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Knutsford case study final report: water sensitive outcomes for infill development

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Knutsford case study final report: water sensitive outcomes for infill development
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Water sensitive outcomes for infill developments
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Executive summary

The population of major Australian cities has recently grown rapidly at rates of 5–10% per year with the majority of this urban growth occurring at the city fringe. In response to estimates of continued growth, state governments are promoting development within the city boundaries, increasing urban densities through infill development (residential dwelling) targets. But infill development, if executed without due care about the quality of design and solely focused on maximising land use, poses challenges for water management and liveability more generally. So, we need to understand infill impacts and create design options that can deliver superior outcomes in terms of urban amenity, local hydrology and water use. The Water Sensitive Outcomes for Infill Development research project (IRP4) responds to this need by proposing an Infill Development Evaluation Framework and using it to demonstrate the range of benefits delivered by water sensitive medium density designs in different case study applications across Australia.

This report documents an application of the Infill Performance Evaluation Framework (Renouf et al, 2020) to a precinct (or large site) with projected infill development in Western Australia. The case study aims to (1) improve understanding of the context-specific water-related impacts of infill development and (2) test how water sensitive design typologies and water servicing variables can improve the liveability, water security and resilience of the precinct. This report should be read in conjunction with IRP4's Infill Typologies Catalogue and a second case study, covering an urban precinct in South Australia that applied the same SUWMBA tool and methodology. These two case studies propose and assess different housing designs adapted to two contexts with different climates, socio-economic status, and water challenges. Learnings from both case studies are integrated in the Water Sensitive Outcomes for Infill Development Final Report. All associated documents are available online, including:

1. Infill Performance Evaluation Framework
2. Infill Typologies Catalogue
3. Water Sensitive Outcomes for Infill Development: Salisbury Case Study – Final Report
4. Water Sensitive Outcomes for Infill Development: Knutsford Case Study – Final Report (this report)
5. Water Sensitive Outcomes for Infill Development – Final Report
6. SUWMBA Tool and User Manual.

This case study focuses on Knutsford, a precinct in the City of Fremantle, Perth Western Australia. The area experiences a Mediterranean climate, with winter-based rainfall, and represents a high socio-economic residential context, with household income 7% higher than the national median. The surrounding area has a legacy of innovative, award winning medium density designs incorporating water sensitive solutions. The study area is characterised by low-rise medium density housing precinct with green laneways and courtyards. This creates high expectations of the site design. The local development agency indicated the site's design should improve water security through innovative water servicing (e.g. through rainwater harvesting or community bores) and test new governance arrangements (e.g. collective utilities, peer-to-peer sharing of services). At the same time, it should provide more infill housing diversity and comply with ambitious water and energy targets that demonstrate its commitment to sustainability. These expectations had to be met amid existing constraints on water management—unlike many areas in Perth, Knutsford's geology and industrial past preclude groundwater use for supply, and obstruct stormwater drainage through soak wells.

The case study consisted of seven steps which included a design stage (steps 1–3, described in chapter 2) and an evaluation stage (steps 4–6, described in chapter 3):

1. **Create dwelling and public space typologies** for the typical existing (EX), business-as-usual (BAU) infill development and alternative water sensitive (WS) infill development. Based on an architectural analysis, EX comprised single storey detached houses on lot sizes of around 600 m^2 with approximately 33% built cover and a net dwelling density of 16 dwellings per hectare. BAU also comprised single storey (typical for the area)

housing with a built cover of 58% roof and 34% pavement and a net dwelling density of 45 dwellings per hectare which is representative of the current BAU development in Fremantle. WS typologies included new designs for multi-storey medium density housing options—apartment units, townhouses, and warehouse units—which provided different net densities depending on building height and typologies used.

2. **Create site plans** for the EX, BAU and WS scenarios in consultation with project stakeholders. For EX and BAU, respective typologies were projected on the infill site, with no change to public greenspace. The WS scenario included two variants with the same built footprint, but buildings with different numbers of stories, generating different net densities (81 and 105 dwellings per hectare respectively). Both WS variants combined apartment, townhouse and warehouse units accompanied by redesigned internal laneways and public greenspace. Each plan defined design parameters, including surface characteristics and areas, imperviousness, vegetation, irrigation assumptions and number of occupants per dwelling.

3. **Define water servicing arrangements** for each scenario. EX and BAU assumed that no public space (road verges) and 50% of gardens are irrigated and that mains water is the only source used (also observed from two years of aerial photography). For the WS case, specific landscape, water management and water servicing plans were developed. Specifically, 100% of gardens and public space would be irrigated using mains water supplemented with sewer mining (capturing, treating and using recycled water locally). Supplementary water supply for indoor non-potable uses would be provided by large communal rain tanks installed underneath each building. Landscape plans included constructing raingardens to treat stormwater and infiltration galleries underneath the internal roads. Different combinations of these technologies were evaluated in the evaluation step.

4. **Estimate urban water flows** for each scenario using the Aquacycle model (Mitchell et al., 2001), which were compiled into urban water mass balances based on the approach described in the Infill Performance Evaluation Framework (Renouf et al., 2020). Flows were estimated for individual years between 2006 and 2018.

5. **Evaluate the architectural and urban space qualities** of each development case using a new qualitative rating scheme developed for the IRP4 project. The key principles for architectural design were developed during a workshop with local stakeholders. They revolve around access to quality outdoor public, communal and private space, on the one hand and dwelling amenity and function, on the other. (For more information on the performance indicators for architectural and urban space quality criteria, refer to Table 10 of the Infill Performance Evaluation Framework.)

6. **Conduct multi-criteria performance assessment** using multiple performance indicators to rate and compare the performance of the BAU and WS infill scenarios against the EX case. These were consistent with the indicators established in the Infill Performance Evaluation Framework (Renouf et al., 2020) and included metrics for water performance (hydrology, water demand and supply, water storage capacity, water for greening) and architectural and urban space qualities. Thermal comfort was not evaluated as part of this assessment.[1]

Following these steps, the study considered performance evaluation in the context of **governance mechanisms** relevant to Western Australia, Perth and Fremantle. This pointed to areas that could be improved relating to leadership, engagement and integration of water and urban planning.

[1] Thermal comfort was not assessed in this study due to scope limitations. A new, separate study currently being conducted will assess thermal comfort.

The evaluation demonstrated WS performs strongly when compared with the BAU scenario in all assessed parameters, with significant benefits of WS in some aspects as compared with EX. In particular, the WS infill scenario with rainwater harvesting and sewer mining can deliver higher dwelling yields while providing higher water sensitive benefits than either BAU or EX. The highest benefits of the WS scenario compared with EX related to water demand and supply, specifically to self-sufficiency and water storage capacity. In other words, the WS scenario reduces the reliance of imported water and improves reliability of water for greening in dry times. Additionally, WS designs mitigate some of the negative effects of increased imperviousness on infiltration and stormwater runoff, reverting hydrology closer to pre-developed state than the EX scenario. While WS delivers similar benefits in terms of access to quality outdoor private space as EX, it significantly improves the access to quality of outdoor communal space. The only evident trade-off of WS is a loss of space for deep canopy trees, although this space is usually not fully used in EX scenarios.

The overall performance of the case study across various target criteria can be categorised into five different aspects: (i) Dwelling yield, (ii) Hydrology, (iii) Water supply and demand, (iv) Greening and (v) Architectural and urban space quality (see Figure 12 and Table 8 for detailed descriptions). The overview of the performance in terms of the five aspects is as follows:

Dwelling yield

- Population and dwelling yield of the four scenarios with a total area 3.99 ha is shown below. The difference between the WS scenarios is the number of storeys which has limited impact on hydrological and greening performance.

Scenario	No. of people	Dwelling yield
EX	90	43
BAU	225	107
WS-Con	323	154
WS-Max	420	200

Hydrology

- Precipitation fraction that infiltrates: In EX, more than one-quarter (29%) of the rainfall infiltrates. However, this is substantially reduced to 11% in BAU which is 62% lower than EX. Meanwhile, WS-scenarios facilitate a higher proportion (30%) of rainfall to infiltrate, a 1 percentage point increase in infiltration compared with EX.

- Precipitation fraction not converted to runoff:[2] In EX, 75% of the rainfall is not converted to runoff, meaning 25% of the rainfall fraction is converted to stormwater runoff. Significantly, only 38% is not converted to runoff in BAU. As expected WS scenarios perform better than the BAU; but interestingly, it also outperforms EX by 12 percentage points, i.e. 87% of the rainfall is not converted to stormwater runoff (and 13% is converted to runoff).

[2] Precipitation fraction not converted to runoff is a complementary event of the common indicator, runoff fraction of precipitation, i.e. 1 – runoff fraction of precipitation. The framework reports runoff in this way to better compare performance across indicators.

Water demand and supply

- Number of people supplied per kL of imported water (inverse of per capita use of imported water): In EX, the demand of 3 people can be supported by 1 kL of imported water (mains water), while it meets demand for 6 people in BAU and 11 people in WS-Con. For this criterion, WS performs better than BAU and BAU better than EX. BAU's better performance is due to the reduced irrigation demand compared with EX and WS. Although BAU performs well in this criterion, this negatively affects its performance in greening and outdoor space quality. Importantly, WS's better performance reflects increased water reuse (i.e. rainwater harvesting and sewer mining), not a reduction in water use.

- Total water storage capacity: This criterion usually consists of water stored within the urban entity. However, this study considers only the storage capacity of the rain tanks case, due to soil characteristics and the size of the wastewater store. In this context, the water storage capacity of the assessed system for the WS-Con is 1.5 ML.

- Water supply self-sufficiency: This indicator applies only to WS, because EX and BAU are assumed not to have any alternative water sources. In WS, rainwater and wastewater combined provide an estimated 63% self-sufficiency.

Greening (Landscaping)

- Reliability of supplementary water in a dry year:[3] This indicators assesses the performance of alternative water sources (rainwater harvesting and wastewater reuse), so it applies only to the WS scenarios. The alternative water sources combined can provide 94% reliable supply even in a dry year for the assigned water demands (indoor non-potable and irrigation).

- Fraction of area with deep root zone: This indicator demonstrates the ability of the design to accommodate large trees that provide urban cooling and amenity. In EX, it is 51% of the total area,12% in BAU and 28% in WS scenarios. Although it seems EX performs better than WS, it is essential to note WS accommodates a significantly larger population than EX. Moreover, EX does not use the available area of deep root zone effectively for, for example, storing water to help grow trees to improve greenspace and cooling.

Architectural and outer space quality

- This aspect of performance is quantified on a scoring index of 0 to 21 across four different qualitative performance indicators: Amenity and function of welling interiors; Quality of outdoor private space; Quality of outdoor communal space; and Quality of outdoor public space. WS scenario performances score higher than 80% for the four different indicators. In contrast, BAU scores a low of 14% in outdoor communal space and a high of 48% in outdoor private space. Meanwhile, EX scores above 80 only in quality of outdoor private space and ranges between 50% and 70% in the other three indicators. (For more information on the performance indicators for architectural and urban space quality criteria, refer to Table 10 of the Infill Performance Evaluation Framework.)

In summary, the BAU infill scenario, although delivering lower densities than WS, scores lower in almost all indicators when compared with both WS and EX. In terms of urban amenity, the BAU design reduces the quality of the outdoor private space and space for supporting canopy trees. It also increases stormwater runoff (240% when compared with EX and 17 times more than the pre-development state) and reduces infiltration. These

[3] Dry year is the year in which rainfall is significantly lower i.e. 10^{th} percentile of the rainfall range for the selected time period (2006–2018).

results are likely to cause further issues considering Knutsford's poor drainage. The only benefit is reduced per person use of imported water, when compared with EX. However, this result reflects reduced greenspace and not improved water efficiency.

This case study was informed by a 'Living Laboratory' research methodology. It was based on broad stakeholder engagement and included elements of co-design and consultation with representatives of planning and water agencies, local government and engineers responsible for the site's design and development at various stages of implementation. The main case study proponent, Landcorp (now DevelopmentWA, Western Australia's land and property developer agency), took an active and leading role in guiding research scope and focus. This was to ensure the project approach and outputs align with end users' needs. This approach meant greater appreciation for case study context (e.g. lack of access to groundwater), but may have reduced the applicability of findings to infill developments across Perth. However, it demonstrated the flexibility of the Infill Performance Evaluation Famework in assessing different infill scenarios, with a broad range of distinct architectural and environmental circumstances. We believe the framework's relative simplicity and adaptability will make it, above all, a useful communication tool that can facilitate dialogue between planners, developers and the community. We encourage use of the framework and case study findings in community engagement efforts, to not only demonstrate the impacts of incremental changes caused by infill housing design on local water cycle, but also to trigger discussion about community expectations about redeveloping established suburbs and their sustainability.

Overall, the case study showed the potential of coordinated architectural and water services design for mitigating adverse effects of infill development, not only in terms of altered hydrology and increased water demand but also overall liveability for current and future residents. This report thus provides a foundation for a more quantified business case for water sensitive development designs and typologies. But the analysis also highlights how governance arrangements underpin successful implementation of more sustainable and liveable designs that challenge current practice. In particular, implementing the ambitious designs presented in this report requires (i) better integrating water, built form and energy planning and expertise (also in planning approval processes), (ii) considering legacy-related constraints of infill settings, (iii) appreciating long-term perspectives in design approaches to built form, (iv) engaging communities in achieving multiple goals set by the design and (v) clearly communicating parameters, trade-offs and alternatives of proposed designs.

More broadly, this case study demonstrates the value of interdisciplinary collaboration in urban water, planning, modelling, engineering and design. Together with the Evaluation Framework, other case studies and typologies catalogue, the work demonstrates a new way of thinking about assessing the performance of urban infill. This approach provides a new language and toolset that are highly relevant to the major challenge of sustainable, resilient urban water, and associated water sensitive development. The challenge remains to fully embed suitable performance metrics into governance and monitoring arrangements.

1.0 Introduction

This document reports the findings from the Knutsford infill case study undertaken as part of the IRP4 project (Water Sensitive Outcomes for Infill Development). The IRP4 project aimed to develop and apply a performance evaluation framework to understand the impacts of infill, develop infill dwelling typologies and create design options and processes that can mitigate impacts, and identify improved governance opportunities for facilitating them. The Infill Performance Evaluation Framework (Renouf et al., 2020) was applied to a selection of case studies, including Knutsford, to help answer the following research questions:

- What are the water-related impacts of infill, and how does it vary in different Australian contexts?
- How do water servicing alternatives influence performance in different contexts?
- Which design and water servicing variables should guide design solutions?
- What performance objectives or targets might be appropriate for infill development?
- What design typologies give good performance in different Australian contexts?
- How might performance evaluation influence governance and planning mechanisms?

This case study applied the Evaluation Framework to a large development site at Knutsford in the City of Fremantle, Western Australia, exploring the research questions in the Greater Perth context.

The study considered ‘mixed use precinct infill’ for the site, as defined in the Infill Performance Evaluation Framework (Renouf et al., 2020). This refers to large scale development or redevelopment within a structure plan that can incorporate uses other than residential (small commercial), and typically provides additional public value common in many capital cities of Australia. Knutsford’s medium to high socio-economic context afforded the opportunity to consider innovative water servicing opportunities that could be accommodated by the higher price bracket of this development type.

The case study was developed in consultation with DevelopmentWA (previously LandCorp), the Western Australian Government land development agency.

1.1 Case study site

Location, landscape, environment, and social context

The 4 ha development site is located 1.5 km from the heart of the City of Fremantle, which is south-west of metropolitan Perth (Appendix, Figure A1). It is one of around 8 brownfield sites radiating off Knutsford St (Appendix, Figure A2), which are in various stages of development under a Knutsford Master Plan (Landcorp, 2016).

Fremantle has a hot-summer Mediterranean climate, with winter-based rainfall and hot and dry summers. The annual rainfall/precipitation ranges from 467 to 861 mm/year, and potential evapotranspiration varies between 1,468 and 1,542 mm/year for the years from 2006 to 2018 (Appendix, Figure A3).

Figure 1: Aerial image of the case study location in Knutsford, Perth
Note: The system boundary assessed is marked with a red line.

The area has shallow soils on a limestone ridge. Typically, stormwater runoff in Perth is managed locally by draining to soak wells, which infiltrate water through the highly pervious sandy soils. However, the poor drainage in the area is a challenge for this site. This context influences the site's hydrology, and is an important consideration for the proposed water servicing arrangements and the hydrological performance evaluation.

There is a history of groundwater contamination in the area, which is a legacy of past industrial activity. Consequently, the shallow groundwater is contaminated with pollutants such as pesticides, oil, asbestos, and fill, and cannot be used as a supplementary water supply.

At the time of the study (2019), the site was a vacant brownfield site (shown in Figure 1), which had previously been used for light industrial or warehousing. The site is bounded to the north by Knutsford St, to the east by Amherst St, to the south by the Western Power site, and on the west by a future road easement. For the performance evaluation, it was assumed the existing reference state contained residential dwellings typical of those in the surrounding residential blocks. This existing housing stock is predominantly modest homes on large blocks on streets with generous verges.

The average number of people per household in the Fremantle is 2.1 (ABS, 2016), which is lower than the Australian average of 2.6. Fremantle's median household income is $1,548/week (~$80,000/year), which is 7%

higher than the Australian median (ABS, 2016). The areas surrounding the site are ranked in the 'advantaged' categories of 4 and 5 (on a scale of 1–5) on the 2016 Index of Relative Socio-economic Advantage and Disadvantage (IRSAD) (ABS, 2018), representing a high socio-economic residential context.

Water supplies

Water Corporation supplies drinking water (potable) which originates from a mixture of sources—in July 2020, 48% of water supplies originate from desalinated seawater, 40% from groundwater, 10% from surface water from dams and 2% from groundwater replenishment (Water Corporation, 2020). Also, Water Corporation is the only utility in Australia to establish indirect potable water recycling of wastewater to recharge aquifers. The water supply infrastructure will be upgraded to service the proposed developments in the Knutsford area. Given the drying climate and stressed groundwater supply, Water Corporation currently has a strong mandate for demand reduction.

The water demand for outdoor use is large due to high evapotranspiration in this hot climate, and irrigation scheduling is in place. Outdoor water restrictions apply for 9 months of the year—two sessions of watering per week using mains water, or three sessions per week if using private bore water. An important limitation for the site is the lack of fit-for-purpose water for outdoor irrigation, since the underlying contaminated groundwater cannot be used. Even though this is a site specific issue, the overall site is representative of a range of conditions that can occur during development. The Evaluation Framework can be adapted to most sites however it is very important to carefully consider local issues when identifying and managing water issues.

1.2 Future development projections

Fremantle is a target area for infill development in the Central Metropolitan Perth Sub-regional Strategy, within the *Perth and Peel @ 3.5 million* planning framework (WA Planning Commission, 2015). In this plan, an additional 520 infill dwellings are targeted for the East Fremantle area between 2011 and 2031.

In relation to the case study area and development site more specifically, the Knutsford Master Plan (Landcorp, 2016) allows for increased density. The vision in the plan is that 'an aged industrial area becomes a high amenity, diverse and adaptable precinct while protecting and incubating Knutsford's unique creative culture and sense of place', and that 'Knutsford will be a community asset and an exemplar for design and sustainability across Perth' (Landcorp, 2016). New development in this area is proposed to be medium density residential on a mix of survey built strata and grouped housing sites (https://developmentwa.com.au/projects/residential/knutsford/overview). Three of the sites in the Master Plan area have already been developed or are under development (https://www.knutsford.com.au/). They are innovative precincts of mid-density, low-rise dwellings which revolve around a series of dissecting laneways and courtyards. The laneways enable cars to be buried within the centre allowing liveable areas and outdoor patios that engage directly with the street.

South of Knutsford is White Gum Valley (WGV), another innovative development featuring a mix of housing types, laneways, community green space, a redesigned, multi-functional stormwater swamp, and a community bore (https://developmentwa.com.au/projects/residential/white-gum-valley/overview). These are an example of the density and style of infill proposed for the Knutsford development area. The WGV development in particular sets a benchmark for water sensitive design in the current market.

The case study site is anticipated to be developed in the next 5 years by DevelopmentWA in a similar vein to these preceding developments. There is interest in the development becoming accredited to the One Planet Living sustainable development framework (Bioregional, 2016) and engaging with Landcom's PRECINX™ precinct sustainability tool.

This case study is an opportunity to fill a current need in the development industry for examples of good medium density development, which are less gridded, with mixed housing (incorporating courtyards, roof terraces, apartments), high liveability, and cross-ventilation from green spaces (deep rooted trees on private lots and green laneways). Higher density areas may be scattered in the development, for example near train stations rather than across the whole precinct. Opportunities also exist for designing the development for fewer cars or no cars, and for greater walkability and public transport. Space for cars due to the higher densities is a constraint for Knutsford.

There are also other urban design and planning initiatives associated with the development area. The first is a master plan for a Precinct Green Spine along Knutsford St (Josh Byrne & Associates, 2017), which aims to provide green space and connectivity for the wider development area. Because the case study site is adjacent to this proposed streetscape development, development plans on the site are expected to connect to it. A second is the CRC for Low Carbon Living's 'Beyond White Gum Valley' research project, which considers opportunities for town planning, community and developer engagement that will support zero carbon development (or better) at a precinct scale. A third is a Smart Cities and Suburbs project (located in suburbs across City of Fremantle) focusing on the energy–water nexus.

