Light Grey Water Recycling (LGW) Potential within the Dutch Urbanscape

Supervisor page

Abstract

The Netherlands is expecting wetter winters and drier summers. Conventional water sources such as surface water and groundwater will be facing too much pressure to meet demand projections. The status quo of centralised water supply is being challenged to become flexible enough to meet more extreme fluctuations and potential increasing water demand. Deltares and Vitens are looking towards decentralised solutions in order to cope with future uncertainties. Looking at applying new technologies to balance and augment centralised water demand at the decentralised scale of the household level requires integrating it into the Dutch urbanscape. As a climate adaptation strategy, LGW is a last resort option concerning alternative water sources as it is the most publically-repulsive option but it can augment seasonal extremities due to its constant supply compared to the seasonal availability of rainwater harvesting. Is LGW feasible in the Dutch urbanscape that is expected to become increasingly compact, and thereby spatially limited?

Acknowledgements

ToC

List of figures

List of tables

Nomenclature

Introduction

Drinking water abstraction from the Meuse has been temporarily halted in Limburg due to the discovery of an unknown substance (Hoofs 2022). This is but the beginning of an impending water scarcity issue within the Netherlands. Drinking water companies should be worried (van der Krogt, Becker & Boigontier 2022). Lowered water discharge levels will occur more frequently and for longer periods of time in the entire river basin (van der Krogt, Becker & Boigontier 2022). We can expect higher contamination due to lowered dilution, meaning news of temporary intake of water from the Meuse will become more common.

Recent summers have past with lowered water discharge, indicating the immediacy of the situation. A report calculated Meuse discharge levels for three varying intensities of climate change up to the year 2085 (van der Krogt, Becker & Boigontier 2022). In all scenarios, we can expect low water discharge (van der Krogt, Becker & Boigontier 2022). So, it is not question of maybe if such and such occurs, then it may happen. Rather, it becomes a question of to what extent.

Such a physical reality has to contend with legal responsibilities of providing a basic human right to water in the Netherlands. Water companies have legal obligations to provide water for private individuals. Companies are granted water if permits are granted for additional drinking water extraction. This year, Vitens had to refuse drinking water applications from companies for the first time (Havermans 2022). The reality is stark: the common Dutch conception of an abundance of water is being challenged.

What is the solution? Is it to urge municipalities and provinces to increase capacity by issuing new permits faster? Such a practical action is necessary to secure water security for the construction of one million new homes before 2030, increasing drinking water demand by 10 to 15% (Havermans 2022). Yet, this will likely further exacerbate the expected low-flow conditions. As a result, securing this water security may push the ecosystem beyond their tipping point (Munson et al. 2018). Although humans are currently unable to predict how ecosystem regime shifts will occur and exactly what feedback loops will ensue, research demonstrates that tipping points lead to an abrupt and possibly irreversible shift towards a suboptimal ecosystem with high societal costs (Munson et al. 2018; Dakos et al. 2019).

This is not an isolated danger to the Netherlands. The upcoming hit motion film, Water Scarcity will be screened in all movie theatres worldwide. New findings into projections of clean water scarcity have been discarded as underestimations in comparison to real world rates, underlining the immediate need for change (Boretti & Rosa 2019). By 2050, 68% of the global population will inhabit urban areas (OECD 2015), exponentially increasing pressure in an area with limited fresh water sources, threatening its water security, considering that withdrawal rates will likely exceed replenishment rates, especially in the face of cascading climate-change impacts.

As a consequence, the natural water cycle is altered beyond recognition due to the vast impermeability of urban surfaces, preventing natural processes of water storage and inducing flash pluvial flooding that damages infrastructure and endanger human life. The intensification of urbanisation not only indicates the negotiation of limited space amongst individuals, how it will be utilised and for whose benefit, but increasing demand for water.

Furthermore, conventional water systems, embedded in traditional infrastructural legacies and design paradigms are shown to be inflexible and slow to adapt to change, redirecting research into improving flexibility through decentralised systems in order to cope with daily and seasonal fluctuations in water supply (Bell et al. 2017). In general, extraction companies do not have a diversified portfolio of water supply options beyond traditional sources such as surface and groundwater. The challenge today is to look beyond these traditional sources (Whitler 2015). As a result, water reuse is a promising system to prevent the depletion of fresh water sources by emulating nature in its way of recycling.

Problem Statement

It can be concluded from this introduction that the quantity of water in the future is subjected to extreme fluctuations between seasons, meanwhile the quality of water in the future is expected to be increasingly degraded, requiring intensified treatment, insinuating higher resource consumption. On the other hand, water demand is expected to increase due to more frequent and intense extreme weather events and rapid rates of urbanisation and population growth.

The discussion of mitigating water scarcity and providing clean water comes down to three main options: (1) improve water use efficiency or (3) use alternative, non-conventional water sources, which mainly points to desalinating seawater, rainwater harvesting, or wastewater reuse.

As a demand-side strategy for water management, WRS can augment water demand for households, as they form 64% of Dutch water companies' processed drinking water in 2020 (CBS 2022), the Netherlands can decrease surface and groundwater abstraction, quenching over-abstraction which leads to salinisation and eutrophication.

Knowledge Gap

Waste water reuse is essential to sustainable water management in the future but its application remains highly contextualised to local factors. This is evident in the fact that WRS have yet to be well-established because of institutional, social, and economic barriers (Sgroi, Vagliasindi, and Roccaro 2018). In general, research into urban WRS is concentrated in developing nations such as India (Goyal et al 2020), Bangladesh (2019), the MENA region (Oertlé et al. 2020), Jordan (Ghunmi et al. 2008), or in arid cities such as California (Binz et al. 2016) due to the fact that they are already experience both physical and economic water scarcity.

In Europe, there are political drivers that encourage water reuse, such as the water framework directive and the circular economy package, indicating a shift in mentality towards integrating sustainability into our socio-technical systems. This means there is a window of opportunity developing that water reuse innovations can take advantage of in order to be adopted into the existing socio-technical system.

As such, decentralised urban WRS is posed as a potential part of the solution to the consequences of the Netherland's changing water patterns. However, decentralised WRS cannot exist in a vacuum. It requires physical space to implement, which presents a challenge in dense urban spaces, and consists of a variety of treatment options which consume more or less energy and resources to produce and operate, as well as other potential benefits that should be taken into account in fostering a climate-resilient urbanscape.

Research Objectives

This thesis comprises an exploratory research into decentralised LGW reuse in the Dutch urban context in order to cope with climate-change-induced high dynamic scenarios. As such, its goals are to:

(1) Conduct a multi-criteria analysis inorder to score emerging and on-the-market GW treatment technologies for LGW reuse for application in the Dutch urbanscape on basis of their treatment train space, hereby defined as the amount of space necessary for all technological components to treat per person equivalent, energy consumption, maintenance level and added value to climate-resilience.

(2) Determine the water saving efficiency of LGW for non-potable and direct potable reuse against other available technologies that would not require source-separation based on two scenarios: current demand pattern and future climate-change enhanced peak factors.

(3) Compare the potential for meso-scale green technologies for LGW reuse in three different Dutch urban morphological samples, each representing a degree of urban compaction.

Then the thesis synthesises the objectives' results to make practical recommendations on whether and how decentralised LGW reuse can be integrated into the Dutch urbanscape and to what extent it can increase the flexibility of the current centralised Dutch water supply system.

Research Background

Context-setting: Problem definition in the Dutch context

Dutch water management today is limited in its ability to cope with extreme conditions induced by climate change. The key problems that arise are safety and localised flooding when high water levels pose a danger to human life and infrastructural damage, salinisation and eutrophication that deteriorate the quality of water and ultimately, water shortages due to insufficient supply to demand (Rijkswaterstaat 2019). These problems demonstrate the changing needs of a city in order to cope.

Changing water patterns

Although general relationships between seasons and temperature are not expected to change with climate change due to the relative invariance of annual solar radiation (Hajek & Knapp 2021), projections concerning the Netherlands are expecting higher average temperature (Ligtvoet et al. 2013). Climate change influences seasonal patterns of precipitation more pronouncedly (Padron et al. 2020), strongly dictating the overall dynamic of ecosystems through its water balance (Stephenson 1990). This is so since ecosystem processes such as primary productivity, respiration, microbial activity, decomposition etc. rely to a certain extent on water availability (Ru et al. 2018). Yet, the net impact of seasonal shifts are complex and unpredictable. The ecosystem has its own checks and balances in place. Furthermore, with an increasing urbanised landscape, the natural water cycle is transformed to an urban water cycle, as visualised in Figure 1, where there is heightened run-off amounts, lowered water infiltration and evapotranspiration due to impermeable surfaces and decreasing vegetation. In general, climate-change-related changes and urbanised environments mean the availability of freshwater is projected to become more extremely fluctuating: periods of water shortages and excessive water, foreboding increasing frequencies of drought and water drainage flooding (Ligtvoet et al. 2013).

On quantity

Water drainage flooding is quite unique to the Netherlands. Considering that land is claimed here through pumping out water towards the sea inorder to keep dry feet, drainage flooding occurs when water is unable to be pumped out fast enough, damaging infrastructure and agriculture (RIZA 2007). Around 60% of the Netherlands is vulnerable to flooding, and 55% of the Dutch population live below sea level or along rivers (Ligtvoet et al. 2013). The main concerns regarding increasing flood risk is sea level rise and higher peak river discharges, particularly in the winter, as suggested by the all KNMI'06 scenarios (KNMI 2009). All scenarios demonstrate that peak discharges will already exceed the safety standard for the Rhine-Meuse floodplain that was designed to tolerate a high water event expected to occur once every 1,250 years before 2100 (KNMI 2009). Research shows that the greatest increase in water drainage flooding will be expected in both low-lying areas, predominantly the west, and areas next to rivers (Immerzeel et al. 2010).

Droughts are attributed to increased excess evapotranspiration, combined with decreases in average river discharge and precipitation (Ligtvoet et al. 2013). Water availability patterns are varied across the Netherlands, the difference more pronounced between the low-lying coastal area in the West and the East. During the spring and summer, the West is drier, while during late summer and autumn, the East is drier (KMNI 2009). Although in general, drought will intensify across the entire country (Ligtvoet et al. 2013). Of concern is the transboundary nature of the rivers, insinuating that upstream activities, for example in Germany and Belgium, will inevitably be felt in the Netherlands. Thereby, unless transnational negotiations of upstream abstraction of surface water are conducted, the Netherlands' water supply is also quite vulnerable to over-abstraction of other nations that inevitably will also have to cope with increasing population and demand.

On quality

In the Netherlands, climate change impacts will be sorely felt in altered surface and groundwater quality. Two particular feedback phenomena of concern degrading water quality is salinisation and eutrophication.

Higher temperatures lead to higher water temperatures, increasing the likelihood of algae blooms due to the exacerbated availability of nutrients in surface waters. Consequently, oxygen-dead zones form towards the bottom of the water body, as algae outcompete other species, reducing species richness which negatively impacts ecosystem functioning (Amorim & Moura 2021). Algae blooms are not exclusive to surface waters and can occur in seawater as well (Villacorte et al. 2014). It seriously intensifies water quality deterioration, increasing water turbidity, salinity, alkalinity, and creating more stratified profiles, as well as endangers the supply of drinking water (Amorim & Moura 2021; Brooks et al. 2016).

In general, urban waters can have a cooling effect. However, a study in Rotterdam demonstrated that as the water temperature of the river Maas increases during the summer, the cooling efficiency decreases. Due to the high heat capacity of water, the river stays warm during summer nights, creating a warming effect and enhanced humidity which can lead to discomfort for residents (Van Hove et al. 2011). Meanwhile, also creating productive conditions for eutrophication.

A discussion about salinisation in the Netherlands remains incomplete without discussing subsidence, as subsidence contributes to salinisation. The peat landscape in the Netherlands typically is highly saturated with moisture. Due to pumping to keep the Netherlands dry and lack of groundwater recharge due to increasing urban impermeability and groundwater extraction, the peat shrivels (Witte, Zaadnoordijk & Buyse 2019). As a consequence subsidence occurs. The Dutch have combatted the phenomenon through frequent sand filling, levelling out the surface, stabilising sub-surface infrastructure and maintaining a safe distance from the groundwater table's free board (Hooimeijer, LaFleur & Trinh 2017).

Salinisation is expected to increase particularly in the low-lying areas, which comprise a majority of the Dutch landscape situated in the West, due to reduced average river discharge and sea level rise, increasing salt water intrusion into rivers and groundwater (Pauw, de Louw & Oude Essink 2012; van den Brink et al. 2019). Furthermore, accelerated land subsidence that increases groundwater table heights lead to more saline soil water and higher probability of leaching through run-off into rivers (Pauw, de Louw, & Oude Essink 2012).

This causes concern as the heightened salt concentrations in surface waters will render it too saline for drinking water production and irrigation, a loss of available water (Beersma et al. 2005). Furthermore, it threatens aquatic biota, therefore, biodiversity, that would eventually lead to compromised ecosystem goods and services (Canillera-Montcusí et al. 2021). Such a threat has been rated as one of the most concerning by the Millennium Ecosystem Assessment (2005).

At the moment, the Netherlands combats the issue of inland salinisation through flushing out the salt with copious amounts of freshwater, posing a catch-22, since freshwater availability, particularly in the summer when salinity is exacerbated, will be compromised (Rijkswaterstaat 2019). The increased probability of low-flow conditions will lead to an increase of contaminants being able to be leeched into the environment due to reduced dilution. Furthermore, the general trend of increase loads of pharmaceuticals and personal care products is worrisome because centralised wastewater treatment plants have not been designed to deal with such compounds, removing only 60 to 70% of them (Hofman-Charis et al. 2018). These emerging compounds has been investigated to originate dominantly from households and associated household products (UKWIR 2018). Drinking water companies are in danger of abstracting subpar quality water, and lacking treatment processes to treat foreign compounds, leading to problems for maintaining drinking water supply.

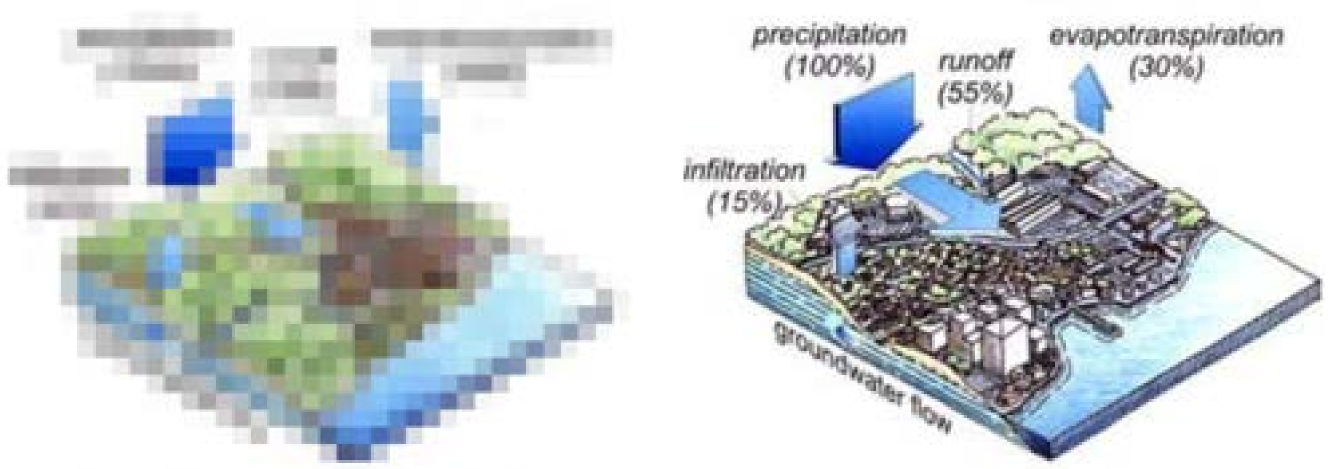


Figure 1: Natural vs urban water cycle

The Stories: Scenarios and Flexibility

As indicated by the changing water quantity and quality patterns, the impacts of climate-change are faster than we realise and water scarcity is imminent. Although framed in a Dutch context, worldwide, there is pressure to provide more efficient usage of water, reduce centralised water system vulnerability to increased climate-related fluctuations, heightened environmental consciousness that has influenced stricter regulations, aging centralised water infrastructure, and increasing potential for inter-regional water conflicts, since the nature of conventional water sources such as surface and ground water is often transboundary (Marlow et al. 2013).

The Netherlands is a self-proclaimed decentralised unitary state where different governmental levels share responsibilities for spatial planning and flood risk management (Dai, Wörner & van Rijswick 2018). Concerning national climate adaption strategies, there is a National Adaptation Strategy and a Delta Programme based on the Water Act to encourage decentralised government agencies to contribute (Dai, Wörner & van Rijswick 2018). One of these decentralised agencies is Deltares, of which this thesis has been written for.

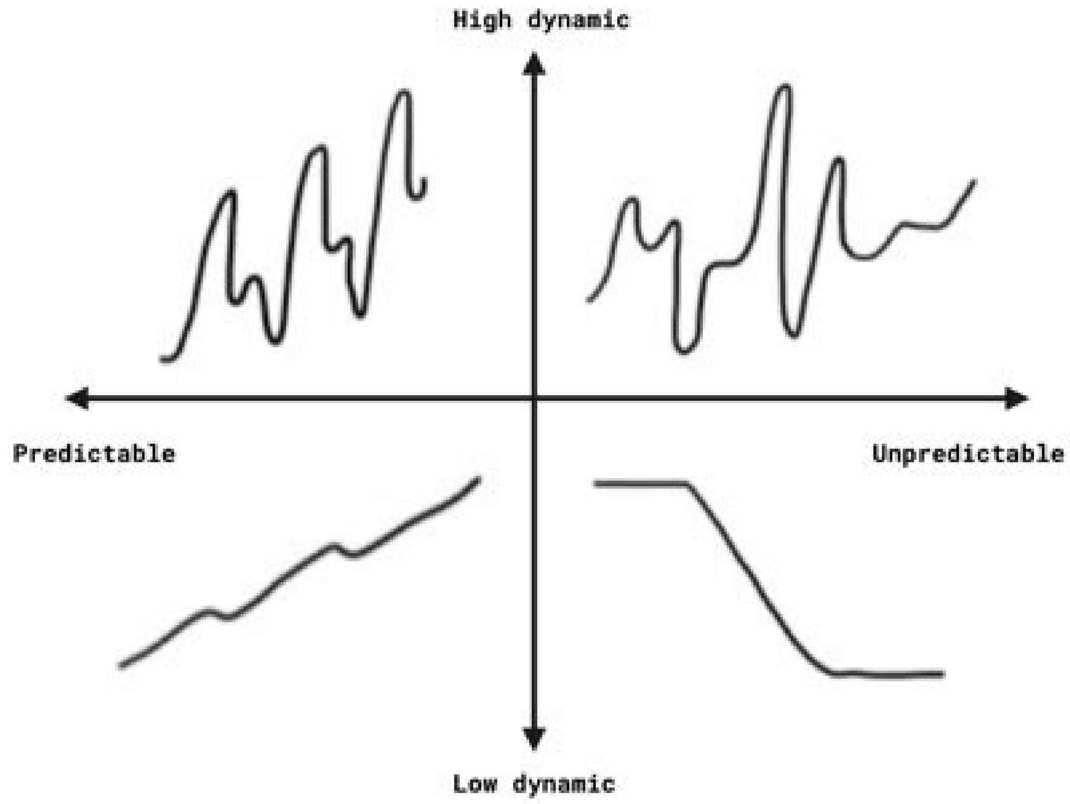


Figure 2: Water demand scenarios in the future

The scenarios presented by Deltares, Vitens, and Ruimtevolk are based on the National Delta Program's Delta Scenarios guide and form the foundational basis of this thesis. It originated to give more clarity to climate and socio-economic developments within the Netherlands as far as 2100. The given scenarios have been primarily defined by water demand dynamics and predictability. The dynamics and predictability depends on the rate of climate change, politics that may or may not incentivise decentralisation, and socio-economic changes. These scenarios are visually represented in Figure 2 above.

The guiding principles of the Delta Programme are solidarity, flexibility and sustainability (Dai, Wörner & van Rijswick 2018). Flexibility has been defined by Deltares, Vitens, and Ruimtevolk as the ability to adapt to and minimise environmental shocks on the quality and quantity of drinking water sources, as described in the preceding section. When applied to the scenarios that are defined by general patterns in water demand of dynamics and predictability, we can simplify flexibility to two fundamental elements: adaptability and reactive resilience. **Adaptability** is the ability to scale up or down to meet expected fluctuations. This quality is also synonymous with the concept of **proactive resilience** which will be expanded upon below. **Reactive resilience** is the ability to respond in a timely and effective manner to unexpected shocks. It can be concluded that the higher the dynamics, the more adaptability is necessary, while the higher the predictability, the less resilience is needed.

Coping with high dynamics through adaptability/proactive resilience

Lots of dynamics is based on rapid climate change that would induce more extreme fluctuations of water demand on a daily and seasonal basis. The extreme seasonal variability means wetter winters and drier summers that have subsequent impacts on water demand. Individuals are prone to use more water during hotter periods, while there is less precipitation, less volume of surface water, and thereby more potential for droughts. The low-flow conditions invoked by the drier summers increase the infiltration of pollutants, requiring more intensive water treatment as well. Such a situation requires immediate action that is institutionally challenging to implement considering its rigidity.

On the other hand, lower dynamics is based on slower rates of climate change. Such modest rates insinuate time for planning and implementing gradual change and means the Netherlands can cope with it with normal adaptive pathways. This scenario is not focussed on within the thesis, as such a scenario would not need decentralisation to increase the flexibility of the system because there would be less uncertainties.

With all these uncertainties and large fluctuations in high dynamic scenarios, resilience is necessary. Resilience is the ability of a system, community, or society exposed to a hazard to resist, absorb, accommodate, and recover from its effects in a timely and efficient manner (Priest et al. 2016). Resisting means developing strategies to reduce the probability of pluvial flooding. Absorbing and recovering means accepting that pluvial flooding is sometimes inevitable, so additional measures should be in place to flexibly respond to flooding when it occurs. Adapting means capitalising on effective learning processes that stimulate adaptive governance and create spaces for experimentation (Dai, Wörner & van Rijswick 2018). Innovation is key here.

The distinction between reactive and proactive resilience is the ability of the WRS to respond to an unexpected shock after it happens and to prevent or minimise the impacts of an unexpected shock before it happens, respectively. In the context of this thesis, proactive resilience is analogous to adaptability. The difference is that water is not stored simply for coping with domestic demand fluxes but to feed into ecosystems in order to maximise ecosystem services. This involves creating a landscape that provides a buffering to natural disasters that are more prone to happen with rapid climate change. This buffer would quench adverse impacts and thereby, safeguard centralised water systems to provide potable water to citizens.

Improving resilience through green infrastructure (GI)

Effectively managing the impact of intensifying extreme events is the challenge. Proactive resilience goes hand-in-hand with this challenge. Green infrastructure (GI) can be defined as the interconnected network of green spaces that conserves natural ecosystem values and functions, providing associated benefits for humans and improving resilience (Miller 2020). Resilience in ecology is defined as the ability of a system to absorb disturbances and still retain its basic function and structure (Walker & Salt 2006). Incorporating these values, a resilient city can continue after extreme events without long-term damage to physical, social, or economic systems by anticipating, learning, and adapting to hazards (Godschalk 2003). This adaptive approach in urban planning is defined as a method to minimise the detrimental impacts of enhanced climate change and explicitly allow for associated uncertainties (Revi et al. 2014).

It is well-known in the literature that GI adoption and implementation, alongside nature-based solutions create more resilient cities (Fleming 2016; Grey 2016; Miller 2020). GI is important for stormwater management, imperative with wetter seasons, micro-climatic modification, imperative for drier seasons, and providing vital services, i.e. water and air quality as well as food security (Miller 2020). GI also contributes to social sustainability through improving community resilience by not only supporting, but encouraging mental and physical health as well as social capital (Coutts 2016).

Seasonality at play

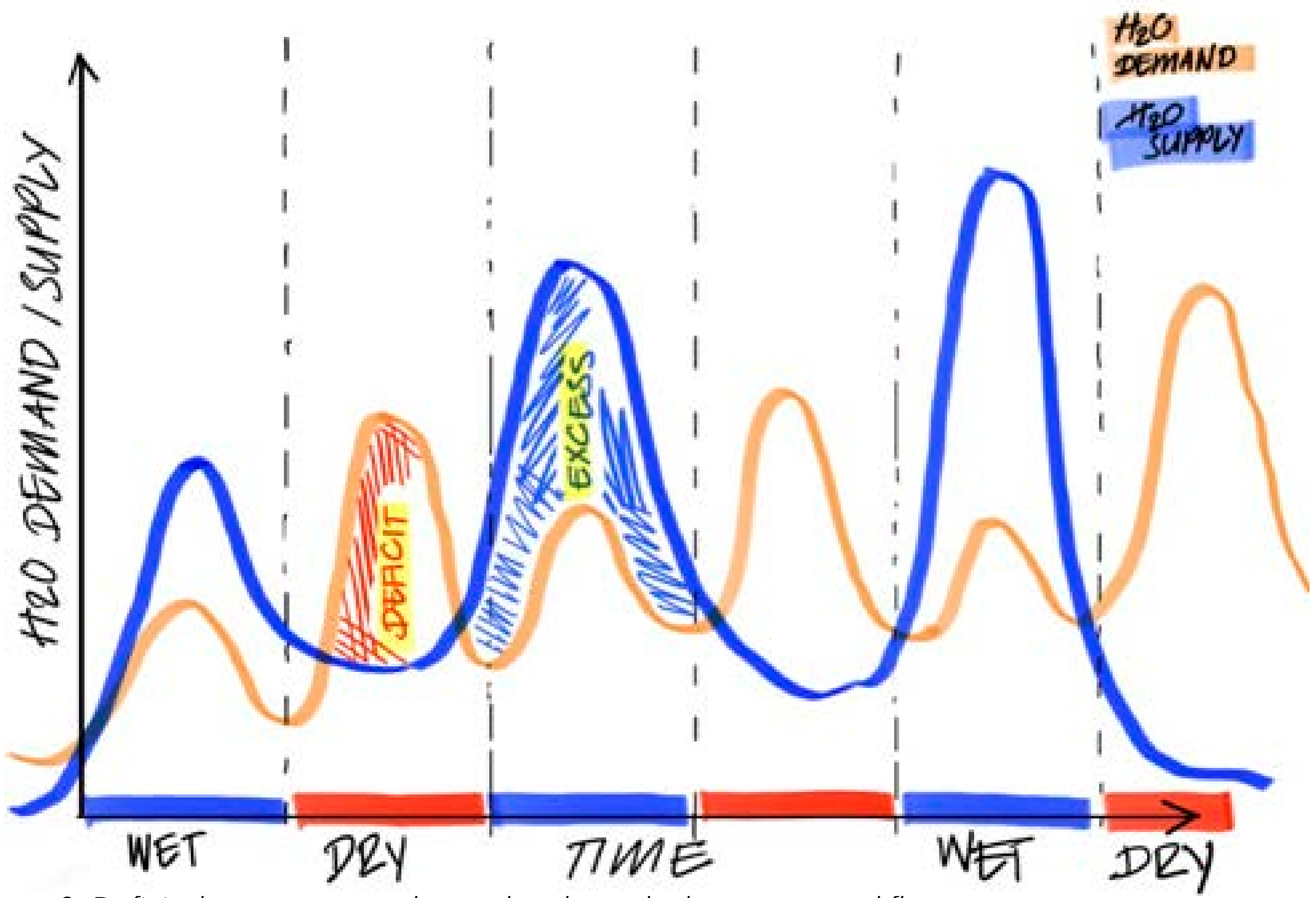


Figure 3: Deficits between water demand and supply due to seasonal fluxes

As described above, high dynamic scenarios insinuate more extreme seasonal fluxes, creating periods of water deficit due to high demand and low supply during the dry season, and periods of water excess due to low demand and high supply during the wet season. This is visually represented in Figure 3. The general logic is that to match supply and demand through these extreme seasonal fluxes, we must deal with storage as buffers. The resulting change in climate demonstrates that excess water during wet periods have the potential to be repurposed into loading periods for water to be extracted for later use, more specifically, for the dry period. There are short-term and long-term storage options for water.

Short-term storage comes in the form of rainwater storage in tanks or in water bodies/reservoirs. This can effectively be used for piped water-supply systems. Other forms include water conservation in the soil profile or surface storage by creating depressions. Such already exists as rain gardens, bioswales etc.

Long term storage is defined by weeks to years. Two main methods exist: subsurface storage on different scales, for example via artificial recharge, and surface storage in small to large dams and reservoirs which are often combined with induced infiltration to groundwater. If grey water can be recycled for indirect potable use as water storage, then despite the extreme fluctuations caused by climate change, low-flow conditions would be less probable, considering that water will not need to be abstracted at rates beyond replenishment. Other benefits include reducing land subsidence and sea water intrusion in coastal areas (Benotti & Snyder 2009). In general, storage can be a means of increasing surface and groundwater availability.

