 (Figure 5(c)). While most of the results in SC5 generally show lower volumes than other SCs, the average storage size at the neighbourhood scale was similar to SC2. SC5 is the smallest sub-

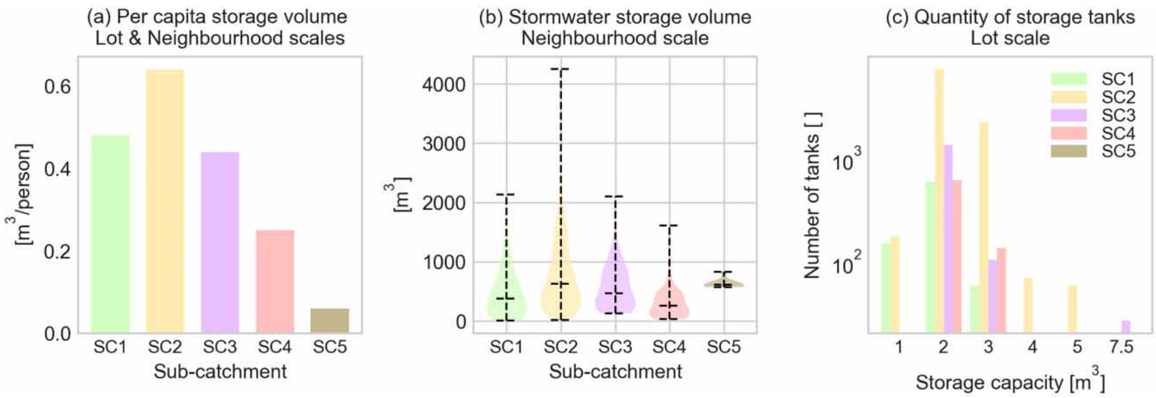

Figure 5 | Summary of baseline results based on 10 modelled outputs by sub-catchment, (a) total storage volume per person entire catchment, (b) changes of stormwater storage volume in neighbourhood scale (centre dashed line depicts medians), (c) density of stormwater tanks in lot scale.

catchment, located along the urban fringe with limited urban development and, hence, limited opportunities for SWHS.

Larger sizes do not always provide better solutions. Here, it was found that smaller-scale solutions were identified more often than larger-scale solutions. Again, SC2 contained a large number of water tanks compared to other catchments, owing to the larger sub-catchment area and its higher population density. The dominant stormwater tank size at the lot scale was 2 m^3. The per-capita required water storage volume in SC2 was 0.64 m^3. With an average household occupancy set in UrbanBEATS at 2.67, this implies that in every six households, a storage volume of more than 9 m^3 is required. Meanwhile, most of the larger storages met the required 9 m^3. As stormwater management has become a priority concern for urban planners, designers and decision makers, evaluating the potential of SWHS in urban areas can be particularly useful for planning purposes to decide where and whether they have the most potential to reduce pressure on the mains water supply, reduce flooding and alleviate disaster emergency (Deitch & Feirer 2019). It has been shown here that flood reduction can be achieved at both neighbourhood and lot scales. Stormwater harvesting tanks have been recommended for household emergency resilience in the case of Wellington (New Zealand) to cope with water supply interruptions due to earthquakes (Harrison & Grierson 2011). The decision regarding small or large scales as well as the number of SWHS will have to be made in conjunction with city planning and private home owners such that stormwater management objectives can be effectively achieved. Potentially, SWHS proposed for the Ōtākaro/Avon River catchment should be able to fulfil multiple functions, reducing pressure on mains water supplies (every storage can save at least 30% of potable water demand) and storing water for future uses during hot days and disaster emergency on the one hand, and on the other hand, collecting stormwater to reduce flood risks (based on the CCC requirement for flood attenuation).

3.3. Future climate scenarios

Whilst the baseline solutions proposed by UrbanBEATS appear to provide a wide variety of layouts (grey violins in Figure 6), future climate scenarios produce a notable shift in layouts, notably contrasted between near and far future cases. The most observable difference between 'baseline' and the future scenarios studied is that, firstly, the number of blocks selected for the neighbourhood-scale system generally increased (apart from the 'far future max' case) from the baseline (Figure 6(a)), suggesting less reliance on lot-scale systems, which appear to be more constrained and decrease in numbers (Figure 6(b)). This is possibly due to the fact that previously suggested storage volumes at the lot-scale are no longer feasible for achieving the desired volumetric reliability. Secondly, even though median storage volumes appear to be unchanged (Figure 7(a)), 'minimum' scenarios have a constraining effect on SWHS options whereas 'maximum' scenarios result in an increased range of extreme storage capacities.