1.3 Opportunities and aspirations

Like many Australian cities, Perth faces climate change and water security issues that require innovative approaches to challenge traditional thinking. Its climate is becoming hotter and drier leading to increasing water scarcity, while urban expansion and intensification increase the demand for water. A key challenge is how to create and maintain a green and highly liveable community for a growing population when natural water sources continue to decline (CRCWSC, 2019).

Consultation with the case study partners (Development WA) identified the following aspirations for the site and the surrounding Knutsford precinct, which aim to address this challenge:

- Improved water security through innovative water servicing:
    - Wastewater recycling via sewer mining to tap into the sewer infrastructure of the wider precinct
    - Harvesting and use of rainwater/stormwater (including off laneways), for local irrigation or for recharge to groundwater to contribute to Perth's wider groundwater recharge objectives
    - (Community bores and treatment and use of groundwater were not considered because of local contamination of groundwater, and strategies for treatment were outside the scope of this project.)
- Development site considered in the context the broader precinct, to explore innovation of the system overall:
    - Staged implementation and flexibility in the water servicing technologies so that infrastructure and services could be scaled up as development in the Knutsford area proceeds
    - Diversity in the infill development enabled without compromising other dwellings in the neighbourhood.
- Performance assessment which can feed into precinct sustainability frameworks:
    - Setting of targets for water and energy management for the development precinct, which could be used within the One Planet Living framework and Landcom's PRECINX precinct sustainability tool

- Water servicing initiatives that enable innovative governance arrangements to be explored:
    - Consideration of collective utilities, peer-to-peer sharing (e.g. person-to-person trading of energy using online systems such as blockchain) of infrastructure and services, and integration of centralised and decentralised systems
    - Improved alignment of the main actors and agencies in terms of their respective governance of the three aspects of the development—design, technology, governance. The project could be an opportunity to proactively trigger changes to governance arrangements. IRP4 tools and this report can inform regulatory standards and evaluation methods for development approvals, including:
        - State Government Residential Design Codes, particularly reforms for medium density development, including built form and orientation, deep soil areas and tree canopy
        - Local government development control policies, which may introduce local variations of the R-Codes
        - National Construction Code reforms.

In relation to governance, the scale of the wider Knutsford development area is useful for exploring the shared utility approaches because more options become financially viable at this scale. The survey strata subdivisions and future community titles may allow for innovative models for providing services with innovative governance systems—precinct-scale, decentralised, collective, shared, combined, multi-utility services for:

- water supply (recycling, rainwater harvesting, stormwater harvesting)
- energy (community battery, shared residential PV, decentralised hot water, microgrids and distribution networks, integration of energy and water management)
- solid waste (including food waste) and wastewater (collective waste management)
- transport (carpooling or shared Electric Vehicle fast charging)
- space (shared laneways spaces governed by the community).

The potential for, and possible issues associated with, shared utility approaches (or other governance solutions) could not be considered in detail in this case study. Further information on governance approaches to innovative integrated urban water management may be available through IRP3, a parallel CRCWSC project.

2.0 Method

2.1 Method overview

The performance of alternative infill scenarios were evaluated using the Infill Performance Evaluation Framework developed as part of IRP4. In this case study, performance was evaluated for a single development site. The performance of a number of alternative infill development typologies was compared with the performance of the typical existing residential typologies. The steps followed are summarised here, and further details can be found in the Evaluation Framework document (Renouf et al., 2020).

1. Create dwelling and public space typologies for the typical existing (EX), business-as-usual (BAU) infill development and alternative water sensitive (WS) infill development (Appendix, Figure A4). These were developed by the IRP4 project team in consultation with project stakeholders using water mass balance tools to evaluate the performance of each typology.

2. Create precinct plans for the EX, BAU and WS scenarios in consultation with project stakeholders (Appendix, Figures A7–A9). Design parameters were defined for each plan, including surface characteristics and areas, imperviousness, vegetation, irrigation assumptions and number of occupants per dwelling.

3. Define water servicing arrangements for each scenario. For the WS case, this involved developing a landscape plan and water management and water servicing plan (Appendix, Figure A12).

4. Estimate urban water flows for each scenario using the Aquacycle model (Mitchell et al., 2001), which were compiled into urban water mass balances based on the approach described in the Infill Performance Evaluation Framework (Renouf et al., 2020). Water flow indicators were compared with context-specific targets where available. If targets (in planning or government documentation) were not available, the project team estimated notional/illustrative targets, guided by our analysis, to help communicate how cumulative indicators at precinct scale can be achieved.

5. Evaluate the architectural and urban space qualities of each development case using a new qualitative rating scheme developed for the project.

6. Generate multiple performance indicators to rate and compare the performance of the BAU and WS infill scenarios against the EX case.

7. Consider performance evaluation in the context of governance mechanisms relevant to Western Australia, Perth and Fremantle.

The site/precinct plan is assessed as a three-dimensional 'system'. The physical boundary of the urban entity comprises (i) a horizontal boundary relating to the precinct/site boundary, and (ii) vertical boundary that ranges from 1 m below ground level to the height of the tallest building or trees in the chosen location. Some of the components of an urban entity are buildings (water appliances), water infrastructure (piped and natural flows and related treatment systems), landscape (to 1 m depth of soil) and associated land surfaces and vegetation, and related water storage/s.

2.2 Development scenarios

The typical existing (EX) development scenario (Appendix, Figure A7) represents dwellings that would typically be present in the study area before infill development. It is the reference case against which the impacts of the infill scenarios were compared. Even though the site was a vacant lot pre-development, we assumed it contained residential dwellings similar to those in the suburban block directly to the north-west of the site (see Appendix, Figure A3). They are single storey detached houses on lot sizes of around 600 m^2 and with 33% built cover on average. This scenario assumes 43 dwellings on the site, with a net dwelling density of 16 dwellings per ha (Figure 2). The average occupancy per dwelling was assumed to be 2.1 (ABS, 2016), giving a site population of 90 people (Figure 3). The built form and surface cover characteristics were measured from prepared CAD drawings of the site onto which the existing residential typologies were transposed (Appendix, Table A7). The overall impervious fraction was estimated to be 0.41 (Figure 5).

A business-as-usual (BAU) development scenario was developed to represent the type of infill that might likely be constructed on the site in the current housing market (at 2019) (Appendix, Figure A8). It is a single storey, affordable dwelling considered to reflect the default infill development occurring nationally, with a built cover of 58% roof and 34% pavement. The site plan incorporates two new internal roads of a typology typically associated with standard infill development. This scenario assumes 107 dwellings on the site, with a net dwelling density of 45 dwellings per ha (Figure 2). The average occupancy per dwelling was assumed to be 2.1 (ABS, 2016), giving a site population of 225 people (Figure 3), which is approximately double the EX case. The overall impervious fraction of the study area increased from 0.41 to 0.75 (Figure 5).

A water sensitive (WS) scenario was developed to represent alternative dwelling styles that can achieve a higher dwelling density and population, but with more green space and communal and public space areas. It was developed in consultation with DevelopmentWA, and with consideration of Knutsford's socio-economic context and housing market. The designs were guided by principles for improving the quality, diversity and performance of redevelopment outcomes (Murray et al., 2011), which includes multiple stories instead of single storey structures (to reduce the amount of built cover), multifunctional internal roads, and communal green space. Three different dwelling typologies were developed for the site to provide diversity—apartment units, townhouses, and warehouse units (Appendix, Figures A4–A6). Internal roads (laneways) and verges on public roads were also incorporated, with consideration given to parking requirements. An area of public green space was incorporated at the northern end of the site to tie in with the proposed Precinct Green Spine along Knutsford St. The dwellings, communal spaces and public green spaces were arranged on the site to generate the plan depicted in Appendix, Figure A9. The overall impervious fraction of the study area would increase from 0.41 to 0.49 (Figure 5).

The WS scenario provides two design variants, which have the same built footprint, but which differ in terms of the number of building stories, hence the number of dwellings and population that can be accommodated. The conservative case (WS-Con) provides 154 dwellings on the site (Appendix, Figure A10), whereas the maximised case (WS-Max) has a greater number of stories and provides 200 dwellings (Appendix, Figure A11). The respective net dwelling densities (not including communal spaces) are 81 and 105 dwellings per ha, respectively Figure 2). For both, the average occupancy per dwelling was assumed to be 2.1 (ABS, 2016), giving a site population of 323 or 420 people respectively (**Error! Reference source not found.**). These populations approximately trebled or quadrupled that of the typical EX case.

Further details of all the typologies can be found in the Infill Typologies Catalogue (London et al., 2020). We note that analysis of the performance of individual sites in the catalogue was developed along with the design by using the SUWMBA (site scale urban water mass balance tool) as published by Moravej et al 2020, and Moravej et al 2021.

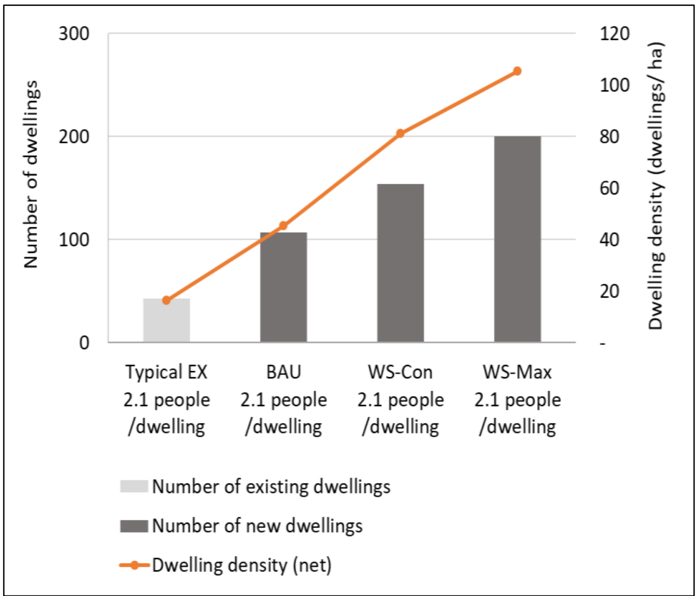

Figure 2: Assumed changes in dwellings

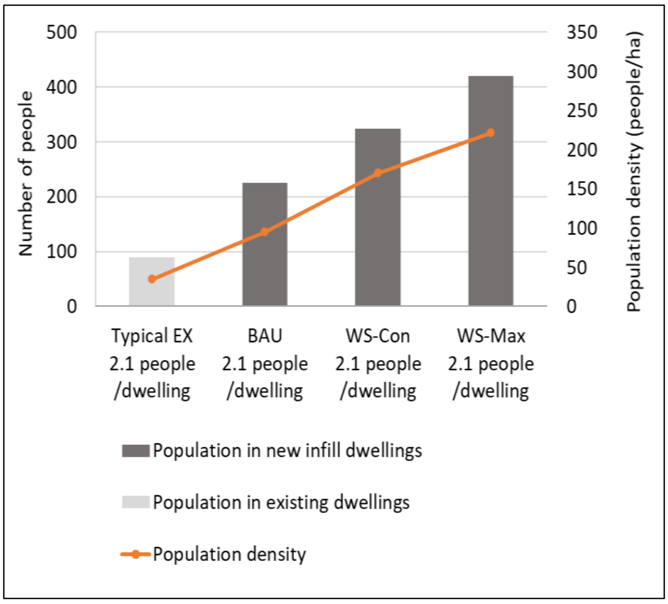

Figure 3: Assumed changes in population

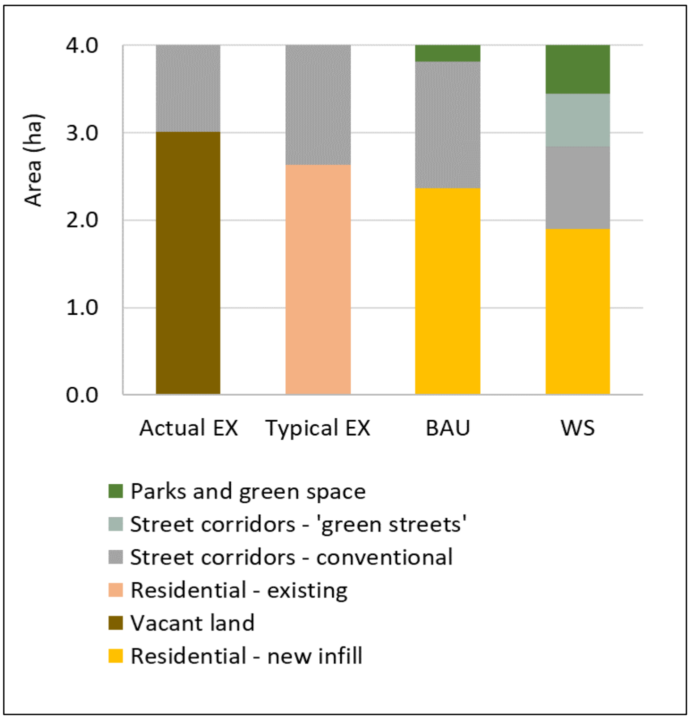

Figure 4: Assumed changes in land use

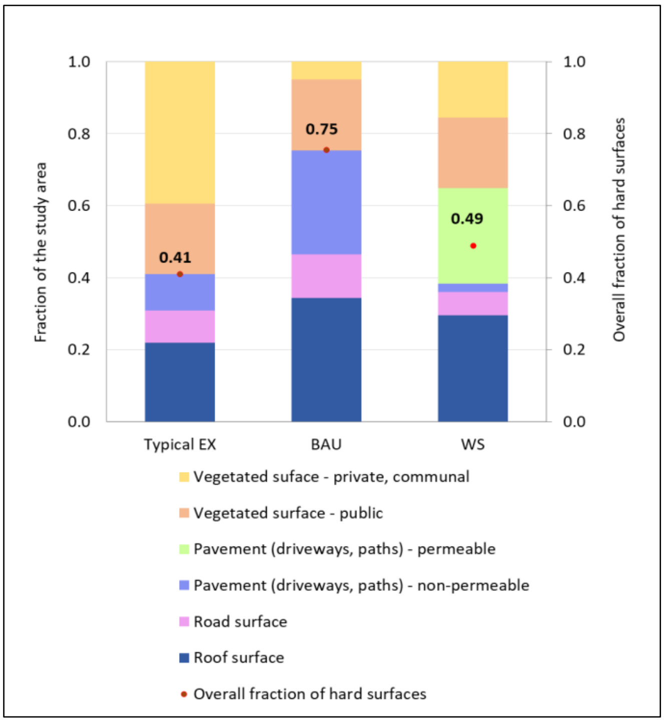

Figure 5: Assumed changes in surfaces and imperviousness

2.3 Water servicing assumptions

Water servicing options for the development scenarios were informed by consultation with Josh Byrne & Associates and a review of supplementary water supply technologies (Pype, 2020).

The EX scenario assumed:

- all water (including for irrigation) is supplied from the centralised mains water supply (imported water)
- 50% of residential garden areas are irrigated
- public areas (road verges) are not irrigated
- no use of groundwater bores due to groundwater contamination.

The BAU infill scenario assumed:

- all water (including for irrigation) is supplied from the centralised mains water supply (imported water)
- 50% of residential garden areas are irrigated
- public areas (road verges) are not irrigated
- no use of groundwater bores due to groundwater contamination.

The WS infill scenarios assumed:

- 100% of residential, communal and public garden areas are irrigated
- 50% of the green area of the Precinct Green Spine along Knutsford St is irrigated
- supplementary water supply for indoor non-potable uses is provided by large communal rain tanks installed underneath each building. They receive rainwater[4] from the roof of the building, and supply toilets for flushing, a cold water tap for clothes washers and bathroom hot water within that building. They were sized to provide target storage capacity per dwelling of 10 m^3 (Table 1). The IRP4 team did not undertake site investigations to determine soil conditions, but we understand this proposal is feasible.
- supplementary water supply for outdoor uses and some indoor non-potable uses is provided by a sewer mining scheme, which supplies treated wastewater for irrigating private gardens and public landscaped areas, as well as for toilet flushing, water features and utility washing such as paths, fences and vehicles (WA Department of Health, 2011). It draws sewage from the sewer main fed by the site (and other development sites in the Knutsford area in the future). The sewage is proposed to be treated in a modular wastewater facility using primary treatment including a screening and an equalisation flow (e.g. septic tank), a secondary biological treatment (e.g., membrane bioreactor), and a tertiary treatment including filtration (e.g., membrane bioreactor) and disinfection (e.g., UV), to a standard suitable for dual reticulation, thus following the Australian Water Recycling Guidelines for non-potable purposes.[5] Residuals are to be directed back to the sewer. The system will include a pump station and wastewater treatment facilities at the Western Power site at the south-east corner of the site, and buffer storage tanks in the north-east corner of the site.
- the landscape plan includes raingardens at the end of each building to act as retention devices to treat the first 15 mm of rainfall (first flush) from internal roads, roofs and parking bays.

[4] To use rainwater for hot water systems (excluding cooking and drinking usage), advice from suppliers is recommended to avoid potential material damage.
[5] The regulation is different if water is used for public space or garden watering. If it is for garden watering, the water needs to have the same standards as a reticulation system for toilet flushing and laundry uses.

- the landscape plan also includes infiltration galleries underneath the internal roads, which receive runoff from the roads, overflows from rainwater tanks, and overflows from the raingardens. These function as inverted leach drains, which capture and detain runoff so it can infiltrate downwards.
- Four water servicing variants were considered (Table 1), to test how different degrees of supplementary water supply influence the performance of the development:
    - no supplementary water supply
    - rainwater (RW) harvesting
    - wastewater recycling (WW)
    - combined RW and WW.

Table 1: Water servicing variants for the water sensitive (WS) infill scenarios

	Conservative water sensitive (WS-Con) infill	**Maximised water sensitive (WS-Max) infill**
No supplementary water		
RW	Under-building rainwater storage capacity with volumes of 110–150 m^3 (10 m^3 per dwelling[6], and depending on number of dwellings) Approximate dimensions of each tank would be 2 m x 10 m x 6–7 m (d, l, w) Total rainwater storage capacity for the site is 1,540 m^3 or 1.5 ML Supplying: - indoor non-potable uses in the building (toilets, clothes washers and hot water)	Under-building rainwater storage capacity with volumes of 110–220 m^3 (10 m^3 per dwelling, and depending on number of dwellings) Approximate dimensions of each tank would be 2 m x 10 m x 6–11 m (d, l, w) Total rainwater storage capacity for the site is 2,000 m^3 or 2.0 ML Supplying: - indoor non-potable uses in the building (toilets, clothes washers and hot water)
WW	On-site treatment and use of household wastewater from sewer mining scheme Assumed storage capacity[7] for treated wastewater is 200 m^3 Supplying: - outdoor irrigation of private and communal garden areas, as well as the precinct green spine along Knutsford St - indoor toilet flushing	On-site treatment and use of household wastewater from sewer mining scheme Assumed storage capacity for treated wastewater is 200 m^3 Supplying: - outdoor irrigation of private and communal garden areas, as well as the precinct green spine along Knutsford St - indoor toilet flushing
RW+WW	Combination of the above RW harvesting and WW recycling RW supplying: - indoor non-potable uses in the building (clothes washers and hot water) WW supplying: - outdoor irrigation of private and communal garden areas, as well as the precinct green spine along Knutsford St - toilet flushing	Combination of the above RW harvesting and WW recycling RW supplying: - indoor non-potable uses in the building (clothes washers and hot water) WW supplying: - outdoor irrigation of private and communal garden areas, as well as the precinct green spine along Knutsford St - toilet flushing

RW = rainwater harvesting and use.
WW = wastewater recycling (via sewer mining).

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[6] A 10 m^3 rain tank was simulated and is considered a large tank. It is possible similar outcomes may be achieved with smaller volume tanks (e.g. 3–5 m^3). However, actual optimal size will depend on water security objectives, whether WW recycling is adopted etc. Further detailed design is recommended when aims are clearer.

[7] We have not undertaken a detailed feasibility study of sewer mining (e.g. we did not assess the suitability of the sewer, the size of the proposed plant or the volume of tank proposed). Rather we assumed this is possible to evaluate the potential influence on performance. Further detailed analysis would be needed to design the tank and ensure water performance objectives are achieved.

2.4 Modelling urban water flows with Aquacycle

The Aquacycle model (Mitchell et al., 2001) was used to estimate annual water flows for the study area. It is more suited than other models to analyse performance at the precinct scale and to investigate the use of locally generated stormwater and wastewater as supplementary water supplies. The flows of interest are precipitation, infiltration, evapotranspiration, stormwater discharge, supply of mains water (imported water), supplies of supplementary water (harvested rainwater or stormwater and recycled greywater or wastewater), and wastewater discharged. The parameters used in this model for the Perth context are detailed in Table 2.