Although one could create water storage through means of 'grey infrastructure', for example large storage detention tanks that cost billions of dollars, these storage systems send excess collected storm runoff to treatment facilities after peaks have passed, proving beneficial for temporary runoff detention but only that (Garrison & Hobbs 2011).

Coincidentally, creating storage for water is intrinsically linked to GI. GI can provide not only detention benefits but retention benefits, preventing precipitin from enter the system and being processed as wastewater, decreasing its burden on treatment facilities that need to spend additional energy to process it (Gaffin, Rosenzweig & Kong 2012). Which subsequently can also be linked to other benefits such as increasing proactive resilience, and mitigating the Urban Heat Island (UHI) effect, increasing liveability of areas, subsequently the well-being of residents (Claessens et al. 2014).

Conventional water retention and storage methods is applicable in a setting with ample space. However, the challenge is water retention in the dense urbanscape, where space for conventional methods is limited.

It can be generalised that adaptability is increased through
(1) Maximising water retention from wet periods via increasing storage in order to match supply with demand
(2) Increasing water use efficiency during the dry periods to decrease the overall demand of water
(3) Maximising water abstraction from alternative water sources during dry periods to minimise compounding impacts of over-abstraction from conventional surface and groundwater sources

Rainwater harvesting (RWH) potential in the Netherlands

Considering these seasonal dynamics, it is tempting to prioritise RWH in order for immediate use and water storage for the dry season. Such a system requires appropriate infrastructure. In this case, a catchment area, most likely a roof, a storage tank and a treatment technology. Rainwater requires less treatment intensity than other water sources, so it has a potential environmental benefit as well, though it is negligible (Hofman-Caris et al. 2019; 2018). Yet, Dutch drinking law prohibits the use of rainwater for potable applications (Hofman-Caris et al. 2019).

However, several feasibility studies for RWH in the Netherlands demonstrated it was not economically feasible for an individual household to implement (Hofman-Caris et al. 2019; Hofman & Paalman 2014). On the collective to centralised level, it is highly contextualised and a CBA is recommended (Hofman & Paalman et al. 2014). However, it can become economically viable, with costs that are comparative to centralised drinking water production (Hofman-Caris et al. 2019). Yet, RWH would only cover 50% of total water demand with a negligible environmental benefit (Hofman-Caris et al. 2019). In the future, as cities become more dense, and thereby vertically constructed, there would be less catchment area for an increasing population, leading to a high probability of less water saving potential.

Subsurface storage of excess water in the Netherlands

Then what about storing the excess rainwater? There are mainly two options for subsurface storage: the wadi system or vertical infiltration. The Netherlands has ample sandy soil coverage that is unsaturated with water. This potential storage availability can be appropriated with a wadi system. By creating depressions, collected rainwater is transported through a porous layer by gravity to groundwater (Hofman & Paalman 2014). Such systems already exist in Enschede (Mondria 2020), and in Utrecht (Hofman & Paalman 2014). They not only recharge the groundwater supply but it doubles as water retention to prevent pluvial flooding. However, a wadi system must be well-maintained to function properly. Such maintenance activities include removing excess debris at least twice a year, hosing down the drainage once a year, and mowing the grass that grow atop the wadi every other week (Mondria 2020).

Implemented in the municipality of Rhenen, rainwater is directly channeled into a deep aquifer through a relatively new but simple and cheap technology. The processes is known as vertical or deep infiltration. Although sandy soils are ample in the Netherlands, a common observation in certain areas is the mix of various horizontal layers of clay, peat or sand. Vertical infiltration overcomes these layers by enabling the infiltration of water directly in a water saturated aquifer, which is the sandy soil layer (Hofman & Paalman 2014). In order to maintain the infiltration capacity, physical filtration of the excess water is necessary to prevent clogging due to small suspended particles that accumulate over time, thereby reducing the infiltration capacity (Hofman & Paalman 2014). Furthermore, the excess water must be thoroughly treated or derived from a first-flush system to remove pollutants it may have come into contact with by air or urban infrastructure (Hofman & Paalman 2014).

Urban form and environmental issues

Urban form is inseparable from the ongoing debate on how best to apply sustainability. This is so since urban form interacts with habitats, ecosystems, species and resource quality through land consumption, habitat fragmentation and increasing impermeability (EPA 2001). As a result, the contemporary city can be perceived as a threat to sustainability, where phenomena such as extensive impervious surface, increasing population, ageing infrastructure, lack of affordable housing, the urban heat island effect (UHI), fragmentation of habitats, and suburban sprawl increases pressure on cities and the environment (Anda 2017; Li et al. 2021; Zhang et al. 2019). On the flip side, one could view urban areas as the most vulnerable habitats to the consequences of climate change (Francesch-Huidobro et al. 2016), where urban areas are becoming more apt risk of extreme weather events: pluvial flooding, storm events, and drought (Horne, Tortajada & Harrington 2018).

Yet, no mud, no lotus. This simultaneously means the city can prove its solution as well if we are able to act collectively to influence human behaviour and the design of urban form (Jabareen 2006; Anda 2017). This transition to sustainable living in compact urban areas would require a thoughtful selection, design, and integration of economically-viable eco-technologies (Anda 2017). Anda (2017) defines eco-technologies as "environmentally-sound technologies for water, energy, and waste systems." The focus on technologies acknowledges that diverse technologies and their scales of operation can contribute to increasing sustainability via reduced costs and resource footprints (Shahabi et al. 2014). In addition, a resilient city is one that reduces the ecological impacts of space fragmentation through GI to increase connectivity. Scattered green spaces dispersed in the city are less effective in strengthening its ecological, productive, and cultural benefits (Wang, Shen & Xiang 2018). This is particularly the case for biological conservation and increasing urban biodiversity.

As a conclusion, high dynamic scenarios would stand to benefit most from added resilience when means the necessity of developing more GI. GI are also a source of eco-technologies that must be integrated into an increasingly compact urban environment.

Future urban forms in the Netherlands: Compaction

Today, increasing density in urbanism is regarded as a sustainable trajectory (Marshall, Gong & Green 2019; Berghauser-Pont & Per Haupt 2010). Jabareen (2006) identified four major arguments for compactness as a sustainability strategy:
(1) The creation of a corollary of rural protection (McLaren 1992)
(2) The promotion of quality of life through physical closeness of services, facilities, and individuals
(3) The reduction of energy consumption through closing loops
(4) The reduction of GHG emissions through minimising travel time, minimising desire for private modes of transportation

However, this should be not confused with the conventional conceptualisation of dense cities: trying to pack as much as possible into the smallest possible area. Rather, it is referred to in the literature as "compactness" (Jabareen 2006) and it insinuates a higher complexity as it seeks to pack as much quality of life into the smallest possible area. Considering the permanence of urban form in relation to human lifetimes, space can be considered a scarce resource and its parcel-drawn monopolisation for what function is being further challenged today in light of anthropogenically-enhanced climate change. At this point in our contemporary civilisation, future urban development would take place adjacent or even atop of existing urban forms (Wheeler 2002). Such a compaction can be viewed as a containment of urban sprawl when we expect increasing urban populations (Hagan 2000).

In the Netherlands, there is a long-standing tradition of reclaiming land, using space efficiently and preserving open landscapes since the post-war period (Mensink & van der Hoeven 2017). The resulting housing shortage and baby boom industrialised housing construction and planning to the national level (Mensink & van der Hoeven 2017). The government feared if the expected rapid population growth was left unchecked, that there would be unacceptable levels of congestion. After discussions, two main goals emerged: (1) concentrating and containing urbanisation and (2) of buffering between pockets of urban forms (Mensink & van der Hoeven 2017). These goals reflect the overarching idea of clustered dispersal, which subsequently changed to compact urbanisation by the end of the 1980s after witnessing an exponential growth in car mobility and fall of public transportation (Mensink & van der Hoeven 2017). The new goals were to (1) restrict car mobility needs and (2) avoid building in open landscapes (Boeijenga and Mensink 2008).

These Dutch spatial policies were able to give direction to planning but is argued to be more corrective than guiding, according to Mensink & van der Hoeven (2017). This is so because policy documents may shape society but is also an expression of that society. It controlled urbanisation processes and facilitated growth in a compact way but have not achieved higher densities, instead, creating suburban areas termed the Vinex extension with an average density of 23 dwellings per hectare (Mensink & van der Hoeven 2017).

Today, the aim of spatial planning in the Netherlands is to densify cities further as the housing market has picked up once more, with a focus on a heathy mixture between different functions of inner-city buildings and better management of water and energy to increase its use efficiency (Mensink & van der Hoeven 2017). So, it is evident that the Netherlands realises the importance of creating more balanced cities, as multifunctionality imbues a space with a more diverse mix of users, and multifunctional buildings provide a way to balance peak demands, especially concerning resource consumption. The next level the Netherlands is focusing on now is developing climate-resilient cities especially in the face of potential growing population, as indicated earlier in the thesis with national climate adaptation programmes. Thereby, in the face of increasing compaction, it is imperative to find suitable eco-technologies that can be integrated seamlessly.

Measuring density

We can assume that density is expected to increase due to the current Dutch spatial planning goals. Therefore, measuring density is necessary to formally categorise the spatial qualities linked to the potential of decentralised LGW reuse.

The application of density as an urban measure was non-existent until late into the 19th century (Berghauser-Pont & Per Haupt 2010). The reason lies in the complexity of quantifying density due to the weak relationship between density and building type/form. Another is in the confusion of defining boundaries and scales in order to make a comparative basis, especially since it largely determines the outcome of density calculations (Berghauser-Pont & Per Haupt 2010). For example, the same dwelling density can be achieved through diverse dwelling design types as depicted in Figure 4 below, while the same design type can be used to obtain different densities (Berghauser-Pont & Per Haupt 2010).

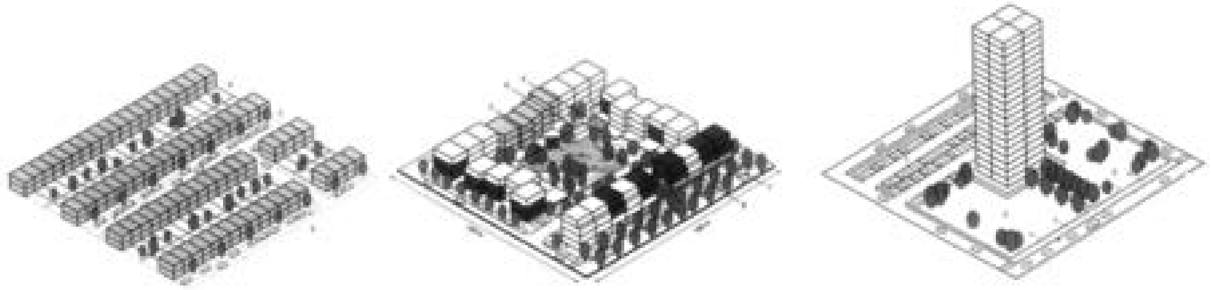


Figure 4: Three areas with 75 dwellings/hectare (Extracted from Fernandez Per & Mozas 2004: 206-207)

The most common application of density measures is population and dwelling density. Dwelling density measures the number of dwellings in an area and population density measures the number of people in a given area (Berghauser-Pont & Per Haupt 2010). A dwelling is defined as a self-contained residential unit. It tends to remain the same meanwhile population density can fluctuate greatly.

There is little relation between population density and urban form. For example, social changes reflected in population density of an area can fluctuate through out history while the number of dwellings remain the same. As such, dwelling density is acknowledged as more robust than population density (Berghauser-Pont & Per Haupt 2010).

In general, different conceptualisations of density yield different measures of density. In general, density measures vary according to how the numerators (A) and denominators (B) are defined (A/B = density) (Churchman 1999). In fact, the denominator which often is defined as the boundaries of an area is crucial in determining the outcome of the density. As such, denominators would do well to remain constant if comparative analyses are intended or must at least be discussed in context when deriving densities.

To reconcile a robust definition of density and improve its productivity in application, Berghauser-Pont & Per Haupt (2010) argues that density must relate to potential urban form and other performances. The conceptualisation of performances is akin to 'urban'-system services, referring to the ability of the built environment to deliver services of interest. For example, daylight access, privacy, and in the case of this thesis, feasibility of meso-scale GI to provide LGW recycling for residents.

Looking again at Fig.X, the available surface area of facades vary, leading to different green technologies potential (e.g. green roofs and green walls) dependent on the slope of the roof, and amount of useable space on both the roof and walls. The spaciousness of these areas also determine

the potential for compact CWs. Thereby, the feasibility of affording the right space to implement green GW reuse technologies directly correlates to the form of the defined area. Furthermore, the form of the defined area can be defined with multiple density measures in order to link general urban morphological qualities to its GI potential. The following measures are relevant for interpretation:

Building Intensity (FSI)

In recent years, a purely physical density measure became popularised: the Floor-Space-Index (FSI). It reflects the building intensity of an area independently of programmatic composition. Similar FSIs can be derived with varying population and dwelling densities. It is insufficient alone to convey urban form, considering that in a study by Berghauser-Pont & Per Haupt (2010), it was demonstrated that three diverse urban forms in Amsterdam, the Netherlands: a typical post-war open block structures, high-rises, and single-family houses all yielded the same FSI. However, this also demonstrates the robustness of the measure, as it is able to reflect these three diverse urban forms have the same FSI, achieved in different ways which can be investigated further.

Coverage (GSI)

Coverage expresses the relationship between the built and non-built environment. Ofcourse, the question is coverage of what and what is covering it? Often coverage compares the footprint of built mass and open, non-built space which is essential to understanding the green-grey composition of the area. However, coverage alone also has a weak relation to urban form. As discussed above, the determination of boundaries impact the derived ratio between the built and non-built environment, as the larger the area boundary, the more likely it is to be heterogeneous (Berghauser-Pont & Per Haupt 2010).

Spaciousness (OSR)

The FSI and GSI express the extent of urban compactness in an objective measure (van den Dobbelsteen & de Wilde 2004). However, they do not express human pressure on the study area. Instead another indicator was developed to relate the total GFA and non-built area, the OSR. However, the non-built areas are not necessarily differentiated between private and publicly owned. If it is privately owned then it could mean that it maybe not be as "spacious" for others who do not have legal access to the grounds.

Yet, calculating the FSI, GSI, OSR, and such a green-technology feasibility measure lacks a baseline or benchmark to compare various study areas that exhibit different urban morphological properties. The determination of the boundary area is crucial and impacts the derived values. For the purposes of this study, a method to create a comparative basis is to count a similar amount of dwellings to determine the extent of an area of interest. In this study, a dwelling is defined as one residential address that correlates to one residential unit, either within a greater building or standalone. By having a similar count of dwellings, we create a constant variable while the changing variable would be the population per dwelling. The average in the Netherlands today is 2.14 people per 'household unit' (CBS 2016). Then these areas of interest can be further defined through the above density measures to interpret the extent and quality of compaction. By doing so, we can link GI potential to density measure values and make practical generalisations that can be applied to other areas displaying similar density measure values.

The future of urban water management: planning for high dynamic scenarios

As noted above, these changing water patterns lead to changing needs for a city. Water in the urban context concerns its supply, distribution, and purification primarily for human consumption. The conventional urban water system in the Netherlands presents an industrial miracle, propelling modern civilisation into unprecedented standards of living through providing centralised water supply, sanitation, and drainage (Franco-Torres, Rogers & Harder 2020). However, it proves inflexible when faced with the consequences of climate change and even exacerbates its impact (Franco-Torres, Rogers & Harder 2020). Now, the conventional system is characterised as rigid and resistant, unable to respond to increasingly complex societal needs, for example being prone to pluvial flooding that causes central sewage overflows, leading to societal costs of property damage and ecosystem costs of spreading sewage pathogens elsewhere (de Haan et al. 2017).

The urban water cycle (UWC) is considered an open cycle that assumes plentiful resources since these activities are heavily embedded with energy. The water sector constitutes 4% of the global total energy consumption, with the most energy-intensive activities being pumping-related, forming 90% of the total (Capodaglio 2020). Despite the conventional UWC's immense energy demands, it is often framed as more economical to treat and discharge our wastewater rather than removing the embedded energy as resources or heat (Anda 2017). Again, this stems from the assumption of resource abundance, which is flawed considering that the Netherlands is facing water scarcity.

Today, new paradigms of sustainable management of the UWC based on new sets of values and framing are being proposed to conventional systems (Capodaglio et al. 2016; Gonzales & Ajami 2017). For example, it mostly involves closing the UWC through a localised approach to water sourcing, use efficiency and water reuse (Anda 2017), which involves valuing wastewater for its embedded energy/ resources as well as reusing and recycling before abstracting conventional water sources since freshwater is becoming scarce.

The emergent field of sustainable urban water management (SUWM) prioritises designing for system connectivity, diversity, and redundancy (Tyler & Moench 2012). These interdependent and synergistic elements are crucial for improving system resilience. There are two kinds of diversity necessary: spatial and functional diversity (Ahern 2011). Spatial diversity means distributing water system assets and functions to create network resilience whereas if a failure occurs at one node, other nodes can compensate, readapt and continue providing services with little obstruction (Ahern 2011). Functional diversity is achieved through securing multiple means to satisfy a particular end (Ahern 2011).

There are three ways to diversify the urban water infrastructure (Sapkota et al. 2014):
(1) Utilising a mixed portfolio of local water sources
This reduces the vulnerability associated with diminishing resources
(2) Configuring system to run on multiple technologies
This facilitates the process of upgrading the system as technologies are expected to improve and change over time, thereby upgrade and replacement operations do not compromise the entire system.,
(3) Installing spatially distributed infrastructure
This avoids what we are witnessing with centralised infrastructure: significant aging or failure of massive extents of infrastructure at once (from a disturbance)

Within SUWM, closed UWC models have been extensively researched and applied. These models emphasise alternative water sources suitable for decentralised systems in compact cities and have already been ordered in terms of priority (Anda 2017):

(1) Rainwater harvesting (RWH) where sufficient quantities are available
(2) Surface water where surface water sources fill or flow adequately nearby
(3) Stormwater runoff where sufficient quantities are available
(4) Groundwater abstraction where aquifers are nearby and replenished/abstracted at sustainable rates
(5) Seawater desalinisation where urban areas is near the coast, so in the Dutch context, this is the Western part of the country which already faces the impacts of salinisation heaviest
(6) Greywater or wastewater recycling

Considering the preceding background research, RWH at a decentralised scale in the Netherlands would not achieved sufficient quantities (Hofman-Caris et al. 2019;2018). Surface water from rivers is currently unreliable, evidenced by the closing of the Meuse river supply to Limburg due to the emergence of an unknown compound. In the future, we also want to prevent low flow conditions, so abstraction to quench the seasonal dynamics is counter productive. Instead, if there is sufficient space, artificial surface water basins can be created for collective purposes, although the space necessary would be considered a rare luxury in a compact urbanscape. Stormwater run-off flowing through an open city system means being exposed to a multitude of forms of human litter and subsequent pollutants (Lefrancois 2015) and would also be seasonally harvested. Furthermore, even if seasonally harvested for use during drier months, an artificial surface water basin would need to be created, again on a collective scale. The end-use of retaining stormwater is perhaps best-suited for preventing pluvial flash flooding, saturating artificial GI with water for the upcoming dry season and potentially recharging groundwater, as already reflected in Dutch policy. This is expanded on at the end of this section. Seawater desalination is viable for the Western coast of the Netherlands. At the moment, conventional costs of desalinisation through reverse osmosis is significantly high, so innovative technologies utilising renewable energy sources are recommended if it is to be pursued on a decentralised scale (Bundschuh et al. 2021).

As a result of reasoning, greywater (GW) or wastewater recycling in the Dutch context is an interesting decentralised alternative water source although listed last in terms of prioritisation. Its constant supply year-round and ubiquitous availability (not limited to say cities along the coast as for desalinisation) is of particular strength when coping with seasonal fluxes, even daily fluxes, as wastewater supply for recycling is almost equivalent to the wastewater demand, due to a very short time lag in between. For example, if an individual during a hot summer day uses more water, the GW generated would likely be equivalent to the demand the next day, which is also likely a hot summer day.

However, as reasoned in the urban form section, these water sources would all require new technologies, engineered interventions if you will, to apply on the decentralised scale and must fit within a compact space.

Particularly with wastewater reuse, to better economise resource recovery, wastewater streams are categorised by their degree of contamination: greywater (GW) and blackwater (BW). The distinction between them correlate to more or less energy intensity to purify: the dirtier, the higher the energy required to clean the water. This is why we have a fit-for-purpose approach to water reuse systems, as the incoming water quality to be treated depends on its source, and the extent it should be treated depends on its intended end-use (Anja 2017).

Better termed as "source separation," the concept adopted at the household level has been proposed as a promising new sanitation concept to reinstate a balance between carbon, nutrient, and water cycles (Tervahauta et al. 2013). Against the backdrop of conventional centralised water infrastructure, source separation at the household level would lead to a hybridisation of the urban water infrastructure, insinuating a transition state. Research into this hybrid system suggests that it would already be conducive to improving energy balance and resource recovery potential even with the cost of structural modifications (Morandi et al. 2018; Sapkota et al. 2014; Ahern 2011; Tyler & Moench 2012).

If we look to such a system in the increasingly dense urban environment, we can extrapolate from one of the most successful megacities in the world: Tokyo. Even before the recent popularity of source separation, water reuse networks for non-potable use were adopted in Tokyo and other Japanese cities in order to reduce pressure on water scarcity (Suzuki et al. 2002). Non-potable water means water that is not treated for human consumption, rather utilised instead for irrigating, cleaning, or flushing.

The paradigm shift already in play reflects a broader transformation from viewing the world mechanistically to organically (Du Plessis & Brandon 2015). Conceptualisations of utopian urbanscapes such as Konjian Yu's much acclaimed design of Sponge Cities questions the conventional urban drainage system with its combined sewage system (Ma, Jiang & Swallow 2020). Its successful projects have inspired the Chinese government to allocate 1 trillion USD in turn for thirty Sponge Cities (Liao & Wishart 2021). The cost is hefty, but rivals the cost of an estimated 1% of China's GDP annually due to flash floods (Liao & Wishart 2021). One extreme flood in the city of Zhengzhou amassed direct economic losses of more than 10 billion USD and over 290 deaths (Liao & Wishart 2021). Comparing the cost of one flood event in one city to the total allocation then makes sense.

Steps towards the Sponge City ideal has already been implemented in the Netherlands. The Three-Step Approach in Dutch water management promotes capturing, storing, and draining water in priority-ranked steps. First, stormwater run-off is to be retained as long as possible in its catchment area. Once the catchment area has reached a limit, the stormwater must be redirected to areas with temporary storage. Once the temporary storage has reached its limits, then excess water should be drained (Dai et al. 2017). The foremost strategy in actualising the three-step approach is creating public infrastructure that doubles as water retention spaces (GI) and promoting private property owners to install GI that separate rainwater from the sewer system or creating smaller water retention spaces, preventing central system overflows (Dai et al. 2017).

This disconnection policy is most promising because technical solutions targeted to increase the Dutch sewage system's resilience by increasing capacity is very costly. Since building and extending sewage systems is the municipality's responsibility, they are hesitant to choose this as it would increase local taxes (Dai, Wörner & van Rijswick 2018). So, disconnecting the sewage system represents an adaptive pathway that delays the need for major investment by decreasing the pressure on the already-existing system. It also involves modifying private property, entailing cooperation with citizens. Yet the bigger issue is retrofitting. The disconnection policy is easier to implement in newly built areas because it is best facilitated during the design and planning process (Dai, Wörner & van Rijswick 2018).

As a concluding remark, the future of Dutch urban water management already implies foresight, as it is planned to cope with increasingly high dynamic scenarios, evident in the recent implementation of the three-step approach and disconnection policy. Although source-seperation and creating Sponge Cities come at an hefty cost, the payback is considerable, especially when expecting high dynamic scenarios. In such a case, GW harvesting is a compelling constant alternative source of water that can help cope with seasonal and daily fluxes at a decentralised level, loosening pressure on the Water Boards that provide centralised water supply and municipalities and provinces that must consider increasing permits for conventional water abstraction which may compound negative environmental consequences.

Background Research Summary

High dynamic scenarios mean intense climate change, leading to extreme seasonal and even daily fluxes, all set within an increasingly compact urbanscape. There are two general interrelated goals to cope with high dynamic scenarios with high unpredictability: increase the resilience of the urbanscape and flexibility of urban water supply.

There are two general interrelated goals to cope with high dynamic scenarios with high unpredictability: increase the resilience of the urbanscape to quench climate-change-related impacts, prevent climate-change-related natural disasters from occuring and minimising damage if it does occur and increase the flexibility of our urban water supply to prevent over-exhaustion of conventional water sources and provide water security for growing water demand in the face of supply uncertainty.

(1) ↑ **Resilience of urban drainage system** via
- Source-separation of stormwater and sewage system
- GI
- Buffers for water retention to prevent hydrological peaks and decentralised infiltration

(2) ↑ **Flexibility of centralised urban water system** via
- Alternative water sources
    - Alt. source of GW requires source-separation of domestic wastewater streams and between non-potable and potable quality water streams
- Decentralisation of water supply (treatment)
- Buffers for intermediate water storage before treatment and use
- Water efficient usage

It is important to note the overlap of necessary ingredients to achieve both goals. For example, the need of creating more buffers is evident but for different functions: improving resilience emphasises buffers for stormwater retention and infiltration while improving flexibility emphasises buffers for intermediate water storage before use. The challenge in the Netherlands is finding the space for creating surface buffers, especially in a compact urbanscape. That is why subsurface water storage in the Netherlands is attractive: it requires otherwise unused space and doubles as a method for aquifer recharge which can provide a buffer of water security during intense droughts. Subsurface storage in the Netherlands possible if there are unsaturated sandy soils available via a wadi system, which can be considered decentralised infiltration, or deep infiltration, more likely to be a centralised strategy considering the public nature of shared groundwater aquifers and the need to regulate the cleanliness of water before infiltration.

In the Dutch context, RWH appears promising due to projected seasonal fluctuations that indicate heavier rain during wet seasons. However, it is already known that it will be a seasonal pursuit and only effective at collective to centralised scales. Surface water is expected to qualitatively degrade through increased water turbidity, salinity and alkalinity, as well as low-flow conditions that prevent the dilution of pollutants in the water, so it would require more intense centralised treatment. The reliability of surface water is also uncertain, considering the discovery of unknown substances would lead to indeterminate inaccessibility to surface water sources.

Stormwater runoff is already being disconnected in newly-built areas within the Netherlands, as a result of new policy measures. This stormwater constitutes a potential alternative source of water as well depending on where the buffer is placed and who can access it. Meanwhile, groundwater abstraction is only viable in certain areas of the Netherlands where aquifers are available and artificial recharge is only viable if there are unsaturated sandy soils present. Seawater desalinisation is going to cost massive

amounts of energy and although innovative technologies are out there that render this concern invalid, this source would be best suited for the Western coast of the country which is actually the most vulnerable part of the country to rising sea levels and flooding. Investing in innovative technologies there require more investigation when weighing with the probability of a massive natural disaster.

Meanwhile, greywater (GW) is available all year round: it is in constant supply and thereby an attractive option when faced with more extreme seasonal fluctuations in the future. Although GW reuse has been proposed as the least prioritised source of water for closing the UWC through decentralised systems, this thesis researches the potential of WRS to be applied in high dynamic scenarios as a way of increasing flexibility through increasing adaptability/proactive resilience and reactive resilience.

Furthermore, the decentralisation of GW as an alternative water source to increase water supply flexibility will require source-separation of domestic wastewater streams and between non-potable and potable quality water streams. Such infrastructural change is expensive and will compromise the self-cleaning design of the current centralised system, so it must be a joint effort with the municipality to prevent negative consequences of less water entering the centralised system. However, once considering the closing of the UWC, this meticulous source-separation increases the potential for energy and resource recovery from wastewater as well. This reusing of water can be considered circular and water efficient usage.

The treatment of GW can be achieved through green technologies such as green roofs, green walls, and constructed wetlands, which are also classified as GI, which would then also mean additional benefits of increased resilience of urban drainage systems.

Water reuse systems (WRS)

Crucial to closing the UWC and achieving SUWM, a potential solution to cope with changing water patterns

WRS capture and treat wastewater for use, often referred to as reclaimed water. It is often cited as an untapped available water resource (UN-Water 2018; National Research Council 2012). Reclaimed water can be allocated for both direct and indirect use depending on the system itself, with indirect use integrating an environmental buffer to discharge reclaimed water into before further treatment for direct use. Wastewater as an alternative source of water poses a distinct advantage: its constant supply, in contrast to other sources, such as the seasonal nature of rainwater harvesting.

The treatment process of wastewater is based on a fit-for-purpose approach. The treatment process depends on its end-use to determine the quality needed: potable or non-potable consumption. Potable water is defined as water that is consumed or had direct contact with skin, for example when cooking or showering, whereas non-potable water is everything else, such as for toilet flushing or irrigation. This distinction is directly related to the quality of water, as potable water must be safe for human consumption.