Stormwater storages for the neighbourhood scale ranged from 5.3 m^3 (min.) to 6,576 m^3 (max.) in future scenarios (see Figure 7(a)), larger than those in the baseline. Again, most of the sizes (99%) were larger than 9 m^3 for all future scenarios. Notably, 'far future max' required fewer stormwater storages, but larger sizes compared to the other scenarios, suggesting a shift towards centralisation, which could be counterintuitive to ensuring disaster resilience where a more distributed approach may be favoured to enable easy access to water or flood retention

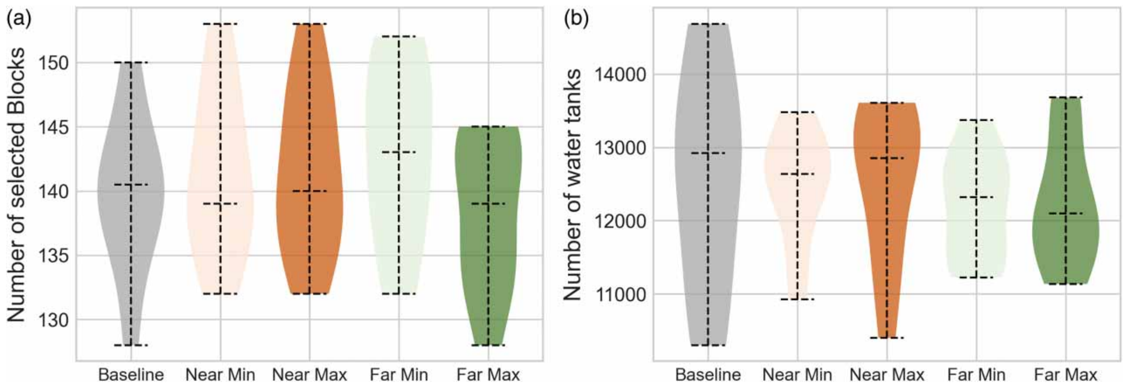

Figure 6 | Distributions of density of stormwater storages density at different scales and scenarios based on 10 modelled outputs (a) number of blocks selected for the neighbourhood-scale system and (b) number of stormwater tanks for lot scale systems.

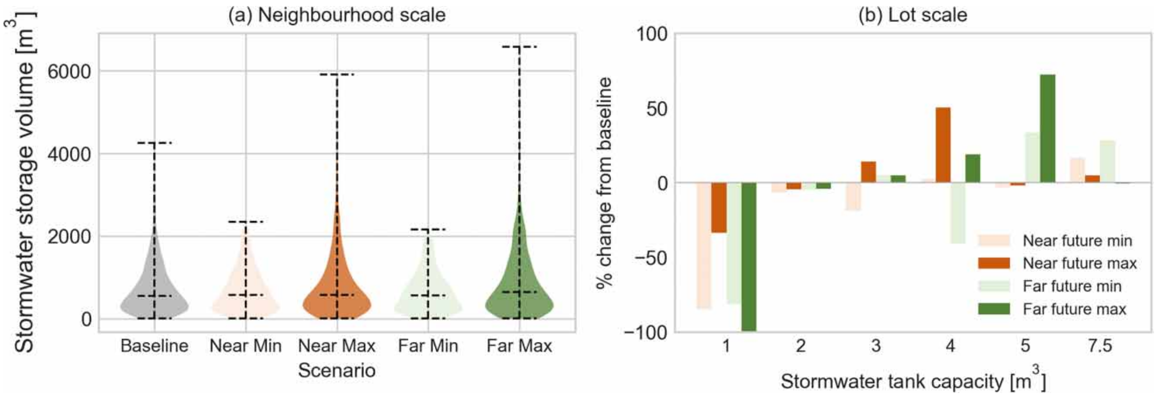

Figure 7 | Stormwater tanks/storages sizes based on 10 strategies, by scale and scenario, compared with the baseline 2011–2020.