Infiltration (I), evapotranspiration (ET), and stormwater discharge were estimated by the in-built rainfall-runoff model within Aquacycle, based on the entered areas and effective impervious fractions of surfaces and the calibration factors detailed in Table 2. Runoff from surfaces on the development site was assumed to drain to the infiltration galleries. Runoff that does not infiltrate in the galleries, and runoff from Knutsford Street (included in the boundary) were assumed to be discharged away from the site to the surrounding roads. In Perth, runoff draining via streets and road surfaces is often directed to soak wells where it is allowed to infiltrate into soil or drain to surface waters via base flow, rather than draining as overland flows directly to drainage channels or surface waters. However, for this evaluation, we estimated the volume of stormwater runoff discharged at the boundary of the development site, and did not model its subsequent fate.

Aquacycle cannot model the functions of detention reservoirs; it models only retention reservoirs for rainwater or stormwater harvesting and storage. So, it was not possible to accurately model the water detention functions of the raingardens and the infiltration galleries. To at least partially model their functions, we assumed the raingardens and infiltration galleries areas had soil profiles with higher infiltration capacities (see Table 2). We also assumed the first flush from the roof surfaces flowed to the raingardens, and the overflow from the raingardens flowed to the infiltration galleries.

Aquacycle estimates of indoor water demand were based on entered per person water demands (L/person/day) for individual uses (bathroom, toilet, kitchen, etc.) and different household sizes. We derived these per person water demands from a regression algorithm developed by Makki et al. (2015), and were based on the key determinants of household demographics, appliance efficiencies and use habits.

Aquacycle estimates of outdoor irrigation demand were based on climate data and an entered ‘trigger-to-irrigate’ factor. Each development case that included irrigation assumed it was triggered only over the summer and the shoulder months, resulting in a ‘trigger-to-irrigate’ factor of 0.6. That is, the irrigation occurs (is triggered) when the field capacity of the soil (i.e. the amount of water in the soil profile) dropped to 60% of capacity. To summarise, this approach assumes some automation to keep soil moisture at target levels.

Rainwater harvesting yield was estimated from the entered roof area and tank capacity, and estimated demand for rainwater. First flush losses were assumed to be 25 L per 100 m^2 of roof catchment (Australian Government, 2011; RHAA, 2020). The rainwater tanks were assumed to be half full at the start of the modelling period.

Table 2: Calibration parameters used in Aquacycle for the Perth context

Parameter name in Aquacycle	Equivalent name in MUSIC	Value for EX, BAU	Value for WS	Comment
Capacity of pervious store (mm)	Soil moisture storage capacity (SMSC)	100	100 /200	200 mm for raingardens and infiltration galleries; 100 m for all other areas
Roof area max. initial loss (mm)	Rainfall threshold	1	1	
Effective roof area (%)		0/100	100	0 for EX as roof runoff assumed to not be generated with rainwater instead directed to soak wells 100 for BAU as roof runoff assumed to be generated and directed to stormwater pipes directly runoff to the road 100 for WS as runoff assumed to be generated and directed to harvesting in rain tanks
Paved area max. initial loss (mm)	Rainfall threshold	1	1	
Effective paved area (%)		D'ways 100, Paths 0	Internal road 0, Paths, carparks - 40	For EX and BAU, driveways assumed to drain to roadway and have 100% effective area; footpaths assumed to drain to soil and infiltrate and have 0% effective area For WS, permeable paving for paths and car parking in communal areas assumed 40% effective area; pavement surfaces on internal roads assumed to have 0% effective area as fully infiltrate into infiltration galleries below
Road area max. initial loss (mm)	Rainfall threshold	1	1	
Effective road area (%)		100	100	
Base flow index, ratio	Groundwater recharge factor	0.9	0.9 / 1.0	1.0 for raingardens and infiltration galleries; 0.9 for all other areas
Base flow recession constant, ratio	Baseflow rate	0.02	0.02	
Infiltration index, ratio	NA	0	0	No infiltration into sewer
Infiltration store recession constant	NA	0	0	
Trigger-to-irrigate	NA	0.6	0.6	

The water flows were estimated with Aquacycle for each development scenario (EX, BAU, WS), and also for the pre-urbanised state (PRE), which is a point of reference for the hydrology indicators.

Flows were estimated for individual years between 2006 and 2018. This range was selected because comprehensive data for both rainfall and potential evapotranspiration was available from the Bureau of

Meteorology (BOM, 2015) for these years. Most performance indicators were generated from the water mass balance for an average rainfall year, which was taken to be 2014 (see Appendix, Figure A3). Some indicators were also generated from the water mass balance of a dry year (2006) and a wet year (2011).

The water flow data were compiled into water mass balances (Appendix, Table A4), as per the Infill Performance Evaluation Framework (Renouf et al., 2020), from which the water performance indicators were generated.

2.5 Analysis of architectural and urban space qualities

This section draws on the report detailing the Knutsford case study workshop held at LandCorp (now DevelopmentWA) in Perth on 17 September 2018. The report was prepared jointly by workshop participants from the CRCWSC and the CRC for Low Carbon Living.

Knutsford offered the opportunity for a precinct-scale sustainable neighbourhood that reflected the City of Fremantle's long-term (20–50 year) agenda for a mixed-use medium density residential precinct internationally recognised for its sustainability. The precinct contains a mix landowners, with the major development areas owned by DevelopmentWA and the City of Fremantle. Workshop participants agreed on the need for a precinct-wide approach that leverages efficiencies of scale to deliver the energy, water and urban design initiatives that would recognise the precinct as an international exemplar of sustainable neighbourhood development.

The existing building fabric provides a distinct identity for Knutsford and useful cues for adjacent new developments. It offers rich potential for a unique building typology with a warehouse character and flexibility of internal use that allows for the range of current uses in the precinct, including residential, commercial, studio, and workshop. Similarly, the existing laneway system and its geometry, formal and informal, provided cues for site layout and urban design.

Workshop participants recognised the risk that BAU development processes could erode the precinct's unique character and varied uses. Additionally, responses to short-term market forces tend to produce a limited range of building typologies, an outcome of developers and investors ' reverting to the familiar' when faced with an uncertain financial climate. Such limitations of type and the associated lack of flexibility in use were thought to be constraints on sustainable urban development.

Given this, participants agreed housing typologies should provide:

- increased density relative to the existing Knutsford development
- a diversity of living options, including living/working, and a diversity of occupants
- integrated solutions for energy efficiency, including orientation, glazing, communal batteries
- integrated solutions for water efficiency, including wastewater recycling, green roofs, rain tanks
- a distinctive urban and architectural identity for the precinct.

These factors were critical in selecting housing types for Knutsford, while the existing patterns of development and site topography determined the configuration and the parking arrangements across the site.

Principles for water sensitive dwellings and urban design

1. Access to quality outdoor public space

Under the pressures of urban intensification and the requirements for more compact living at higher densities, provision and access to quality public realm, such as parks, reserves and plazas, becomes essential. With more public and shared amenity, activated street frontages increase the sense of safety and neighbourliness, and encourage walkability, reducing the high dependence on cars so prevalent in Australian suburbs.

Considered design strategies for residential precincts, with a range of suitable dwelling typologies allowing diverse household types, can complement and encourage use of nearby public open spaces. Higher densities and mixed-use typologies, with home/work options, can generate additional services and functions over time. This can include cafés, grocery shops, pharmacies and other small businesses, increasing use and passive surveillance of public spaces.

Public spaces designed to allow different activities maximise their use. For example, 'slow' streets may be used as access to residences, for bicycle connectivity and, as linear parks with generous tree canopy cover, allowing communal recreational activities in a pleasant and comfortable environment able to be occupied at different times of the day and year.

Pedestrian and cyclist-friendly infrastructure (e.g. designated paths, bicycle racks, rest and recreational areas) reduce car dependence and carbon footprint while encouraging connectivity and use of public open spaces.

2. Access to quality outdoor communal space

Consideration of shared amenity becomes significant in higher density infill development. To increase overall site amenity and reduce individual water and energy demands necessary for upkeep, shared BBQ, vegetable garden, play area, grouped car and bicycle parking areas may be included.

Efficient design strategies, including compact design and organisation of buildings on site, allow for quality communal spaces, functional and accessible to all residents, and adaptable to multiple uses. Certain common spaces, when well-designed, could serve multiple purposes: for example, shared driveways may also be used for play and other recreational activities.

A balanced transition between private and communal spaces is important to maintain a sense of privacy and individuality, and ensure adequate sound and visual barriers. Adequate setbacks, positioning of balconies and windows, and choice of screens and fences, will help minimise overlooking from more activated street frontages.

3. Access to quality outdoor private space

This refers to the provision of courtyards, terraces, rooftop terraces, balconies and similar, providing good solar access, ventilation, outlook and sufficient soil and space for large canopy trees.

High quality outdoor private space is flexible and adaptable, designed to facilitate a variety of uses. Multiple use is supported when such spaces are considered in terms of their length and width, and the height of surrounding walls with their effect on sun and ventilation throughout the year. Courtyards adjacent to living and dining areas may be used as an extended living room, guest entertainment area, garden, and transitionary space between different house zones. An open carport may also be used as an outdoor space.

Landscaping solutions (including well-positioned large canopy shade trees, pergolas and trellises) offer shade for improved thermal comfort, and can provide sound and visual privacy barriers when private areas face communal and public spaces.

4. Dwelling amenity and function

Water sensitive design strategies are used to deliver quality higher density living solutions, without compromising on amenity and function. Building footprints are reduced and the number of floors increased to yield sufficient well-considered space for both private and communal outdoor areas on site, allowing more deep soil space to accommodate large canopy trees. Reducing parking space from the usual two car bays to one per dwelling makes additional usable space available. Further space is gained by grouping parking on site, and open car ports (grouped or individual) allow for permeable paving areas.

Flexibility in internal spatial arrangements is crucial for increasing usability, supporting a range of occupancies and adapting to changing requirements over time. Flexible internal space is designed to support diverse uses: for example, a room with separate services adjacent to a street could be used as a home office, games room or additional bedroom. Internal spatial amenity and functionality is enhanced by direct physical and visual connection to quality outdoor spaces, achieved by designing living areas adjacent to courtyards, terraces and other outdoor areas.

Position and orientation of a dwelling on the site will improve overall site usability, thermal comfort and energy efficiency. Facing windows to the north and north-east will provide favourable solar orientation, and windows in two walls of a room will allow good cross-ventilation and light quality. Adequate shading from the direct sun on the east and west sides is achieved with well positioned greenery or by using shading systems. On unfavourably positioned sites, lightwells may be considered for access to natural light and breeze.

2.6 Performance indicators used for analysis

Performance indicators aim to represent how the each infill scenario performs relative to the existing reference case. The performance criteria relate to hydrology, water demand and supply, greening, urban heat, and architectural and urban space qualities.

Figure 6 summarises the cause and effect relationships between urban design parameters (on the left) and performance criteria (on the right). It also shows the indicators that can be used to quantify performance, either at the end-point (actual performance) or at a mid-point (key determinants of performance) in the cause-effect chain. The performance indicators reported for Knutsford are those highlighted in red in Figure 6.

Refer to the Infill Performance Evaluation Framework (Renouf et al., 2020) for an explanation and justification of these indicators, and how they were derived from the urban water balance data (Appendix, Table A4).

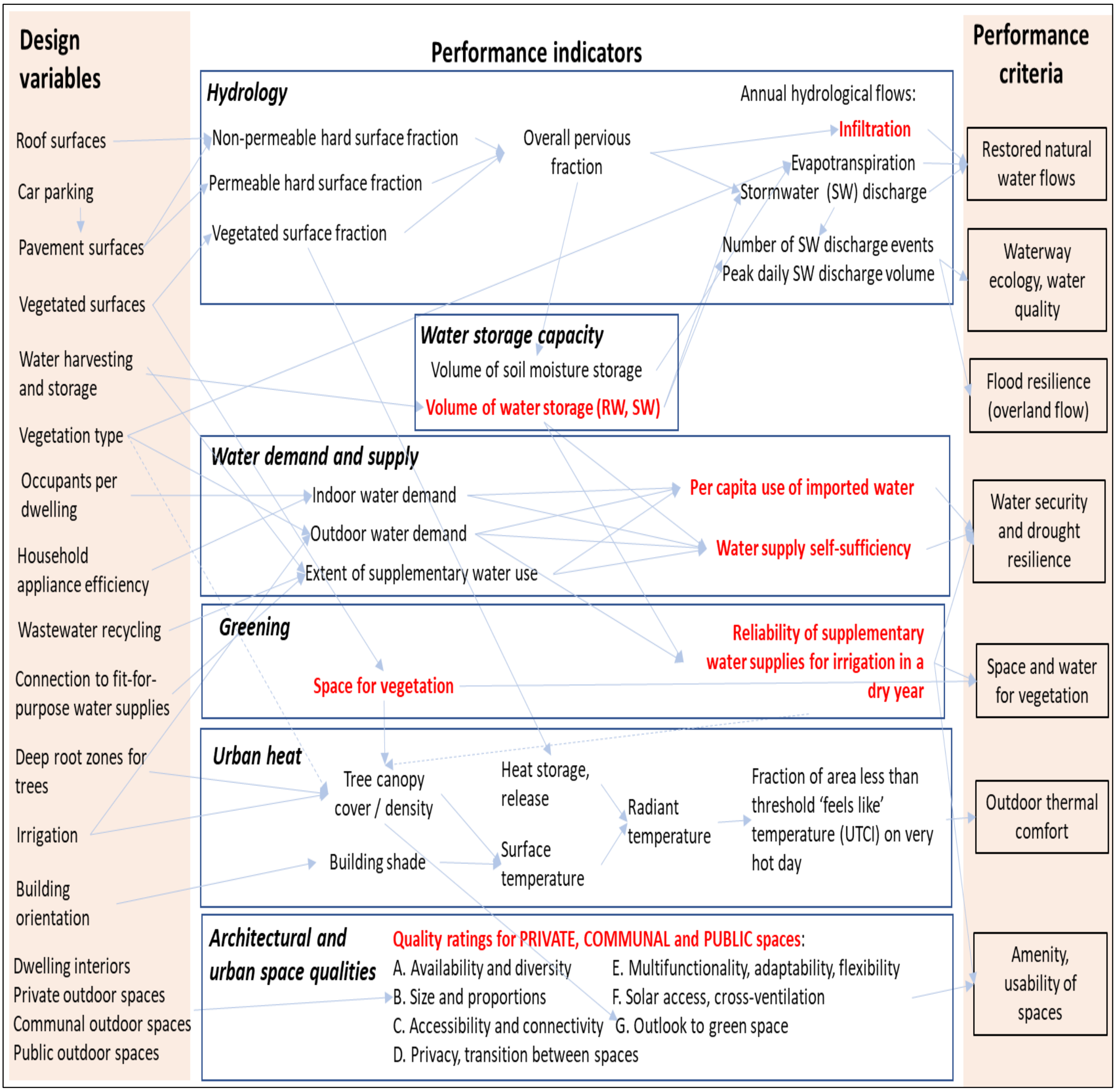


Figure 6: Cause-and-effect relationships between design parameters and performance criteria

Note: Those most relevant for the Knutsford case study highlighted in red.

3.0 Performance evaluation

3.1 Hydrology

The performance principle for hydrology is that ‘ infill design does not further adversely alter the natural hydrology (infiltration, evapotranspiration and stormwater discharge) of the development area, and ideally aims to mimic the pre-urbanised hydrological water balance’ (Renouf et al., 2020, p. 35).

Changes to the annual hydrological flows—infiltration (I), evapotranspiration (ET), and stormwater discharge (SW)—due to infill development on the site can be observed in the BAU and WS scenarios compared with the EX and PRE (pre-urbanised) scenarios (Figure 7). It is useful to compare the annual flows for the BAU and WS infill scenarios against those for the EX and PRE reference states to see how they have changed. The annual amount of rainfall is also shown in Figure 7 to see how rain falling on the site is partitioned between ET, I and SW.

For the PRE reference state (i.e. the natural landscape), the total amount of flows accounted for equals the annual rainfall (674 mm/yr or 27 ML/yr in 2014). For some development scenarios, the totals are higher than the rainfall due to the input of additional imported water for irrigation, which converts to ET. This is a transfer of water from the urban water cycle into the natural hydrological cycle.

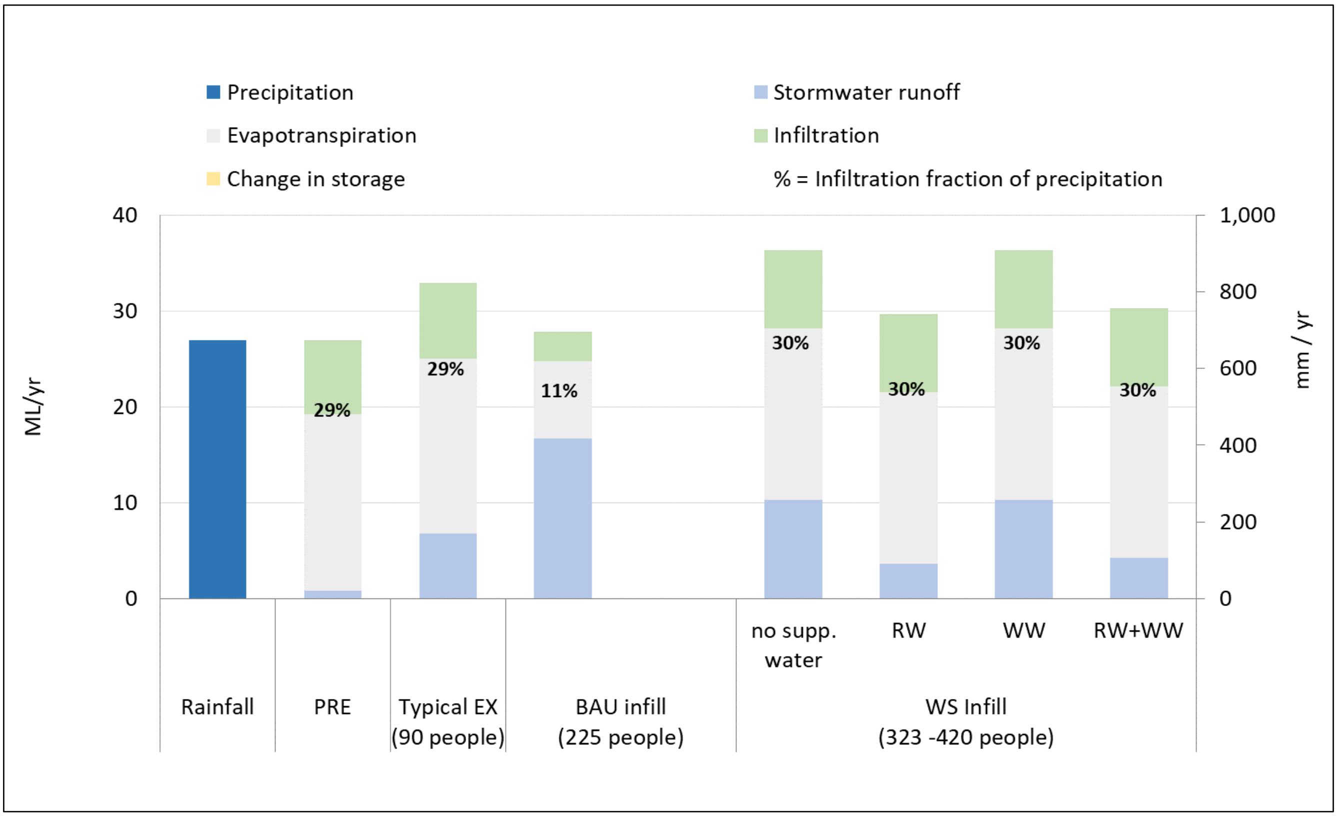


Figure 7: Hydrological flows in an average rainfall year (2014 with rainfall of 674 mm)

The naturally sandy soil means that infiltration (I) of rainfall into soils is very high particularly in areas not influenced strongly by limestone rock. Changes in hydrology are driven by reduced ET due to there being less vegetation and more runoff due to the increase in surface imperviousness. The consequence of reduced ET and reduced I is increased SW. Rainfall that does not evaporate, transpire through vegetation, or soak into the ground must go somewhere, and it drains away as runoff. The SW runoff discharged from the boundary of the site may in fact be directed to soak pits somewhere outside the study boundary, and ultimately end up infiltrating. If the study boundary was expanded to capture the ultimate fate of the SW discharged from the site, then the partitioning profile would be different from that shown in Figure 7. The evaluation framework, with a foundation in mass-balance, accounts for all flows into, out of, and stored within the defined (three-dimensional) study boundary (also referred to as the urban entity) typically including the top 1 m of soil. Information provided suggests the water table is deeper than 3.3 m below the land surface.

In the context of this case study, the hydrological process considered to be important is the infiltration (I) that occurs on the site, to maintain moisture in the soil to support vegetation and recharge Perth’s aquifers. As in other areas, SW discharge is also important in terms of the downstream infrastructure needed to manage the runoff. Therefore, in this case study infiltration (I) as well as SW discharge are both important hydrological performance indicators (see Table 3).

Table 3: Indicators of hydrological performance

	Reference case		Infill scenarios			
	PRE (natural)	EX (90 people)	BAU (225 people)	WS-Con (323 people) RW	WW	RW+WW
Infiltration as a fraction of rainfall (%)	28%	29%	11%	30%	30%	30%
Infiltration ‘naturalness’ (I relative to PRE I)	1.0	1.01	0.39	1.05	1.05	1.05
SW discharge as a fraction of rainfall (%)	3%	25%	62%	13%	38%	16%
Stormwater ‘naturalness’ (SW relative to PRE-SW)	1.0	7.92	19.44	4.18	11.95	4.91

RW = rainwater harvesting and use.
WW = wastewater recycling (via the proposed sewer mining scheme).