WRS goals can be divided into four main categories based on end-use (Capodaglio 2020):

(1) Direct potable reuse (DPR)
(2) Indirect potable reuse (IPR)
(3) Non-potable reuse (NPR)
(4) Industrial reuse (IR)

WRS for DPR faces higher social barriers, as will be discussed below. Ironically, de facto reuse is an undisputed certainty in all water systems although it occurs unintentionally. Take for example, when one community discharges their treated wastewater into a surface water body that another community withdraws from to process into drinking water. It is true, the Dutch are drinking German toilet water. This demonstrates the disconnection between individual beliefs and natural system functioning with recycling as a fundamental process (note: ecosystem processes being described as cycles). A particular point of interest with adopting decentralised wastewater reuse is its potential to adjust consumer perception, starting with non-potable reuse.

Yet, in the Netherlands, tap water is processed to potable water quality and used for non-potable activities as well, causing concern for the extent of treatment intensity to produce this water. However, as demonstrated in a case-study on the feasibility of WRS in Beijing, the absence of financial penalties and tap water pricing render municipal tap water cheaper than the costs of WRS (van Dijk & Liang 2012). This is also reflected in the current water price in the Netherlands, where centralised tap water is considered too cheap to motivate conservation (Dai, Wörner & van Rijswick 2018). Thereby, the financial feasibility of WRS can already be assumed to be low, lest in a high dynamic and unpredictable scenario that motivates individuals to secure their own water supply. Coupled resource-recovery would also increase its feasibility. In a predictable high dynamic scenario, government can penalise individuals who use excessive amounts of water or incentivise individuals to find alternative water sources, which would motivate decentralised WRS since individual RWH in a compact urbanscape is ineffective.

Centralised v.s. decentralised WRS

Water reuse systems have largely been categorised in the literature as centralised or decentralised systems with the defining denominator being scale, as decentralised systems are utilised for domestic units (households) or clusters of units (apartments/neighbourhoods) (Sgroi, Vagliasindi, & Roccaro, 2018). Treatment technologies applied for centralised WRS can be likewise applied for decentralised WRS (Capodaglio et al. 2017).

Overall, both centralised and decentralised WRS would increase the adaptability of the current centralised water infrastructure network which would be struggling to cope with their projections of future water demand (Whitler 2015). However, on a decentralised scale, the shortening of water reuse circuits can lead to more sustainable urban drainage system and ensure treated wastewater discharge into the environment when climate-change threatens the urban drainage system by causing central sewage overflows that damage infrastructure and degrade urban water quality (Capodaglio 2020). Dealing with increasing uncertainty through increasing overall resilience however, requires a transition away from fully centralised systems towards decentralisation (Leigh & Lee 2019).

A drawback would be the need to redesign combined urban drainage systems to be fit for source separation (Hering et al. 2013). However, such a redesign reflects sustainability ideals for the future,

	Advantages	Disadvantages
Centralised	Economies of scale in management and treatment costs (Hering et al. 2013) Can serve a wider array of agencies through potable and non-potable applications (Wilcox et al. 2016)	Significant investment in large-scale conveyance systems (Hering et al. 2013)
Decentralised	Harvesting alternative sources of water e.g. rainwater Increases potential for water conservation and reuse (Makropoulos & Butler 2010) Increases resiliency of centralised water infrastructure network (Ibid.,) Reduce costs of infrastructure replacement (Ibid.,) Distribution network can take advantage of gravity flow (Capodaglio et al. 2017)	Meticulous source separation necessary for optimal performance Typically treatment for non-potable use

Table 1: Pros and cons of centralised versus decentralised WRS

such as the Sponge City concept. Furthermore, one of the greatest flaws of the centralised water system is its aging infrastructure. At such a magnitude, the costs of upgrading and replacing it is immense (Leigh & Lee 2019).

Decentralised WRS also offer less extensive infrastructural modifications considering the short-circuiting of WRS systems to micro-scale and meso-scale (collective-scale) (Capodaglio 2020). Although not a focal point in this research, research involving WRS is increasingly coupled to resource and energy recovery as a result of alternatives to the business-as-usual paradigm, such as the circular economy. The coupling greatly increases the WRS' economic feasibility.

Centralised WRS are able to channel wastewater from households towards a greater scale of retention. For example, aquifer recharge. However, in the Netherlands, this is most interesting in the centre of the Netherlands where the Veluwe, the biggest aquifer in the Netherlands is located. Wadi systems and deep infiltration are also promising depending on soil characterisation and strata. Furthermore, although collective to centralised-scale RWH is potentially effective during the wet season, long-term storage of rainwater still remains uncertain. In recent years, a ground of opportunistic pathogens (OPs) have been detecting in rainwater tanks globally (Zhang et al. 2019). These OPs can cause infections, especially for immunocompromised beings. Their regrowth potential post-disinfection shows a general trend of increasing with higher temperatures (Zhang et al. 2019). Applying this new information, we can see how capturing and storing rainwater for use during the dry period where temperatures will become hotter comes with a higher risk of OPs even with disinfection methods. Even if we place the rainwater tank in a cool area, it must be retreated or disinfected before use, costing energy and resources (depending on the method of disinfection). Most likely the cool area insinuates underground water storage, which in the context of generally high water table levels in the Netherlands (Waternet 2021), we cannot ensure sufficient drainage around the tank. Instead, underground polyethylene or fiberglass tanks would be used (Lawson et al. 2009). The material intensity of providing massive underground storage tanks should be considered and negotiation of sub-surface space in a compact urbanscape where hundreds of apartment residents share a minute amount of ground space.

A matter of viewing WRS in this thesis is to take a bottom-up approach. Decentralisation is utilised exactly because centralisation of WRS is a long and arduous journey of public and political debate, and negotiated through extensive back-and-forth bureaucratic processes to integrate institutionally (Leigh & Lee 2019). It requires the institutional establishment of new agencies for developing and maintaining such a large-scale infrastructural projects. Decentralised efforts can begin today due to an individual's or collective's choice and action, with lower capital intensity and shorter construction timelines (Capodaglio 2020). Trials at a small-scale could expediate the adoption of decentralised water technologies into the current social-technical-system through winning political support and public acceptance that can motivate larger investments (Leigh & Lee 2019). These efforts to source-separate should not be considered futile, because if municipalities want to later centralise WRS, then decentralised units can re-connect to new centralised GW pipes and non-potable water pipes systems (Leigh & Lee 2019). The integration of decentralised water technologies such as WRS offers the potential for urban water systems to be more efficient, ecological, robust, and adaptable (Leigh & Lee 2019).

As a concluding note, the alternative of a decentralised system includes disadvantages as well. The increased flexibility endowed by decentralisation is a double-edged sword. It may prove a barrier to adoption, as it increases the complexity of system design and management due to overlapping facilities for water collection, storage, treatment, and distribution over multiple scales and as insinuated by the source-separation, requires duplicate water networks for NP and P water (Sapkota et al. 2014). Specifically with WRS, disconnecting GW can increase the concentration of pollutants in wastewater, leading to corrosion and deposits in sewer pipes that increase wastewater treatment costs and may even require additional water to flush the system out (Sapkota et al. 2014). Yet, even when considering these disadvantages, decentralisation of the urban water system is promising due to the inherent limitations of centralised design: robustly fail-safe compared to resilience-oriented safe-to-fail ideals.

WRS and public acceptance

There's already a major barrier, however this is a social phenomenon shaped by human values. We can expect there may be changes in human values. Thereby this research thesis can be considered exploratory.
Before exploring public acceptance of WRS, it is crucial to understand the current state of public awareness of urban tap water. Awareness of tap water can be defined as a condition whereby customers know the costs to produce potable tap water and have it flow out of their taps at home (Ntengwe 2004). In a survey conducted within the Netherlands, this tap water awareness has been divided into three dimensions (Brouwer, van Aalderen & Koop 2021):

(1) Cognitive awareness: aligned with Ntgenwe's definition (2004)
(2) Affectional awareness: extent people take tap water for granted
(3) Behavioural awareness: extent people are conscious of wasting tap water

The results of the survey demonstrate ample room for improvement in the average Dutch citizen's tap water awareness, which amounted to 53.5% of the maximum achievable score (100). One third of all surveyed are not familiar with their water utility's name. The participants were grouped by descriptive archetypes and on average, those who are "aware and committed" cared the most for water and shared a sense of responsibility towards it. However, the archetype of "down to earth and confident" assumes great trust in centralised water utilities, displaying the least care, sense of responsibility and behavioural awareness, despite on average having better understanding of the water system. The level of understanding of the water system is positively correlated to the trust in the conventional system. This demonstrates that knowledge may not play a significant role in behavioural change, rather it is the beliefs within an individual, which may or may not be shaped through knowledge.

The paper expresses it succinctly, "the level of personal responsibility for preserving clean and sufficient drinking water is positively related to heart (affectional awareness) and to a lesser extent with hands (behavioural awareness)" (Brouwer, van Aalderen & Koop 2021). This is further evidenced by Moya-Fernández et al. (2021) who concluded that general measures will not be enough to increase acceptance of WRS, meaning environmental awareness campaigns would have little to no effect in the level of acceptance, especially for DPR. Instead, practical demonstrations to normalised WRS is suggested (Moya-Fernándex et al. 2021). Along the same lines, overflooding lay people with information about the consequences of climate change can render an individual helpless and they usually resort to demoralisation and apathy of environmental issues (Salomon, Preston & Tannenbaum 2017).

This provides a leeway to understanding why public acceptance of WRS is still low. There are two extents of acceptance: one for direct NP reuse, and another for DPR. A major determinant of the low degree of acceptance is the "yuck factor" especially concerns direct contact, thereby DPR (Moya-Fernández et al. 2021; Fielding, Dolnicar & Schultz 2017). Another study on consumer perception shows low acceptability and trust for its safety (Amaris et al. 2020). The fear can be statistically-backed by Stec's survey (2018), where 79% of the surveyed sample is afraid of using greywater, the least polluted stream of wastewater. In contrast, 60% were afraid of using rainwater. In Southern Spain, WRS is considered the least acceptable option of alternative sources (López-Ruiz et al. 2020). Direct experience with water scarcity, community smallness, and governance strongly influence DPR acceptance (Scruggs, Pratesi & Fleck 2019).

Making sense of this information, we can apply it to the scenarios. In a high dynamic scenario that

insinuates an higher probability of water scarcity, it is more likely that citizens will accept WRS. However, before that, it is more likely they would accept rainwater harvesting, indicated by the higher acceptability in Stec's survey (2018). Such an alternative source of water also ranks highest in terms of priority in contrast to WRS that ranks lowest (Anda 2017). Furthermore, source-separation simply becomes more viable, so WRS will have lower barriers to entry if other streams of water are also being utilised for energy and material recovery in the future.

In high dynamic scenarios with low predictability, bottom-up action is most likely to be motivated in order to secure basic needs, such as water, especially when centralised politics is too fluid to assure water security. This means perpetually changing values and policies each political term. In this case, rainwater harvesting is most likely to be utilised first as well. However, considering the seasonal extremes, unless long-tern water storage can be secured within the locality, rainwater harvesting is a seasonal pursuit. In contrast, wastewater is a constant supply year round. So, WRS should be introduced via non-potable uses and perhaps began during dry seasons when rainwater is low in supply (Moya-Fernández et al. 2021). In the future, it is suggested that local, collaborative, transparent, risk-based regulations be formulated and standardised to encourage acceptance and adoption of WRS as it ensures safety (Mukherjee & Jensen 2020). Then DPR should be considered. Furthermore, introducing WRS citizens can encourage awareness of emerging substances in our water due to household and personal care products and perhaps motivate proactive measures against using them.

Individual versus Collective Choice

In the case of this thesis, the collective is considered neighbouring residents of dwellings within an area of interest. Beyond simply adopting water reuse on a decentralised scale, the difference between an individual and collective choice can also impact the lifetime of the eco-technology. Particularly with GW recycling, it is generally considered "novel" technology. Although some technologies are on-the-market, advancements in GW recycling, such as with membrane technologies, have yet to be fully commercialised. The lack of support services for using these green(er) products is presented as a barrier to their adoption. This especially concerns support services for repair and maintenance (Nath et al. 2012). On an individual level, we cannot expect a layperson to be utilising an experimental GDMBR without aeration, and even if we did, perhaps technical issues present themselves that the individual has no idea how to solve, or must expend effort to seek the appropriate help from experts.

Environmental psychology has traditionally investigated pro-environmental behaviour as a process of individual decision-making that simultaneously defines and represents an individual's sense of identity (Bamberg 2013). Yet it is argued that if the climate crisis is a product of collective behaviour, then it must be solved on a collective level (Barth et al. 2021).

The powerful perception of being part of a social group can overcome helplessness by motivating the individual beyond their sense of self-limitation, where if an individual perceives they are unable to do something themselves but as a part of something greater, "we" may stand a chance (Barth et al. 2021). The extent to which a group is effective in accomplishing its goals is defined as collective efficacy (van Zomeren, Postmes & Spears 2008). Individual beliefs about the extent of collective efficacy also feeds into personal efficacy beliefs (Jugert et al. 2016).

Facilitating WRS adoption

Successful case studies of adopting local design responses to water scarcity are attributed to the creation of communities of practise, diffusion of narratives and creation of pilot projects (Franco-Torres, Rogers & Harder 2021). Peculiarly, respondents in two studies were found to be more willing to use reclaimed water for their laundry if they had their own small treatment unit (Chen et al. 2013; Pham et al. 2011), warranting research into micro-scale decentralised WRS. The creation of practise also aligns with observations that individuals have increased confidence for WRS from other people's success stores (Chen et al. 2013). Similar insights into practise is reflect in another study where involvement of citizen science projects could modify beliefs and demonstrate the unique nature of constant clean tap water (Brouwer, van Aalderen & Koop 2021). The interrelation between government and individual efforts is highlighted, as governments can foster WRS support through investment, urgency, and communication (Hartley, Tortajada & Biswas 2019). Thereby, although WRS lacks public acceptance at this stage, its implementation at the smaller-scale can overcome the "yuck factor" and garner more support to expand its scale.

Waste water origins	L/per/day
Light grey wastewater	**71.7**
Shower	*49.2*
Washing machine	*14.1*
Washbasin (in bathroom)	*5.2*
Bathtub	*1.9*
Washing clothes (by hand)	*1.3*
Heavy grey wastewater	**7.2**
Washing up (in kitchen)	*3.5*
Dishwasher	*2.5*
Food preparation	*1.2*
Black wastewater	**40.4**
Toilet	*34.6*
"Other"	*4.5*
Drinking water (expelled)	*1.3*
Total wastewater	**119.3**

Table 2: Average domestic wastewater distribution, 2016 (Vewin 2020)

Water demand	Litres/person/day
Potable demand	**66.1**
Shower	*49.2*
Washbasin (in bathroom)	*5.2*
Washing up (in kitchen)	*3.5*
Dishwasher	*2.5*
Bathtub	*1.9*
Washing clothes (by hand)	*1.3*
Drinking water	*1.3*
Food preparation	*1.2*
Non-potable demand	**53.2**
Toilet	*34.6*
Washing machine	*14.1*
"Other"	*4.5*
Total demand	**119.3**

Table 3: Average domestic water demand distribution, 2016 (Vewin 2020)

Greywater (GW) & Domestic Water Demand

It is imperative to know the composition and characteristics of the intended wastewater in order to design and operate wastewater treatment (Englande, Krenkel & Shamas 2015). GW is defined as domestic wastewater streams from baths, showers, hand basins, washing machines, dishwaters and kitchen sinks (Li, Wichmann & Otterpohl 2009). Its constant availability through out the year with low organic content make it quite suitable and cost feasible for recycling and thereby augmenting water supply (Singh et al. 2018).

It origins define its quality, as Table 2 demonstrates. GW is further divided between light and heavy GW, of which Figure 5 shows the typical distribution in domestic wastewater. Heavy GW (HGW) is characterised by higher loadings of grease and oils. These streams are from kitchen basins and dishwashers and constitute 6% of domestic wastewater. Based on Vewin's statistical findings (2020), the average Dutch citizen expels 71.7 L/person/day of LGW and 78.9 L/person/day of combined GW. According to Figure 5, LGW constitutes the most economical stream for treatment considering it amounts to 60% of household wastewater and treating LGW is often less costly than combined GW, considering its lowered pollution load (Leiva et al. 2021). Combined GW would amass to 66% but would require specific removal steps to prevent operational issues due to higher loads of grease and oil, and thereby space i.e. grease intercepters or methods of gravity separation (Englande, Krenkel & Shamas 2015).

Household water consumption is influenced by the seasons (Reynaud 2015). Climate conditions play a significant role to water consumption in the Netherlands. As reported by the EC, increasing the summer time evapotranspiration by 10% results in increasing residential water consumption by 0.8% (Reynaud 2015 p. 166). Only in cities where during the summer residents tend to travel, higher temperatures can result in lower water consumption (Arbués & Villanúa 2006).

On the other hand, next door in Germany, it has been found that water consumption decreases as the number of rainy days increases (Schleich & Hillenbrand 2009).

When the wastewater is treated, it is referred to as reclaimed water. The treatment process of wastewater depends on its end-use and whether is will be suitable for potable or non-potable consumption. Potable demand is defined as water that would come into contact with humans, whether indirectly through skin or directly down an orifice, while non-potable demand is the opposite of that. The relation between type of demand and household activities can be seen in Table 3. Reusing domestic wastewater for domestic water demand is attractive, considering that it creates a circular loop within the household system boundary and the lowest treatment intensity that yields non-potable demand can already satisfy 45% of total domestic demand, as seen in Figure 6.

GW characterisation

Contaminants found in GW are largely associated with household products (Oteng-Peprah, Acheampong, & de Vries 2018). Subsequently, the choice of products as well as domestic activities depends on the individual's lifestyle. Overall, GW has good biodegradability in terms of the COD: BOD5 ratios (Li, 2009) meaning easily biodegradable organic content and sometimes biological microbes such as faecal coliforms.

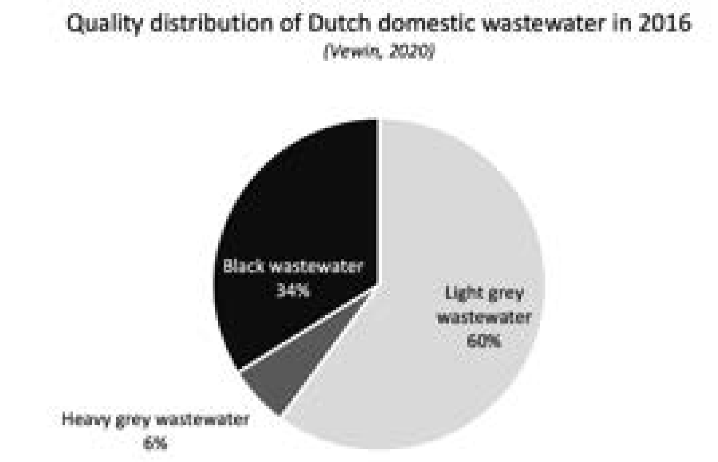


Figure 5

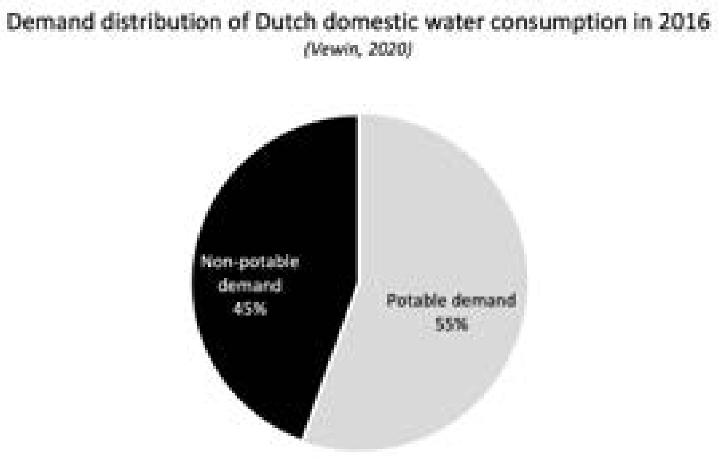


Figure 6

However, emergent pollutants have consistently been traced in GW as well. These include pharmaceuticals, xenobiotic organic compounds (XOCs), toxic heavy metals, and endocrine disrupting compounds (EDCs) that are linked to adverse toxicological effects in aquatic species (Benotti & Snyder 2009; Fatta-Kassinos et al. 2011; Eriksson et al. 2010). Furthermore, new compounds are continually being manufactured and entering the environment (Yu, Bouwer & Coleman 2006). The removal of these emergent pollutants depend on the treatment process (Englande, Krenkel & Shamas 2015).
GW treatment

GW treatment trains can vary from simple to extremely complex. Typically, WRS involve a GW storage tank that feeds water into the treatment process and subsequently stores the reclaimed water into a green water storage tank awaiting direct use (Liu et al. 2010). The treatment process itself follows a conventional wastewater treatment sequence: primary/pre-treatment, secondary, then tertiary/post treatment (Oteng-Peprah, Acheampong, & de Vries 2018). Pre-treatment often involves solid-liquid separation, secondary treatment tend to be either physical or biological, and post-treatment involves disinfection to meet microbiological requirements (Oteng-Peprah, Acheampong, & de Vries 2018).

Physical treatment filters out particles through physical mesh wire or membranes. Generally it removes suspended solids and reduces turbidity (Arugam, Ghadimi & Change 2018). These include filtration, adsorption, reverse-osmosis and more. Biological treatment utilise microbes and oxygen manipulation, with treatments such as activated sludge systems, trickling filters, rotating biological contractors, membrane bioreactors, constructed wetlands and more.

WRS sizing & storage

It was found that water saving efficiency of WRS was directly, not linearly related to GW storage tank volume (Butler, Dixon & Fewkes 1999).

There are three general storage options (Eslamian 2016):
(1) a raw GW collection tank, often including pretreatment and can be utilised to regulate flow into treatment system
(2) a treatment unit that simultaneously stores raw GW for treatment (e.g. bioreactor, constructed wetland)
(3) a green water tank that stores treated GW

The optimal storage capacity for treated GW should be determined via the peak treatment rate, capacity of treatment process, and demand pattern. Considering that GW effluent tends to be constant, storage equal to one day's use is considered sufficient (PUB 2014). For most applications, collection tanks would be sized to provide 8 to 10 hours of storage but no more than 24 hours (WSD 2015). Although seemingly straight-forward, the storage would then have to account for peak factors in demand patterns. Peak factors in light of climate change is theorised to increase up to 21.3% by 2050 (Vonk, Cirkel & Blocker 2019). Tourism fluxes also impact the peak factors to the point where ignoring them may result in under- or over-estimation of peak factors (Vonk, Cirkel & Blocker 2019).

Ultimately, only treated water should be stored. Still, research has suggested microbial regrowth occurs when reclaimed water is stored too long (Harju 2010; Liu et al. 2010; Lawson et al. 2009) and can attract mosquito breeding (PUB 2014) or release odours (Domínguez et al. 2017). The Singaporean government's guide on GW treatment system adamantly insists against the storage of raw GW, allowing only temporary storage less than 24 hours (PUB 2014). Similarly, a 24 hour residence time limit is claimed for both raw GW and treated GW (Domínguez et al. 2017). Liu et al. (2010) recommends water residence time less than 48 hours but this can significantly reduce the water saving efficiency of the WRS. Instead, it is suggested that higher water saving efficiency be gained with smaller GW tanks, greater green water tanks, and an additional disinfection treatment when residence time exceeds 48 hours (Liu et al. 2010). Furthermore, the potential of microbial regrowth appears to be dampened with lower temperatures (Zhang et al. 2019). So optimal water storage conditions of cool, dark spaces, unexposed to light should be favoured.

Water saving efficiency (WSE) of WRS

Water saving efficiency (WSE) is defined as the amount of tap water saved by reusing GW (Liu et al. 2010). Based on simulation studies, there are four key factors that influence the extent of WSE of household GW reuse (Liu et al. 2010):

(1) Household occupancy
(2) Storage volumes
(3) Treatment capacity
(4) Operating mode

For a given treatment capacity, WSE increases with higher volume of green water tanks. However, the rate of increase weakens to a certain point. This point was found to be directly related to treatment capacity. When treatment capacity is low, in the paper this was 20 L/day, a maximum WSE of 20% was achieved regardless of how big the green water tank is. From 20 L/day to 140 L/day, the maximum WSE increases with increasing treatment capacity. Beyond 140 L/day, WSE remains unaffected by higher green water tank volumes. Therefore, WSE is maximum at a treatment capacity of around 200 to 350 L/day. (Something to consider for collective action?).

In terms of household occupancy, it follows logically that increasing occupancy correlates with greater volume of total storage tanks required. However, the total storage tank required per capita decreases with increasing occupancy. This pattern only applies to households greater than three people.

Although it is logical to assume that increasing the treatment capacity means more GW can be treated, this may result in less GW being reused because overflow occurs from the green water tank which would simultaneously mean a deficit of GW for further treatment at better timing for usage. In fact, it was observed that the nearer the operating mode approaches an household's actual toilet usage pattern, even higher WSE can be achieved. Therefore, with intermittent feeding, an average of 4% extra WSE is achieved.

Unfortunately optimisation of WRS is highly contextualised. It was clear from the paper that relationships between the WSE with tank size and treatment capacity is too complicated to express in simply equations (Liu et al. 2010). However, it is suggested that a targeted WSE be specified then treatment capacity and tank sizes can be determined.

Innovative technologies and Maintenance

Resilient cities rely on eco-technologies for construction, maintenance, and sustainable growth (Aithal & Aithal 2016). Maintenance is crucial to consider when dealing with innovative or unfamiliar technologies (Rogers 1962). In order to facilitate the adoption of innovative technologies, the technology should be perceived by potential users as easy (Aiztrauta et al. 2015). In a study of foreign technologies in developing countries, a foreign technology is considered technically sustainable only if there is a well-established framework for its maintenance within the community it is applied (Dunmade 2002). In a case study of 41 power-related projects in sub-Saharan Africa, the sustainability of its physical improvements became uncertain due to the lack of effective maintenance (Covarrubias 2010).

In general, the more components a technology has, the more components risk failure (Galar 2014). Thereby part of adequate maintenance is to ensure availability of spare parts (Dunmade 2002). An additional factor is the availability of technical know-how within the community, otherwise repaired may require the presence of costly technical experts from even abroad. However, such an idea would most likely be applicable for larger-scale infrastructure (Dunmade 2002). For household-related products, the digitisation of maintenance (eMaintenance), is particularly interesting to implement (Johansson, Roth & Reim 2019). This is so because maintenance requires discovery of the reasons for errors and remedies in a timely manner (Galar 2014). Thereby the digitisation of this information is interpreted as added value to provide decision support without needing physicality (Johansson, Roth & Reim 2019). However, eMaintenance requires not simply technical solutions but an entire organisation of external actors, of whom their working methods are changed through digitisation (Kajiko-Mattsson, Karim & Mirjamdotter 2011).

So in terms of innovative WRS technologies, it is more feasible to implement if there is less complex mechanisms that enable technical know-how from non-experts or if there is available customer support through suppliers and/or eMaintenance. Often this means the technology must be an on-the-market product. A form of eMaintenance could be the availability of Youtube videos that educate citizens on common problems or issues with certain innovative technologies. At the scale of decentralised technologies, there is always the option to send parts to the manufacturer, although some parts may be bigger than others.

Non-source separated technologies

Recirculating showers

Although there are a variety of recirculating showers on the market, these calculations are based on a published thesis on ShowerMagic, an open-sourced recirculating shower design, now commercially known as Showerloop (Selvarajan & Holland 2013). Recirculating showers work by relooping used shower water and treating it simultaneously, subsequently also offering energy savings by reducing the energy needed for heating water. Different recirculating shower technologies require varying degrees of fresh tap water to supply the shower. Shower wastewater is characterised by personal care products such as soap, shampoo, hair dyes, toothpaste etc. (Boutin & Eme 2016). It is high in suspended solids, hair and turbidity while exhibiting lower levels of BOD and thermotolerant coliform (Boutin & Eme 2016). Overall, it does not require high treatment intensity to treat for subsequent use as safe bathing water.