storage. We also see this shift in Figure 7(b), where future lot-scale tank sizes were compared with the baseline case. Sizes varied from 1 to 15 m^3 (note that 15 m^3 was the only size recommended in 'far future max'). Compared with the baseline, for all future scenarios, a clear shift is observed from tanks sized up to 2 m^3 to tanks sized larger than 2 m^3. No 1 m^3 stormwater tanks were identified for the far future max scenario. The biggest increase in the number of stormwater tanks occurred for the near future max (+50%) for 4 m^3 and far future max (+73%) for 5 m^3. This need to increase storage capacity signals the possible drop in supply reliability due to the changing effects of rainfall patterns due to climate change and our general trends appear consistent with observations made by Zhang *et al.* (2019a), who assessed these on a system-by-system basis using downscaled future rainfall data and the MUSIC model (eWater 2014).

The stormwater storage capacities were proposed based on the rainfall intensity and variability. Here the climate change scenario RCP 8.5 was selected to determine the potentially required storage sizes and locations for the most undesirable climate change scenario. Due to changes in future climate (more rainfall predicted in the near and far future max, less rainfall predicted in the near and far future min), larger storage sizes were required at both scales in the near and far future max to achieve the set targets. Furthermore, far future max compensated the impact of climate change by using much larger storage sizes, at larger and smaller scales.

Decision makers and stakeholders should choose the stormwater storage sizes considering the potential impacts of climate change and other related uncertainties. Zhang *et al.* (2019b) showed that a larger storage in some cases could ease or remedy the impacts of climate change, while Imteaz & Moniruzzaman (2020) pointed out the variability of water savings and reliabilities in different projections of climate models. This 'rule-of-thumb' should also apply here as the urban form appears to be able to accommodate larger sizes. Notable, however, is that we simulated these scenarios under the assumption that urban development remains static, which presents a key limitation. As such, results should be interpreted in terms of the resilience of the current state, with an outlook to future climate change. With evolving urban development, possible locations of SWHS are also likely to be affected and space is likely to become scarcer. 'Baseline' results have already shown that the density of lot-scale systems peak in the medium population density ranges and is likely to become unfeasible with further densification.

The sizes and volumes of SWHS were optimised to achieve 70% reliability and 30% potable water substitution. All SCs can achieve the targets with the shift towards larger system sizes, even under future climate conditions. Looking at the maximum achievable potable water substitution, which UrbanBEATS also determines before filtering out options, Table 1 shows the limit of what is achievable has been reached in SC5. It also shows that future climate impacts are not as straightforward as one might suspect since variable rainfall patterns matter just as much as a general increase or decrease in rainfall volumes. Climate adaptation will thus have to not only encompass rigorous analysis of future conditions, but also look at solutions tailored to the individual characteristics of each sub-catchment and, perhaps, more holistic and regional cross-catchment solutions are required if climate vulnerability and disaster risks are to be mitigated.

3.4. Further discussion

3.4.1. Benefits of storage systems for individual households

In order to establish a successful city-wide storage system, the individual parts of the system, i.e. the individual households, need to contribute. Their willingness will likely depend on the benefits. Potential water savings via stormwater harvesting have been reported for a range of locations in the literature. For example, 30% to 90% of potable water savings were reported in a study focussing on Ireland (Li *et al.* 2010); 40% to 60% were found in case studies in Sweden (Villarreal & Dixon 2005) and up to 40% of potable water use were reportedly saved in parts of regional Victoria, Australia (Muthukumaran *et al.* 2011). In the current study, the storage sizes, density and locations were determined to identify options to save at least 30% of potable water use, a conservative, but significant goal. When defining the savings goal for a given municipality it must be considered that the storage size is directly proportional to storage reliability and inversely proportional to benefit–cost ratio values (Hajani & Rahman 2014; Preeti & Rahman 2021). At the lot scale, reliability depends on several variables including climatic conditions, roof area, tank volume and household water demands (Imteaz *et al.* 2012), while the financial viability of a stormwater harvesting system is affected by tank size, water requirements, climate conditions and rainfall variability. However, Imteaz *et al.* (2012) found that even with a very large tank ($10\,m^3$) and a roof size of $100\,m^2$, it was not feasible to achieve 100% reliability. It will depend on the purpose of using stormwater in each household, either for outdoor use (car washing and irrigation) and/or indoor use (toilet flushing and laundry). To achieve the best financial outcome for home owners, it has been recommended that stormwater tanks should be connected to toilet, laundry and outdoor irrigation (Rahman *et al.* 2012). To select the right tank size for each household, however, requires further investigation on a case-by-case basis. The same holds true for lot, street, neighbourhood and sub-catchment scale. Additionally, at the neighbourhood scale, larger systems can be highly applicable if there is the involvement of public (through societal benefits) and private (through return on investment) sectors (van Dijk *et al.* 2020).