The annual volume that infiltrates (I) in the PRE reference state was estimated to be 28% of rainfall in an average rainfall year. The typical EX case increases this slightly to 29% of rainfall, due to the import of mains water for garden irrigation, some of which will infiltrate. The BAU scenario is expected to decrease infiltration to 11% of rainfall due to the significant decrease in pervious surfaces (impervious fraction increasing from 0.41 and 0.75 in **Error! Reference source not found.**). The WS scenarios are expected to enhance infiltration relative to EX, to be 30% of rainfall. Therefore, the WS scenarios can triple or quadruple the population on the site while enhancing infiltration. In contrast, increased dwelling density under BAU will reduce infiltration to 0.4 of the PRE state.

Regarding stormwater (SW) discharge, the PRE state has very little runoff, being only 3% of rainfall. The typical EX case increases this to 25% rainfall, and the BAU scenario increases it significantly to 62%. The WS scenarios reduce it to at least 18%, which is less than for EX. With harvesting, storage, and use of rainwater, SW discharge can be reduced to around 4%.

The favourable performance of WS infill over BAU infill is due to three factors. The first is the purposeful design of the built form to include as much permeable and vegetated surfaces as possible to promote the desired infiltration, and also to promote evapotranspiration. The second is the incorporation of detention devices (raingardens and infiltration galleries) that capture and hold the surface runoff from impervious surfaces, to make water available in the soil profile for trees, and facilitate downward infiltration. The third is rainwater harvesting and use, which not only provides supplementary water supply but also reduces runoff. Operational and maintenance considerations of the proposed scheme were not considered in detail and warrant further analysis.

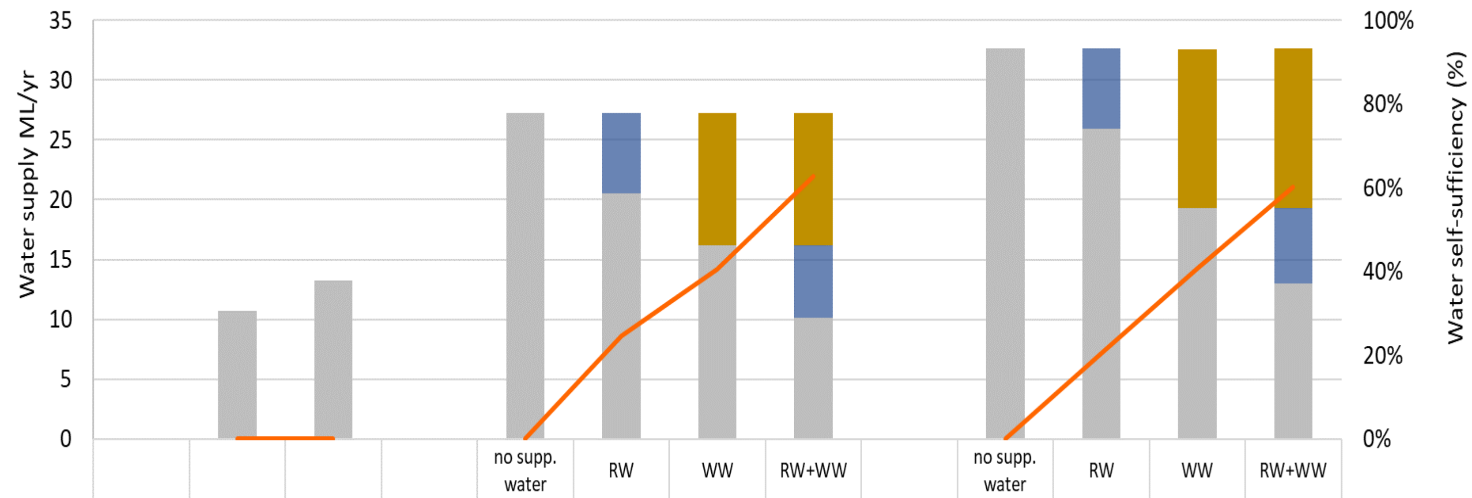
3.2 Water demand and supply

In relation to water supply, the Evaluation Framework distinguishes between water sourced from within the urban system—in this case harvested rainwater (RW) and recycled wastewater (WW)—and water imported from outside the urban system—in this case mains water supplied by Water Corporation. The performance principle for this aspect is that ‘ infill designs enable reduced reliance on imported water through use of supplementary water supplies’ (Renouf et al., 2020, p. 36). The degree of water self-sufficiency is the indicator for this, which represents the percentage of water demand that is met by water sourced from within the urban system (in this case RW and WW). The impacts of the infill scenarios on water demand and supply and on water self-sufficiency in an average rainfall year, compared with the EX state, are shown in Figure 8.

The increased population on the site from 90 in the EX case to 225 in the BAU case will increase water demand by a factor of 1.2 compared with EX demand. Because no supplementary water supplies are assumed for either of these cases, there is no water self-sufficiency for the EX and BAU cases.

The population increase for the WS-Cons case (to 323 people) will increase water demand by a factor of 2.4 from EX, which is higher than for the BAU case because of the greater number of people on the site but also because of the greater extent of irrigation that is assumed to occur to promote greening. However, supplementary supplies of rainwater and/or recycled wastewater reduces the use of imported water by various degrees.

The harvesting and indoor use of rainwater (RW) alone provides 25% water self-sufficiency. This concurs with other estimates that suggest ‘an appropriately sized rainwater tank could supply up to 20% of a household’s total water needs’ in Perth (WA Government, 2020). The outdoor use of recycled wastewater alone provides an overall 40% water self-sufficiency, meeting all of the outdoor water demand. The combined use of both provides 63% self-sufficiency, which brings the demand for imported water to be less than the BAU case, with the added benefits of a higher population yield and greening supported by irrigation.



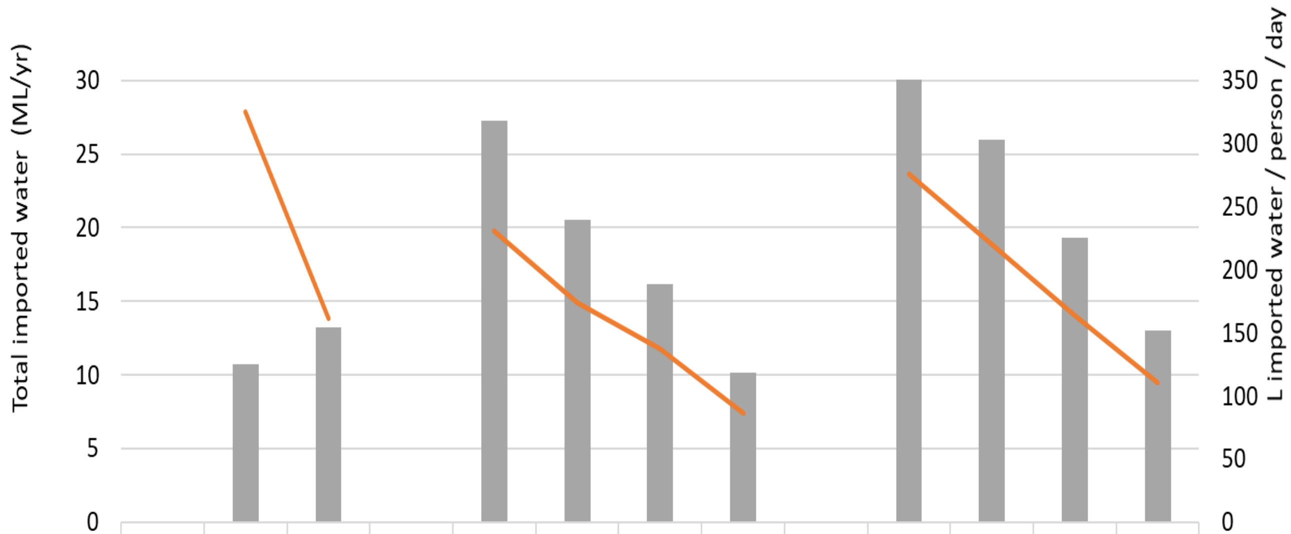
	PRE	Typical EX (90 people)	BAU infill (225 people)		WS-Con Infill (323 people) no supp. water	WS-Con Infill (323 people) RW	WS-Con Infill (323 people) WW	WS-Con Infill (323 people) RW+WW		WS-Max Infill (420 people) no supp. water	WS-Max Infill (420 people) RW	WS-Max Infill (420 people) WW	WS-Max Infill (420 people) RW+WW
Wastewater		0	0		0	0	11	11		0	0	13	13
Rain water		0	0		0	7	0	6		0	7	0	6
Imported water	0	11	13		27	21	16	10		33	26	19	13
Self sufficiency		0%	0%		0%	25%	40%	63%		0%	20%	41%	60%

Figure 8: Water supply and self-sufficiency, in an average rainfall year (2014)

The resulting changes in per person use of imported water can be seen in Figure 9. Per person use of imported water for EX was estimated to be 325 L/person/day (117 kL/person/year) This compares reasonably well with the figures reported by Water Corporation (2010) of 290 L/person/day, and Makki et al. (2015) of 335 L/person/day. It should be noted that this study assumed water for irrigating gardens was supplied from centralised mains water supply (imported water). In contrast, the lower Water Corporation figure is assumed to not include some garden irrigation water that would be supplied by private groundwater bores.

For BAU, per person use of imported water was estimated to fall relative to EX to 161 L/person/day. This result reflects substantially less garden irrigation due to there being very little garden available to irrigate. Consequently, this scenario could be interpreted as being more water efficient than existing, but no greening value is obtained.

For the WS-Con and WS-Max scenarios that uses supplementary water, per person use of imported water could reduce to 86–174 L/person/day and 110-220 L/person/day respectively. The current target for household water use efficiency in Perth is 300 L/person/day (reported as 110 kL/person/yr) (WA Government, 2019). Therefore, the WS scenarios will more than meet this target. BAU will also meet this target, but without the benefits of greening.



	PRE	Typical EX (90 people)	BAU infill (225 people)		WS-Con Infill (323 people) no supp. water	WS-Con Infill (323 people) RW	WS-Con Infill (323 people) WW	WS-Con Infill (323 people) RW+WW		WS Infill (323 people) no supp. water	WS Infill (323 people) RW	WS Infill (323 people) WW	WS Infill (323 people) RW+WW
Total imported water (ML/yr)		11	13		27	21	16	10		33	26	19	13
WS per capita use of imported water (L/person/day)		325	161		231	174	137	86		276	220	164	110

Figure 9: Per person use of imported water, in an average rainfall year (2014)

3.3 Water storage capacity

As can be seen from the previous sections, performance in terms of hydrology and water demand and supply can be influenced by the storage capacity in the urban system. The performance principles for this aspect are that 'infill designs incorporate water storages to facilitate the availability of supplementary water supply, and slow / retain / detain runoff' (Renouf et al., 2020, p. 35).

In many cases, storage capacity includes reservoir stores (e.g. tanks, retention basins, storage aquifers etc.) but also soil moisture storage in the soil profile. However, in this case study, the highly pervious sandy soils do not provide significant soil moisture storage. Consequently, only reservoir storage capacity has been considered as a performance indicator, in particular the under-building rainwater tanks. The site plan also has buffer treated wastewater holding tanks associated with the sewer mining scheme. However, the supply of treated wastewater as a supplementary water supply is not constrained by storage capacity, and the tanks function as buffer storage to help with continuity of supply. As such it has not been included in the water storage capacity.

Figure 10 shows the total water storage capacity for the Knutsford case study development site under each development scenario. Both WS scenarios includes considerable rainwater storage capacity.

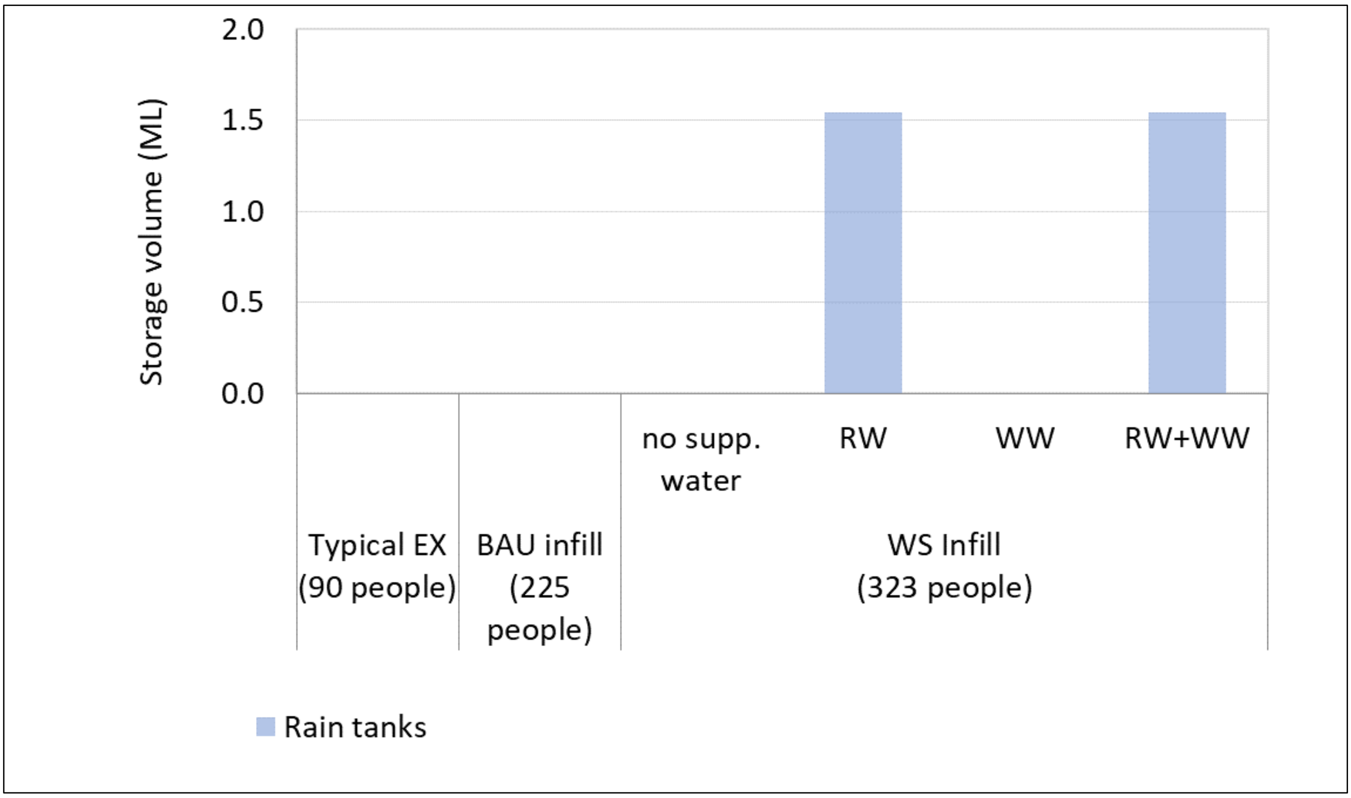


Figure 10: Water storage capacity in the study area (WS-Con shown).

3.4 Space and water for greening

This aspect recognises the importance of space and water for supporting vegetation, cooling, amenity etc. The performance principle is that 'infill designs include space and deep root zones for vegetation and large trees, and enables their irrigation with supplementary water supplies, to provide greening for cooling and amenity even in dry years' (Renouf et al., 2020, p. 36). Space and water for greening are represented together in Figure 11.

Space for greening is represented by the fraction of the study area that is vegetated and the fraction of the study area that provides deep root zone for large trees. The vegetated area of road verges (as in the EX and BAU cases) were assumed to typically have 80% deep root zone, except where the verges incorporate parking bays, in which case 50% deep root zone was assumed. Public open space areas were assumed to have 100% deep root zone. Compared with the EX case with 59% vegetated area, BAU will reduce this to 25%, and the WS scenarios will maintain it at 35% of the study area.

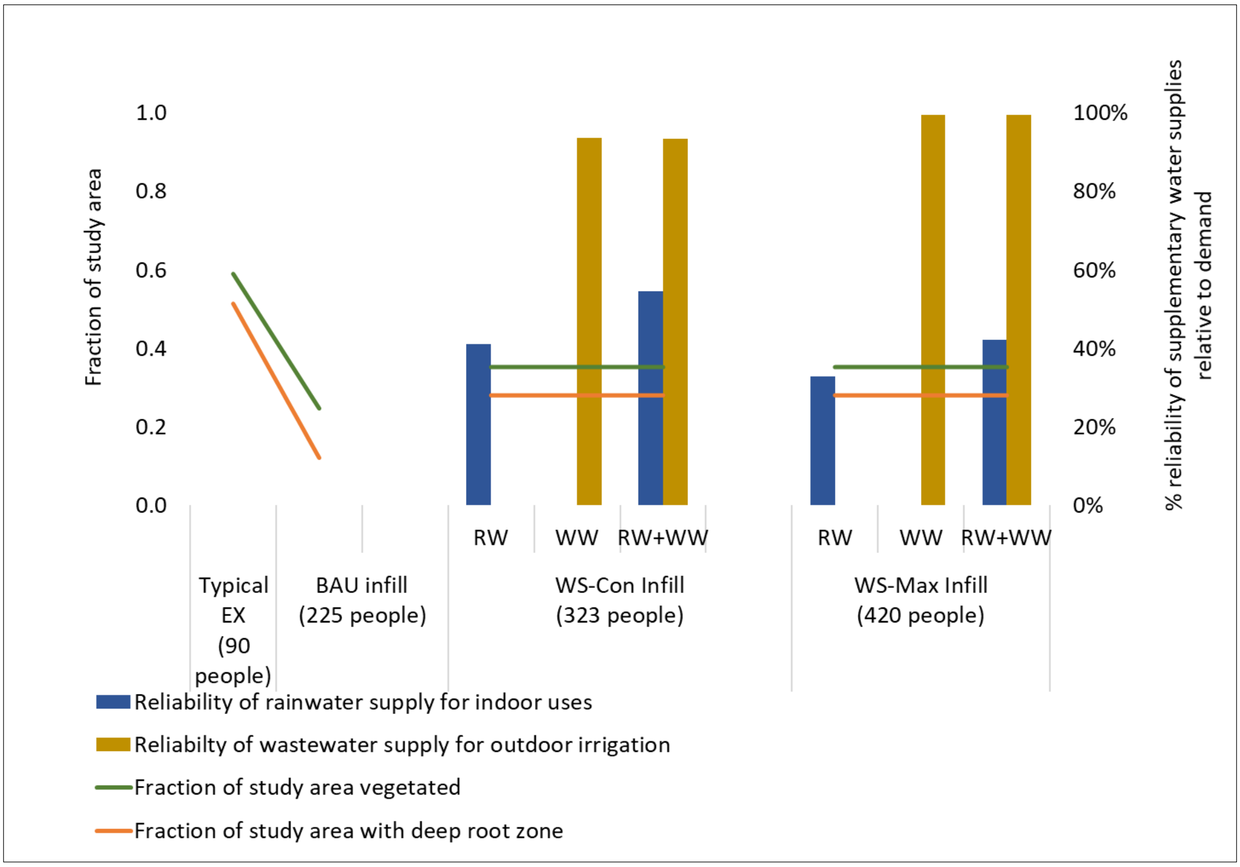


Figure 11: Water and space for greening in a dry year (2006)

More important is the fraction of the study area that has deep root zones to support large trees with substantial tree canopies, which is key to mitigating urban heat. For the typical EX case, 51% of the study area was estimated to provide deep root zones. BAU reduces this to around 12%, all of which is present in public spaces, and none in the gardens of the new infill dwellings. The WS scenarios are estimated to provide around 28% deep root zone, which is distributed across both the private and communal gardens and the public green space.

Garden irrigation for maintaining vegetation is often the first to be restricted during drought periods. However, the concept of water sensitivity promotes the importance of water for greening even in the hot, dry times when the need for cooling is most needed. This challenges the need for reducing water demand for irrigation. The objective is to not constrain outdoor water use for irrigation, but instead to make supplementary water available for irrigation during dry periods. This is a particular challenge for Perth, which receives most of its rainfall in the winter, but needs water for irrigation in the hot summer.

Therefore, in addition to the water demand and supply indicators (in section 3.2), the Framework also includes indicators that promote the availability of sufficient supplementary water for maintaining vegetation in dry periods. Water for greening is represented by the volumetric reliability of supplementary water supplies for meeting irrigation demands in a dry year (in this case 2006), which is the percentage of irrigation demand which can be met by supplementary water supply.

The EX and BAU cases assume no supplementary water supply, so any irrigation would need to use imported mains water which is likely to be restricted for irrigation in dry periods. For the WS-Con and Max scenarios, which use treated wastewater for outdoor irrigation, there is good supply reliability with all outdoor irrigation demand being met by the treated wastewater in this dry year. Hence there is a greater chance of establishing maintaining the quality and density of vegetation and canopy cover.