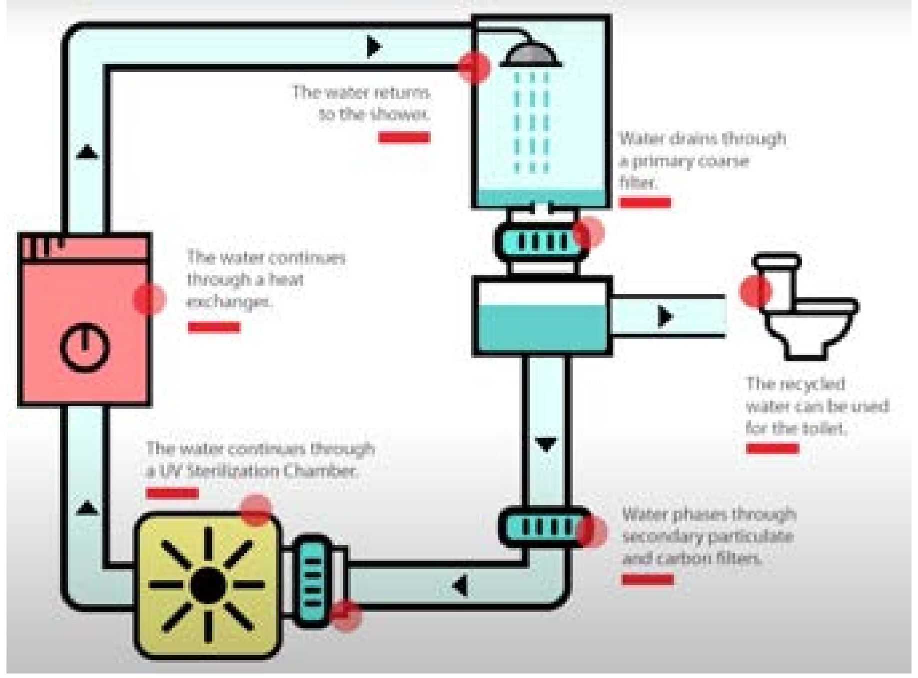


Figure 7: Recirculating shower schematic (Mar 2021)

In ShowerMagic, the purification system utilises physical filtration for bigger bodily debris, then particulates, suspended solids, organic and inorganic compounds are removed through a sand and granular activated carbon filter, reducing turbidity (Selvarajan & Holland 2013). As a tertiary treatment, an ultraviolet irradiation reactor disinfects the water. The removal efficiency was over 98% for particulates, 92% for suspended solids, a log 5 reduction in escherichia coli bacteria, but 50% for inorganic compounds (Selvarajan & Holland 2013).

Results indicate that its installment effectively reduces the daily shower consumption of 49.2 L/day for an average Dutch person (Vewin 2021) to 10 litres per day. These numbers are very similar to the Dutch company's Upfall shower's external KIWA results, where daily shower water consumption has been decreased by 80% (KIWA 2016). Overall, it reduces daily water consumption by 32.89%, thereby augmenting domestic water demand by the same percentage.

In consideration of higher numbers of showers during the summer time, it is unclear whether the recirculating shower quenches water use to a constant rate of 10 L/day regardless of the amounts of showers taken. Spatially it is extremely friendly since it does not take up additional space, rather standing in the space of a conventional shower. However, rates of failures and subsequent repairs are not known about the shower. Another point of concern would be the human habit of peeing in the shower and how this would affect it. As a counter, the awareness of having a recirculating shower may reduce this habit. The disadvantage of a recirculating shower lies in its hogging of shower water, which reduces a considerable share of GW. Therefore, it may not be synergistic as a combination strategy with WRS.

Water-efficient micro-components

Instead of relying on water reuse, it can be considered that we install more water-efficient micro-components in the house. Often, there are filter add-ons to faucets or more water-efficient alternatives to bigger micro-components (e.g. washing machines, dishwashers, showerheads etc.). The impact of replacing existing taps in the household with aerators would save 28.9% of water demand (Marinoski, Rupp, & Ghisi, 2018). Furthermore, water-efficient appliances were the strategy with the greatest environmental benefit (Marinoski, Rupp, & Ghisi, 2018).

However, as water demand is reduced through water-efficient micro-components, so will wastewater from households. This can be problematic depending on how the sewage system is designed. According to sewage design principles, pipe flow velocity depends on pipe slopes, diameters and wastewater flow quantities (Basupi 2020). In addition, there is a general rise in fat, oil and greases in the water, as well as new technologies such as kitchen sink food waste disposers and low-flush toilets that change the characteristics of wastewater effluent (Mattsson et al. 2015). Changes to these variables through new household practises have the potential to cause an increase in solids deposition that could effectively reduce the pipes' self-cleansing velocities (Mattsson et al. 2015), increase doors, generate sulphides, methane, and microbial induced concrete corrosion (Marleni et al., 2012). It is theorised though, that generalised diurnal patterns of wastewater discharge will prevent impacts to the self-cleansing properties (Mattsson et al. 2015). However, daily water consumption patterns vary due to lifestyle differences, and wastewater discharge is now observed to be more evenly distributed through out the day, referred to as the "metropolitan lifestyle" (Ellis & Bertrand-Karjewski 2010). Of most concern would be the sewers with extensive sagging that are most sensitive to increased solid deposition (Mattsson et al. 2015). Furthermore, although wastewater quantities will be reduced, mass loadings rates of COD, TKN, BOD, TSS and total phosphorus would remain constant (McKenna et al. 2018; Min & Yeats 2011).

Water reuse treatment technologies

Wastewater treatment technologies can largely be categorised as grey or green (Castellar et al. 2022). Grey technologies are generally advanced and highly efficient in pollutant removal while having smaller footprints, as such it is appropriate for the dense urban setting (Andersson et al. 2017). Such technologies include membrane filtration, advanced oxidation and electrochemical processes, adsorption techniques, and disinfection methods (Castellar et al. 2022). However, these grey technologies tend to come with high energy, implementation and maintenance costs as well as toxic by-products that could compromise its sustainability (Garrido-Cardenas et al. 2020).

Green technologies that are termed nature-based solutions (NBS) are known for their low energy, implementation and maintenance costs (Boano et al. 2020). Such solutions include constructed wetlands, ponds and lagoons, green walls and green roofs, all of which require substantial amounts of space that must be negotiated at a meso to macro-level, between neighbourhoods to city authority (Castellar et al. 2022). On a favourable note, these NBS can be implemented in cold regions as well (Kobayashi et al. 2020). Furthermore, a survey regarding WRS treatment options demonstrate respondents' preference for natural processes (Rozin et al. 2015).

Compared to public acceptance and financial considerations, technical barriers are almost non-existent in WRS, considering the diverse array of existing technologies (Capodaglio 2020). Thereby, WRS can be implemented in a multitude of ways depending on the chosen treatment technology, each yielding their own pros and cons.

Treatment technologies have been subject to LCA studies to determine their impact on a larger scale, but not necessarily by their spatial footprint (Dominguez et al. 2018; Banti et al. 2020; Pasqualino, Meneses & Castells 2011; Friedrich, Poganietz & Lehn 2020). This is so perhaps due to decentralised water treatment being a decision made in the absence of conventional water infrastructure. As such, its spatial setting assumes rural land with plentiful space.

Based on the fit-for-purpose approach, wastewater treatment is a sequential process with treatment intensity depending on the influent and desired effluent water quality (von Sperling et al. 2020). EU guidelines for water reuse only require secondary treatment, either chemical or biological treatment, then a final disinfection stage (Jabornig 2014). In general, the combination of physical filtration, biological processes, and disinfection is considered the most economical and feasible solution for GW recycling to yield high-quality reclaimed water (Li, Wichmann & Otterpohl 2009; Yoonus & Al-Ghamdi

2020; Oteng-Peprah, Acheampong, & de Vries 2018; De Gisi et al. 2016). Reflectively, EU guidelines only require secondary treatment, either chemical or biological treatment, then a final disinfection stage for non-potable reuse (Jabornig 2014).

Grey treatment technologies

Membrane Filtration

The principle of membrane-based technologies is the selective filtration of influent through pores size (Hamingerova, Borunsky, & Beckmann 2015). Its advantages lie in the need for fewer treatment stages, smaller footprints, and scalability due to its modular design. (Hamingerova, Borunsky & Beckmann 2015). Pressure-driven membrane processes (RO, NF, UF, and MF) separate the feed solution into permeate, the desired water quality, and retentate, the by-product (van der Bruggen et al. 2004).

In a study, primary treatment of GW happened in a septic tank then secondary treatment involved a submerged spiral-wound UF membrane filtration system (Li et al. 2009). Over two weeks of operation, the permeate flux of 10 l/m2/h decreased to 6.1/m2/h, indicating membrane fouling, of which dissolved organic matter was found to attach itself to the membrane, reducing flux (Li et al. 2009). Total organic carbon content (TOC) was reduced with an average rate of 83.%, had <1 NTU, and was free of suspended solids (Li et al. 2009). However it did not meet EU guidelines for bathing water due to higher concentration of organic substances (Li et al. 2009). However, if combined with RO or advanced oxidation, the effluent is suitable for unrestricted non-potable use (Li et al. 2009).

Another study with an integrated UF and RO membranes was able to treat 400 L of GW daily, producing 300 L of green water, 80 L of concentrated detergent solution and 20 L of turbid water (Venkatesh & Senthilmurugan 2017). Membrane fouling was prevented through a backwash-back-flush technique, enabling stable membrane performance (Venkatesh & Senthilmurugan 2017). The combination of UF as pretreatment preceding RO achieves high removal efficieny, qualifying effluent for both indoor and outdoor non-potable use (de Oliveira, Benatti & Tavares 2020). However, if it is utilised with average to bad water qualities, then it would need more frequent cleanings and membrane fouling would occur earlier (Bonnélye, Guey & Del Castille 2008).

Ultimately, membrane filtration appears a suitable technology integrated with other processes. For example the MBR. It must be combined with other pre-treatment methods to prevent the rate and magnitude of membrane fouling.

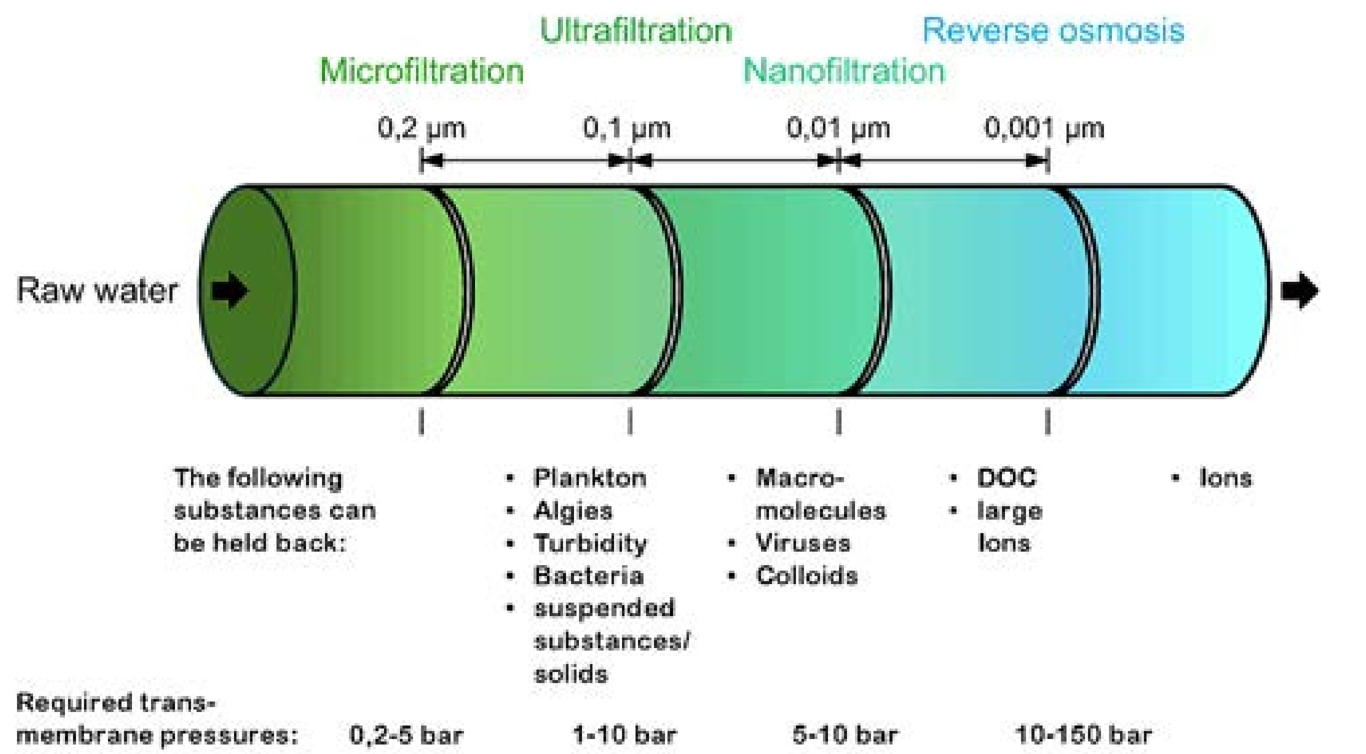


Figure 8: Membrane Filtration Process (Hydrogroup 2022)

Membrane Bioreactors (MBR)

MBR systems utilises a biological degradation process to achieve high clarity water (Deowan, Bouhadjar & Hoinkis 2015). The systems are usually designed in combination with physical membrane filtration such as micro- and ultra filtration and are commercially accessible (Hamedi et al. 2018; Deowan, Bouhadjar & Hoinkis 2015). As such, a majority of commercial residential GW recycling systems rely on MBR as a secondary treatment process (Jabornig 2014). Studies into economic feasibility demonstrate that MBRs are suitable for buildings of more than 37 stories or a collection of several buildings together (Friedler & Hidari 2006).

Widespread use of MBRs are limited by elevated operating expenses and membrane fouling phenomenon (Meng et al. 2009). This phenomenon occurs as a result of undesired suspended solids attaching to membrane surface, lowering membrane permeability and subsequently increasing flow resistance (Kim et al. 2013). Literature suggests that MLSS concentration and inorganic foulants are correlated to the caking of the membrane, lowering permeation flux (Le-Clech, Chen & Fane 2006). Thereby, treating higher strength water would insinuate more regular replacement of the membrane. MBR systems rely on pumps and blowers to not only convey flows but scour the membrane, effectively cleaning it and regaining filtration efficiency (Ding et al. 2017). Aeration comprised almost 50% of total energy requirements (Gil et al. 2010).

A variety of MBR variations are available. Aerobic MBRs are conventionally used to treat municipal and industrial wastewater (Hamedi et al. 2018). It can operate at high volumetric loading rates and short HRT (Hamedi et al. 2018). The submerged MBR (SMBR) configuration was developed as an innovative alternative compared to the conventionally-designed side-stream MBR due to its significantly lower energy consumption and fouling probability (Yamamoto et al. 1988). It has a smaller footprint because the two mechanisms can be combined in a single tank, eliminating the need for a settlement tank and secondary clarifier (Hamedi et al. 2018). This formation can be defined as bioreactor-based, as the GW collection tank and treatment unit membrane are combined.

Anaerobic MBRs (AnMBR) are another promising variant compared to conventional aerobic because of reduced energy consumption and sludge production (McCarty et al. 2011), leading to economic and environmental advantages (Pretel et al. 2016). It also has resource recovery potential to capture biogas (Deowan, Bouhadjar & Hoinkis 2015). However, AnMBRs have more pronounced issues with membrane fouling (Deowan, Bouhadjar & Hoinkis 2015). Thereby, the higher maintenance may be unsuitable on the residential scale, as personal biogas capture is not typically on the agenda in urbanscapes.

Novel MBR configurations exist that attempt to mediate the issue of membrane fouling and its subsequent impact on performance and maintenance, thereby requiring high energy consumption and chemical cleaning. This tends to be a barrier concerning decentralised GW processing (Ding et al. 2017). Forward-osmosis variants does not require pump energy to drive the membrane operation process (Deowan, Bouhadjar & Hoinkis 2015). Synthetic GW was found to be processed to very high water quality, being recommended with high potential in integral processes for treating GW (Xiao et al. 2018). Another alternative is the gravity-driven membrane process (Ding et al. 2017). In an experiment with synthetic GW, it was found that although membrane fouling occurred with longer operation times, the layer was loosely adhered onto the membrane, so that hydraulic flushing was sufficient to restore

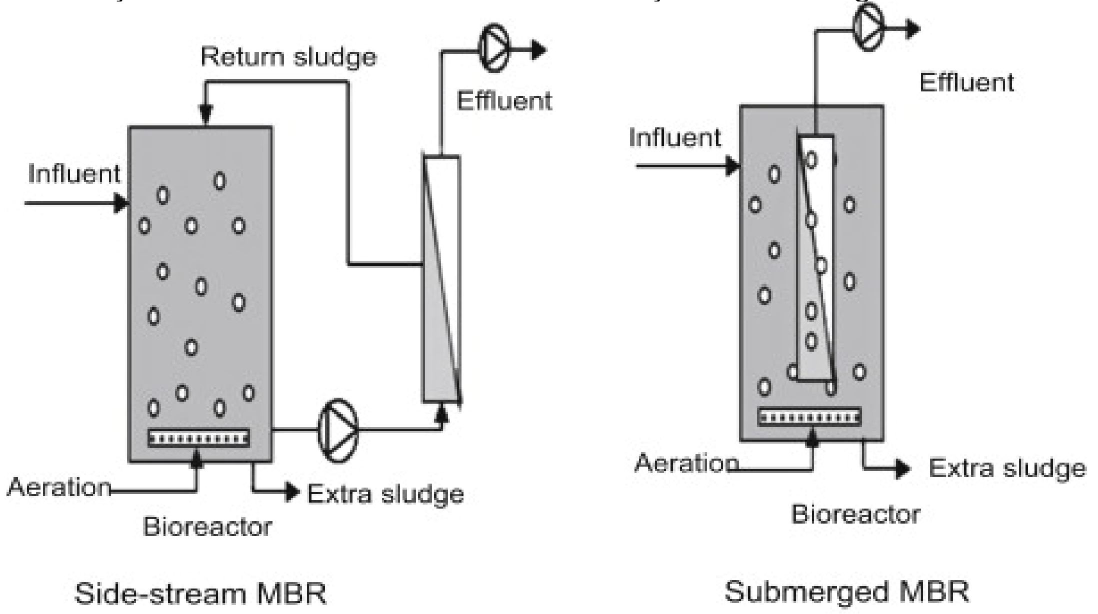


Figure 9: Comparison between side-stream MBR and submerged MBR (Deowan et al. 2015)

flux instead of chemical cleaning (Ding et al. 2017). Between an aerated pilot and non-aerated pilot, the lowered energy consumption is correlated to larger membrane size, while the flux was halved for the non-aerated pilot (Ding et al. 2017).

The reason for high robustness of MBRs are due to its consistent effluent that has a large reduction efficiencies of physical-chemical (COD, BOD, and TN) and microbiological pollutants, meaning it is highly reliable (Gil et al. 2010). Performance of a SMBR + UF treatment yielded reclaimed water suitable for the most stringent non-potable reuse standards (Bani-Melhem et al. 2015). Another study with the same system achieved high quality effluent with removal efficiencies of 81% for COD and 98% of BOD with a 5 to 8 hour hydraulic residence time (HRT) (Friedler et al. 2006). HRT is the amount of time collected GW remains in the treatment tank before flowing out, which often correlates with removal efficiencies (Najmi et al. 2020). A SMBR + UV disinfection system also achieved such standards (Fountoulakis et al. 2016; Merz et al. 2007). However, bacterial contamination could not be guaranteed due to bacterial re-growth, meaning the reclaimed water should be re-disinfected if not immediately used (Mer et al. 2007).

Performance of SMBR for removal of personal care products (PCPs) demonstrated an excellent degradation capability for all categories of PCP contaminants typically present in GW (Najmi et al. 2020). A16 hour HRT exhibited the best performance (Najmi et al. 2020). Likewise, another study demonstrated consistently high removal rates greater than 86.5% for endocrine disrupting chemicals (Trinh et al. 2012).

There is general consensus the MBR is a robust, flexible and reliable solution for decentralised WWTP, meeting lower effluent demand and spatial requirements (Judd & Judd 2010; Atanasova et al. 2017; Winward et al. 2008). However, it is best particularly in collective urban residential buildings (Li, Wichmann & Otterpohl 2009).

Moving bed biofilm reactor (MBBR)

Often a combination of a moving bed biofilm reactor and membrane filtration in one tank, also realising a more compact design (Jabornig & Favero 2013). The reactor is filled with growth-media tidbits that biofilm eventually grows attached to, maximising surface area contact, thereby, treatment capacity as it relies on biological treatment. MBBRs do not require as much fouling control in order to maintain high flux (Jabornig & Favero 2013). Furthermore, it was found to achieve non-potable effluent quality (Jabornig & Favero 2013; Saidi et al. 2017), was effective in removing anionic surfactants often found in household products by 98% (Zhou et al. 2020) and can have a lowered energy demand of less than 1.3 kWh/m3 of water treated (Jabornig & Favero 2013).

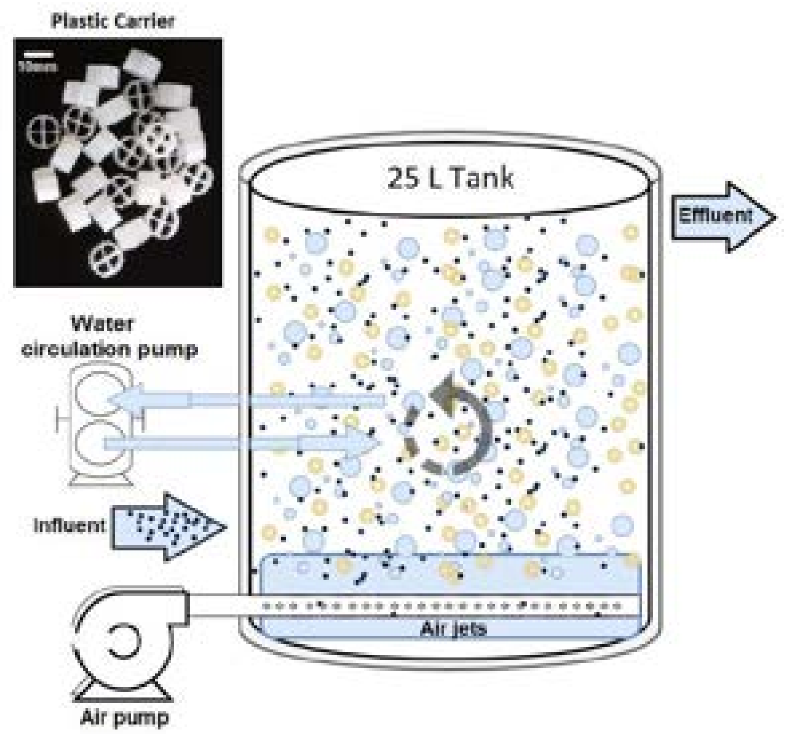


Figure 10: MBBR Bioreactor (Aldris & Farhoud 2020)

Membrane Distillation

Membrane distillation (MD) as been cited as a low-cost solution for treating wastewater generated by oil industries (Said et al. 2020). It is chemical-free, requires low energy and has almost 100% dissolved solids rejection (Said et al. 2020). Its application on a household level has been tested out by Fraunhofer's Mediras project but specifically catered to solar MD for residential-level desalinisation (Raluy et al. 2012). Case studies were demonstrated in areas with a relatively warmer climate i.e. Tunisia, Spain, Tenerife, and Italy and performance demonstrates a direct relation between solar radiation and distillate volume which renders its performance non-conclusive in the Netherlands (Raluy et al. 2012).

Further research has yielded an integrated solar-driven membrane distillation system that simultaneously purifies water and generates energy (Kumar & Martin 2014; Li et al. 2019). Such a system could be applied on rooftops of buildings, making it space efficient while providing potable water and domestic hot water (Li et al. 2019). Its performance has likewise correlated to the degree of solar radiation (Li et al. 2019), warranting cause for a feasibility study of whether its application in the Dutch climate would be appropriate.

Figure 11: Solar thermal modules (left) and desalination membranes (right) in Tenerife (Raluy et al. 2012)

On-the-market equivalents

Aqualoop

The Aqualoop system by Intewa utilises their patented PURAIN pre-filter then biological treatment in a moving bed reactor, termed the AQUALOOP membrane cartridge, and is lastly treated through a UF membrane (Intewa 2022). One membrane cartridge treats an average capacity of 300 L/day with adjustable HRT, although the suggested HRT is 6 hours for biological treatment before filtration (Intewa 2020). This system is intended for residential use, even at the micro-scale but can be scaled easier with additional membranes and increased storage capacity. The technology is NSF 350(C) certified which means effluent is guaranteed for indoor and outdoor non-potable use. The expected membrane life is greater than ten years and membrane maintenance frequency is recommended for every nine months. The same technology can be utilised to treat rainwater and surface water into potable water quality. An Intewa representative cites that GW treated through the Aqualoop has too much dissolved oxygen content to be treated into potable water quality, suggesting that additional RO treatment is necessary if potable quality desired.

Figure 12: Aqualoop placed in house (above) and schematic (bottom) (Aventia 2022)

Hydraloop

Hydraloops are able to treat and distribute shower, bath, and 50% of washing machine wastewater. The water is converted for use in the toilet, washing machine, irrigation and optionally for the pool. The company prides itself on their purification system's lack of reliance on filters, membranes, and chemicals, rendering it more user-friendly and low-maintenance. Their patented technology process consists of sedimentation, floatation, dissolved air floatation, foam fractionation, an aerobic bioreactor, and ultraviolet light disinfection (Hydraloop Technical 2022). Inorder to ensure more safety, the Hydraloop is programmed to disinfect stored water every four hours.

Although the Hydraloop functions automatically, the company has also developed an app to

Figure 13: Hydraloops placed in homes (Hydraloop 2022)

monitor the system in real time. The sensors in the system give you accurate data on how much water is recycled and thereby saved. The app has nudges with tips on how to optimise water savings. Furthermore, being able to access this data for end-users can help them moderate their water consumption pattern in order to minimise pulling from external sources.

Green treatment technologies

Green treatment technologies are at a scale so large that we consider them green infrastructure (GI) (Matthews, Lo & Byrne 2015). Although such a scale could entail barriers such as spatial costs, as well as social resistance because it may impede rights of private property owners, major restructural changes in both the built environment and conventional management practises and can impact future property development options (Bulkeley 2013), in this case, GI is comparatively inexpensive, easy and quick to implement, is popular and politically benign (Bowler et al. 2010).

The most popular variants of green treatment technologies are constructed wetlands (CW), green roofs (GR) and green walls (GW), where purification of water relies on physical and biological mechanisms (Casteller et al. 2022). The broad appeal of green technologies is due to its added value in contributing to climate-resilient cities (Emmanuel & Loconsole 2015). This is because it is often compared to the new status-quo of cities: areas compromising of large impermeable surfaces that exacerbate environmental issues such as pluvial flooding and the UHI effect (Field et al. 2012). The extent of its added-value is dependent on scale. It makes sense that the greater the green area, the more area would be insulated year round thanks to it.

The limitations of implementing GI has been extensively covered and divided into biophysical factors and socio-political factors (Byrne & Yang 2009). Biophysical factors include the available area for greening, urban morphology, site contamination, engineering and geological issues, vegetation characteristics, and local climate (Byrne & Yang 2009). Socio-political factors include governance systems, fiscal constraints and potential of public involvement in decision-making (Byrne & Yang 2009).

Concerning the future of more compact urban forms, there are a myriad of sustainability opportunities for tall buildings. Tall buildings in this context are not just limited to single projects, but considers that future building development would take place atop of existing urban forms, creating overall taller structures. It is argued that mixed-used buildings are more suitable for dividing risk and increasing the overall marketability of GI since it would reduce peak service loads (Tamboli et al. 2008).

Compact CW: Klosternga CW

The Klosternga CW is relevant case study of a compact CW made for dense urban areas. GW from the apartment block is pumped into a courtyard's septic tank, as pre-treatment, then pumped into a vertical down-flow aerobic bio filter and subsequently into a SSHF CW (Jenssen & Vråle 2003). The resulting system requires 1 m2 per person, a depth of 1.8 m, and has consistently produced effluent fit for unrestricted non-potable reuse (Jenssen & Vråle 2003). CW are also effective in removing suspended solids, BOD, COD, heavy metals, nutrients, pathogens, PCPs and pharmaceuticals (Wu et al. 2016; Auvinen et al., 2017).

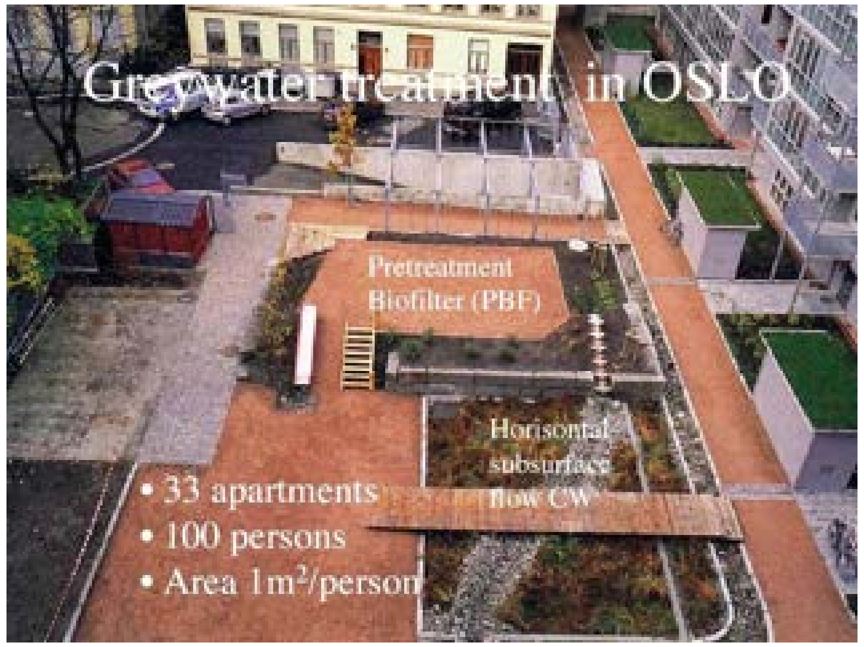


Figure 14: Klosternga CW schematic (Jenssen & Vråle 2003)

Green walls (GW)

Although GW may sound straight-forward, a variety of ways to implement GW exist in the scientific literature. The total value wall (TVW) design is module, where panels fitted with geotextile bags were filled with a mixture of 50% lava, 25% organic soil, and 25% biochar (Lakho et al. 2022). Twelve plant species were added to each panel and the green wall was placed in Ghent, Belgium, with a similar climate to the Netherlands (Lakho et al. 2022). The system's ideal flow should be below 10 L/m2/day to avoid leakages onto the street below (Lakho et al. 2022). Furthermore, the TVW provided insulation year-round, cooling the building during the summer while retaining heat during the winter (Lakho et al. 2021).