3.4.2. Overcoming barriers to implementation of storage systems

Not surprisingly, the expensive installation of appropriate stormwater tanks discourages residents to install them (Brown *et al.* 2016). Additionally, ongoing operating and maintenance costs need to be covered (Marsden Jacob

Table 1 | Maximum achievable service levels of stormwater harvesting (percentage of potable water substitution) at a reliability of 70% for each sub-catchment under different scenarios

		Near future		Far future	
Sub-catchment	**Baseline**	**Max**	**Min**	**Max**	**Min**
SC1	71%	68%	70%	71%	67%
SC2	54%	54%	53%	55%	54%
SC3	46%	49%	49%	49%	49%
SC4	55%	58%	55%	55%	58%
SC5	30%	32%	30%	39%	29%

Associates & Australia National Water Commission 2007). Other reasons residents may be reluctant to use stormwater tanks include a lack of information about their effectiveness and the required tank size under the specific site limitations (Imteaz *et al.* 2011b). The number of new private dwellings with the voluntary installation of SWHS in Germany, for example, has resulted from people's motivation to be environmentally conscious by reducing stormwater discharge into streams and the concept of self-reliance (Schuetze 2013). The motivation of implementing a sustainable urban drainage system has increased new installations in the UK (Ward 2010) and Sweden (Villarreal & Dixon 2005) in both individual and communal dwellings. Due to the experience of the Millennium Drought across Australia during the 2000s, those wanting outdoor uses (watering the garden or car washing) were more willing to pay considering the investment to overcome future similar events (Tapsuwan *et al.* 2018). In South-East Queensland, Australia, Mankad *et al.* (2012) found a high degree of acceptance of stormwater tanks and satisfaction for applications around private homes. Yet, participants sought greater transparency regarding the use and maintenance of stormwater tanks. Public dissatisfaction, through having insufficient information to anticipate future needs, is likely to affect their willingness to pay for the maintenance of stormwater tanks (Mankad *et al.* 2012). Bos (2021) found that rainwater tanks were typically afforded a low relative priority for repair when compared with other residential assets. Bos (2021) infers that this low relative priority could be a primary driver for the reported delay between when a fault occurs with the tank and when it is repaired. These aspects lead to the conclusion that councils will have to make an effort to provide information to the general public regarding the advantages, potential disadvantages and responsibilities that come with installing and maintaining SWHS in order to achieve large-scale uptake.

Furthermore, incentives and/or regulations are likely required to encourage the public to use stormwater tanks, for example, discounted city rates (Rahman *et al.* 2010) or water-saving technologies such as smart meters (Tapsuwan *et al.* 2018). The Australian government has encouraged the use of stormwater tanks through subsidy provisions and regulations to respond to water supply demand and approaching crisis due to rapid population growth, urbanisation and water scarcity during droughts (Sharma *et al.* 2016). A few regional authorities (such as Gore, Masterton and Carterton) in New Zealand have encouraged residents to capture stormwater through various incentives, e.g., rebates or targeted rates to make installation cheaper (Marshall 2020). However, if water shortage challenges increase due to climate change and/or disaster risk, there may be a requirement for all households to incorporate such infrastructure. Sharing water storages among households through communal storages is a potential way of reducing costs for individuals and designing more efficient systems at a neighbourhood scale, as has been demonstrated for an Auckland, NZ, case study (Vaakesan *et al.* 2013). Yet independent of the solution, education and support programmes that aid owners to maintain their tanks will be essential to minimise the time when systems are non-operational (Bos 2021).