3.5 Architectural and urban space qualities

Application of key design principles in the Knutsford water sensitive test case

In approaching the design of the water sensitive test case, we sought to adapt design principles from the typologies catalogue and apply them to the specific opportunities and ambitions for the site as outlined above. The first design (here denoted as WS-Max) represented what the design team and project partners considered to be an appropriate or optimum density for the development, with reference to long-term potential of the location and the precinct master plan. A variant of this design (denoted as WS-Con) at lower heights/dwelling densities was also developed in response to current 2019 market forces in Perth that favoured lower height building types. Both designs have the same basic urban street pattern and block structure.

Access to quality outdoor public space

The primary public open space of the precinct in the WS cases is the proposed ‘Knutsford St Linear Park’, which forms the northern boundary of the study site. This street has been designed by Josh Byrne & Associates and DevelopmentWA as a pedestrianised spine that reduces paved road area and increases space for vegetation, tree canopy and public recreational uses. The proposed WS site designs acknowledge this by providing a landscaped setback to the north, locally increasing its width and importance through a central urban plaza. A central north-south connecting path starts from this plaza and connects all apartments to the linear park along a series of small pocket-size green open spaces that are linked to raingardens. The other parts of the public open space network are the internal cross laneways that run east–west across the site and function as both vehicular access and stormwater infrastructure. Water infiltration galleries located beneath each street direct water to roots of trees planted on the south side.

Access to quality outdoor communal space

New dwellings on the site (both apartments and row-houses) are grouped into a series of blocks, which would be constructed at the same time and allow some sharing of facilities such as underground water tanks. The north-facing frontage of each block contains a garden setback with space for canopy trees, providing shade to the buildings and to the ground level shared landscape, encouraging its use and influencing the social character of the cross-laneways. All vehicles enter the buildings through garages on the south side, and these are arranged to allow their easy use as workshops or other types of external covered space in the case where cars are not present. Both front gardens and rear garages are intended to foster an informal use of the cross-laneways as social spaces. In other words, the internal streets are conceived as multi-purpose communal spaces and not limited to vehicular circulation, especially given the relatively low number of car trips and low speeds expected.

Access to quality outdoor private space

Three-level row houses have a private north-facing front garden at ground level, and a private roof terrace, allowing for different types of uses at different times of day. Apartments and warehouse-type dwellings have a north-facing semi-enclosed covered space with two levels of protection from wind and weather, allowing for simple temperature control with adjustable shading devices. All private open space is north-facing and visually connected to the street, encouraging social interaction and 'eyes on the street' as no space is more than 4 levels above ground. Private open space is directly and conveniently accessed from internal living space. Shade to private open space is provided by a combination of canopy trees and planted trellises.

Dwelling amenity and function

Internally, the dwelling typologies have been selected for their simple, robust and flexible spaces, and 'warehouse-like' qualities that could easily accommodate a range of functions: from living to home-office, workshop-studio type making spaces, or semi-commercial uses at ground floor with living above. A range of smaller and larger dwellings are provided, each following the same principles. With a north–south orientation, access from two sides and generous width between party walls, the dwelling types provide flexible and high amenity 'shells' that can be fitted out in a range of ways to suit diverse ways of living both now and into the future.

Landscape systems and design

The design intent for the outdoor spaces is to create a cooling landscape with a sheltered microclimate. The integration of water flows through the site (including rainwater, stormwater and recycled wastewater) is integral to achieving this objective. Deciduous canopy trees on the northern side of buildings provide summer shade while allowing winter solar gain. Slope is used to convey water where possible to minimise pumping.

Permeable surfaces that capture rainfall and allow air into the soil profile below create an environment conducive to tree root growth beyond the immediate deep root zone allowance in the private courtyards. Excess flows, as well as stormwater captured off adjacent roads, are directed into infiltration galleries located under the laneways providing deep soil moisture hydration and groundwater recharge.

A series of densely planted 'feature' rain gardens run down the centre and western flanks of the precinct, capturing diverted 'first flush' events from the roofs of the adjacent buildings. 'Clean' rainwater flows are directed to underground storage tanks beneath the buildings for designated indoor uses. Tank overflow is directed to the underground infiltration galleries under the laneways on the lower side of each building, essentially acting as a cascading series of recharge points using gravity.

Summer irrigation demand will be met by recycled water from the sewer mining treatment plant, ensuring landscape water demand is adequately met year round, with wastewater flows being generated from the precinct and future adjacent development. The availability of this water means a densely planted landscape can be sustained, including areas of turf and leafy understory plantings beneath the canopy trees to create a sense of lushness and summer reprieve at the ground plane.

Table 4: Architectural and urban space qualities scoring for dwelling interiors

Rating	NA	0	1	2	3
Scoring	**Not applicable**	**Absent**	**Low**	**Medium**	**High**
Performance criteria	**Performance indicator**	**EX**	**BAU**	**WS-Cons**	**WS-Max**
		Rating	**Rating**	**Rating**	**Rating**
A. Availability and diversity	Dwelling diversity on site, a range of dwelling sizes (number of bedrooms and bathrooms) and types (e.g. townhouse, apartment and other)[8]	1	1	2	3
B. Size and proportion	Adequate internal spatial arrangement (size, proportion, and position appropriate for the use)	2	2	3	3
C. Access and connectivity	Appropriate accessibility (e.g. multiple access points separating residential from office, or pedestrian from car access); and appropriate internal connection between spaces	2	1	2	2
D. Privacy and noise—balanced transition	Privacy and noise proofing through appropriate positioning of windows, screens, fence (e.g. bedrooms not directly facing private open space used by all occupants or communal/public space)	2	1	2	2
E. Multifunctionality, adaptability, flexibility	Dwelling that accommodates a range of occupancies (e.g. flexible space on ground floor could be adapted as office space, granny flat)	1	1	3	3
F. Solar access, cross-ventilation	Adequate solar access including positioning of surrounding buildings and deep root zone for trees, avoids excessive westerly exposure, adequate cross-ventilation to all living areas	1	2	3	3
G. Outlook to gardens, vegetation, trees	High quality outlooks to open space, gardens, canopy trees	3	1	3	3
Overall scoring for dwelling interiors		**12**	**9**	**18**	**19**

[8] For principles on how evaluation was established, refer to the Infill Performance Evaluation Framework.

Table 5: Architectural and urban space qualities scoring for outdoor private space

Rating	NA	0	1	2	3
Scoring	**Not applicable**	**Absent**	**Low**	**Medium**	**High**
Performance criteria	**Performance indicator**	**EX**	**BAU**	**WS-Cons**	**WS-Max**
		Rating	**Rating**	**Rating**	**Rating**
A. Availability and diversity	Adequate number and types of private outdoor space, (e.g. garden, courtyard, balcony, rooftop terrace) Spaces of different orientation and levels of exposure/protection	2	1	3	3
B. Size and proportion	Appropriately sized and proportioned in length, width and height for usability	3	1	2	2
C. Access and connectivity	Accessible to all occupants (e.g. direct accessibility from living areas vs accessibility from a master bedroom only)	3	2	3	3
D. Privacy and noise—balanced transition	Balanced connection between private and communal/public spaces, considering privacy and noise (e.g. shades, screens, fences, etc.)	2	2	2	2
E. Multifunctionality, adaptability, flexibility	Supports a number of uses and users (e.g. balcony accessed from master bedroom will have fewer users/uses compared with a terrace accessed from living area)	2	2	2	2
F. Solar access, cross-ventilation	Adequate solar access including positioning of surrounding buildings and deep root zone for trees, adequate cross-ventilation, avoids ‘wind tunnels’	2	1	3	3
G. Outlook to gardens, vegetation, trees	Deep root zone providing sufficient space for and adequate positioning of large canopy trees/vegetation	3	1	3	3
Overall scoring for outdoor private space[9]		**17**	**10**	**18**	**18**

[9] For principles on how evaluation was established, refer to the Infill Performance Evaluation Framework.

Table 6: Architectural and urban space qualities scoring for outdoor communal space

Rating	NA	0	1	2	3
Scoring	**Not applicable**	**Absent**	**Low**	**Medium**	**High**
Performance criteria	**Performance indicator**	**EX**	**BAU**	**WS-Cons**	**WS-Max**
		Rating	**Rating**	**Rating**	**Rating**
A. Availability and diversity	Adequate number and type of shared facilities (e.g. vegetable garden, play area, BBQ area)	2	1	3	3
B. Size and proportion	Appropriately sized and proportioned in length, width and height for usability	1	0	2	2
C. Access and connectivity	Accessible to all residents, with physical connections between private and communal spaces	2	1	3	3
D. Privacy and noise—balanced transition	Transition between communal and public open spaces considering privacy and noise (shades, screens, fences, etc)	2	0	2	2
E. Multifunctionality, adaptability, flexibility	Supports a number of uses and users	2	0	2	2
F. Solar access, cross-ventilation	Adequate solar access including positioning of surrounding buildings and deep root zone for trees, adequate cross-ventilation, avoids 'wind tunnels'	2	1	3	3
G. Outlook to gardens, vegetation, trees	Deep root zone providing sufficient space for and adequate positioning of large canopy trees/vegetation	3	0	2	3
Overall scoring for outdoor communal space[10]		**14**	**3**	**17**	**18**

[10] For principles on how evaluation was established, refer to the Infill Performance Evaluation Framework.

Table 7: Architectural and urban space qualities scoring for outdoor public space

Rating	NA	0	1	2	3
Scoring	**Not applicable**	**Absent**	**Low**	**Medium**	**High**
Performance criteria	**Performance indicator**	**EX**	**BAU**	**WS-Cons**	**WS-Max**
		Rating	**Rating**	**Rating**	**Rating**
A. Availability and diversity	Adequate number and variety of open public spaces (e.g. linear park, pocket park, sports fields, nature reserve)	1	1	3	3
B. Size and proportion	Appropriately sized and proportioned in length, width and height for usability	1	1	3	3
C. Access and connectivity	Adequate bicycle and pedestrian accessibility and connectivity (i.e. walking distance; pedestrian and cycling infrastructure; multiple access points) Public transport provision	1	1	3	3
D. Privacy and noise—balanced transition	Balanced transition between public and residential spaces, considering privacy and noise, i.e. commercial/office space facing streets; setbacks; access points	2	1	2	2
E. Multifunctionality, adaptability, flexibility	Supports a number of uses and users, being suitable for a wide demographic and social mix (appropriate to dwelling diversity of the surrounding area)	2	1	2	2
F. Solar access, cross-ventilation	Adequate solar access including positioning of surrounding buildings and deep root zone for trees, adequate cross-ventilation, avoids 'wind tunnels'	2	2	2	2
G. Outlook to gardens, vegetation, trees	Deep root zone providing sufficient space for and adequate positioning of large canopy trees/vegetation	3	1	3	3
Overall scoring for outdoor public space[11]		**12**	**8**	**18**	**18**

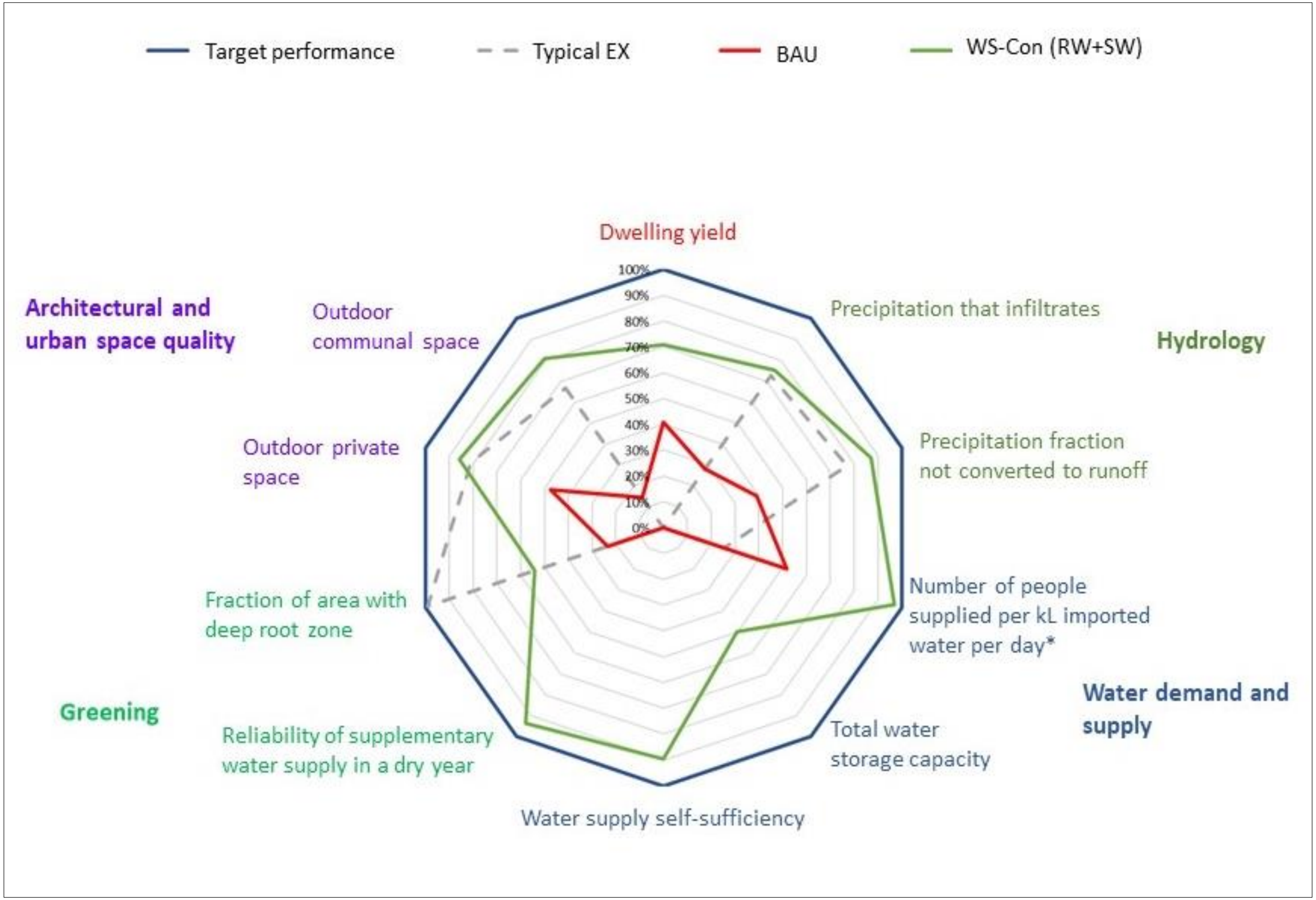
[11] For principles on how evaluation was established, refer to the Infill Performance Evaluation Framework.

3.6 Multi-criteria performance assessment

An overall comparison of performance across all the criteria are shown in Figure 12 , with the associated performance ranges and performance ratings shown in Table 8. Figure 12 visually synthesises the desired performance outcomes described in the preceding sections. The larger the envelope the better the performance. The criteria of 'dwelling yield' has also been added to recognise that achieving a particular dwelling/population yield for the site is also a desired outcome for infill development.

The WS-Con infill scenario (with rainwater harvesting and sewer mining), shown by the green envelope, can deliver higher dwelling yields, while also providing water sensitivite and amenity benefits. The stand out benefits, relative to the EX case, relate to water demand and supply, specifically the extent of water self-sufficiency and water storage capacity. This leads to a significantly reduced reliance on imported water and increased reliability of water for greening in dry times. WS also considerably improves acess to quality of outdoor communal space. In terms of access to and quality of outdoor private space, the WS typologies offer similar performance to EX typologies. In terms of hydrology, the WS designs can actually mitigate against the adverse effects of impreviousness on infiltration and stormwater runoff, by increasing infiltration (with constructed raingardens and infitration galleries) and holding back stormwater runoff (with large scale rainwater tanks). One evident downside of WS infill is a reduction in the deep root zone areas for supporting canopy trees. However this does not mean that there will be an actual reduction in opportunities for canopy trees, it just means that there will be less total space. In contrast, the EX state may have ample deep root zone for canopy trees, but may not be used for such.

By comparison, the BAU infill scenario (shown by the red envelope) can deliver increased dwellings, but there is an erosion of some performance aspects relative to EX. The quality of the outdoor private space is expected to be significantly reduced, as is the deep root zones for supporting canopy trees. In terms of hydrology, significantly less infiltration is expected, as is significantly more runoff. The per person use of imported water is reduced compared with EX, but this because no or little water is used for irrigation because there is little green space to irrigate. So the improved water use efficiency, which would seem to be a positive in terms of the household water efficiency targets being set by the WA Government, is at the expense of urban greening.



* This indicator is the inverse of the more familiar water use efficiency indicator of L/person/day. It is represented this way so that the higher the number the better the performance.

Figure 12: Overall performance comparison across multiple performance criteria

Table 8: Performance ranges and ratings

	Performance range		Performance rating		
	Lower limit	Target[B]	EX	BAU	WS-Con (RW+WW)
Precipitation fraction that infiltrates	0.0	0.4	0.3	0.1	0.3
Precipitation fraction not converted to SW runoff	0.0	0.97	00.7	0.4	0.8
Total water storage capacity (ML)	0.0	3	0.0	0.0	1.5
Number of people supplied per kL imported water per day[A]	0.0	12.0	3.1	6.2	11.6
Water supply self-sufficiency (%)	0.0	0.7	0	0	0.62
Reliability of supplementary water supply in a dry year	0.0	1.0	0	0	0.9
Fraction of area with deep root zone	0.0	0.5	0.5	0.1	0.3
Quality of outdoor private space (score)	0.0	21	17	10	18
Quality of outdoor communal space (score)	0.0	21	14	3	17

[A] This indicator is the inverse of the more familiar water use efficiency indicator of L/person/day. It is represented this way so that the higher the number the better the performance. For further details refer to Appendix, Table A5.

[B] Targets were identified using site relevant information where available, or expert opinion in the absence of existing information, to enable comparison of performance. Targets are notional/illustrative as explained in Section 2.

4.0 Conclusion

This analysis of Knutsford demonstrates the water-related impacts of infill are large, and can be significantly influenced by architectural and water services design. Alternative and water sensitive designs can considerably mitigate adverse effects on runoff, infiltration, evapotranspiration and other beneficial changes. This case study demonstrates it is possible to provide housing for additional (beyond target) population growth, and simultaneously mitigate existing previous negative consequences of relatively unplanned (hydrologically) development. Specifically, it shows incorporating large scale supply of supplementary water supplies into the design (in this case rainwater harvesting and sewer mining), significantly reduces reliance on imported mains water supplies and the reliability of water supply for greening in dry times. It also shows under-building water storage capacity and under-road infiltration galleries can reverse the adverse hydrological effects of increased urban densification. Therefore, WS designs can increase the dwelling yield on the development site while mitigating and even reversing the potential adverse impacts of densification. It also demonstrates the significant influence of water service options, integrated with architectural design, can significantly improve urban space quality and greening (which has implications for urban heat management; see the IRP4 Final Report and Salisbury Case Study).

Water-related impacts and water services

Stormwater runoff could increase 240% under BAU development, compared with the existing situation (and grow to 17 times pre-development levels). Similarly, infiltration would drop to one-third (0.11) of the existing situation. Water Sensitive options incorporating rainwater harvesting and sewer mining can maintain, and much more closely mimic natural flows. This has additional benefits of significantly reducing reliance on imported mains water supplies, improving reliability of water supply for greening and consequently positively influencing water security and liveability. Further, providing water storage (e.g. 10 m^3/dwelling and 200 m^3 for wastewater recycling) is key to achieving these performance levels. Consequently, WS designs and servicing options can increase the dwelling yield on the development site while mitigating and even reversing the potential adverse impacts of densification.

This case study provided quantitative evidence that with water sensitive interventions (planning, design and technology) WS infill can outperform BAU in all aspects and EX in all but one criteria, as well as support 43% and 360% more population compared with BAU and EX respectively. Some of the exceptional performances of the WS scenario are:

I. Reduced conversion of rainfall to stormwater runoff -– It reduces the stormwater runoff by 79% compared with BAU and decreases the EX runoff by 48%. Further, it increases runoff by only twice that of the PRE-development state.

II. Reduced reliance on imported water demand (dependency on the mains water supply) – The WS scenario is approximately four times less dependent on mains water than EX, despite the increase in population and similar irrigation demand. This reduction is due to wastewater reuse and rainwater harvesting. One of the critical performance indicators of the supplementary water sources is their reliability; it is reassuring that supplementary water sources have 90% reliability even during a dry year. Interestingly, the WS scenario can meet 63% of its water demand.

Architectural and urban space and quality

A range of design variables were observed to strongly influence hydrological outcomes (in addition to storage and water servicing options). For example, the overall pervious/impervious fraction of the site, and degree of local use of water, had significantly affected most outcomes such as stormwater runoff, infiltration and evapotranspiration. Storage was also highly influential on the water servicing options considered, and in particular the degree of self-sufficiency enabled by each different scenario. This work provides a foundation around which future performance objectives and targets (e.g. for hydrological performance or infill self-sufficiency of supply) could be considered for this development area, noting that performance can be strongly influenced by annual shifts in rainfall, as well as local conditions such as soil types and consistencies.

Future potential investigations and governance implications

This work provides a significant foundation quantifying and monetising water sensitive outcomes and building a business case for new development designs and typologies. Many of the performance indicators could be used to quantify or score benefits (or put actual costs or financial gains), and developing a cost–benefit analysis is a worthwhile next step. For example, the impact on water supply, wastewater flow, and building costs of the designs could be quantified, as could community reaction to the style of development they afford.