Its in-field application involved mixed GW that also passed through a degreaser. There were high removal efficiencies of 90% for TSS, 82% for COD, 95% for BOD5, and 98% for total coliforms (Lakho et al. 2022). The effluent met the standards and was utilised for indoor non-potable use.

Considering the potential extensive sprawl of building walls, the majority of energy use is for pumping. The case study suggests using efficient pumps and then relying on gravity to convey effluent be stored in the green water tank (Lakho et al. 2022). Maintenance is generally low, with no mention about the frequency of maintenance or repair of the green wall (Lakho et al. 2022; Lakho et al. 2021). Furthermore, green walls are also a legitimate form of water retention spaces. In a simulation study, green walls decrease stormwater runoff by 55%, demonstrating its effectiveness (Law & Mah 2018).

Figure 15: TVW utilised in Lakho et al. studies (2021; 2022)

Figure 16: GR utilised in Zapater-Pereyra et al. study (2013)

Green roofs (GR)

GR are actually another term for a variant of constructed wetlands: the shallow CW (SCW). SCW is identical to CW in the system's utilisation of porous media and macrophytes, of which feed water goes through interactions with both elements to achieve purification (Thomaidi et al. 2022). However, the major difference is that SCW utilise light weight substrates instead to remain within the roof's load-limit (Thomaidi et al. 2022). The can be an advantage, considering that lightweight fillers in a green roof effectively store more water than traditional soil culture (Xu et al. 2020). The constructed wetland requires seasonal harvesting of macrophytes inorder to restore removal efficiencies. Maintenance is considerably lower when grass species are planted instead (Zapater-Pereyra et al. 2013).

Due to shallow depth and unsheltered location, SCW is liable to changes in its physical and hydrological conditions. In addition, the bulk of research on shallow CW on roofs is bounded to Asia (Van et al. 2015; Tanh et al. 2014; Bui et al. 2017; Liu et al. 2021). Thereby, productivity of the plants are fairly constant year-round in contrast to the Dutch climate. This could be perceived as a high probability of treatment failure. However, SCW tested in the Netherlands demonstrated that although its hydrology was highly weather dependent, the treatment efficiency remained constant (Zapater-Pereya et al. 2016). Similar findings were reported in a hydroponic green roof system where it treats GW separately during dry season and simultaneously with rainwater during wet season (Xu et al. 2020).

As with other CWs, the treatment capacity depends significantly by the type of plant, bed material, depth, and feeding pattern (Nguyen et al. 2021). Although it is assumes that substrates do most of the purification, plants contribute up to 33% additional pollutant removal (Liu et al. 2021).The multi-functional aspect of a SCW includes limiting stormwater runoff, purifying air pollution, increasing urban biodiversity, noise reduction, as well as providing insulation, reducing the urban heat island effect (Zehnsdorf et al. 2019; Bui et al. 2017; Oberndorfer et al. 2007).

A certain variant of the SCW could be considered the hydroponic green roof system (HGRS). It treats GW separately during dry season and simultaneously with rainwater during wet season (Xu et al. 2020). The hydroponic system is optimised to reduce bulk density, replacing traditional soil culture with a small amount of lightweight filler in a green roof, effectively storing more water (Xu et al. 2020). As a result, the total weight of the roof was around 156 kg/m2 instead of 200 kg/m2 (Xu et al. 2020).

In an experiment by Thomaidi et al. (2022), high removal efficiencies of over 90% for COD, TSS, and turbidity was achieved by a minimum 20 cm of substrate depth on roofs, specifically vermiculite and Atriplex helimus species (Thomaidi et al. 2022). It was found that recirculation improves effluent quality, while total nitrogen removal was more dependent on plants (Thomaidi et al. 2022). A 30 cm diameter pot received approximately 3.2 L of GW daily. The effluent complied with non-potable reuse standards (Thomaidi et al. 2022).

Within Tilburg, the Netherlands, a SCW was constructed as secondary treatment for GW, following septic tank pre-treatment (Zapater-Pereyna 2013). Bed size was 3 x 25.5 m and CW depth of 9 cm of LECA and PLA beads topped with grass, resulting in a HRT of around 3.8 days (Zapater-Pereyra et al. 2016). The total input of GW was 4 L/day/m2 and output for reuse was 2.5 L/day/m2 (Zapater-Pereyra et al. 2016). All major wastewater quality parameters were highly removed, 79-99.8%, and effluent was utilised for non-potable reuse (Zapater-Pereyra et al. 2016).
After a year, no deterioration of the roof was noticed (Zapater-Pereyra et al. 2013). In the summer, the large surface area led to zero-discharge, causing drought, but it naturally restored itself when more water was applied or there was less sun intensity. During the wet season, the system's HRT was highly

reduced but water quality was not negatively affected (Zapater-Pereyra et al. 2016). Ultimately, the area required was calculated through COD content to be around 170 m2 per person equivalent (Zapater-Pereyra et al. 2016). Energy consumption in the system is due to a reliance on pumps for pumping feed water from septic tank and then the effluent was conveyed via gravity due to the slope designed into the SCW (Zapater-Pereyra et al. 2013).

Filter medium	
Drawer 1	Gravels; effective size 4.75 mm
Drawer 2	Silica; effective size 1.18 mm
Drawer 3	Silica; effective size 600micron
Drawer 4	Silica; effective size 75micron
Drawer 5	Silica; effective size 1.18mm and 600micron
Drawer 6	Granular activated carbon
Depth of media	10cm (for each drawer)
Perforation – for each drawer – except the lowest one	Orifice size=4mm Orifice spacing=10cm Number of orifices =15

Figure 17: DCSF pilot (left) and filtering schematic (right) (Assayed, Chenoweth & Pedley 2014; 2015)

Drawer compacted sand filter (DCSF)

Ofcourse, not all green technologies are on the infrastructure scale. Originating from conventional sand filters, a novel sand filter design has been experimented with in Jordan (Assayed, Chenoweth & Pedley 2015), it features modules of 10 cm sand-filled drawers vertically stacked to treat greywater. Its application in lab and onsite has demonstrated its high reliability as a GW treatment method with minimal spatial requirements, demanding around 80 cm width x 80 cm length x 160 cm height at most (6-drawer model) in order to received up to an 142 L/m2/day hydraulic loading rate and organic load of 30g BOD5/m2/day (Assayed, Chenoweth & Pedley 2014).

The design is mean to overcome issues in conventional sand filters such as clogging, bad odours, and high spatial demands. The maintenance is relatively low where users can slide out a drawer to mix up the sand media then leave it to rest for 24-48 hours, not disrupting the whole system while restoring the drawer to its initial efficiency (Assayed, Chenoweth & Pedley 2014). There is very low energy consumption needed to operate the DCSF.

Effluent was utilised for unrestricted non-potable consumption. In the lab experiment, it was found that the highest pollutant removal was achieved with a cascade of at least four drawers of sand. Field studies demonstrate a relatively high removal efficiency range: over 69-98% of TSS and 78-96% of BOD5 and COD (Assayed, Chenoweth & Pedley 2015). The E.coli removal was varied between the users but an additional disinfection unit is recommended.

Floating water treatment

Floating water treatment basically emulates traditional wetlands but are instead supported by artificial buoyant mats (Shahid et al. 2018). They are sometimes termed floating treatment wetlands (FTWs) or hydroponic root mats (HRMs). These floating treatments have been utilised for combined sewer overflow (van de Moortel et al. 2011) and domestic wastewater (Afzal et al. 2019) among other purposes. It is also effective in preventing and improving surface water bodies with eutrophication

Figure 18: Active Island Reactor technology application in urban waterways (Biomatrix Water Solutions 2022)

(Veetil et al. 2021). Removal efficincies depends on macrophyte selection, their hydraulic retention time, and the presence of solar radiation (Rigotti, Pasqualini & Rodrigues 2020).There is a positive relationship between temperature and nutrients removal (Shehzadi et al. 2014). Its performance varies seasonally, where during warmer periods the microbial proliferation and plant growth enhance pollutant degradation and during colder periods, there is a decrease in removal efficiency (Shehzadi et al. 2014). As around half the nutrients accumulated in the plant tissue itself, harvesting is part of the maintenance regime to improve pollutant removal in the long term (Tanner & Headley 2011). To maximise the remediation potential of the wastewater, it is imperative to combine both the use of plants and bacteria (Shahid et al. 2018), and to ensure coverage of around 20% of the water basin to achieve decent water purification (Rigotti, Pasqualini & Rodrigues 2020).

Note: Considerations about high rises and pumping water for green technologies is further discussed in the appendix. In conclusion, energy consumption related to conveyance is not directly correlated to increasing building height, it is possible to minimise the energy consumption but this warrants innovative pump layout design considerations.

Achieving direct potable water quality

Direct potable water reuse (DPR) is referred to as the direct process to purify wastewater into drinkable water without an environmental buffer in between (Tchobanoglous et al. 2015). There is a scarce amount of literature available to convert GW to potable water quality and no guidelines available on direct potable water treatment. Although it is technically feasible, the majority of resistance is due to public perception (Nagel 2015). Nonetheless, the non-potable effluent from above technologies can be processed further to achieve potable water quality. The main issue with converting non-potable to potable water quality is eliminating remaining constituents such as conventional pollutants i.e. total dissolved solids (TDS) and emerging contaminants (Wilf & Aerts 2010).

In California, DPR faces difficulties in legitimising (Binz et al. 2016). Nevertheless, due to the water scarcity of the region, DPR regulations are being developed and they focus particularly on RO membranes to achieve potable water quality (Bernados 2018). Their interest in DPR is due to the fact that it is drought-proof and diversifies their water portfolio to make the state resilient to climate change (Nagel 2015). In general, a number of treatment trains for DPR are already in use. A common one is low-pressure membrane filtration at the MF or UF level, high-pressure RO, then a disinfection step through UV-advanced oxidisation process (Holloway et al. 2016).

Advanced oxidisation process (AOP) is able to transform organic compounds into simpler stable inorganic compounds with little to no sludge production, eliminating the need for additional treatment steps (Kumar & Shah 2021). However, it also requires the use of chemicals, insinuating a dosage-dependent process. Particularly, AOPs utilise H2O2 that is harmful to humans. Furthermore, the costs rake up when considering the amount of costly chemicals and increased energy consumption needed for its operation (Kumar & Shah 2021). So, it is excluded as a viable technology for residential use.

RO has been utilised to produce highly purified reclaimed water compared to other technologies due to its ability to filter out a broader range of contaminants with high reliability (Tang et al. 2018). This broad range includes emerging pollutants such as pharmaceuticals, endocrine disruptors and PCPs (Bernados 2018). However, a particular issue with RO treatment is the management of brine (Bernados 2018). Although the system may flush it out into the sewer system, it would lead to an higher strength of concentrated sewage that would take more treatment intensity. However, research indicates that RO brine can be recycled by constructed wetlands (Scholes et al. 2021), suggesting the creation of circular reuse system for hybrid green-grey treatment trains.

In a cascading filtration experiment, it was found that TDS removal was not significant until effluent was processed by a reverse osmosis (RO) module (Kant & Jaber 2020). Likewise, MF and UF membranes are not effective in TDS removal (Wu 2018). RO also proves an effective barrier against emerging micro and nano-contaminants compared to other conventional treatment technologies (Albergamo et al. 2020; Zhai et al. 2020). RO can be synergistically utilised with other green water technologies. For example, research into one-step RO (OSRO) combined with river bank filtration (RBF) in the Netherlands qualifies as a technically, economically, and environmentally-friendly water purification technology, removing 99.9% of contaminants in RBF-derived feed water and providing drinkable water (Zhai et al. 2020). Although energy costs were comparable to conventional water treatment, its smaller footprint, reduced chemical use due to only membrane cleaning, and labour costs yielded a lower total expropriate cost (Zhai et al. 2020). If RBF is unavailable due to unfavourable hydrogeological situations, artificial bank filtration (ABF) is a viable alternative (Zhai et al. 2020). Furthermore, in a study of a mobile CW, the effluent was upgrade to potable drinking water quality (Lakho et al. 2020). The potable water treatment train was designed to be a modular system with an UF membrane and RO membrane, remineralisation and passed through UV lamps for disinfection (Lakho et al. 2020). The effluent of RO membranes are unable to distinguish between good and bad minerals, so remineralisation is utilised, primarily utilising alkaline water or calcite filters. It is important to remineralise the water, especially for drinking considering that the lack of minerals in RO effluent cannot be compensated by diets (WHO 2014).

Considering that the in-field subsequent potable water treatment that produced potable water quality were modular, incorporating different arrays of membranes, it is safe to say that membrane selection can be optimised for the effluent quality and subsequent potable water quality can be achieved (Lakho et al. 2020; Lakho et al. 2021).

Methodology

OBJ(1) Multi-Criteria Analysis

To evaluate LGW treatment technologies, a multi-criteria analysis (MCA) was chosen because we want to understand the technical feasibility of placing the technology in a dense urban environment and provide a comparative basis to compare grey and green technologies. Such a methodology has been applied successfully in the field of environmental sciences due to its usefulness in making more holistic decisions in a field where trade-offs and uncertainty dominate (Huang, Keisler & Linkov 2011). In addition, since the goal is to compare innovative technologies, its experimental nature means there is not enough data to make a perfectly informed assessment, thereby a decision framework cannot be developed soundly. Instead, the MCA's final product will be a performance matrix in which each row will describe a technology and each column its performance relative to criterion. This shortens the traditional MCA at the point that calls for weighing the options (Dodgson et al. 2009; Keeney, Raiffa & Meyer 1993). Assigning weights for each option is not desirable in this thesis, considering that a stakeholder analysis was not conducted to determine a preference choice.

The resulting performance matrix is visualised as a radar chart. This form of charting data is particularly functional for presenting multivariate data that does not necessarily share the same metric units and scales. The radar chart requires the data to be normalised in order to generate visually compatible ranges. As such, the normalised common scale prevents distortion in the differences between values.

Selection of alternatives

As previously mentioned, there exists a variety of LGW treatment options. To funnel a smaller selection of case-studies, a set of criterion is determined based on scale, treatment type and performance. The selection of case-studies are based on a literature review on Google Scholar and Semantic Scholar to find conventional GW treatment options as well as innovative pilot-scale options, and Google search for on-the-market equivalents. On-the-market options are included in this study. They are particularly interesting due to their ease of acquisition and available customer support which pilot-scale systems lack, considering they are highly specialised and experimental in nature.

Scale

As we are focused on the decentralised scale, the system is most likely going to be privately or collectively-owned and operated. So, relevant case studies must be applied on a micro or meso-scale. The micro-scale is defined as the domestic unit of one household. In the urban content, the domestic unit is likely to be an apartment unit within a larger complex. Nationally, Amsterdam has the smallest housing area of all Dutch cities. Here, 61% of households live in areas less than 72 m2 (CBS 2016). With urban densification in mind, we can imagine other urban centres will reach similar statistics as well. The meso-scale is defined as the scale of a cluster of domestic units, such as an apartment building or row of townhouses.

LGW treatment type

Following the reasoning of application on a decentralised scale, it is imperative that it is safe in nature for laypeople to handle. Thereby, chemical treatment is excluded. Only physical and biological treatment methods are chosen. Exceptions to this are physical and biological treatment that may require occasional chemical cleaning.

Performance

The case-studies must demonstrate that their GW treatment system produces non-potable effluent quality suitable for unrestricted indoor use. Green technology case-studies are usually open systems, exposed to the external environment. It is well known that the performance of nature-based solutions are intertwined with the microclimate. Thereby, case-studies were only chosen if they were applied in similar climate conditions to the Netherlands. This means their geographical location must with within the Netherlands or surrounding countries such as Belgium or Germany.

Bioreactor-based case-studies were chosen based on its innovativeness. A common issue with membrane-based wastewater treatment is its high energy consumption due to fouling control, sludge production and chemical cleaning required. Case-studies based on membrane technologies were chosen if they were able to overcome one or more of these common issues.

Available data

All case-studies must have enough data to be able to calculate treatment capacities.

Selection of criterion for LGW treatment system evaluation

The selection of criterion for LGW treatment systems is largely restricted by available data in the literature. The main points of interest is how much space it takes, energy consumption, maintenance level, and added value of the LGW treatment system. The social aspect of the LGW treatment trains would involve user experience studies which is not available in all the selected case-studies but if available, interesting notes will be added to relevant technologies.

Quantitative criteria

Treatment train space

The treatment capacity of a LGW treatment technology is defined as the volume of space necessary to treat a per capita load of GW. The volume of space comprises the entire treatment train, including holding tanks for raw GW and treated effluent. There are varying opinions about how spatial needs for treatment systems should be calculated. Wastewater teatment processes are conventionally sized on the basis of BOD as it is the biological load that has to be treated (Englande, Krenkel, & Shamas 2015). However, by utilising case studies that are already based on LGW and have achieved sufficient removal efficiencies, it is justified that instead of mass biological loading, person equivalent can be obtained by dividing the daily treatment capacity by hydraulic design flow per person to convert into necessary space. Furthermore, it must be noted that these loading rates are conventionally used for design purposes (von Sperling et al. 2020), and do not reflect the actual performance of the systems, but these loading rates are meant to achieve adequate performance.

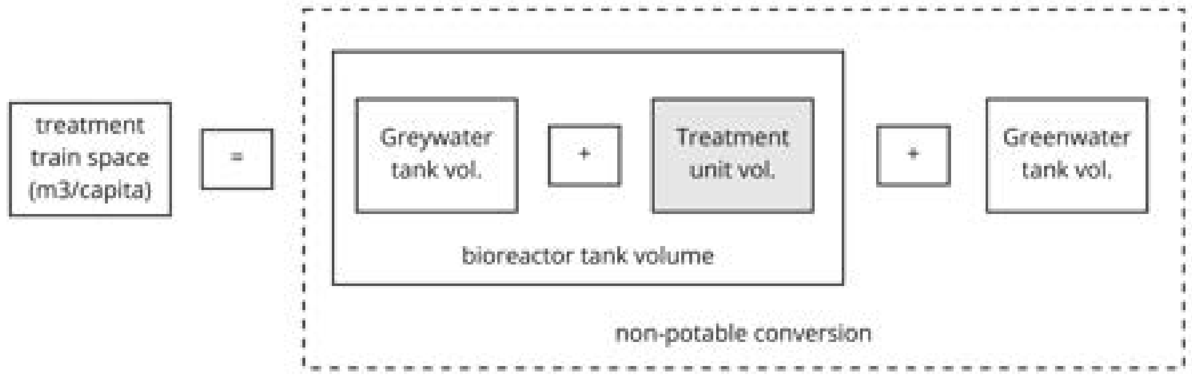
The FFBM and GDMBRs utilised submerged membranes. This operational distinction allows a treatment train set up with forgoes the need for a raw GW holding tank, as instead it is combined with the bioreactor tank. As such, volume footprint calculations are based on the needed maximum capacity, which is the per capita load and the needed bottom water level in the bioreactor inorder to provide minimum HRT of 6 hours and enough balancing volume for the influent peaks.

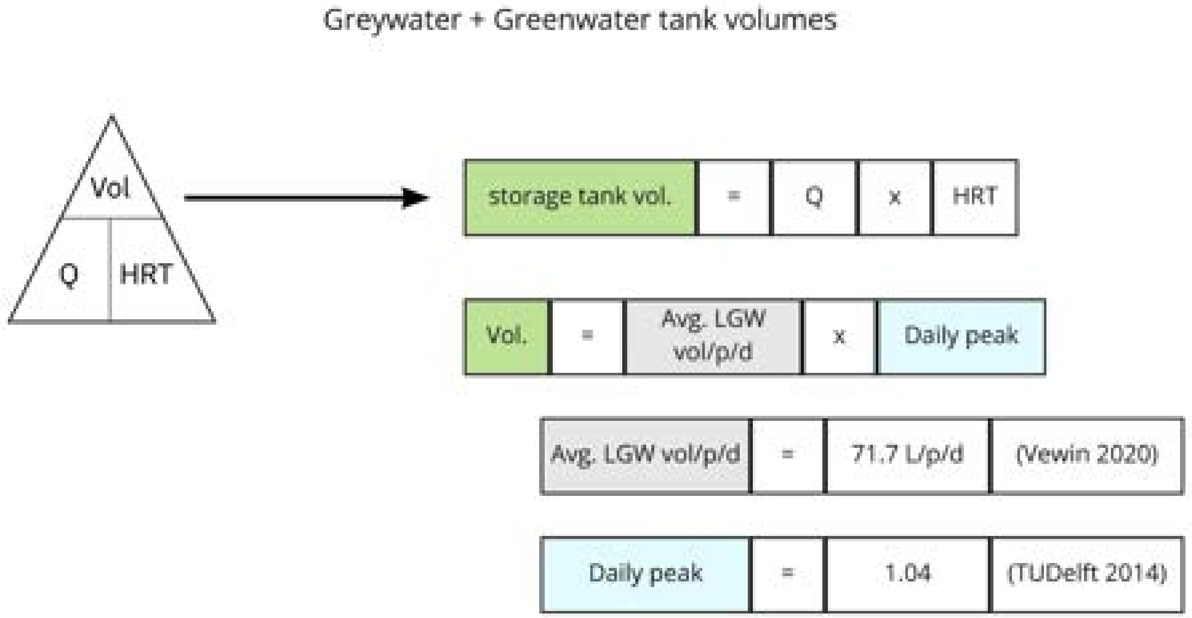
The Hydraloop and Aqualoop were also evaluated as on-the-market options, considering that residents are unlikely to build their own systems. This methodology insinuates that the on-the-market options' spatial needs are a continuous variable, which is not true considering they are upsized according to number of membranes, which effectively would scale the treatment capacity by a certain factor. However, it provides a representative basis for comparison to other cases.

Since treatment capacity will depend on design load, the chosen design load is as recommended by water storage literature review: sufficient for accumulating one day's worth of LGW and average daily peak factor. Further technical optimisation or increasing occupany greater than three residents can and will reduce water storage needs, thereby overall space necessary for decentralised WRS. This optimisation warrants its own research and is best applied on a contextualised bases, aka, to a case study, which is beyond the scope of this study. Specifc calculations on how each technology was scaled can be found in the appendix.

Energy consumption

The energy consumption of LGW treatment options is defined as the amount of energy to process 1 m3





of LGW. These values are derived from case-studies themselves or if unavailable, extrapolated from other case-studies that have comparable LGW treatment technology. In the case of the DCSF and Compact CS, comparable cases were unable to be found. The energy consumption is generalised descriptively as involving a pump for conveyance but values are not available, and intentionally left blank.

Financial cost

Financial cost is a major factor in decision-making, however, it was not considered in this exploratory research. LGW reuse is already assumed to be repulsive to the majority of the public. Thereby, the financial cost of application is less imperative compared to understanding how GW reuse can fit within the conventional water system and other novel ideals of urban water management. The cost of a major restructural change towards manifesting sustainable resilience spaces already dons a massive price tag of USD 90 trillion by 2030 (Global Commission on Economy and Climate, 2016).

Furthermore, the case-studies considered do not all have enough financial data to make comparisons. Since, the case-studies were chosen to compare innovative greywater treatment options in the academic literature, which are pilot-scale, its tangible construction for laypeople may not even be possible. Finally, Dutch tap water is already considered cheap (need to ask water profs for some reference). Thereby, the financial cost of producing a certain volume of treated water is assumed to be the same, if not more expensive.

Maintenance level
The maintenance level of each LGW treatment option is based on multiple factors: the frequency of system cleaning, replacing components, ease of repair, and whether chemical cleaning is necessary or not. Although maintenance level can be rated by frequency, it does not necessarily demonstrate other qualitative aspects such as the availability of customer support afforded by on-the-market options. Thereby maintenance level is difficult to quantify. However, not impossible.

The general goal for scoring maintenance is the higher the sum value, the more the maintenance. The replacement rate and cleaning rate are converted into a frequency, which is (1/years). If there are multiple components to replace, the frequencies are summed. The cleaning rate is sometimes given in a range. If so, then the average of that range is calculated.

The tricky part is weighing the boolean values for the remaining two indicators: chemical cleaning or availability of customer support. If chemical cleaning is necessary, it is counted as 1. If not, as 0. The availability of customer support is 1 for none, 0.5 for maybe, and 0 for yes. It is not a continuous measure which complicates matters on its weight if we sum all these values to derive a "sum of maintenance."

These values can be further weighted but this involves a subjective understanding of what activities take more or less energy, effort, and time for an individual. Instead, the closest to an objective quantity is desired. So all categories were weighed the same (25% each).

If the value is not available, i.e. the compact CW does not have a known cleaning rate, then it is simply nullified into the weighted sum as a 0 value.

Qualitative criteria

Added value

In the dense urban setting, space is a valuable commodity and creates surface and subsurface competition (Hooimeijer, LaFleur & Trinh 2017). Thereby, treatment technologies also merit through co-creating other benefits, such as doubling as a recreational space or urban GI that can create more climate-resilient cities in general. This added criteria is largely meant to distinguish the added value of green technologies for comparison to grey technologies.

OBJ(2) Water saving efficiency

Essentially, there are two possible LGW reuse scenarios. First is to convert to non-potable effluent quality and the second is to convert LGW further into potable effluent quality. Considering that LGW reuse mainly constitutes source-separation that requires extensive infrastructural modifications, these two scenarios are compared to two other scenarios that conserve residential water without requiring source-separation: recirculating showers and water-efficient micro-components.

Using the principle of mass balance, we can derive the water saving efficiency of each scenario, where it is defined as the percentage of tap water saved by reusing GW.

Considering that the design flows utilised to find treatment capacity are calculated in order to cope with varying peak LGW influent amounts, with the assumption of 100% recycling efficiency, we can assume that 100% of non-potable would be achieved. The 100% recycling efficiency is based on the fact that most case-studies involved a closed system for LGW recycling. Open systems such as most cases of green technologies, rely more on the physical filtration of their media instead of planted vegetation. Being exposed to rain means it indirectly collects rain for processing. Rain is considered a cleaner source of water and dilution for the LGW in the system, since the case studies do not report an effect on the removal efficiency of the system, producing acceptable effluent quality year-round (Lakho et al. 2021; Zapater-Pereyra et al. 2016).

The excess non-potable effluent is calculated as the LGW influent subtracted by non-potable demand. This is then multiplied by the RO unit's recycling efficiency to determine how much water can be augmented from potable kitchen demand, since the RO unit is placed as an under sink model (Figure 19).

The exact process to achieve objective 2 is summarised in the flowchart.