3.5. Limitations and future work

UrbanBEATS was used here for the purpose to focus on multi-functional use of SWHS focusing only on rain/stormwater tanks due to the limitations of designing other BGI options in the New Zealand context. We also acknowledge the fact that urban land use will not remain static and that land-use change should ideally be accounted for, especially when considering the far future time horizon of 100 years. Even though UrbanBEATS can assess how dynamic changes in land use impact BGI planning and implementation (see, e.g., Bach *et al.* 2015; Prodanovic *et al.* 2022), this kind of information has currently to be developed and provided to the model manually and is, therefore, an extensive process fraught with large uncertainties. Although we assumed an unchanged urban form, our interpretation of model results was made in the context of proposed future developments with the City of Christchurch (e.g., surrounding the Cranford basin and Ōtākaro/Avon River Corridor). This study also did not quantify how much stormwater can be captured in the eastern part of Christchurch, which suffers from flooding due to high groundwater levels and coastal inundation.

Future work should include the investigation of combined BGI such as raingardens, wetlands, infiltration systems, ponds and swales alongside SWHS to explore their spatial distribution at different scales and their effects on different land uses and climate change scenarios. Rainfall intensity and frequency in different climate change scenarios will be the next step to further refine the determination of storage volumes. Furthermore, multiple alternative water sources (e.g., greywater) will be explored in terms of reducing potable water demands and economic factors. Studying the eastern city area will also reveal whether SWHS and/or other measures can help to reduce the contribution of stormwater to flooding. Finally, linking this with a dynamic urban development model could provide greater insight into whether the observed shift towards more centralised approaches will be viable if the city plans to further densify in the future. Considering how BGIs can be planned to cope with changes in land use, climate and disaster risk prevention will provide planners with a better understanding of designing resilient, cost-effective and viable solutions.

4. CONCLUSION

This study explored SWHS as a multi-functional approach for managing urban stormwater. UrbanBEATS was used to identify and optimise their locations, densities and sizes to achieve set targets for baseline and climate change scenarios. The benefits of SWHS, if implemented in Christchurch, comprise a reduction of the demands on potable water supply from mains system by 30%, providing necessary resilience, especially in the event of droughts or major disasters. Furthermore, storage of stormwater to reduce flood peak and volume could potentially be fulfilled as design engineers and planners consider recommended capacities for this purpose. Storage sizes needed to be adjusted to accommodate anticipated climate change impacts, but this cannot be achieved by a simple correlation with rainfall volumes, as rainfall variability will likely have a notable influence on the overall stormwater harvesting approach. Clearly, climate change needs to be considered in any urban design and planning of SWHS as part of BGI strategies to manage potential future changes in stormwater volume. Final decisions regarding storage size selection will require further local/regional investigations in terms of population density, water demand and future climate, as well as consideration of local/regional long-term plans. Here it was nonetheless shown that SWHS can contribute to overall water sustainability for the Christchurch area and, likely, other areas, which face challenges in water supply security and disaster risk. This information will prove useful for decision makers for the planning of strategies to cope with urban stormwater management in general as well as climate change adaptation.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the NZ National Institute of Water and Atmospheric Research for granting access to data.

AUTHOR CONTRIBUTIONS

T.T.N., P.M.B. and M.P. conceptualized the main ideas; T.T.N. played a vital role in data curation; T.T.N., P.M.B. and M.P. made the formal analysis; T.T.N., P.M.B. and M.P. developed the methodology; P.M.B. played a major role in providing resources and software; P.M.B. and M.P. supervised the findings of this work; P.M.B. and M.P. validated the project; T.T.N. and P.M.B. contributed to visualization of the data; T.T.N. and P.M.B wrote the original draft; T.T.N., P.M.B. and M.P. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

FUNDING

Thuy Nguyen received scholarship support by a Department of Civil and Natural Resources Engineering Doctoral Scholarship, University of Canterbury.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details. The modelling software UrbanBEATS can be downloaded at www.urbanbeatsmodel.com.

CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

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First received 25 March 2022; accepted in revised form 25 May 2022. Available online 3 June 2022