The report that followed the 2018 Knutsford workshop identified a need to focus on governance to realise the ambitions set out in this case study. Governance was considered under three headings: Leadership, Integration and Engagement and the following points have been summarised here:

Leadership

- More comprehensive design-based approaches and supporting governance and financial structures need to be developed that will allow for longer timeframes to support optimised urban resilience projects. The majority of work on sustainable and resilient urbanism has been associated with greenfield or brownfield sites with one owner/manager guiding the development. Moving into mixed sites such as Knutsford, with long established uses, a specific local character and identity, and multiple landowners requires a new and innovative approach.

- The current thinking around built form is highly constrained by short-term market fluctuations but has a major impact on the long-term build character. Investigation is needed into built form typologies that are more flexible and adaptive than those currently available.

Integration

- Energy, water, built form and community must be understood as linked, rather than as separate systems, and their integration within precincts prioritised. Greater understanding of the overall system should assist with discussions through better understanding across different disciplines.

- This ambition is easily thwarted by current planning and approval practices in which each specialisation focuses on their area of expertise then sequentially passes the project to the next group of experts.

Engagement

- Local structures which include existing communities are required to organise trade-offs, efficiencies, and synergies in environmental sustainability across a whole precinct.

- Such structures require processes that compare different development scenarios, together with optimisations possible within these scenarios, so that multiple targets can be met.

Overall conclusions

Collaboration across design and performance analysis was critical in developing both the approach and the resultant designs, particularly for water servicing options. While this case study did not evaluate a wide range of water servicing options, assessing the performance of a wider range of water service options should be a priority in future because higher levels of development will lead to greater demand and production of water and wastewater respectively. This increased pressure on centralised infrastructure can be reduced by employing a portfolio of water sensitive urban design infrastructure. Throughout this case study, the terminology used for performance, analysis and design developed and evolved iteratively between all study components (performance framework, case studies, typologies and modelling tools). The final language and terminology is best represented in the Infill Performance Evaluation Framework document. Principles, which are emerging for the effective design, water servicing and performance of infill, will be further elicited by comparing across multiple case study sites.

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Appendix A

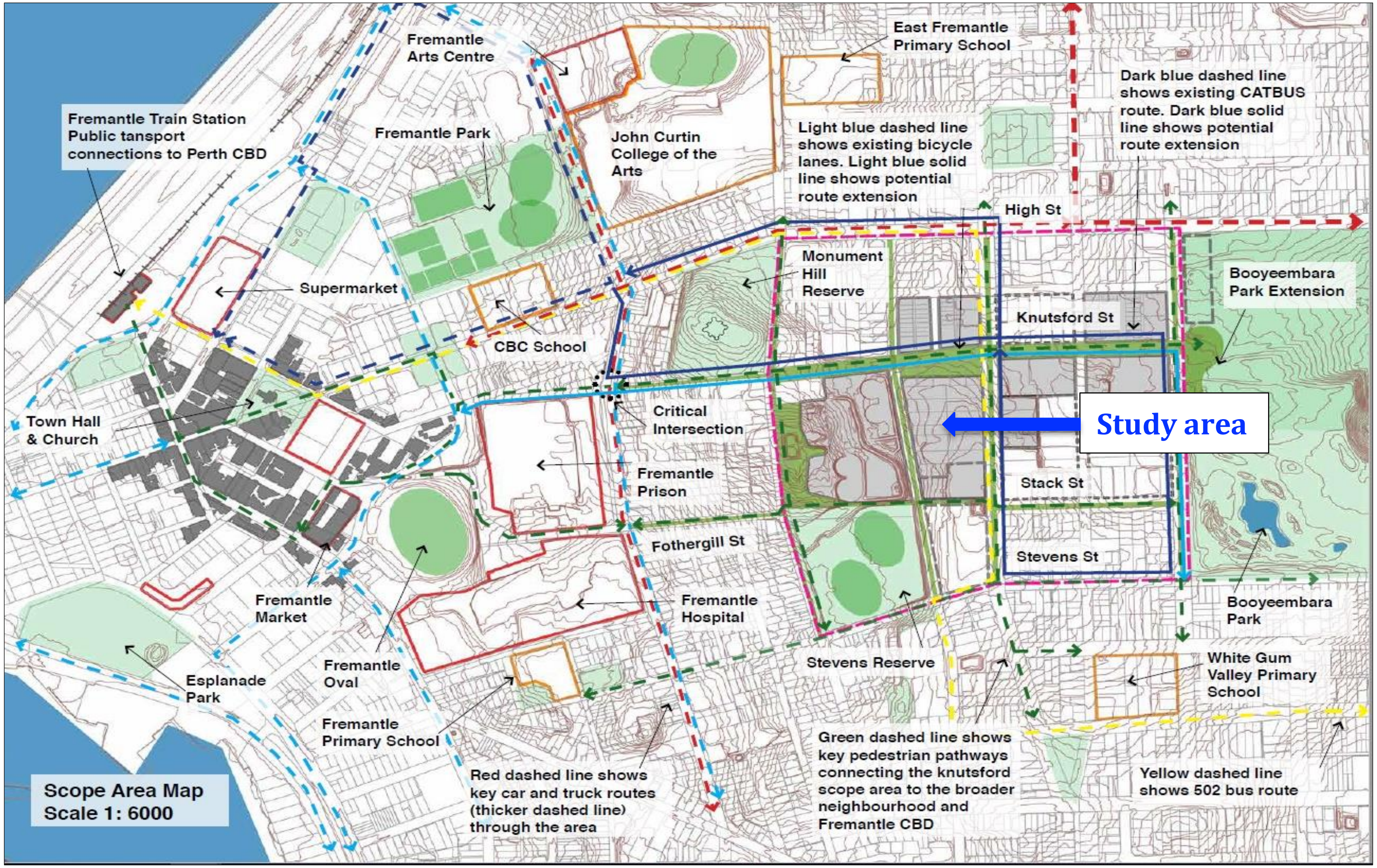


Figure A1: Context map of wider study area of Fremantle and developments sites in Knutsford (see also Figure A2)

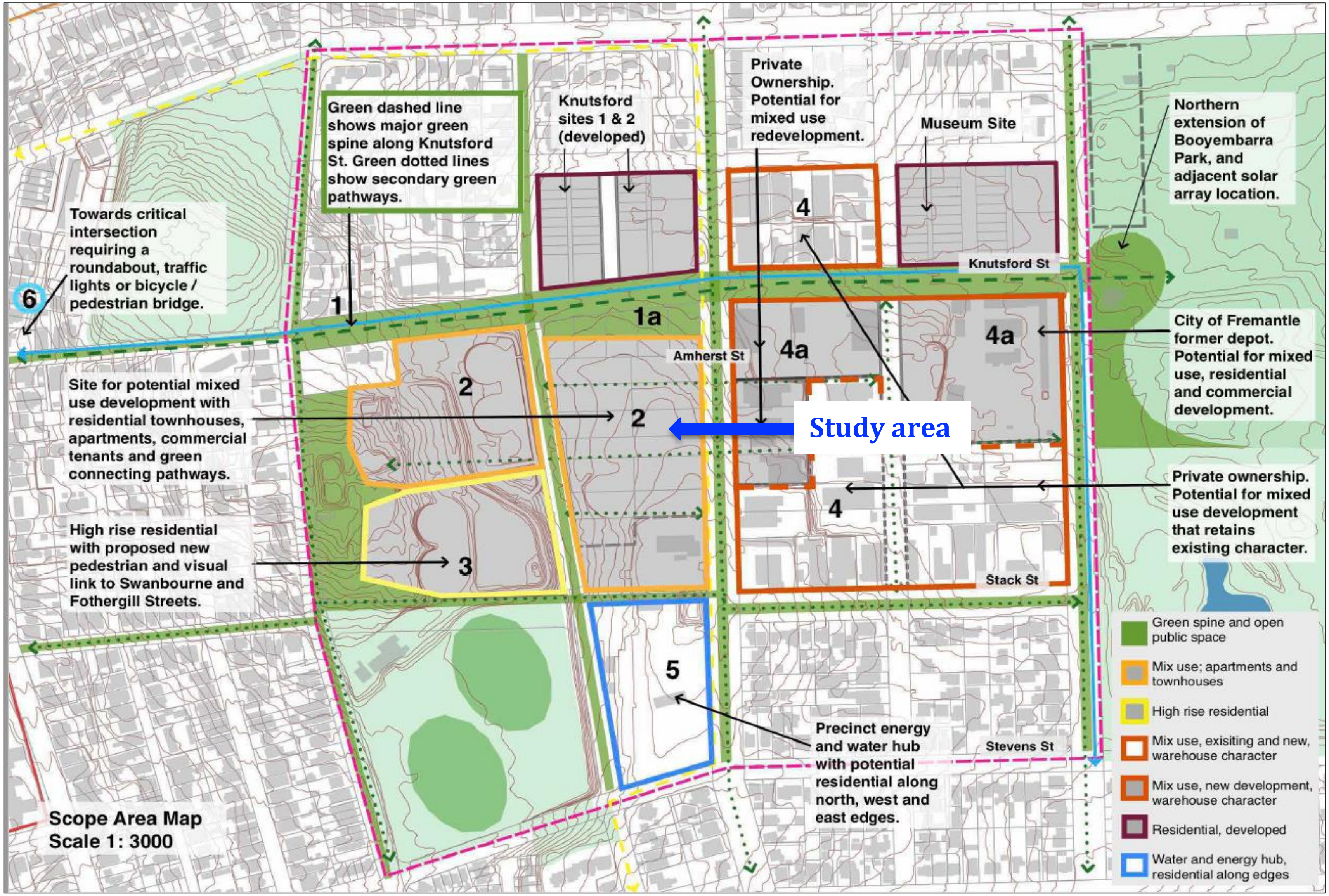


Figure A2: Detail of Knutsford development sites and the case study site (#2)

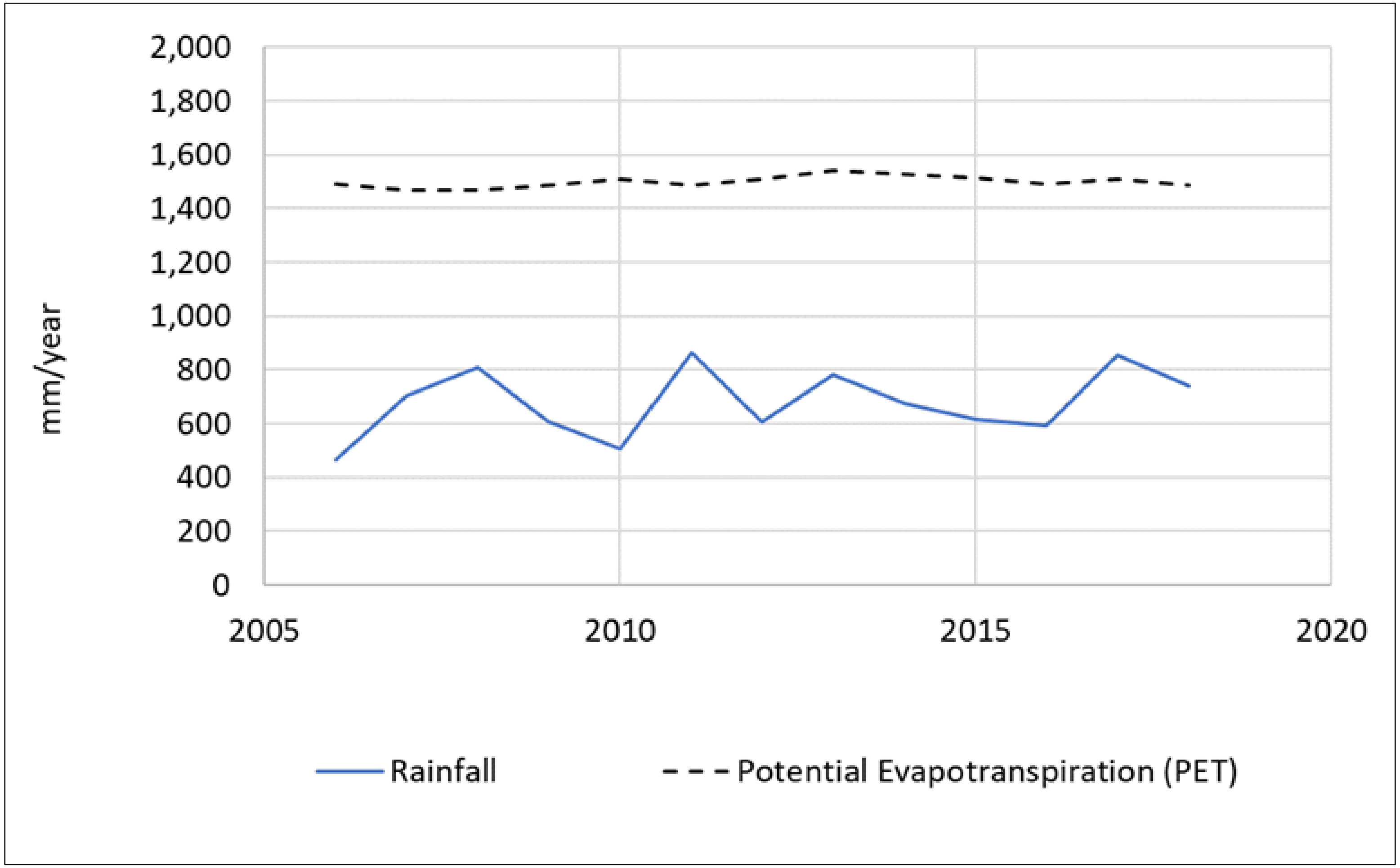
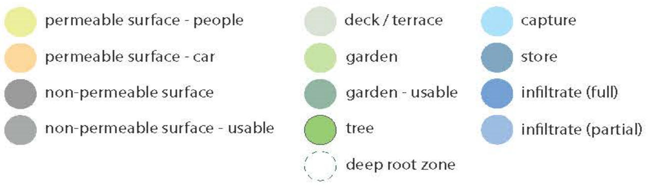


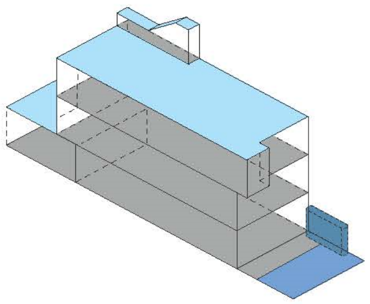
Figure A3: Rainfall and potential evapotranspiration for study area, derived from BOM (2015) for the 'Perth (009225)' rainfall station and 'Perth' evapotranspiration station

Category 1:
Courtyard, Terrace, Townhouse

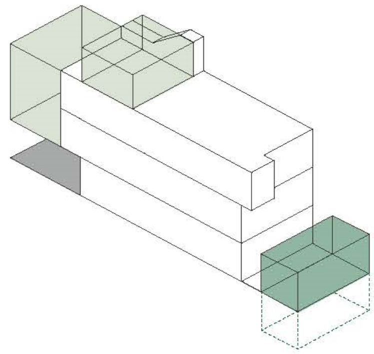
Heller Street Terraces

Six Degrees Architects 2011

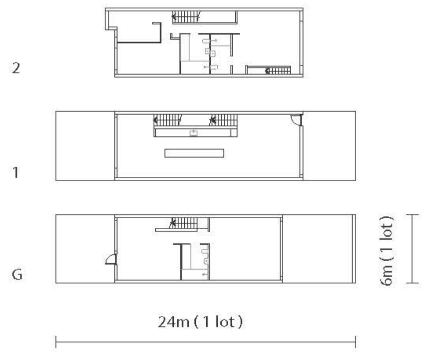




axo (water)



axo (landscape)



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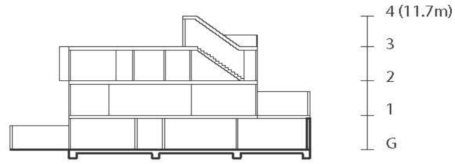

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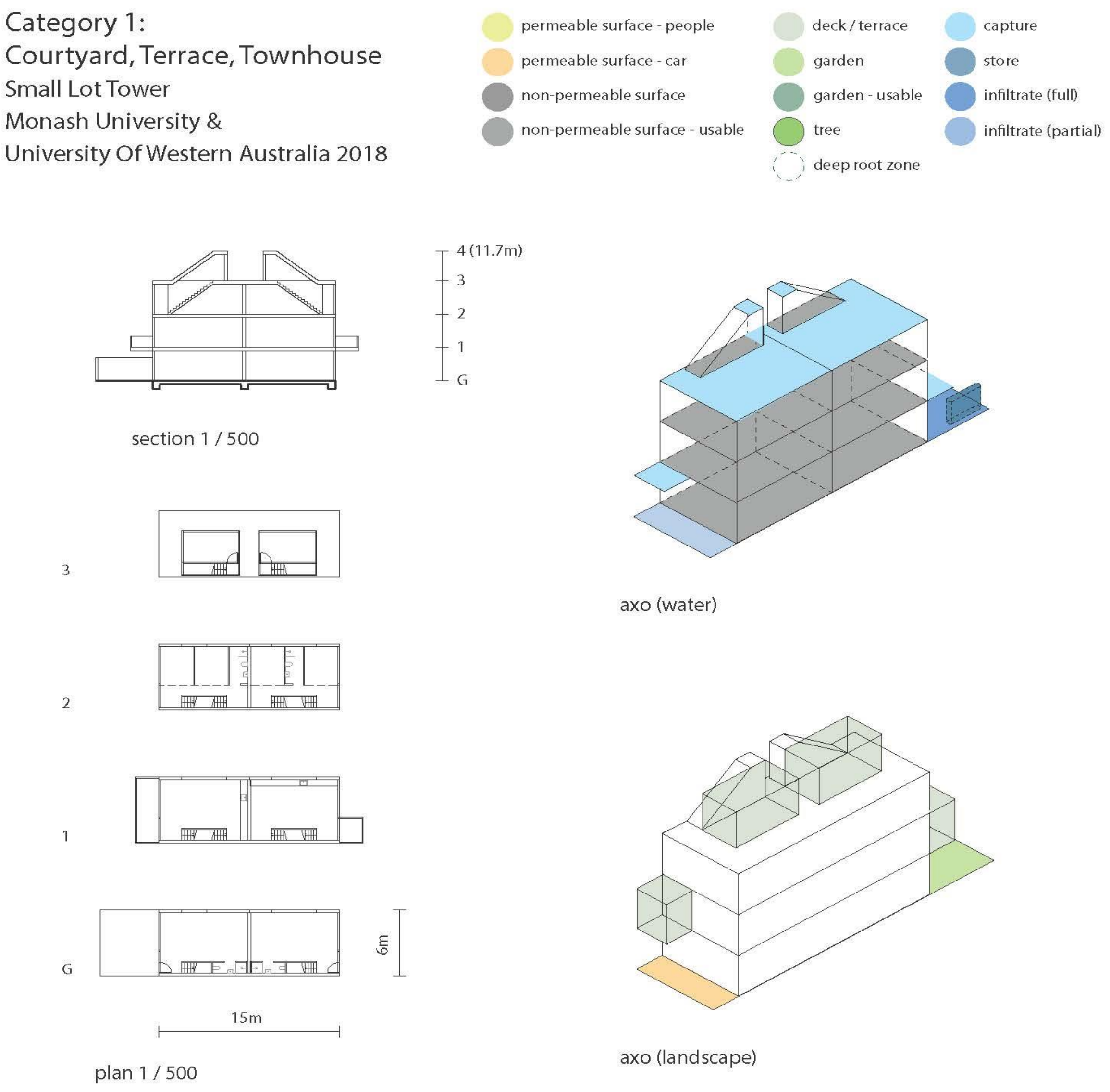
Dwelling Data:			
Bedrooms:	4	Floor Area (deck):	40 m2
Occupants:	3 to 5	Garden Area:	28 m2
Cars:	2	Roof Surface Area:	82 m2
Building Storeys:	3 + roof terrace	% of roof area connected to rainwater storage:	100%
Building Footprint:	82 m2	Rainwater Storage Capacity:	5000L
Floor Area (building):	235 m2	Household water appliances: (per dwelling)	3 x shower, basin, wc, 1 x kitch sink, laun tub, wm, bath.



Dwelling Data:			
Bedrooms:	2 (per dwelling)	Floor Area (deck):	12 m2
Occupants:	2 to 5 (per dwelling)	Garden Area:	14 m2 (roof)
Cars:	2 (per dwelling)	Roof Surface Area:	45 m2
Building Storeys:	2	% of roof area connected to rainwater storage:	100%
Building Footprint:	45 m2	Rainwater Storage Capacity:	2500L
Floor Area (building):	120 m2	Household water appliances: (per dwelling)	2 x shower, basin, wc, 1 x kitch sink, laun tub, wm.