Figure 19: iSpring RO500-BN Tankless RO Filtration System 2:1 Pure to Drain ratio (iSpring 2022)

Methodologies

OBJ[2]

FLOW CHART
SIMPLE CALCULATIONS

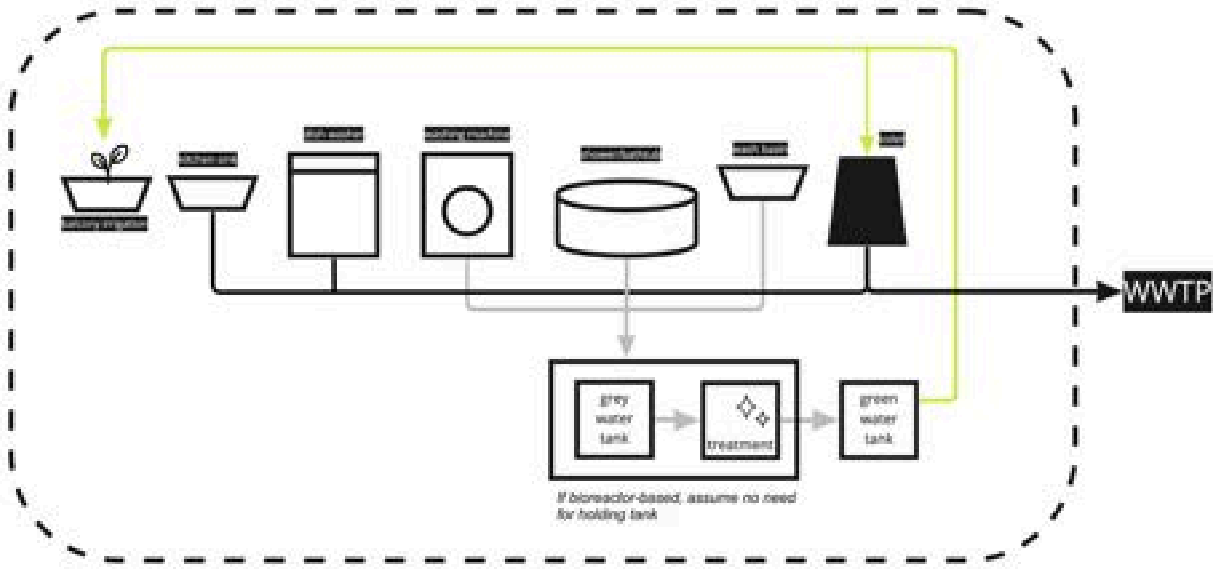
[1] SELECTION OF ALTERNATIVES 4 COMPARISON

- No need for source-separation
  - recirculating shower
  - water-efficient micro-components

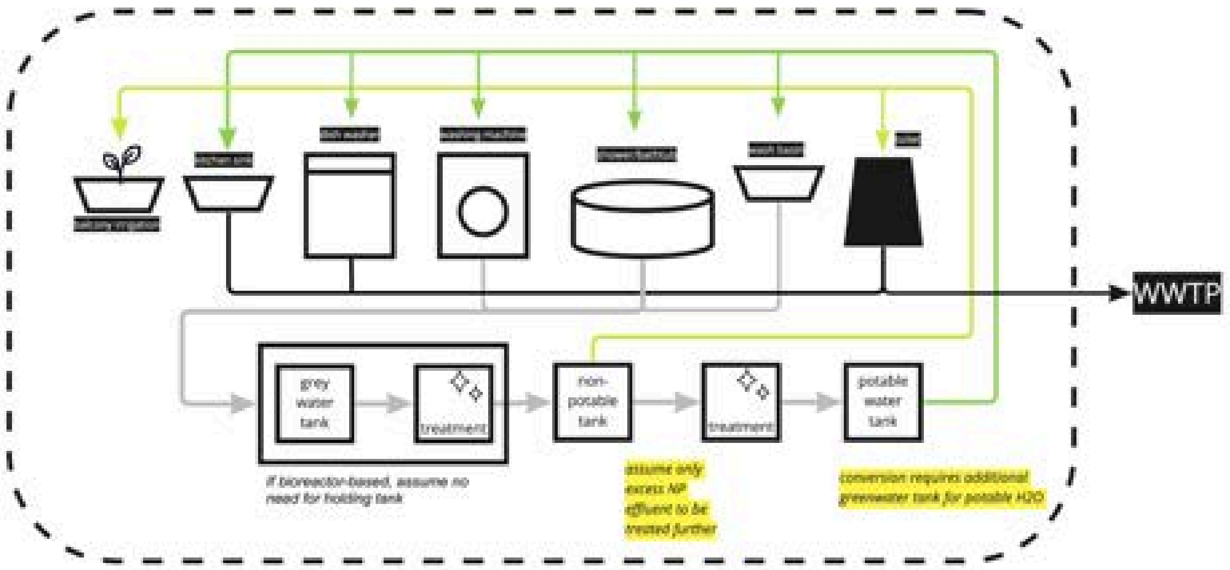
[2] CONCEPTUALISING POTABLE CONVERSION

- assume only excess NP effluent to be treated further
  - excess NP = Q - NP demand
- NP quality is not P quality b/c of remaining TDS and emergent pollutants (Wilf & Aerts 2010)
- RO is an appropriate method to remove above (Leal 2010)
- Chose two on-the-market options as RO unit proxies
  - Express 11-stage Filtration Unit // 1: 3 (water: brine)
  - iSpring RO500AK-BN Tankless RO Unit // 2:1

LGW to non-potable



LGW to potable



[3] DESIGN FLOWS

Design flows									
Q1	=	Q	x	Daily peak					
Represents avg. influx on a maximum day									
Q2	=	Q	x	(	Daily peak	x	Summer peak	)	
Represents avg. influx on a maximum day during the summer									
Q3	=	Q	x	(	Daily peak	x	Summer peak, climate change	)	
Represents avg. influx on a maximum day during climate-change enhanced summer									

Composite peak factors		
Daily peak (TUDelft 2014)		1.04
Summer peak (TUDelft 2014)		1.08
Summer peak, climate change (Vonk, Cirkel & Blokker 2019)		1.28
Q	=	avg. LGW / person

[4] WSE EQUATION

- Based on mass-balance principle
- Assume 100% recycling efficiency

Water saving efficiency		
100	x	Amt. of LGW reused / Residential water demand

OBJ(3) Green Technologies Application

The goal of this objective is to apply the green technologies within the Dutch urbanscape. As previously discussed, Dutch cities are expected to become more compact. The chosen sample areas were manually chosen to represent a range of compaction. As density measures are dependent on the

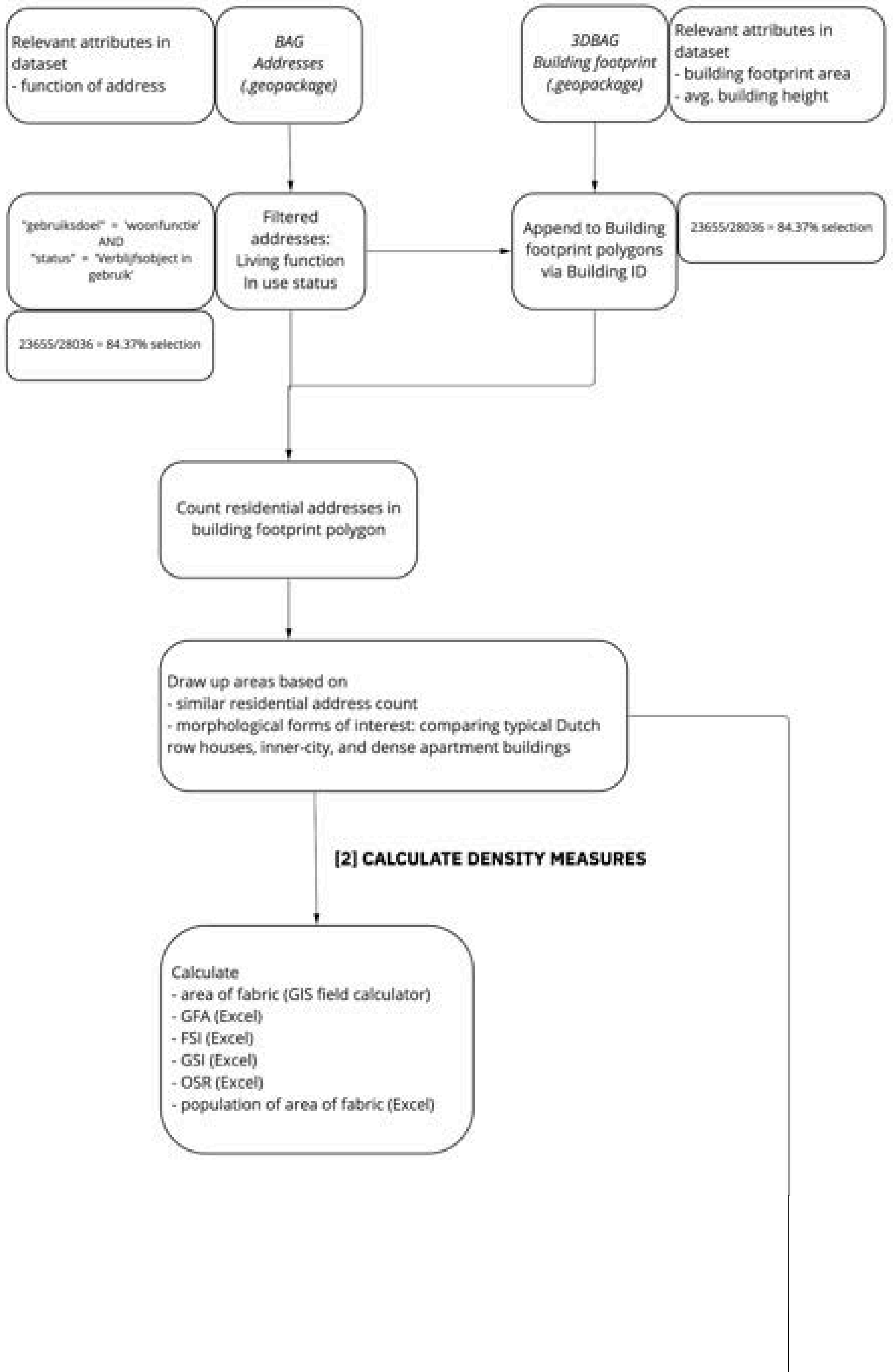
Methodologies

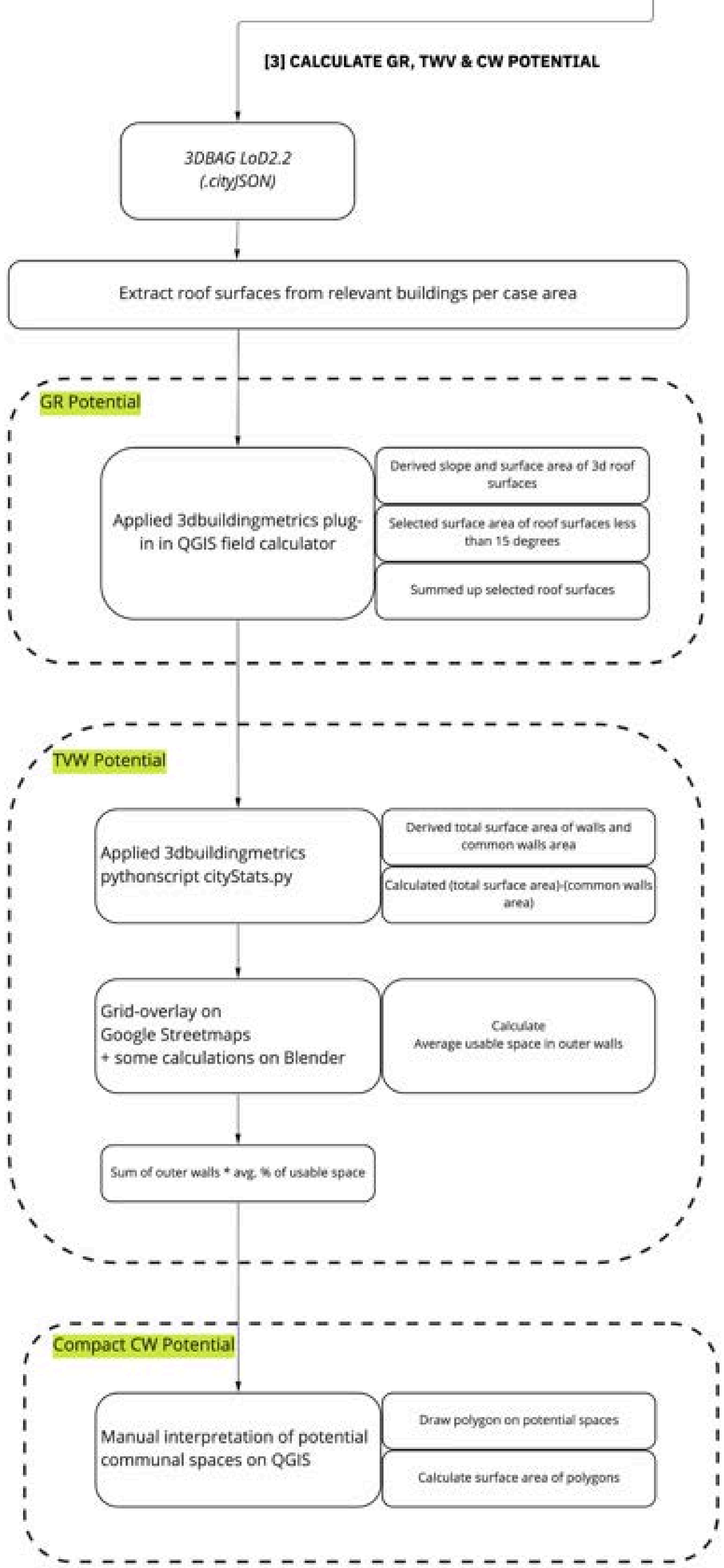
OBJ[3]

FLOW CHART
GIS//3DBUILDINGMETRICS SCRIPT

[1] CHOOSE THREE STUDY AREAS

- Based on similar residential address count
- Within Zeist because it is within Viten's area

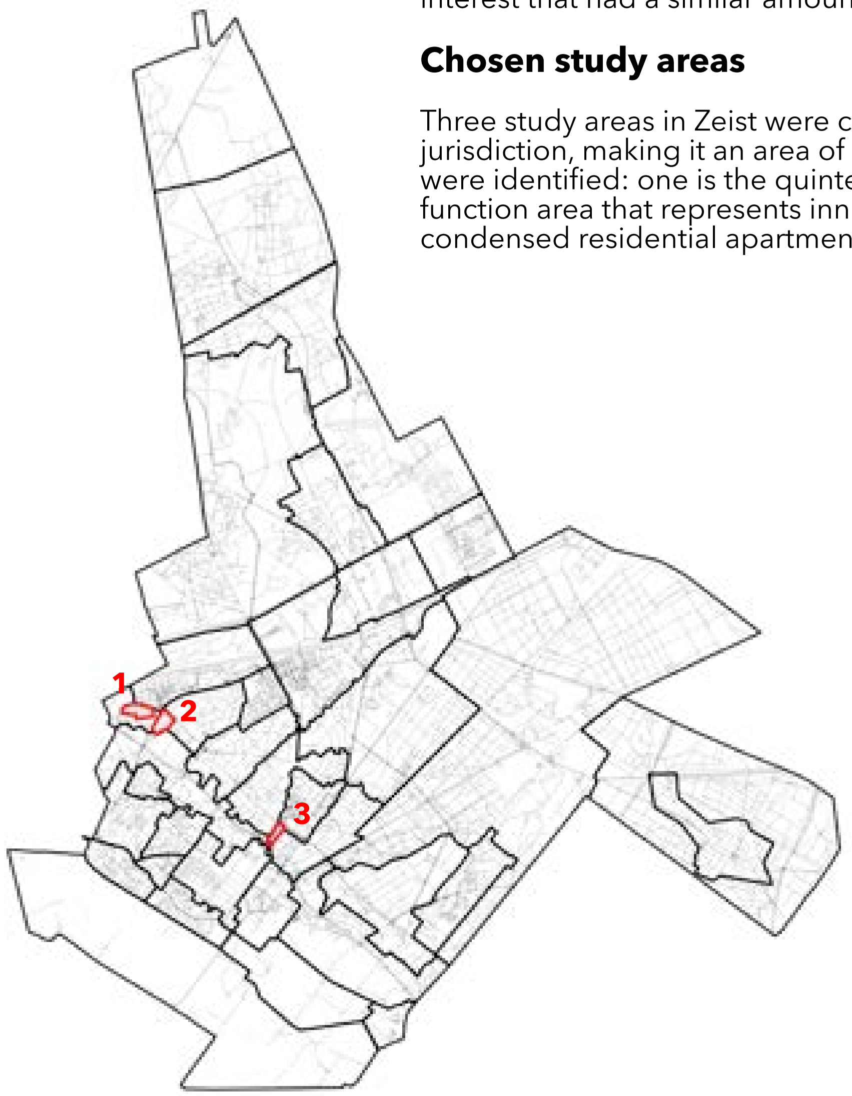




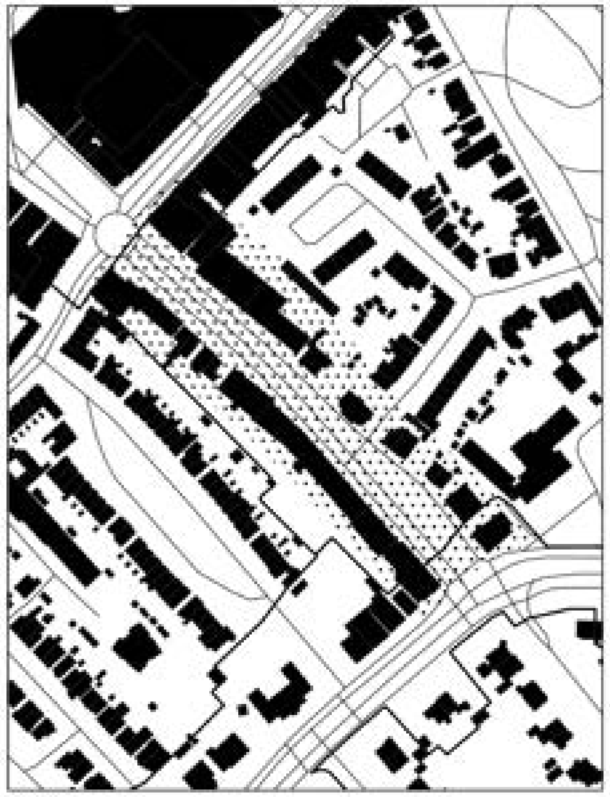
discretion of how the fabric is drawn up, in order to have a baseline to compare the study areas, it was decided to draw up a fabric with morphological forms of interest that had a similar amount of addresses per sample (+- 20 addresses).

Chosen study areas

Three study areas in Zeist were chosen. Zeist is an area within Viten's jurisdiction, making it an area of interest. Three types of urban morphologies were identified: one is the quintessential Dutch row house, another a mixed function area that represents inner city living and finally a third that represents a condensed residential apartment building situated in an open area nearer to the suburbs of the city. These samples areas are labelled as row, in-between, and dense respectively. These samples areas are then objectively compared by their density measures.

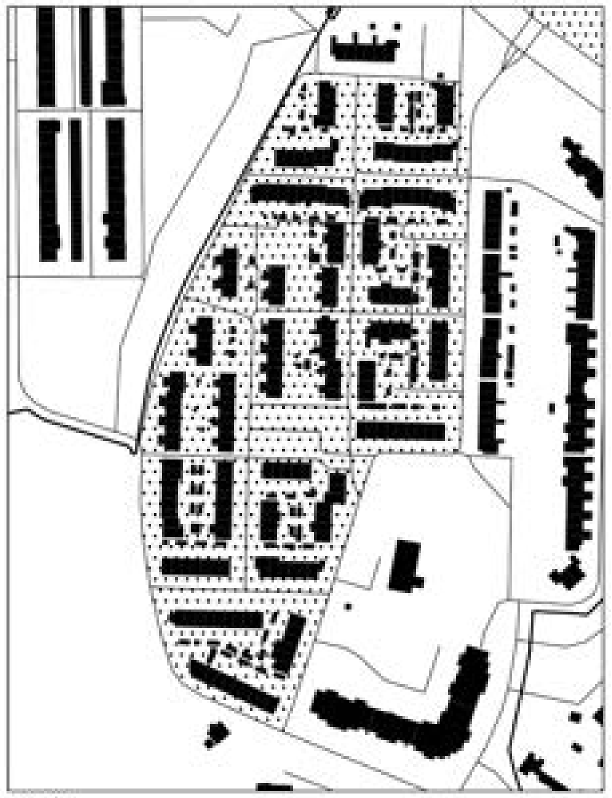


3 in-between



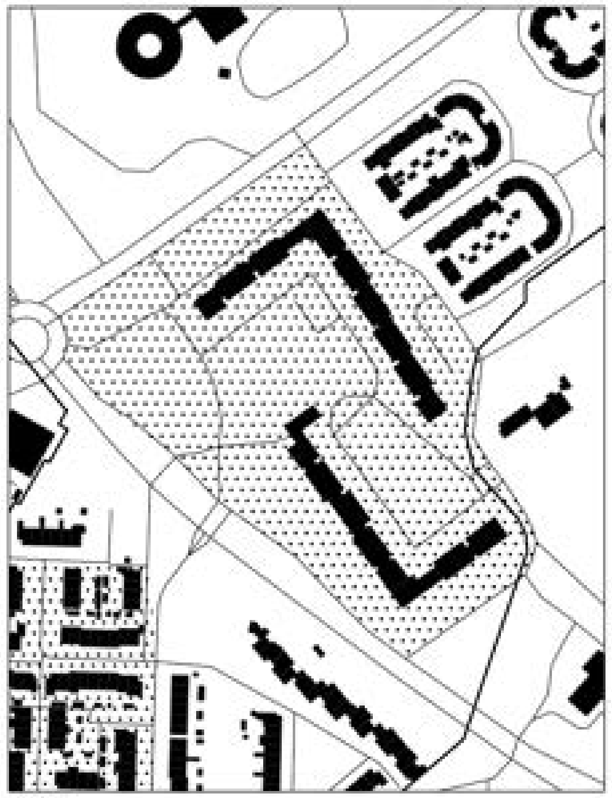
1:2500

1 row



1:2500

2 dense



1:2500

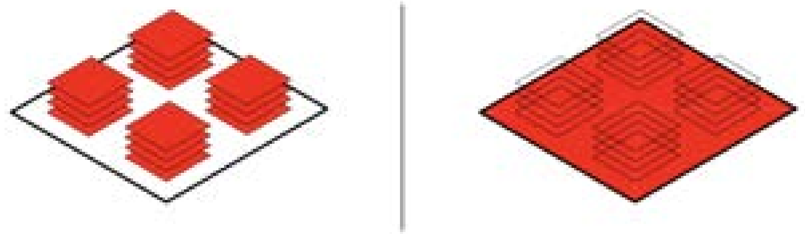
Density measures calculations

The building intensity (FSI), coverage (GSI), and spaciousness (OSR) of the study areas were calculated.

$$FSI_x = F_x / A_x \quad (2)$$ where

F_x = gross floor area (m²)
A_x = area of aggregation x (m²)
x = aggregation (lot (l), island (i), fabric (f), or district (d))

This index uses the unit square metres per square metres (m²/m²).



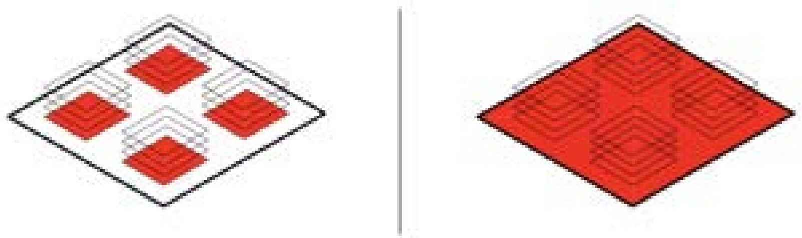
Gross Floor Area (m2)

GFA = (avg. height of building * building footprint)/ 3m [avg. floor height] (Pont et al. 2017)
So instead, with CityJSON data
GFA = (dak_70_height * building footprint)/3m

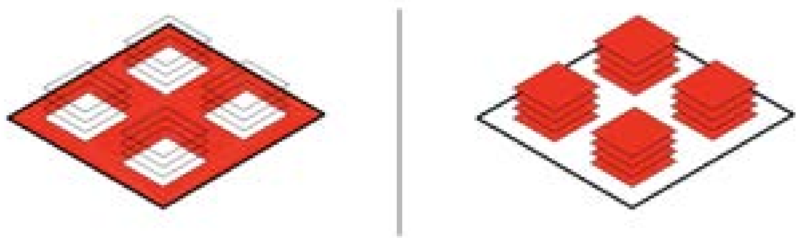
$$GSI_x = B_x / A_x \quad (3)$$ where

B_x = footprint of (m²)
A_x = area of aggregation x (m²)
x = aggregation (lot (l), island (i), fabric (f), or district (d))

This index uses the unit square metres per square metres (m²/m²).



$$OSR = (1 - GSI_x) / FSI_x \quad (5)$$



The exact calculations are visualised by the following illustrations, extracted from Berghauser-Pont & Per Haupt's book, *Space, Density, and Urban Form* (2010).

Data

BAG addresses
3DBag LoD 0
3DBag CityJSON model, LoD2.2

BAG Database

The BAG is an abbreviation of "Basisregistraties Andressen en Gebouwen", which is the Addresses and Buildings Key Registry, an automated system that stores information on local addresses and buildings (Government.nl 2022). Within this dataset, every building nationwise has an unique id and attached to the unique id are addresses and their functions i.e. residential, business etc.

3D Data

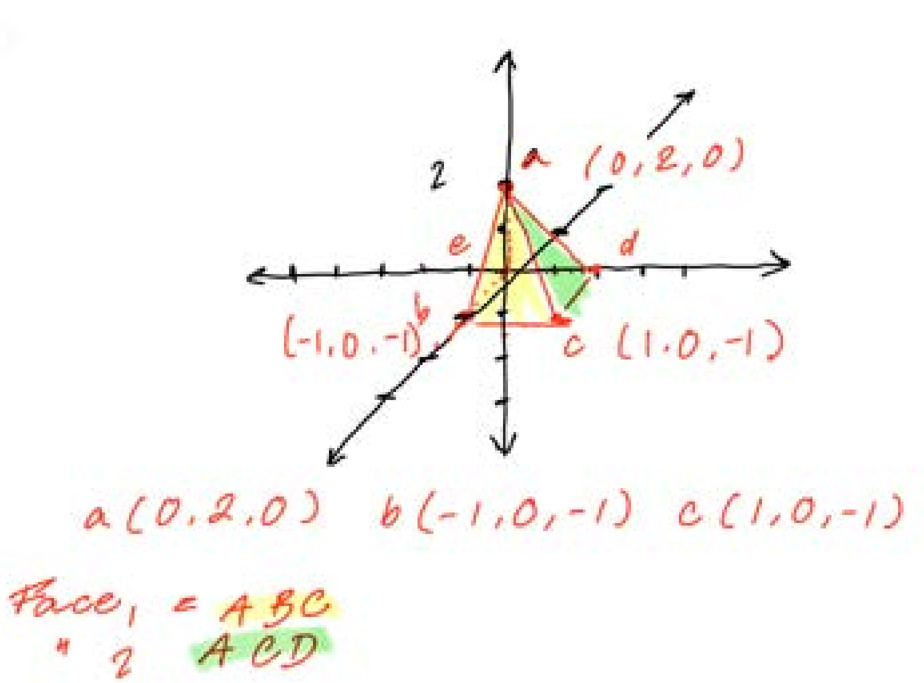


Figure 20: 3D data structure on Cartesian coordinates

Compared to 2D data that utilises points and lines to create polygons, 3D data must be represented with an additional dimension. This is achieved through using a coordinate system with the z-axis. Just as we utilise Cartesian coordinates to represent a unique point in space with x and y values relative to the origin, 3D coordinates do the same. These points in space are called vertices but these do not represent the faces of the polygon. The faces of the polygon could likewise be defined by coordinate points but then a duplication burden ensues between vertices and faces associated with the same coordinates. Thereby, a separate data structure was developed to represent the faces of the vertices, that is the vertices are defined both by using numerical 3D coordinates, and for each set of x,y,z coordinates is defined as an unique vertex value, as illustrated in Figure 20.

Essentially, 3D data of the Netherlands is currently available as a CityJSON model, under 3D Bag data set (3DBag 2022). The CityJSON object represents one 3D city model of a given area. Within this digital twin includes various levels of detail (LoD), which is the defining class representing the extent of detail capture in the 3D model. A CityJSON object is defined by coordinates of its geometries' vertices. These vertices are represented in the data as an array of coordinates of each vertex of the city model as explained above. Although stored as an integer, it is subsequently transformed in the 3D space with a scaling factor that represents its actual dimensions. In order to achieve this objective, the 3D model requires details of roof and wall surfaces for our area of interest, which is represented by LoD 2.2 that recognises realistic features, as visualised in Figure 21.

Calculating green technologies potential

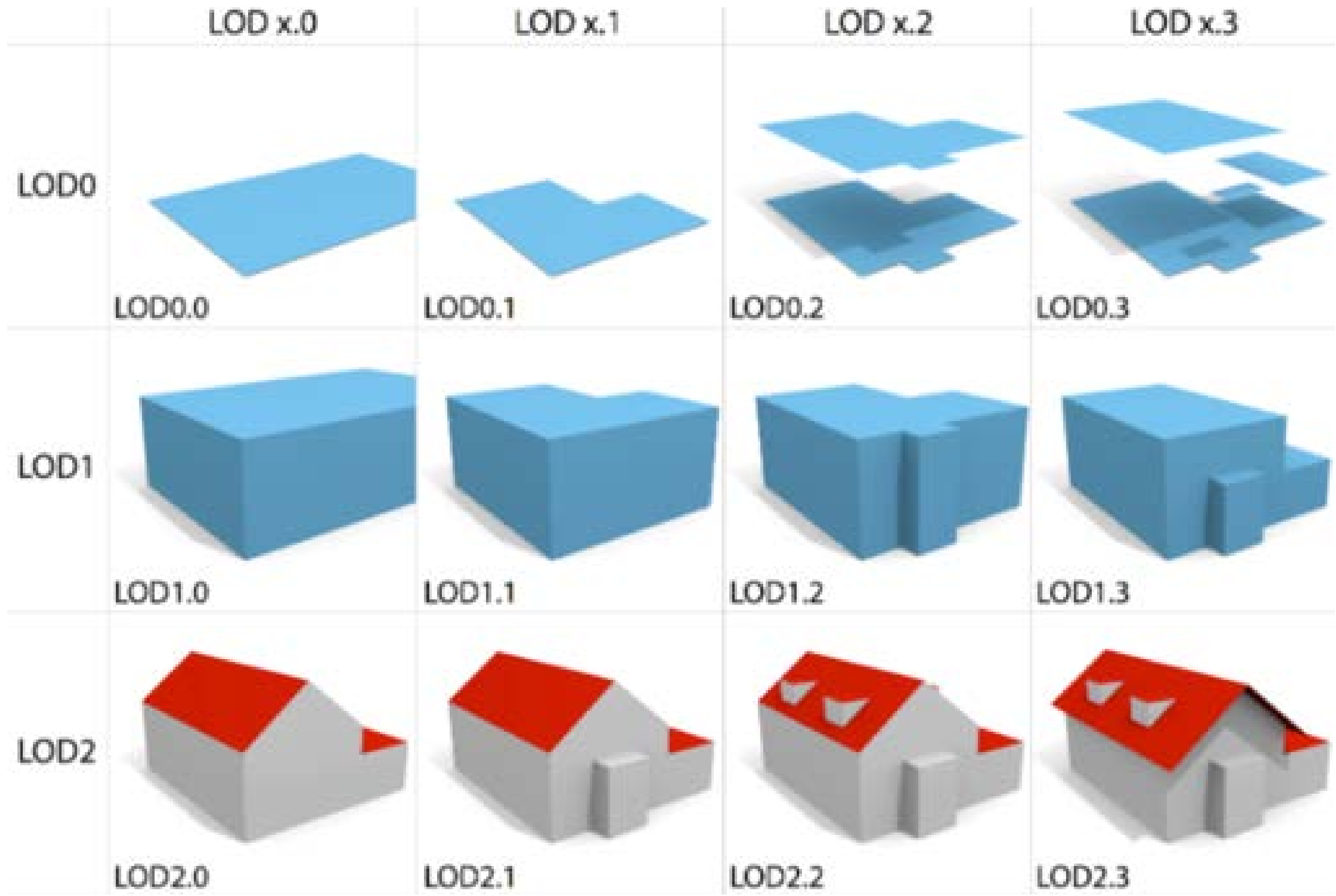


Figure 21: Level of Detail (LoD) specification for 3D building models. Extracted from Biljecki, Ledoux & Stoter (2016)

The GR potential was calculated by extracting the roof surface polygons within the study area from the CityJSON model in QGIS. By applying the 3D Building Metrics plug-in, personally provided by Vitalis (2022) in the QGIS field calculator, each roof polygon's slope and surface area was derived. The 3D Building Metrics tool was developed to compute shape metrics from 3D geometries for buildings (Vitalis, Labetski & Peters 2022). According to the GR case study, the maximum slope that is suitable for its design is 15 degrees. Therefore, only roofs that are angled less than 15 degrees are filtered and this selection's 3D surface area was calculated.

The GW/TVW potential was calculated through applying the 3D Building Metrics cityStats script. The relevant case study is an academic study of an actual product by the Belgium company Muurtuin (Muurtuin 2022). Technical details about the TVW was described as a facade-grid system that can be overlaid on existing surfaces. The vegetation choice is made according to its microclimate. For example if the space is shady, vegetation preferring shady spaces are chosen. So, it is assumed that all outer wall space can be converted into a TVW except for windows. Outer wall space can be calculated through the cityStats script as the difference between two derived values: the total surface area of walls and common walls area. However, with we cannot assume that all outer wall space is viable for TVW considering that we have functional features on outer wall spaces too, i.e. windows and doors.

This level of detail is not yet available in the CityJSON model, so unusable space such as windows and doors are accounted for by random sampling of segments of walls in each sample area between the CityJSON LoD2.2 model surfaces and Google Earth Streetview. Since a direct measurement of windows was not possible, a grid was overlaid on the Google Earth Streetview images in order to determine an average ratio of the window to wall space. This process is best visualised in Figure 22.

The compact CW potential depends on the amount of available space within a sample area. It is interpreted as a communal space that is not simply suitable for compact CW but also as a larger-scale storage buffer. This can be calculated as the unbuilt space of the sample area (total area - building footprints). However, this does not reflect the impermeability of the surface. For example, it would not be able to discriminate between roads or sidewalks which would be inconvenient to repurpose. In that case, potential communal space is manually calculated on QGIS by drawing polygons over subjectively-interpreted potential areas and then its area is calculated and divided by the surface area necessary.

Sacrifices that would need to be made to repurpose the space will be noted in the Results section.

Determining usable wall space

Dense sample

From classifying one wing, the general form of the building are balconies on both sides and vacant wall space being side walls. We can assume two scenarios. One is a reasonable scenario that only "common" walls/space are represented. These are the walls that would cause little concern as impeding an individual's choice/private space. These vacant sidewall spaces are assumed to be common since there is minimal access to reach these sidewalls for use or they surround common hallways.

The other scenario is a maximising scenario because it involves each dwelling unit's balcony. It assumes that a GW can be placed on the other side of the balcony railing, as it is a grid system that overlaps walls. It would not obstruct the view unless it is unkept, so we can imagine some maintenance of trimming. However, in the case of this thesis, the first scenario is utilised.

Since the sample comprises of two buildings that are almost symmetrical, we assume the distribution of side wall and balcony space to be similar. Thereby, on Blender we compare the CityJSON semantic wall surface geometries of one wing to its Google Earth street view and classify the wall as obstructed, meaning unable to be built on due to balconies, and vacant, meaning it is unobstructed. These walls are then grouped and classified together to create a distribution of usable and non-usable wall space by

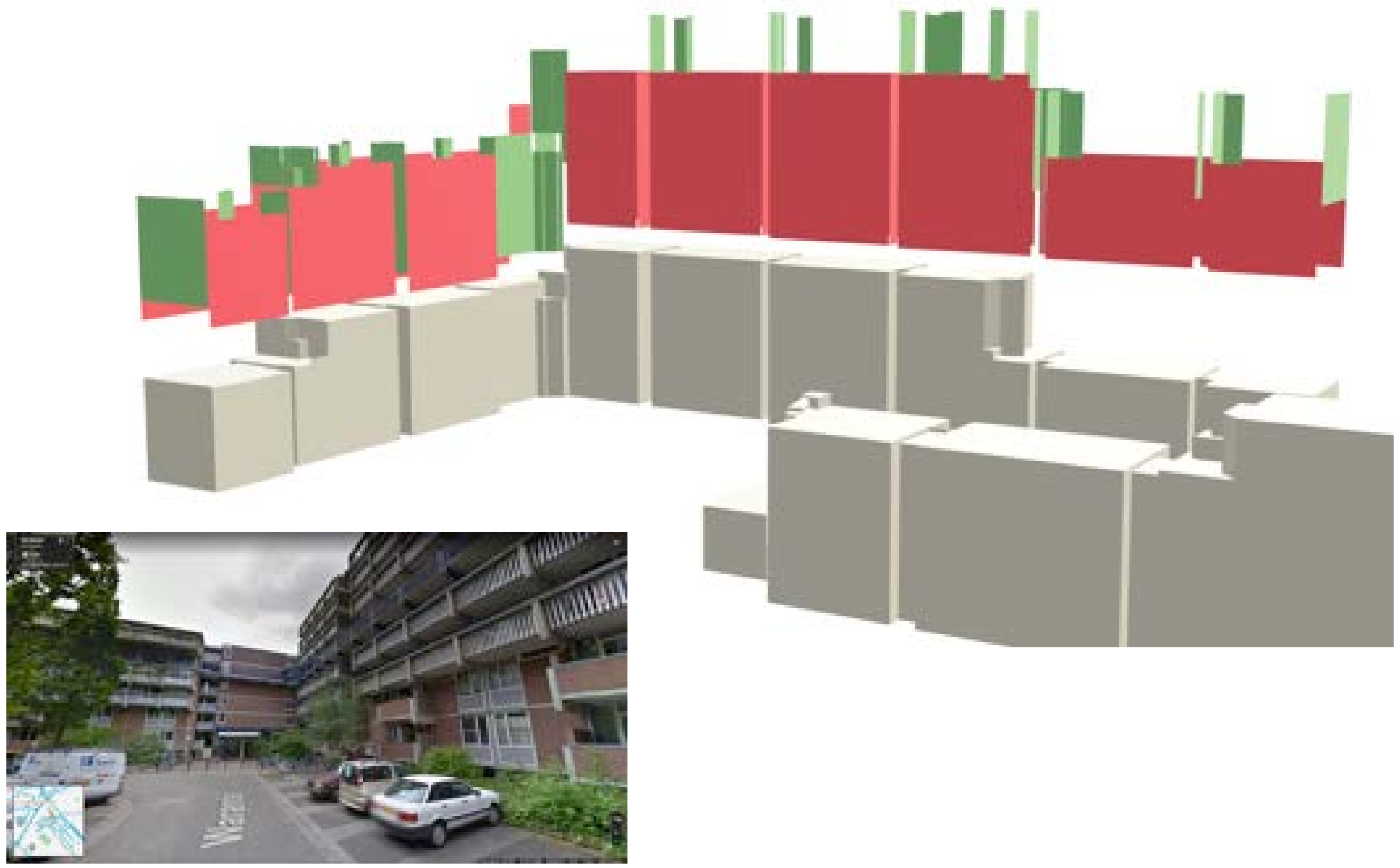


Figure 22: Dense sample surface classification on Blender through cross-comparison on Google Street Maps

measuring the surface area on Blender (Blender has an inbuilt measure tool). The CityJSON models are also to scale since the geometries are already set in the right CRS.

Row Sample

When comparing the CityJSON semantic wall surfaces' LoD 2.2 to Google Earth street view, it is evident that the row archetype is a repetition of one unit's form. Thereby, the row archetype can be defined by one unit. In this sample area, one unit consisted of two faces with varying roof steepness. One side where the roof ends at the second floor and another when it ends at the first floor.

Considering that the outer wall space represented in CityJSON is a surface model that hold raster data, we can created a distribution of useable versus unusable space by overlaying the row unit with a grid, effectively pixelating it. Two facades were pixelated: one with a lower or higher roof. The windows and door spaces were also included. As a result, it was found that for the low hanging roof facade, around 20.4% is usable, while for the higher roof facade, around 46.3% is usable.

We calculate the ends of each block that represents a large amount of vacant space by counting the number of blocks and assuming each block will have two ends. Altogether there are 34 blocks and thereby, 70 end faces. The end of one side is measured on Blender to yield 64.8 m2, so the total would be (64.8 m2/end face * 70 end faces) 4536 m2.

The sum of outer wall surfaces is first subtracted by the sum of end faces. The result is then divide by two, yielding x. We then find 20.4% of x and 46.3% of x, add them up, then add the sum of end faces

Figure 23: Row wall samples cross comparison on Blender and Google Street Maps

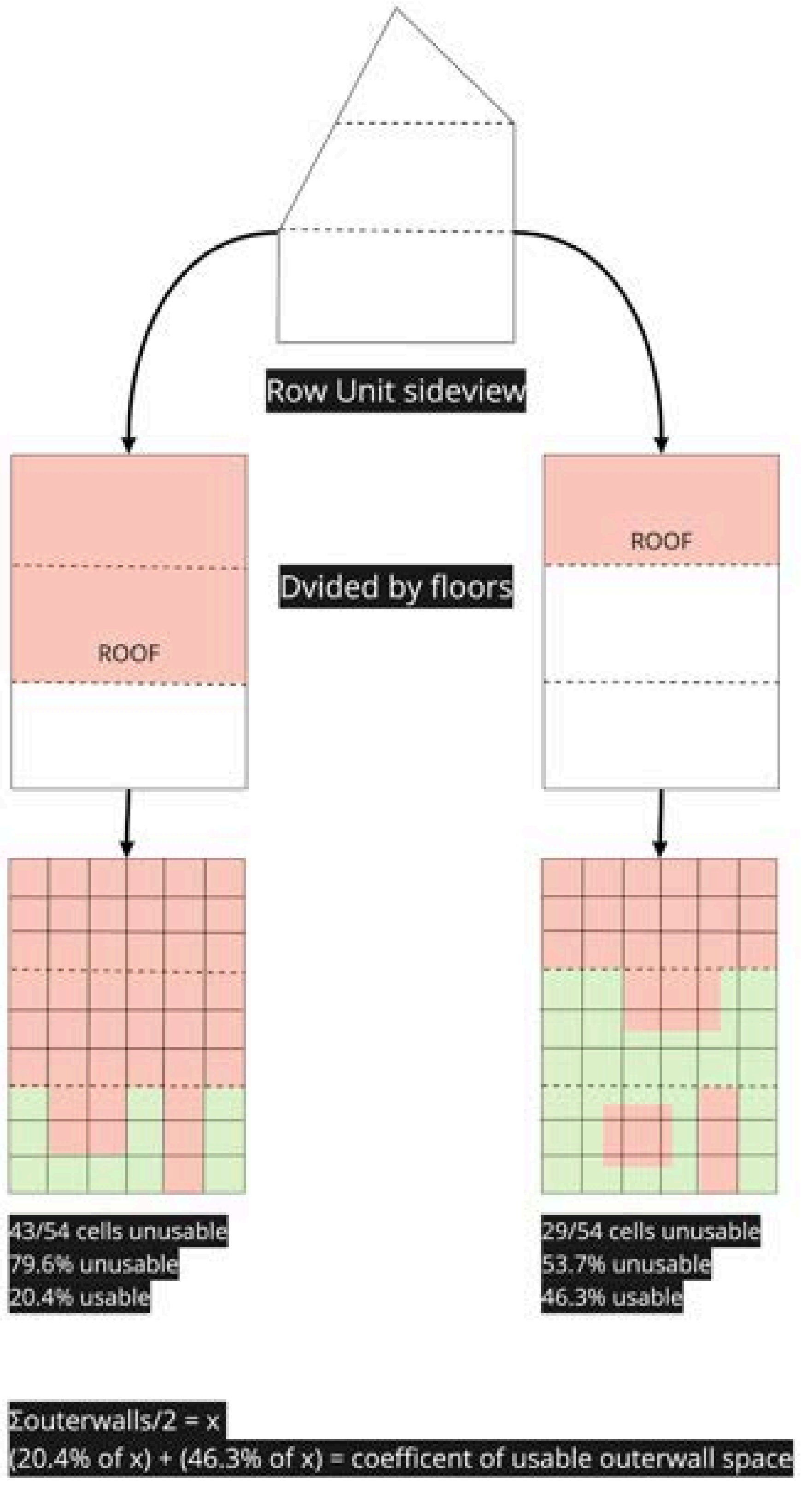


Figure 24: Grid mapping of row unit

once more.

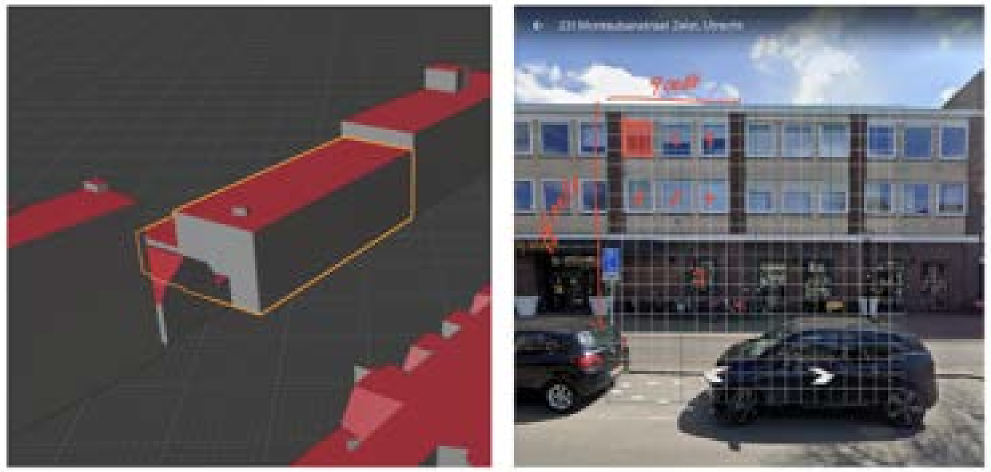
In-between Sample

Following the same investigative procedure, it is evident that the in-between sample features a distinct mix of around twelve different building designs, having all various window-wall ratios, as seen in Figure 25. This makes sense as this is the only sample area that hosts buildings with functions other than residential. The extent of variation already indicates there may be too many stakeholders to organise

Figure 25: In-Between wall samples extracted from Google Street Maps

collective effort. Perhaps with mixed-function buildings there would be stricter regulations on what can be hosted on the façade.

By selecting and grid mapping the three largest building footprints in the sample area, the average usable wall coefficient was averaged. Since it was difficult to access views of the backside of these buildings, it is assumed that the same ratio can be applied, considering that snippets of the backside in all three buildings had balconies and windows as well.



Windows = (2*2)7 = 28 cells
Σ Unit = 9 * 14 = 126 cells
Σ Unusable = 28 cells
Σ Usable = 98 cells

Figure 26: Example of grid overlap on one buidling in In-Between sample area

Results

OBJ (1) MCA of GW Treatment Technologies

Technologies	Treatment train space (m3/person)	Surface area (m2/person)	Energy consumption (kWh/m3)	Maintenance Level	Added Value	Notes
Aqualoop (MBBR)	0.12	-	1.3 (Jabornig & Favero 2013)	63%	-	-
SMBR + UV (Fountoulakis et al. 2016)	0.13	-	4.2	100%	-	Even more energy intensive than RO desalinisation (2 kWh/m3)
Hydraloop300	0.16	-	1.6	0%	-	Designed to be self-cleaning and thereby very user-friendly and low maintenance. Cannot use cleaning products with bleach in shower
TVW (Lakho et al. 2021 & 2022)	0.22*	7.39*	1.79	7%	Provides insulation that reduces energy necessary for heating and cooling Capable of capturing PM10 and CO2 from air. Impact dependent on scale of TVW	Leaching can lead to yellowish effluent
FFBM (Jabornig & Podmirseg 2014)			1.4	41%	-	Very low amount of sludge production
GDMBR with aeration (Ding et al. 2017)	0.35	-	0.04	27%	-	Requires lower membrane area than variant without aeration since flux is doubled; infinite sludge rentention time
GDMBR without aeration (Ding et al. 2017)			0.019	33%	-	No need for aeration which saves significant energy costs. Requires higher membrane area to cope with influx, considering that without aeration flux is halved; infinite sludge rentention time
DCSF (Assayed, Chenoweth & Pedley 2014 & 2015)	0.70	-	N/A	92%	-	Designed to be technically user-friendly; intuitive and simple for repairs and maintenance
Compact CW (Jenssen & Vråle 2004)	1.87	1	N/A	7%	Part of treatment system used as playground: space can be multipurpose and add social value	Compact design is achieved through 1.8 m depth of horizontal flow CW
GR (Zapater-Pereyra et al. 2013 & 2016)	4.31*	46.22*	N/A	14%	Provides insulation that reduces energy necessary for heating and cooling Capable of capturing PM10 and CO2 from air. Impact dependent on scale of GR	Does not operature during the winter when bed temperatures were below 2 degrees C Rainy days decreased HRT but water quality not negatively affected Summer water deficit threatens macrophytes. Supplemental irrigation necessary. Cope via surplus overflow or higher hydraulic loading rate or lower roof slope degree

* Due to utilisation of otherwise unexploited space, can be considered 0 m2/person in additon to necessary storage volume

Table 4: Performance matrix of GW treatment technologies

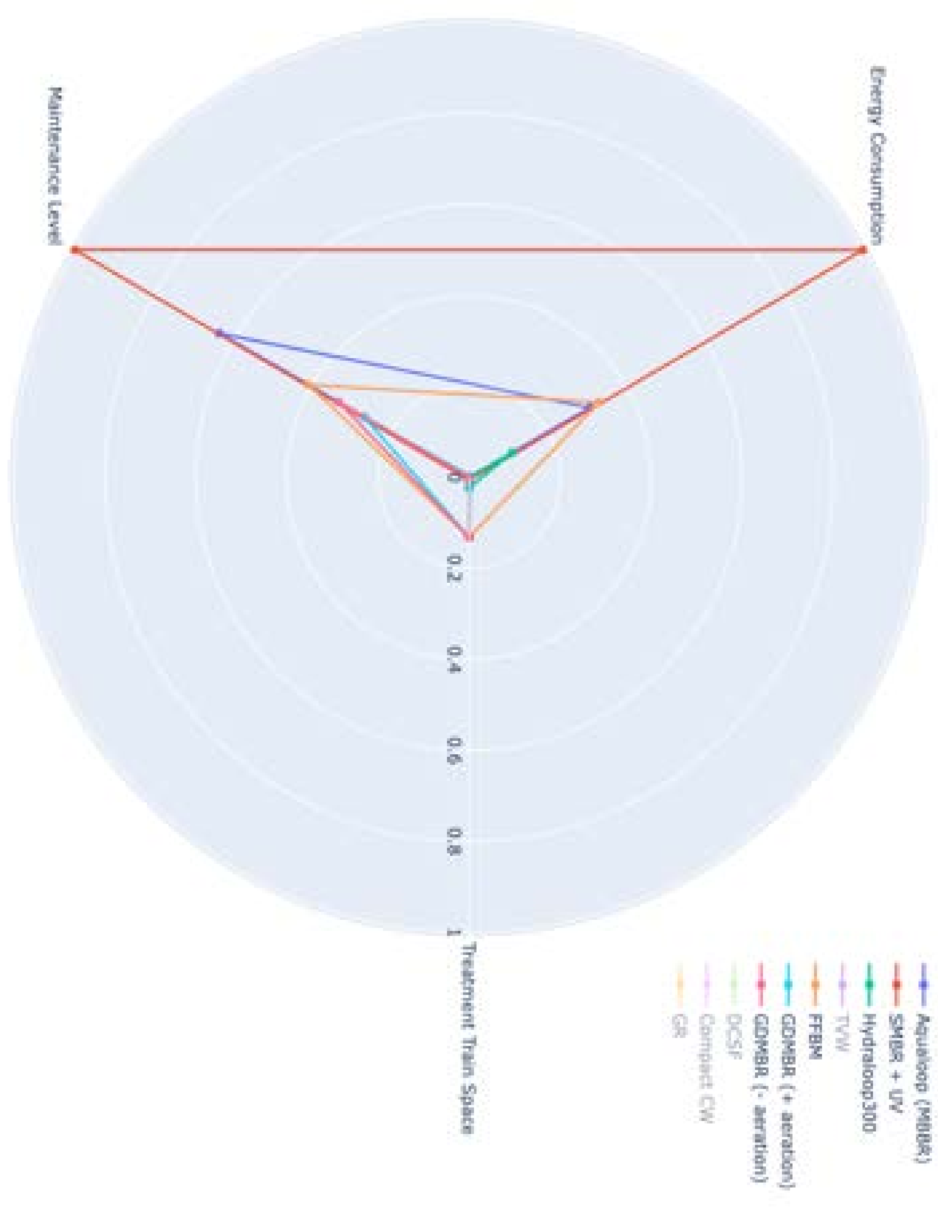


Figure 27: Radar chart of grey technologies

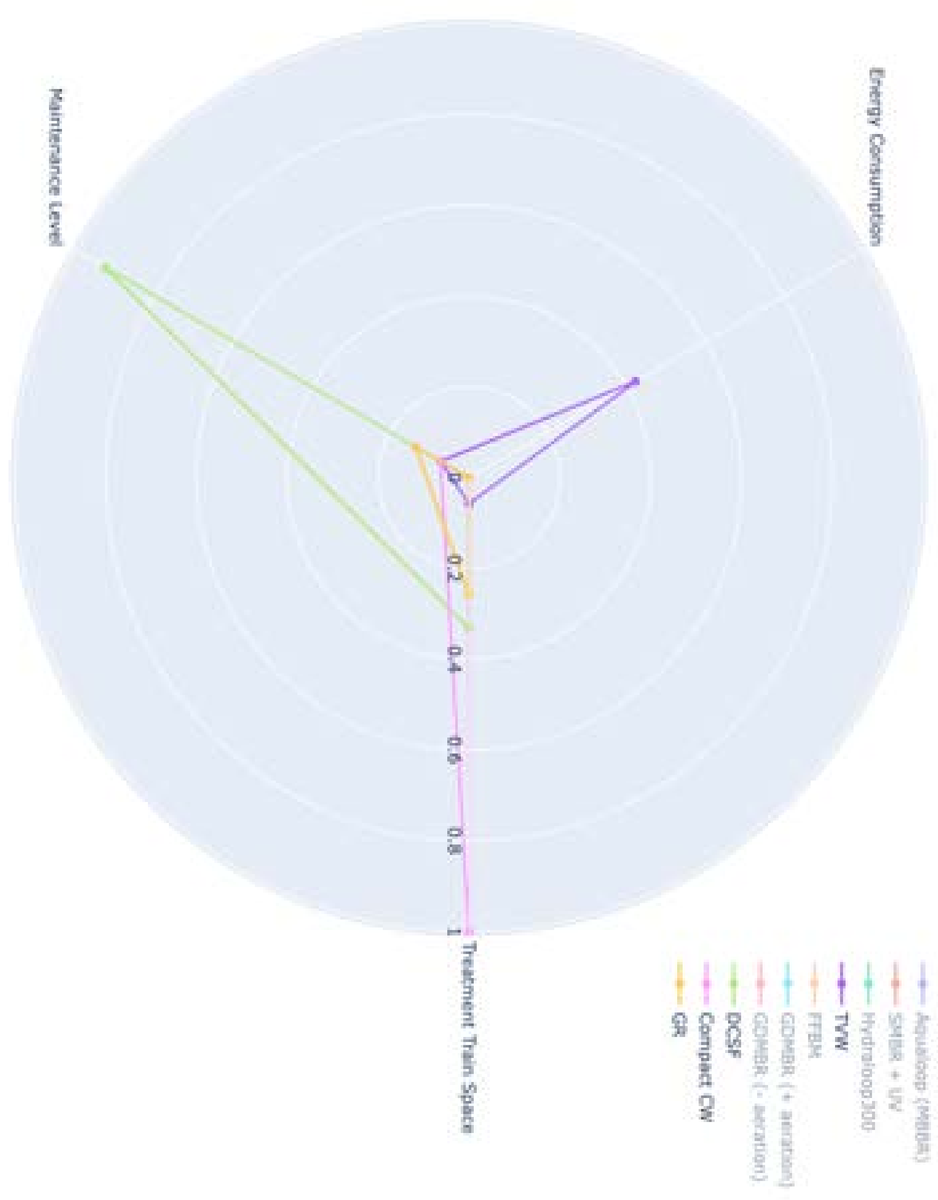
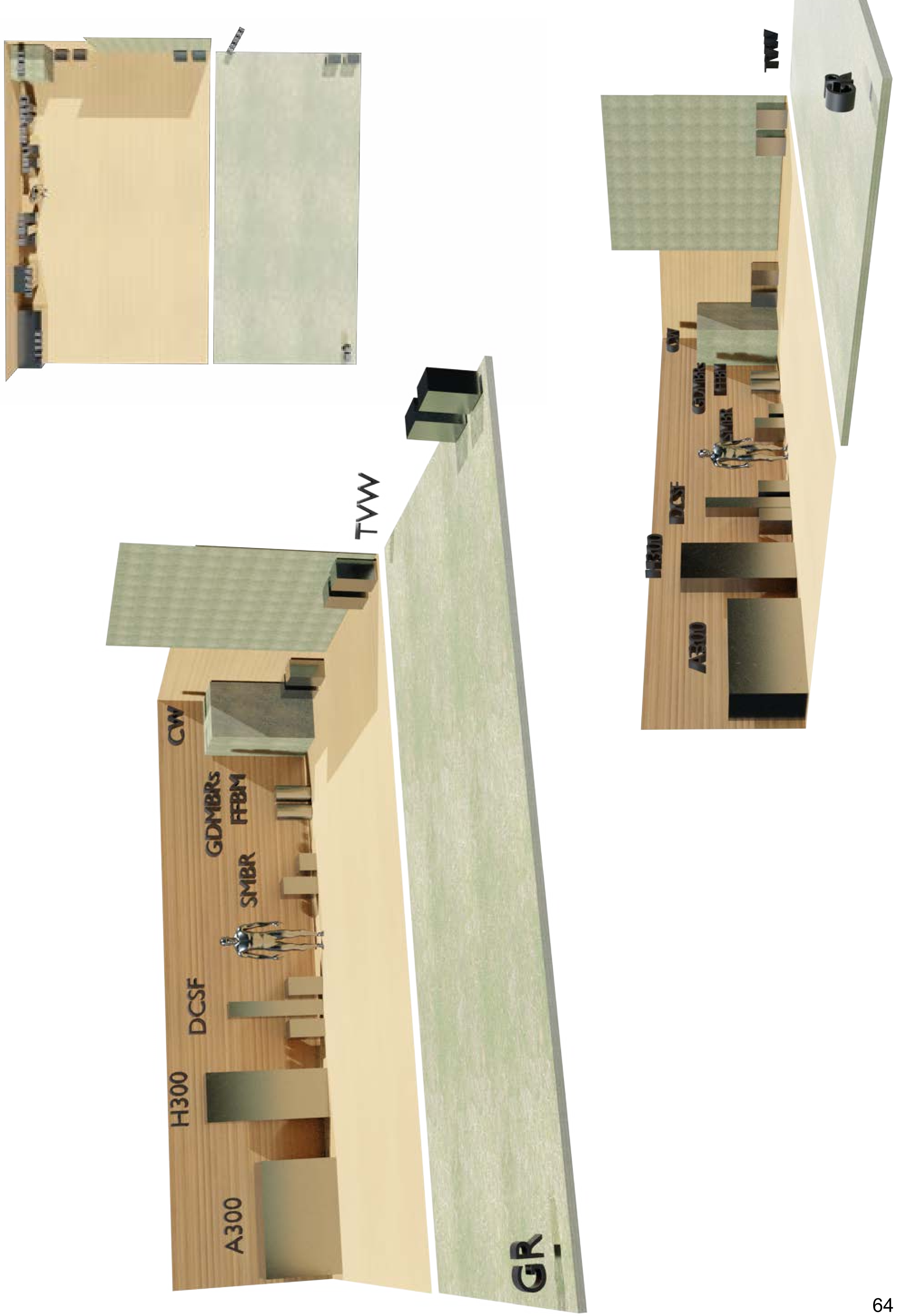
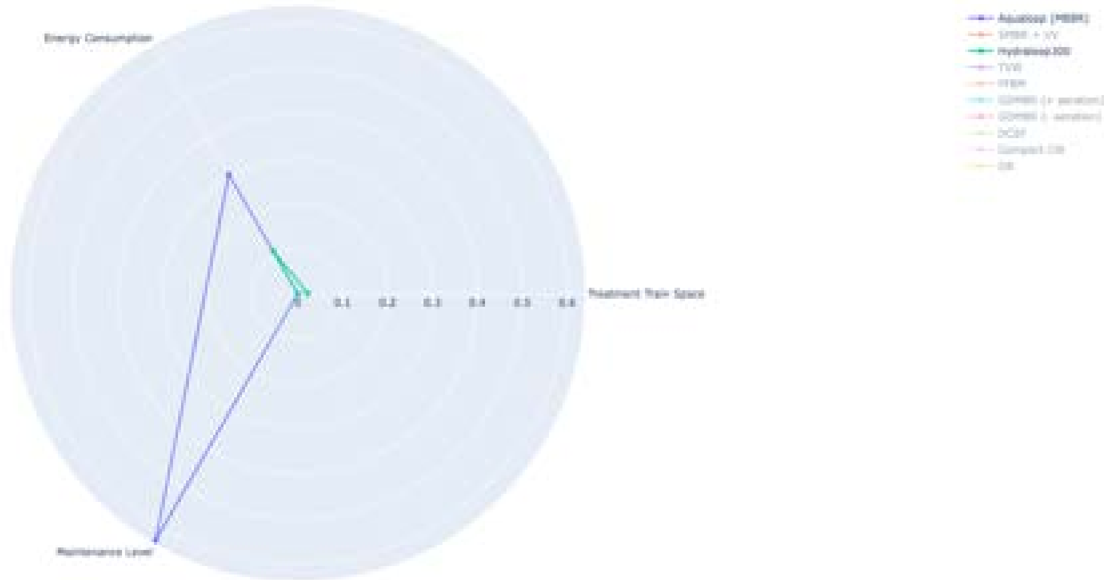