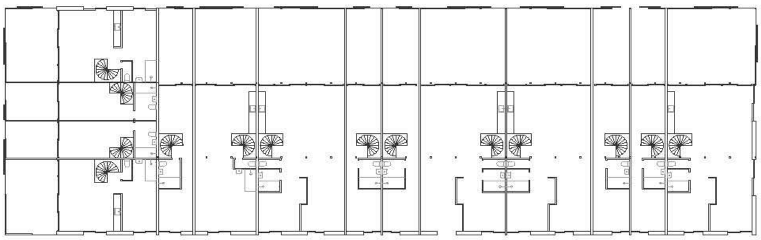
Figure A4: Townhouse typology in the water sensitive scenario
(Source: London et al., 2020)

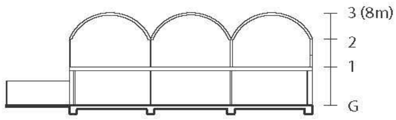
Category 2: Stacked, Cluster

Cite Manifeste, Mulhouse (variant)
Lacaton & Vassal Architects, 2005

- permeable surface - people
- permeable surface - car
- non-permeable surface
- non-permeable surface - usable
- deck / terrace
- garden
- garden - usable
- tree
- deep root zone
- capture
- store
- infiltrate (full)
- infiltrate (partial)

1





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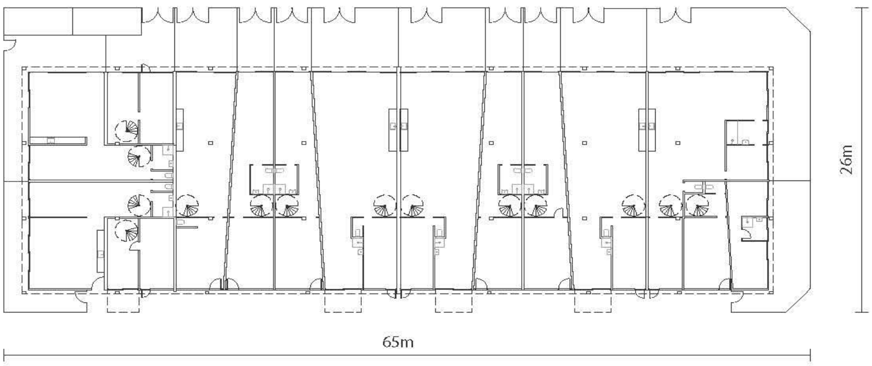

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Dwelling Data:			
Bedrooms:	2 and 3 (per dwelling)	Floor Area (deck):	390 m2 (all dwellings)
Occupants:	2 to 5 (per dwelling)	Garden Area:	472 m2 (all dwellings)
Cars:	1 (per dwelling)	Roof Surface Area:	1175 m2 (all dwellings & garages)
Building Storeys:	2	% of roof area connected to rainwater storage:	50%
Building Footprint:	1175 m2 (all dwellings & garages)	Rainwater Storage Capacity:	2500L (per dwelling)
Floor Area (building):	1850 m2 (all dwellings & garages)	Household water appliances: (per dwelling)	2 x shower, basin, wc, 1 x bath, kitch sink, laun tub, wm.

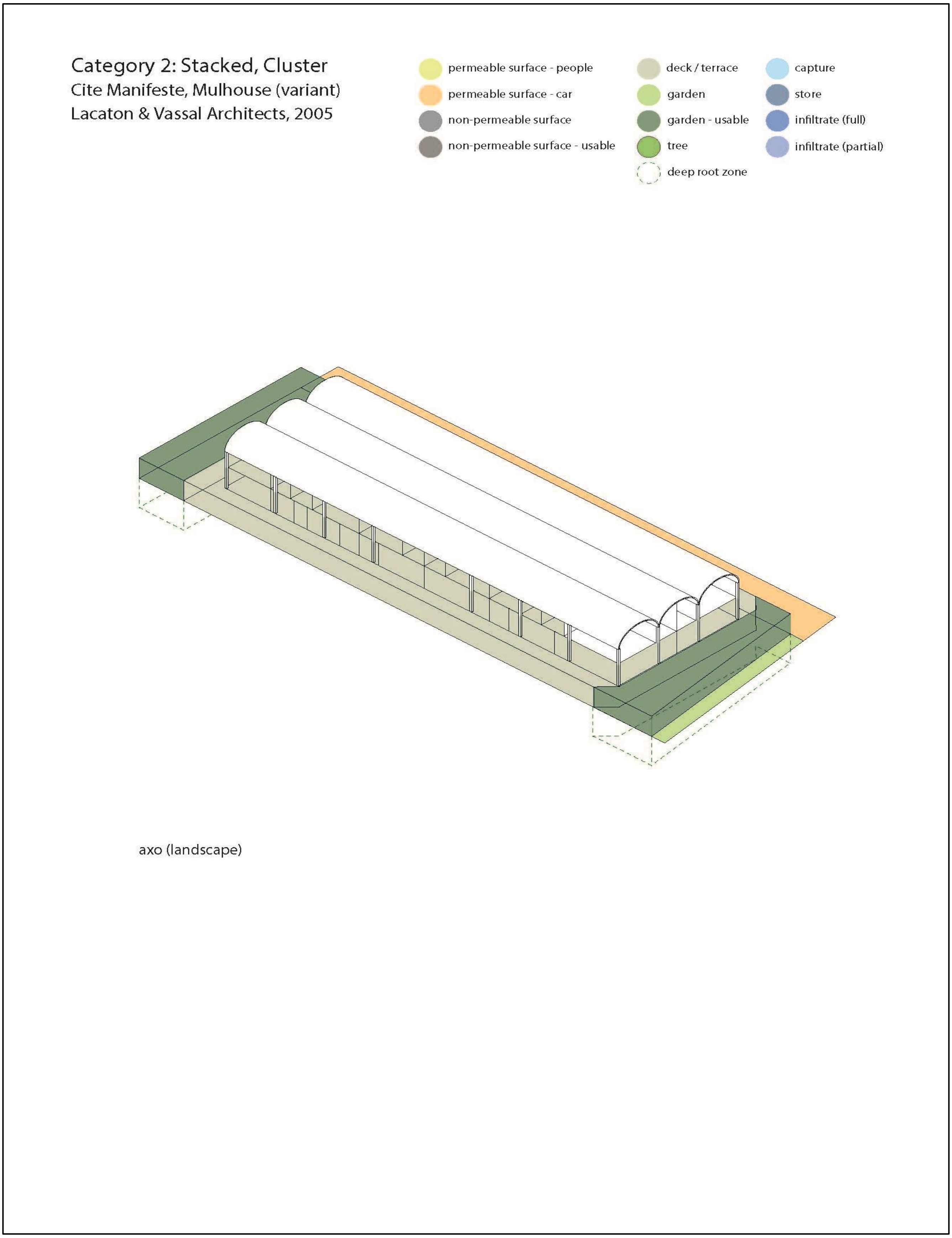
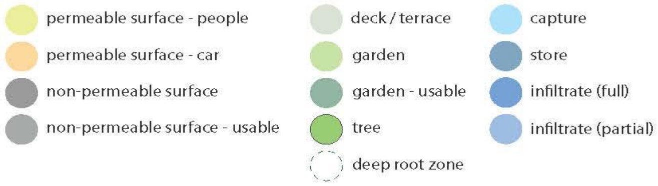
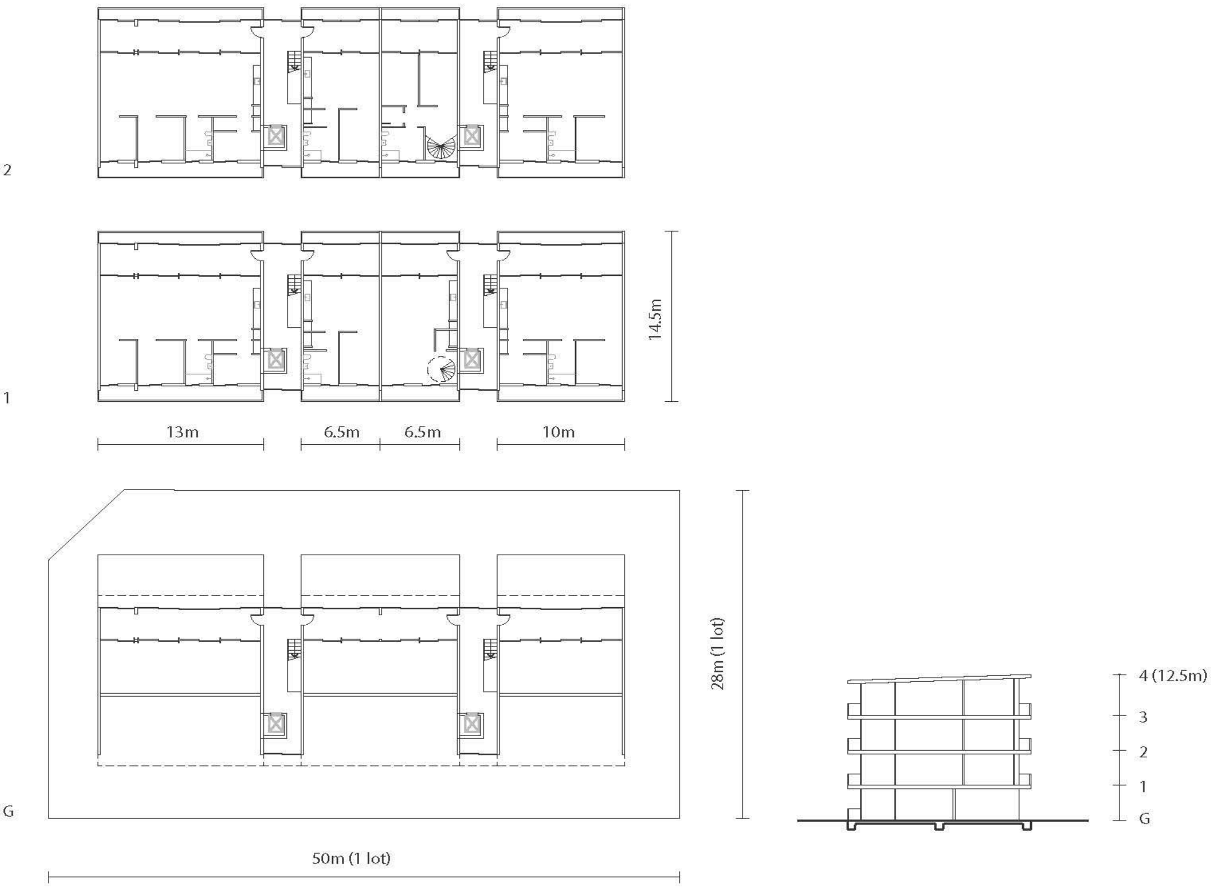


Figure A5: Warehouse typology in the water sensitive scenario
(Source: London et al., 2020)

Category 4:
Mid-rise Apartment Buildings

Water Sensitive Design, Knutsford, WA
(Adapted from Lacaton & Vassal architects, Neppert Gardens, 2015)





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section 1 / 500

Dwelling Data:			
Bedrooms:	1-3 (per dwelling)	Floor Area (deck):	371 m2
Occupants:	2-5 (per dwelling)	Garden Area:	560 m2
Cars:	1 (per dwelling)	Roof Surface Area:	565 m2
Building Storeys:	4	% of roof area connected to rainwater storage:	100%
Building Footprint:	565 m2	Rainwater Storage Capacity:	25,000L
Floor Area (building):	1100 m2	Household water appliances: (per dwelling)	2 x shower, basin, wc, kitchen sink, 1 x bath, laun tub, wm.

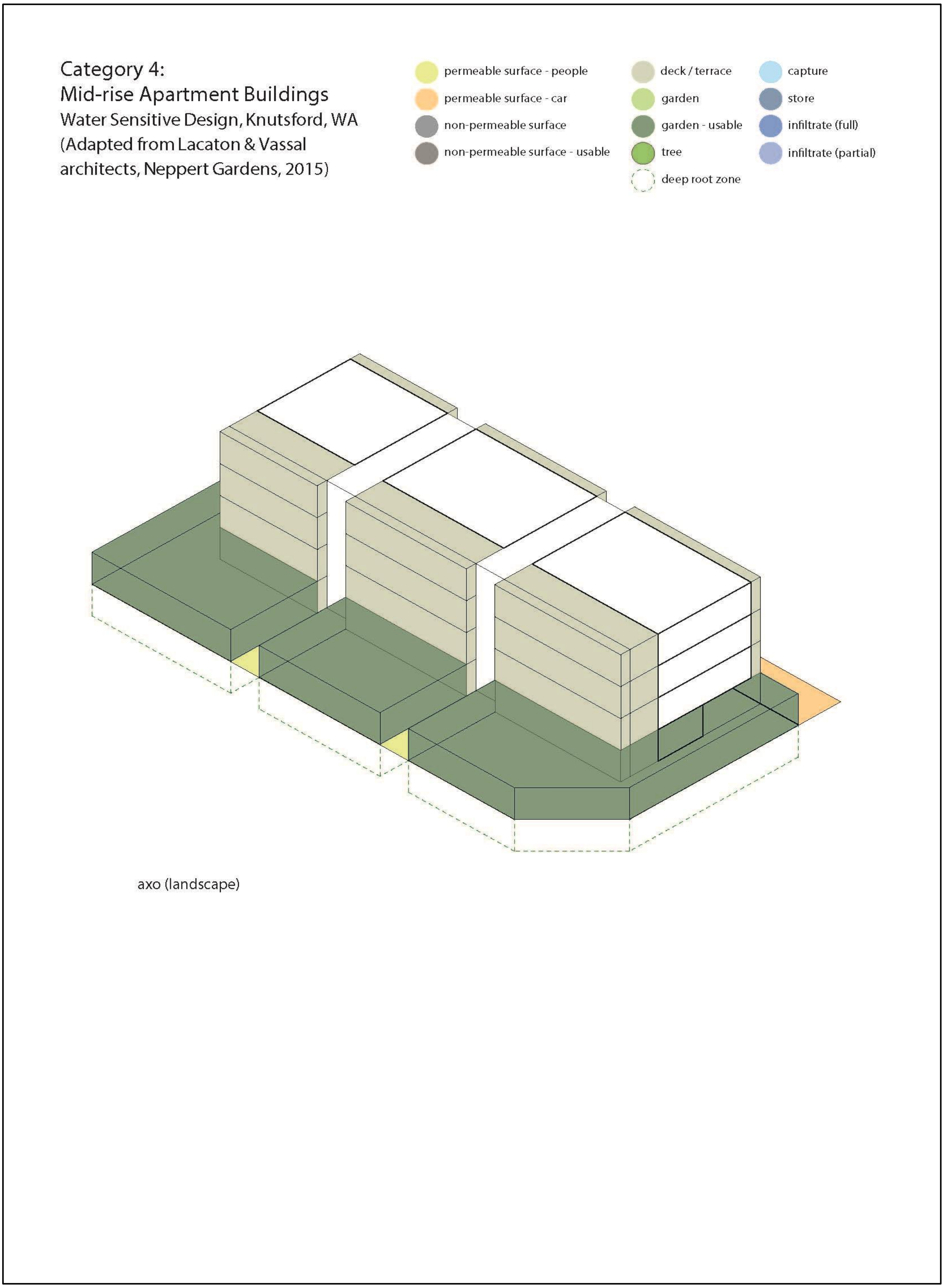

Figure A6: Apartment typology in the water sensitive scenario
(Source: London et al., 2020)

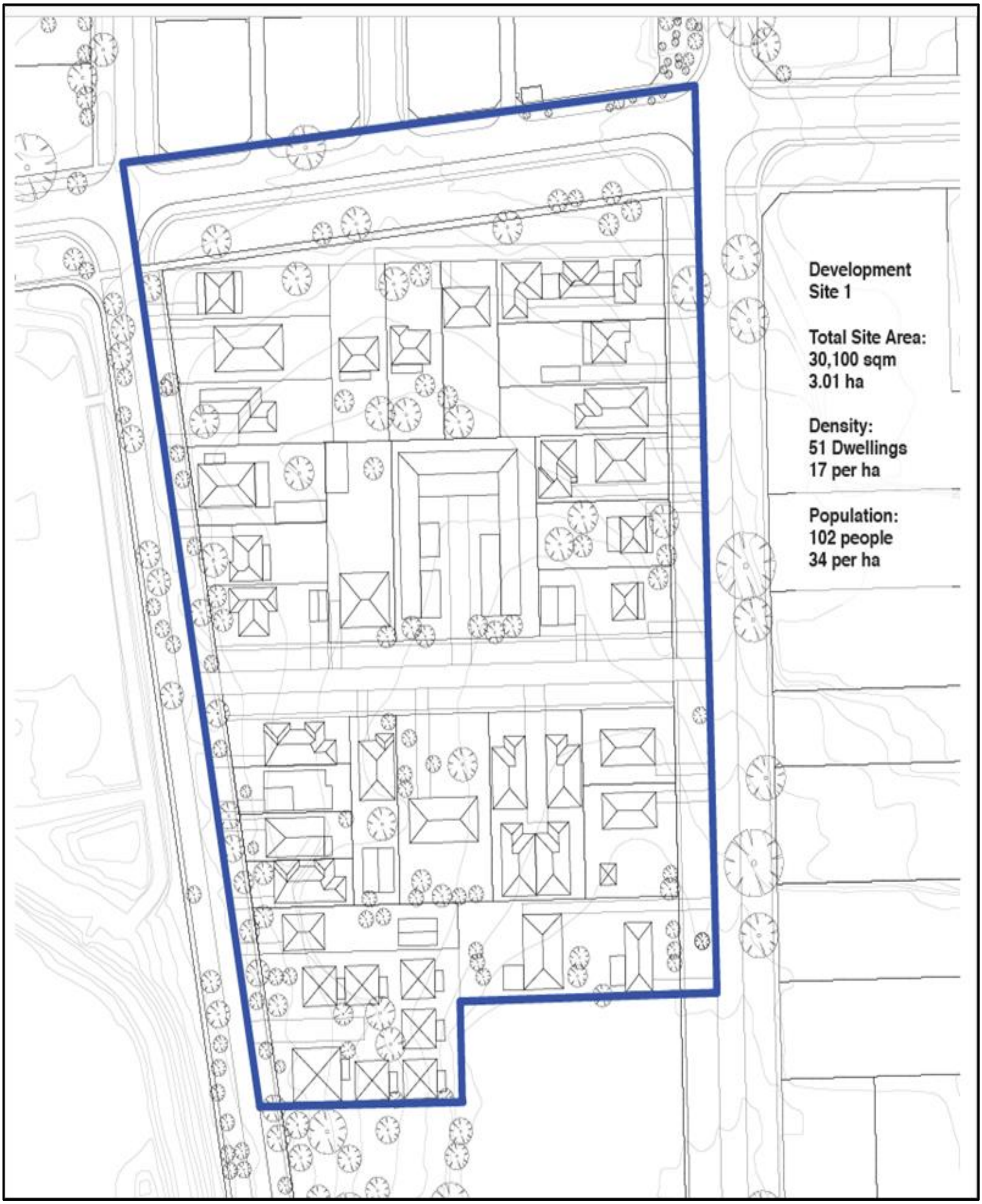

Figure A7: Site plan of the existing (EX) development scenario

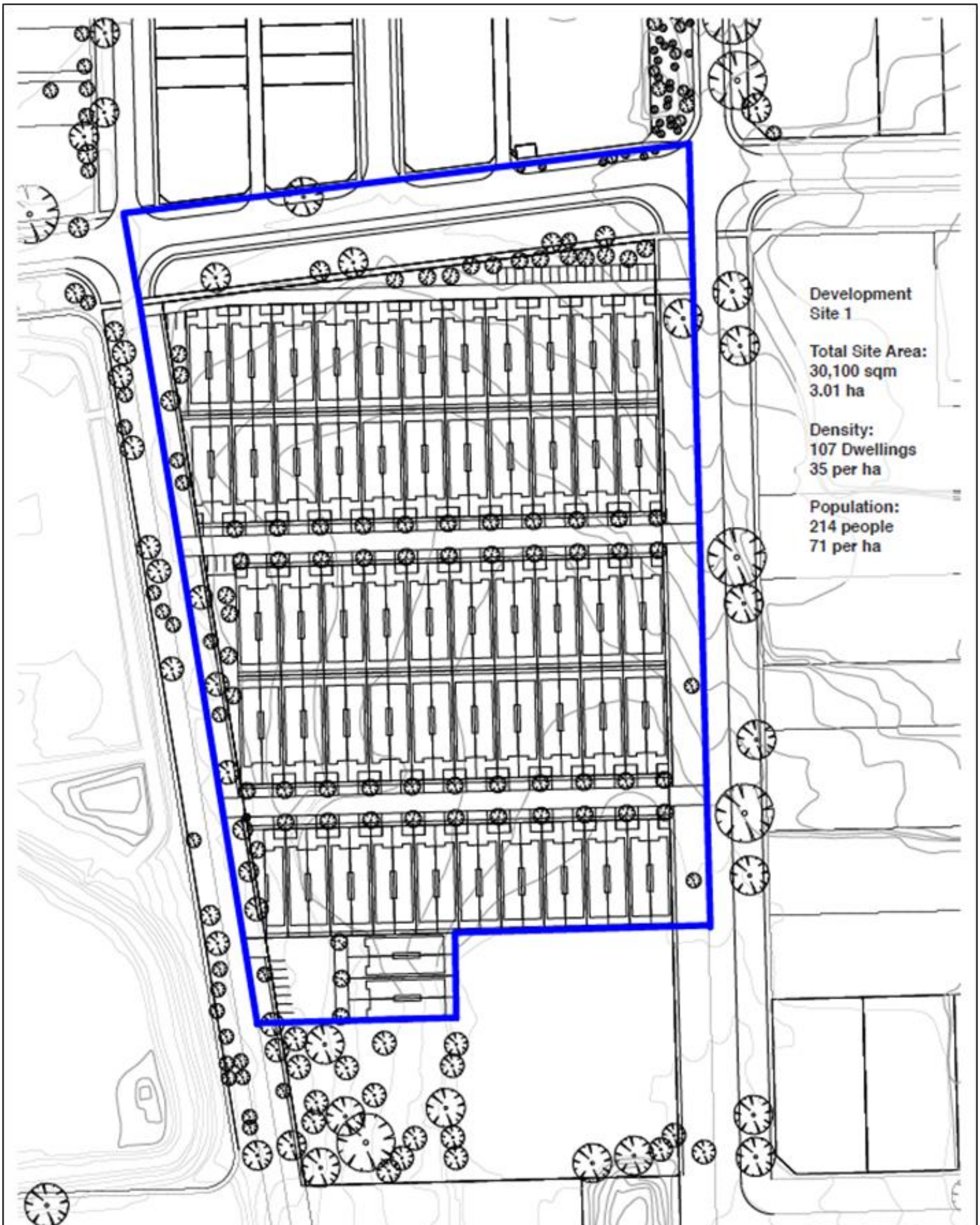

Figure A8: Site plan of business-as-usual (BAU) development scenario

Figure A9: Site plan of water sensitive development scenario (the boundary of the site evaluated is marked in blue)

Figure A10: Cross-section of the conservative water sensitive scenario (WS-Con)

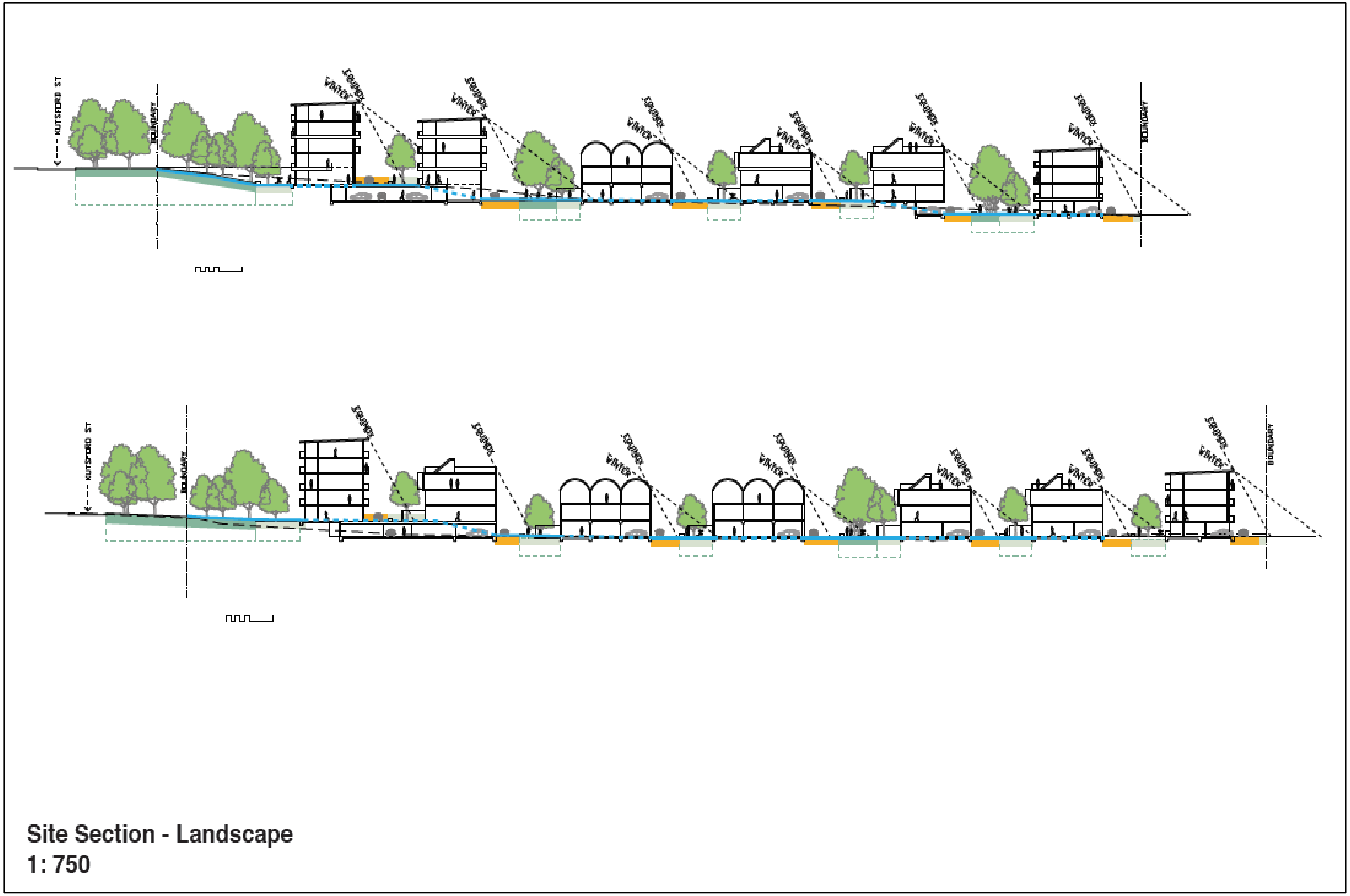

Figure A11: Cross-section of the maximised water sensitive scenario (WS-Max), and including landscape services

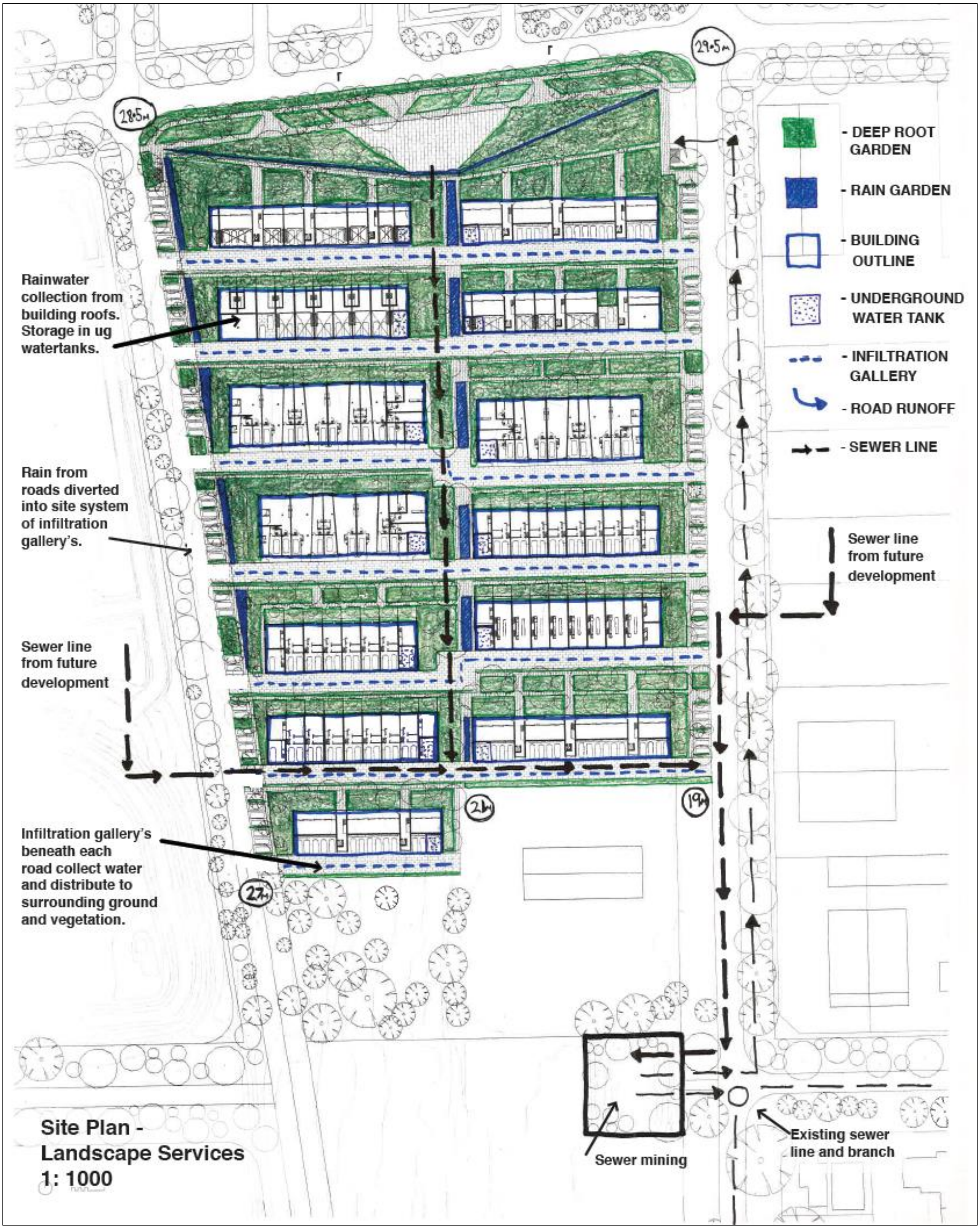

Figure A12: Site plan of water sensitive scenario, including landscape and water services

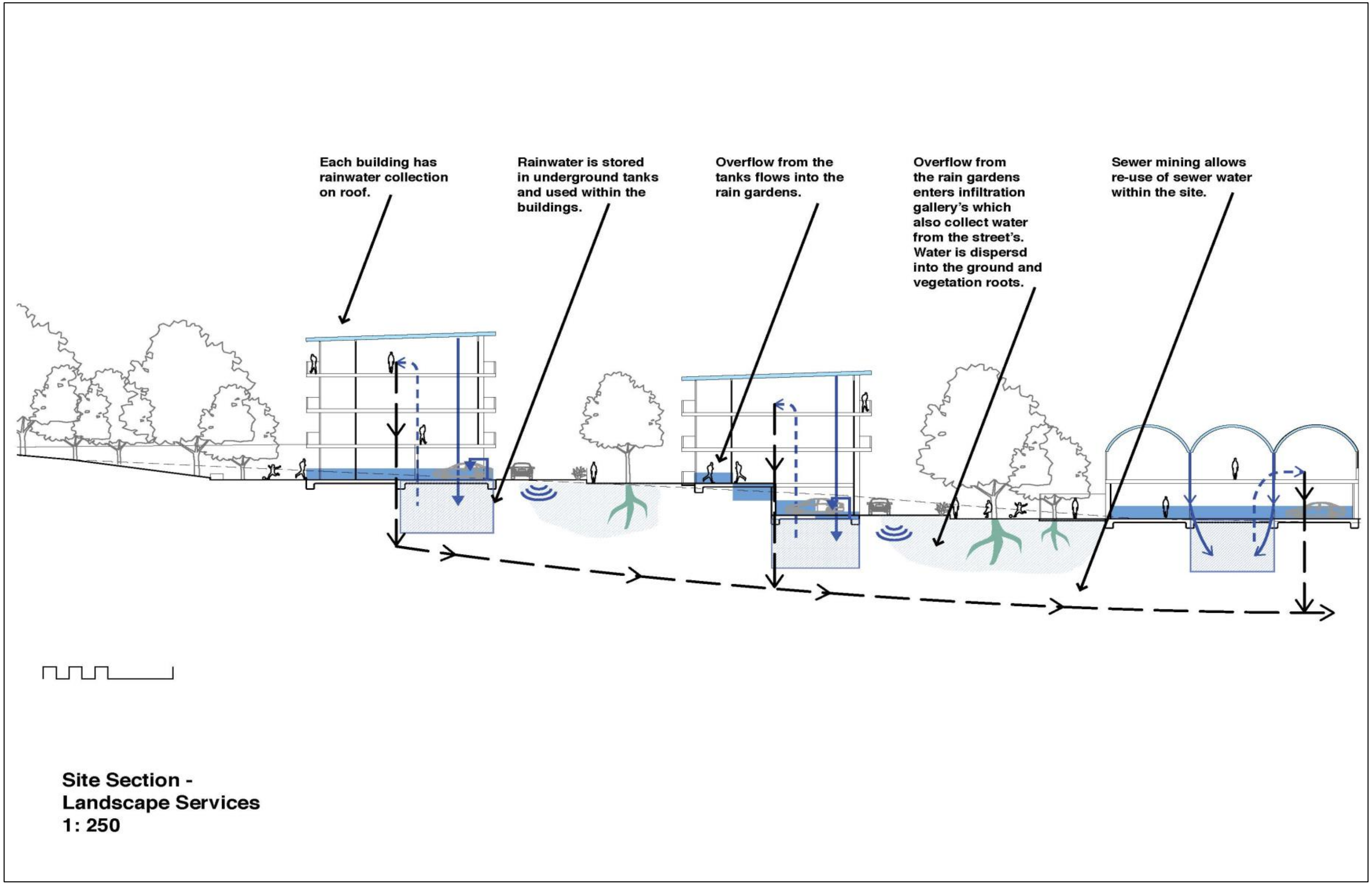

Figure A13: Site section for the maximised water sensitive scenario, including landscape services in detail

Table A1: Parameters for the existing (EX) scenario

Existing	Cluster number					
	1	**2**	**3**	**4**	**5**	**6**
	Ex dwellings	**Internal road**	**Perimeter—east**	**Perimeter—west**	**Perimeter—north**	**External rd—Knutsford**
Total area (m^2)—sum of all the components	26,364	3,703	2,388	1,468.22	2,562	3,504
Number of blocks (dwellings)	43					
Roof/road (m^2)	8,761	997				2,566
Pavement/driveway (m^2)	1,860	351	714	502.90	258	375
Garden (m^2)	15,743	2,354	1,674	965.32	2,304	563
Roof/road (%)	33	27	0	0	0	73
Pavement/driveway (%)	7	9	30	34	10	11
Garden (%)	60	64	70	66	90	16

Table A2: Parameters for the business-as-usual (BAU) scenario

Business-as-usual	Cluster number						
	1	2	3	4	5	6	7
	BAU dwellings	Internal road	Perimeter —east	Perimeter —west	Perimeter —north	External rd—Knutsford	Common Area
Total area (m^2)—sum of all the components	23,649	4,532	2,388	1,468.22	2,562	3,504	1,885
Number of blocks (dwellings)	107						
Roof/road (m^2)	13,714	2,290				2,566	
Pavement/driveway (m^2)	7,972	1,345	714	502.90	258	375	406
Garden (m^2)	1,963	897	1,674	965.32	2,304	563	1,480
Roof/road (%)	58	51	0	0	0	73	0
Pavement/driveway (%)	34	30	30	34	10	11	22
Garden (%)	8	20	70	66	90	16	78

Table A3: Parameters for the water sensitive (WS) scenarios

Water sensitive	Cluster Number									
	1	2	3	4	5	6	7	8	9	10
	Apartments	Warehouses	Townhouses	Perimeter—east	Perimeter—west	Perimeter—north	Common areas	Rain-gardens	Internal rd/ infiltration gallery	External rd—Knutsford
Total area (m²)—sum of all the components	7,271	5,263	6,459	1,469	1,582	2,562	4,979	537	6,363	3,504
Number of blocks (dwellings)—Conservative	59	38	57							
Number of blocks (dwellings)—Maximised	87	58	55							
Roof/road (m²)	4,096	3,217	4,529							2,566
Pavement/driveway (m²)	500	83	352	1,118	1,409	296	1817		5559	375
Garden (m²)	2,675	1,964	1,578	351	172	2,226	3,163	537	804	563
Roof/road (%)	56	61	70	0	0	0	0	0	0	73
Pavement/driveway (%)	7	2	5	76	89	12	36	0	87	11
Garden (%)	37	37	24	24	11	88	64	100	13	16

Table A4: **Urban water balances generated using Aquacycle for the average rainfall year (2014)**

(Refer to the Infill Performance Evaluation Framework for details of the water balance method).

Mass balance elements	Flow descriptor used in Evaluation Framework	Symbols	Flow descriptor used in Aquacycle	EX	BAU	WS-Con (RW+WW)
				ML/a		
Inflows	**Precipitation**	P	Precipitation	26.96	26.96	26.96
	Mains water supply—from outside urban system	W-Ex	Imported water volume	10.7	13.29	10.14
	Surface water from dams and rivers					
	Desalinated water from seawater					
	Groundwater via scheme					
	Groundwater via private bore					
	Recycled water supply—from within urban system					
	Recycled greywater from site	W-ReGW	Subsurface Greywater use			
	Recycled wastewater from site	W-ReWW	Onsite wastewater treatment unit use			
	Recycled wastewater from cluster	W-ReWW	Cluster wastewater treatment unit use			
	Recycled wastewater from catchment	W-ReWW	Catchment wastewater store use			13.28
	Harvested water supply—from within urban system					
	Rainwater from site	W-Rain	Rain tank use			6.302
	Stormwater from cluster	W-SW	Cluster stormwater store use			
	Stormwater from catchment	W-SW	Catchment stormwater store use			
	TOTAL INFLOWS			**37.6**	**40.1**	**56.54**
Outflows	Evapotranspiration	ET	Actual evaporation	18.26	8.07	17.94
	Stormwater runoff discharged	SW	Surface runoff	6.80	16.7	4.22
	Infiltration through soil (to 1 m below surface)	I		7.84	3	8.14
	Infiltration downwards		Groundwater recharge			

	Infiltration returning to surface		Baseflow			
	Wastewater discharged	WW	Wastewater output	5.01	12.74	17.95
	Wastewater sent to recycling					11.03
	Greywater sent to recycling	GW-Re				
	Wastewater sent to recycling	WW-Re				
	Wastewater recharged to storage aquifer	WW-ASR				
	TOTAL OUTFLOWS			37.85	40.47	59.21
	Mass balance check (Total Inputs – Total Outputs)			**0**	**0**	**-2.66***
	% change in Storage			**0**	**0**	**4.70%**

*The difference in 2.66 ML/year 'change in storage'. This 4.70% difference is because Aquacycle uses the AWBM model where excess soil moisture recharges the groundwater store, and the groundwater store is drained as base flow based on the Baseflow recession constant. It also assumes that during excess soil moisture stormwater infiltrates the wastewater and that drains to the wastewater system. But the UWMB of the urban entity only accounts for the infiltration below 1 m of the ground level and does not include groundwater recharge, baseflow recession and stormwater penetration (infiltration) to the wastewater system. Hence this difference in inflow and outflow is considered as a change in storage.

Table A5: Estimation of performance indicators
(Note: Water performance indicators derived from Table A4 above)

Aspect	Indicator	Unit	Performance threshold			Scaled value				
			EX	BAU	WS-Con	Bad	Good	EX	BAU	WS-Con
Built form	Dwelling yield	No. of dwellings	43	107	154	43	200	0	41%	71%
Hydrology	Precipitation fraction that infiltrates	%	0.251	0.096	0.265	0.0	0.4	63%	24%	66%
	Precipitation fraction not converted to runoff	%	0.76	0.4	0.87	0.0	0.97	78%	41%	90%
Water demand and supply	People supplied per kL of imported water per day*	People/kL/day	3.1	6.2	11.4	0.0	112	26%	52%	95%
	Water supply self-sufficiency	%	–	–	0.62	0.0	0.7	–	–	88%
	Total water storage capacity	ML	–	–	1.7	0	2.00	–	–	77%
Greening	Reliability of supplementary water supply in a dry year	%	–	–	0.42	0.0	1.0	–	–	54%
	Fraction of area with deep root zone	%	0.51	0.12	0.28	0.0	0.5	99%	23%	54%
Architectural and urban space quality	Dwelling interiors	–	12	9	18	0.0	21	57%	43%	86%
	Outdoor private space	–	17	10	18	0	21	81%	48%	86%
	Outdoor public space	–	14	3	17	0	21	67%	14%	81%
	Outdoor communal space	–	12	8	18	0	21	57%	38%	86%

Table A6: Calculation basis of key indicators from Table A5 for hydrology and water supply and demand

Indicator	Formula	EX	BAU	WS-Con
Dwelling yield	No. of unit block (dwelling)	43	107	154
Precipitation fraction that infiltrates	Infiltration through the soil/ Precipitation	5.93/24	2.3/24	6.26/24
Precipitation fraction not converted to runoff	1 – (Stormwater runoff discharged/ Precipitation)	1-(5.70/24)	1-(14.12/24)	1-(3.042/24)
People supplied per kL of imported water per day*	(Mains water supply—from outside urban system/no. of days/ population)$^{-1}$ x 1000	(10.58 x 10^6/365/90)$^{-1}$ x 1000	(13.23*10^6/365/225)$^{-1}$ x 1000	(10.39 x 10^6/365/323)$^{-1}$ x 1000
Water supply self-sufficiency	(Recycled water supply - from within urban system + Harvested water supply - from within urban system)/ total water supply			(11.02+5.63)/ (11.02+5.63+10.39)
Total water storage capacity	Rain tanks capacity			1.5

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