Figure 28: Radar chart of green technologies



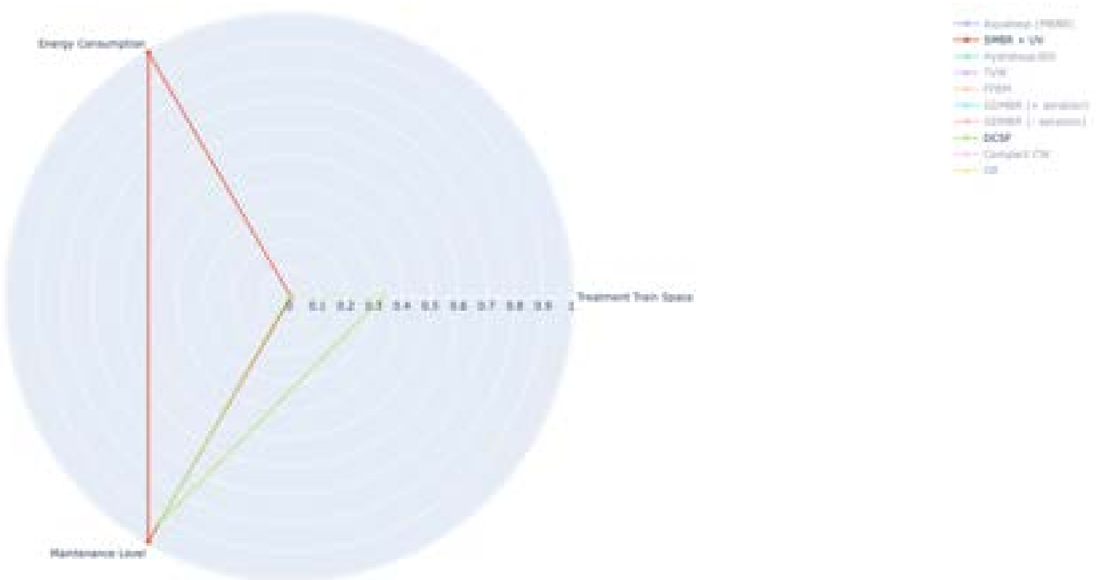
Hydraloop300

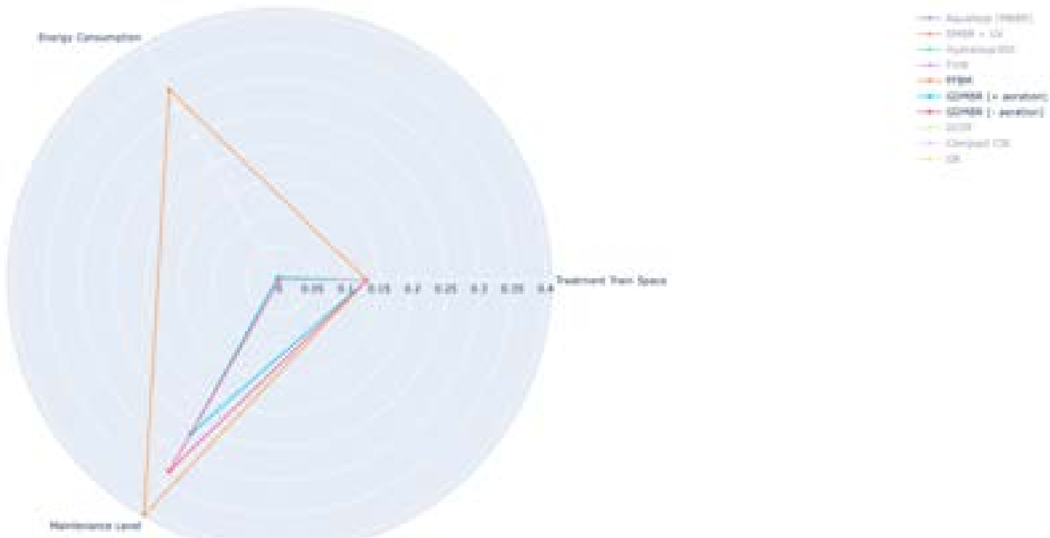


Aqualoop300

DCSF

FFBM/GDMBRs





SMBR+UV

Treatment train space (TTS)

In the performance matrix, Table 4, the TTS is derived from Q1, an assumed influx of average GW flow multiplied by the average daily peak factor. It appears that the Aqualoop and SMBR are the smallest options. This is to be expected, considering that there are bioreactor-based technologies, meaning the GW treatment tank and treatment process tank are combined. The membranes are submerged and take up very little space within the bioreactor as well. There is a general trend of grey technologies taking up the lower range of TTS and green technologies at the higher end of TTS except for the TVW.

Other bioreactor-based technologies should be around the same range considering that sizing ultimately depends on storage volumes but compared to the Aqualoop at 0.12 m3/person, the FFBM and both variants of GDMBR is almost triple that at 0.35 m3/person. This is mostly likely due to the HRT utilised to calculate the design bioreactor volume (a product of Q and HRT). All the GDMBRs and FFBM were designed for an average HRT of 24 hours. In constrast, the HRT of the SMBR + UV and Aqualoop options is 16 hours. The reason for this differentiation is due to the case studies' recommended HRT to achieve desired NP quality. If the SMBR + UV was calculated with a HRT of 24 hours, it would yield a TTS of 0.149 m3/person. The Aqualoop would equal to 0.148 m3/person. This still renders them smaller than other bioreactor-based technologies. A possible explanation for the SMBR + UV option could be related to the massive amount of electricity it needs and the membrane efficiency. With a submerged membrane, it must be air-scoured to retain its purification efficiency. Perhaps it is able to clean with less space because the membrane's permeation flux is maintained higher than the other bioreactor-based options.

For the Aqualoop system, it relies on membrane cartridges to determine its GW cleaning capacity. Thereby, the modularity of this cartridge system mean an additional cartridge inside the bioreactor would enable it to treat double the amount of GW. As such, Intewa defined the Aqualoop's cleaning capacity/tank volume by the amount of cartridges it holds inside even though we are scaling the tank dimensions. The other bioreactor-based technologies is instead scaled from the tank dimensions of pilot-scale studies.

The technologies with the greatest TTS are green technologies, as expected with the exception of the TVW. This is most likely due to the nature of the TTS unit: volumetric measure. With a thin depth, the total yielded volume derived is smaller compared to the surface area value, which would be greater than the surface area measure of other grey technologies. Furthermore, although green technologies tended to have higher TTS, it can be reasoned that specifically concerning the TVW and GR, the space it would take up could be considered almost 0 due to the fact that it utilises otherwise unused space (for example, facades of walls and rooftops). Furthermore, compared to the only green technology that is considered micro-scale in the case-studies, the TVW is one third the TTS size than the DCSF which is a relatively small and simple intervention, easily achievable by an individual layman and can be comfortably housed indoors or outdoors with weather-protection.

Energy consumption

It is important to keep in mind that the energy consumption data of three green technologies were not available (DCSF, Compact CW, and GR). However, based on the remaining data, the SMBR + UV option, considered a conventional grey technology had the highest energy consumption, which is expected. The large consumption of energy is attributed to air scouring needed to maintain flux. In contrast, the innovative GDMBRs had the lowest energy consumption at 0.019 kWh/m3 of treated water and 0.04 kWh/m3, which the difference is attributed to the energy required for aeration. This demonstrates that newer generation variants of membrane-based technologies are promising as a sustainable alternative and can redefine the previous reputation of grey technologies.

Purification-related demand is in the range of 0.3 - 2.1 kWh/m3 of treated water within the EU (Capodaglio & Olsson 2020). Although it is unclear whether this means treatment until fit for NP or P quality, we will assume NP quality. As such, the range in this MCA is from 0.019 to 4.2 kWh/m3. The spectrum demonstrates that innovative decentralised purification technologies can achieve even less energy consumption than EU's centralised water system meanwhile compared to economies of scale for conventional technologies, the 2.1 kWh/m3 is halved that of a SMBR + UV process at home (4.2 kWh/m3).

It is generalised in the literature review that green technologies would consume less energy, which is not reflected in these results. This may simply be due to the lack of data present. However, the TVW utilises even more energy than the Hydraloop300 though it is by a margin (0.19). This is so because the majority of energy used in the TVW is attributed to pumping. It could be lowered by using an efficient pump and distribution system (Lakho et al. 2022). To what extent it would decrease energy

consumption remains unknown, although logically if utilising a conventional pipe distribution layout, the more distance tends to mean more energy utilised for conveyance.

Maintenance level

In general, the maintenance level metric was developed to reflect the more components in the technology, the more components you have to replace, thereby the higher the maintenance. Ofcourse, this accumulated effort is generally true with higher replacement frequencies but in this case when applied, some technologies suffer from imperfect information so perhaps some components were not taken into account. For example, Compact CW, GR and TWV case studies did not necessary delve into maintenance-related information. Seeing that the maintenance level for TVW and compact CW is amongst the top three, this factor in addition to the "maybe" availability of customer support may be why.

The lowest maintenance level is the Hydraloop. This makes perfect sense considering that the system is self-cleaning, only requires a UV light replacement every three years, and has customer support. Although the DCSF is quite high for maintenance level, coming in as the second highest, the original innovators behind it intended for the nature of the DCSF to be user-friendly. Thereby, perhaps the lower rank can be attributed to the lack of available customer support, although it may be unfair since it is designed to not need customer support. If facing clogs or poor performance, the go-to solution is to shake up the drawers of sand and leave it to settle for 24 hours. Trials of the DCSF in Jordan demonstrate that this usually solved technical problems that users faced (Assayed, Chenoweth & Pedley 2015). The SMBR + UV option has the highest maintenance and highest energy consumption, which perhaps would render it not as user-friendly. On the other hand, the innovative MBRs have moderate maintenance, most likely due to the infinite solids retention time, which means there is no sludge that must be disposed compared to conventional grey technologies.

Furthermore, considering that maintenance does not necessarily reflect the behavioural changes that users would need to implement to maintain their GW systems. For example, it is not recommended for all products to use cleaning produces with bleach in the shower, as this would compromise the safety of treated water.

Added value

The added value is a qualitative assessment of additional benefits these technologies can bring. Although all these technologies serve to increase the overall resilience of the urbanscape and centralised water system, they can double to serve other functions. As previously discussed, the two goals of achieving a sustainable drainage system and water provision system is highly interrelated.

Only green technologies had added value. The coverage through GI provides natural thermal and acoustic insulation and passive air quality filtration. Ironically, the extent of added value depends on the size of the GI, with the larger area providing more added value due to additional coverage. The compact CW demonstrates the potential recreational benefits such spaces can bring. Although it could be seen as disguised as a typical green space, a compact CW might as well be multi-functional in providing water treatment. The associated mental and health benefits of being surrounded by green spaces is hard to quantify but in this case we can assume it can help.

Furthermore, GI relies on photosynthesis more directly than other grey technologies. In that case, although this added value is insinuated, the degree of insulation and air pollution filtration depends on the substrate volume for optimal insulation and macrophytes health for optimal air filtration.

Global warming potential

Although energy consumption demonstrates the amount of energy required for operation, the GWP represents the sum of emissions released from the entire supply chain in CO2 equivalent. This is important due to the fact that if decentralised treatment is to become mainstream, more products will have to be produced inorder to cope with demand, requiring energy and resources. For the TVW, the GWP potential has already been calculated in the paper itself. However, if possible, the GWP is extrapolated from other case studies with comparable GW treatment technology. It must be noted that the system boundaries are varied between different LCAs but GWP for construction and operation phases are utilised.

As for pilot-scale studies based on membranes, GWP was derived from a LCA on hollow fibre membrane technology (Yadav et al. 2021). The selected value was based on the most frequent solvent-polymer combination for membrane production (n-methyl-2-pyrrolidone-polyvinylidene fluoride) against the backdrop of a European electricity mix. To compare with the potential for a greener alternative, another value reflecting the use of a green solvent (ethylene carbonate-PVDF) was also chosen. As the functional unit is the production of 1000 m2 of hollow fibre membranes, the GWP was scaled to the required surface area of case-studies.

The LCA was based on a preliminary filter, submerged MBR and MF for bacteria and virus removal. Within the study, it was shown that the highest contribution to impact categories was the treatment energy required, which majority is used for scouring of the membranes in order to retain permeate flow (Jeong et al. 2018). Since the innovative membrane technologies chosen did not require fouling control of the membrane through continuous air scouring, back-flushing and chemical cleaning, it is not a fair comparison. Furthermore, there is little to no sludge production which its handling is accounted for in the LCA.

Another concern is the system boundaries and how importantly, the differences between them. It is hard to compare a LCA that evaluates the construction and operation phase of a certain technology to another LCA that evaluates from cradle to grave for another.

Thereby, GWP was not chosen as a criterion to score and compare amongst case-studies. Instead, it will be discussed when evaluating the results.

OBJ (2) WSE Calculations

Treatment train	Volumetric footprint (M3/person)	NP Demand Fulfilment	Avg. excess for further treatment	P Demand in Kitchen Fulfilment	WSE	Avg. excess
LGW to NP, grey technology	0.12 - 0.35	100%	18.5 L/day	-	45%	-
LGW to NP, green technology	0.22 - 4.31					
LGW to P, iSpring + UV	+ 0.062	100%		100%	52%	3.57 L/day
LGW to P, Xpress + UV	+ 0.023	100%		53%	48%	None
Recirculating shower	0	-	-	-	33%	-
Water-efficient micro-components	0	-	-	-	28.9%	-

Table 5: Potential WSE from LGW reuse, compared to non-source-separated technologies

In order to better compare these GW treatment technologies, the WSE of non-source-separated technologies that also save water were calculated. They can be considered as 0 m3/person since they a placed atop already existing objects (shower and faucets). The maximum design load WSE would amount to 45% if fit for NP quality, however, with the addition of RO modules, the remaining excess reclaimed LGW can be further treated to P quality, fulfilling around 52% of total residential water demand.

Since the derived values are actually a reflection of how much influx we want to be able to recycle, the difference between Q1, Q2, and Q3 is akin to a scaling factor. If we want to be able to cope with Q2, all components of the treatment train must increase by 9%. If we compare bioreactor-based technologies to green technologies, this scaling factor would manifest in very different ways: the bioreactor-based technology has to increase the volume of water it can store, meanwhile the membrane inside would increase in a negligible amount. Green technologies end up needing to increase both their surface area and water storage volume. If treatment capacity is comparable, WSE increases with increasing volume of green water tank (Liu et al. 2014) Furthermore, in order to reach P quality, an additional 0.062 m3 per person would be necessary, which would increase the WSE by +7%.

When we compare these treatment train spaces to alternative influxes Q2 and Q3, we see to cope with Q2, which further accounts for the average summer peak factor, treatment train space has to increase by 9% (relative to Q1) and for Q3, which accounts instead for the climate-enhanced summer peak factor (Vonk, Cirkel & Blocker 2019), it has to increase by 29% (relative to Q1). To put that into perspective, if we upgraded to cope with Q2, we would need to increase treatment train space by 18.5% to cope with Q3.

OBJ (3) Green technologies application

Archetype: Row

Density characteristics

This is the quintessential Dutch urban morphology. It is characterised by lower FSI and mid GSI, as well as relatively high OSR. The GSI and OSR values correlate to the presence of private backyards per each row unit. Combined with the lower FSI indicates relatively short buildings, thereby less floor space. Therefore, it can be generalised that the Row unit represents a private household, most likely a family of three to five, with private outdoor space. Shared values-wise, these residents are more likely to prioritise family and family-related activities, recreational fun that would tend to happen within their private outdoor space in comparison to the shared streets.

Potential communal spaces

It is appealing to collectively break down exterior tool sheds and inner parking lots to create a shared surface storage area, for example, a pond. As a result, the Row as a collective would have an alternative source of water year-round. Such an intervention had potential to create eight lakes as visualised. This source of water during emergencies should be able to be converted to P demand using NP LGW processing technologies and without needing RO as it qualifies as surface water. The total area of all eight ponds is 4555 m2 and with a depth of 1 m, it would create a volume of 4555 m3, which is immense. In comparison, the collection would need max ~140 m3 of water storage for climate-change-enhanced loads. In that case, it can seem a bit excessive to construct all eight lakes. However, this total volume indicates a share of the total can be repurposed for communal subsurface treated water storage of both NP and P quality, instead of each individual household hosting their own water storage.

In that case, it is important to consider water table levels. As a precaution, water tank material should not be concrete because there is no guarantee of sufficient drainage around the tank. Instead, underground polyethylene or fibreglass tanks are an interesting option. They are convenient to install, require little maintenance and due to its underground nature, does not risk UV-degradability (Lawson et al. 2009).

Furthermore, socially such archetypes tend to be more family-oriented, as such, with the sacrifice of private backyard space, it is imperative to compensate, perhaps by creating communal recreational spaces. This would create a small hub of biodiversity and a space of possible random interactions with neighbours, potentially creating unexpected bonds and thereby strengthening the collective identity and even motivation for maintaining shared resources.

The issue with such a suggestion is the cross contamination if the treatment technology has been handling LGW. It is unknown whether a thorough cleaning of the treatment technology would render the water safe from cross-contamination.

Green technologies potential

In the row sample, we can sub-classify the units to yield four sub-archetypes with different spatial availability: the in-between unit or end unit, with or without a garden tool shed. All units have an extended area of the house that does not have a sloped roof nor is part of the tool shed. This is referred to as the extension. Let us assume that a row house would like to utilise GI for LGW recycling as an individual entity, relying on their private space. In that case, all sub-archetypes do not have the potential for GR. As for TVW potential, all sub-archetypes except for an in-between unit without a shed have enough wall space to satisfy three to four residents for both normal flow and climate-change enhanced flow. The in-between unit would only have enough space to satisfy three residents with normal flow.

It is evident that the Row has the least potential for GRs because each unit's roof is too steep. Instead, the steep roof is potentially more suitable to harness rainwater. Furthermore, the installation of solar panels atop these roofs would not obstruct RWH and can even facilitate it. That way, there is no need for an additional RO unit to covert LGW to direct potable reuse. Instead, using GW treatment technologies with rain water should yield potable water quality.

With the compact CW, considering that the backyard of each row unit is approximately the same footprint as the building itself, there is an average of 46 m2 of backyard space with a shed and 54 m2 without. Therefore, it would easily satisfy the amount of space necessary for meeting even climate change enhanced peaks, as this would call for 5.3 m2 total for a four person household, which is a fraction of total backyard space. Ironically, this also means that it is easier for private individuals to construct their own miniature CW in their backyard without going through negotiations with the rest of the neighbourhood to draw out shared communal CW space

row

Density measures			Green technology potential			Water storage needs	
GSI	FSI	OSR	TVW surface potential	GR surface potential	Communal space potential	Q1	Q, cc
0.24	0.97	0.78	47.83%	13.56%	4555 m2	80.75 - 107.66 m3	104.23 - 138.97 m3

	Demand	Q1						Q, climate change					
	Green technologies potential	GR Potential		TVW Potential		CW Potential		GR Potential		TVW Potential		CW Potential	
	Residents	*3*	*4*	*3*	*4*	*3*	*4*	*3*	*4*	*3*	*4*	*3*	*4*
Sub-achetypes	In-between unit (with ext.)	99%											
	In-between unit + shed												
	End unit (with ext.)												
	End unit + shed												
Collective neighbourhood		99%	74%					77%	57.8%				

**Percentages demonstrate how much of residential water demand can be fulfilled*

Archetype: In-between

Density characteristics

This sample has the highest FSI and GSI, as well as the lowest OSR, which insinuates a more compact setting, with less open space and higher floor area and built ground space. In general, this sample has the largest portion of built surfaces in general. Albeit labelled as the "in-between" space, this sample area is practically the most dense archetype. The inner-city location insinuates mixed functions of buildings which is the case for this as well. The only private spaces available to apartment units are balconies and behind these buildings are private parking spaces.

Potential communal spaces

The potential communal spaces here are all overlapping private parking spaces that are indeed separated by private ownership, evident in the bordering fences seen from Google Maps. Private parking lots were justified as potential communal spaces due to the compact city ideal of convenient mobility, where the public transport infrastructure is optimised to be as efficient as possible, decreasing the necessity of private automobiles. However, if a joint collective were to be formed, there could be a potential 1522 m2 that can be repurposed into a buffer or compact CW. For both normal demand and climate-change-enhanced demand, there is more than sufficient space for a communal water storage for LGW and green water tanks. Even in this dense urban setting, if compromises are reached with trade in in private parking lots, a buffer for seasonal water storage and LGW TTS-related water storage.

The best form of communal storage in this case would be subsurface storage, considering the higher concentration of pollutants within an urban setting that gets washed up into open waters. With subsurface storage, the In-between residents would have to separate their water streams and water storage to both NP and P quality systems if they want to increase their WSE through meeting P demand as well.

Yet, the benefit of surface water storage is that it can be directly converted into P quality with the same LGW conversion technologies, such as the Aqualoop, due to the lower concentration of TSS. As mentioned, a potential way to curb this would be passive filtration through macrophytes. Furthermore, due to the compact nature of the In-between archetype, the quality of life of residents can improve through closer green spaces. However, with smaller and more surface storage bodies in such a dense area with high percentage of impermeable surfaces, the heat absorption during the summer in combination with the high specific heat capacity of water means during the night it will radiate heat as well, causing discomfort for residents. A potential solution would be to create surface storage bodies next to shops or offices where users are not present during the night.

A possible issue could be the fragmented nature of these communal spaces, but at the same time, that means if one communal subsurface water storage or buffer overflows, there can be multiple levels of safety measures as the overflow is redirected to another less frequently used or filled communal subsurface storage. If a record rain event occurs, there should still be last-line-of-defense connections to the public sewage system towards WWTP when buffers are full.

Green technologies potential

Considering the compact nature of apartment units where the average unit size is 60 m2, it is very space-intensive to install green technologies individually. Furthermore, although the compact CW requires only 1 m2, considering the depth of 1.8 m, that is not possible to install in an apartment.

Interpolating from the density characteristics, it is no surprise that with a high share of built surfaces, the In-between has the highest potential for TVW. Methodologically, it is an extrapolated average of the biggest buildings in the area. However, even decreasing the usable outerwall coefficient to 50% gives us the highest TVW surface potential of all archetypes. This is perhaps due to the mixed function buildings and superimposition of newer buildings over the years. Thereby, window and balcony space is not necessarily considered before or retrospectively when converting other functional-use spaces into residential spaces or vice versa, creating more bare surfaces. Furthermore, in the inner-city, it is more likely that buildings will be built on top on each other, meaning there will definitely be an increase in TVW that may be able to compensate for additional population density.

The GR potential of the area is high at 67%, with enough surface area to provide for all residents in this area. Furthermore, when disaggregated into detached buildings, there is sufficient surface area per detached building to provide for the estimated amount of residents within (2.14 people per address). Therefore, each detached building has the capability to create a smaller collective for installing their GR, which can simplify the negotiation and implementation process of approving and installing the GR.

As discussed above, a potential critique of the fragmented area would be conveyance compact CW is clogged or needs maintenance, the decentralised networking perspective means redirecting that influx towards other compact CWs

Density measures			Green technology potential			Water storage needs	
GSI	FSI	OSR	TVW surface potential	GR surface potential	Communal space potential	Q1	Q, cc
0.30	1.67	0.42	69.57%	67.02%	1522 m2	47.47 m3	61.28 m3

Demand	Q1			Q, climate change		
Green technologies potential	GR Potential	TVW Potential	CW Potential	GR Potential	TVW Potential	CW Potential
Residents	2.14 (CBS 2016)					
In-between unit						
Collective neighbourhood						

Archetype: Dense

Density characteristics

The Dense archetype is characterised by the lowest GSI, halved that of the other archetypes and with the highest OSR. From these numbers it is evident that the quality of space shows a large share of public green space. Its relatively low FSI demonstrates the dense nature of the building itself rather than the overall ground surface. As such, this is a quintessential example of more peri-urban forms of the future, especially in the case of the Netherland's new compact policy since a prioritisation is to separate green areas from urban areas.

Potential communal spaces

The potential communal spaces overlap the parking lots within the centre courtyard of the buildings. However, on the outskirt of the buildings, these areas are non-built and feature a lovely outdoor green space for residents to enjoy. Overall, the highest OSR value correlates to the highest communal space area potential at 11,625 m2, which is a massive amount, more than sufficient for climate-change-enhanced loads (~71 m3). Repurposed into a seasonal buffer or LGW TTS-related water storage with a depth of 1 m would amass 11,625 m3. Therefore, perhaps the peri-urban space has potential to create seasonal water buffers for a share of the inner-city population as well. Although this insinuates kilometers of conveyance pipes, it is usually less lengthy than centralised water conveyance, more localised and therefore easier to manage, investigate, and solve if an issue arises i.e. of unknown contaminants. It is worth considering since the sub-surface will need to be organised to increase climate resilience of cities. Furthermore, these buffers be repurposed into multifunctional spaces for recreational activities, considering that individual residents do not have access to private gardens. Ultimately, in such an high OSR setting, surface storage buffers are recommended due to its multi-beneficial contributions to not just climate adaptation but residential livelihood.

Green technologies potential

Individually, each unit does not have sufficient space to integrate green technologies for LGW reuse. The balcony railing area is insufficient for TVW installation for one person, even if it were to be double sided. Furthermore, individual GR space would be hard, if not impossible to negotiate in the Dense archetype. The packed nature means more floors, so a compact CW is also out of the question when it needs a depth of 1.8 m and there is no access to private gardens.

However, as a collective, the potential for green technologies is immense. Methodologically, the useable outer wall surface was calculated as the share of common walls that do not necessarily belong to a particular unit, i.e. balcony space. These are walls that are vacant with no windows or balcony railings and would otherwise be hard to reach. Even then, the relatively low sum of these surfaces, at 26.75% of total outerwall space, is sufficient to provide for all the residents. The roofs are characterised as flat surfaces and is unused, as Google Maps shows. Therefore, perhaps the residents do not have access to the roofs or a reason to go there. If the residents do not have roof access, it would be even easier to repurpose the roofs into a GR as it would not compromise any previous function. In such a case, these GRs can be combined with solar panels or compact wind turbines to general renewable energy to maintain the higher conveyance demand of bigger buildings.

dense

Density measures			Green technology potential			Water storage needs	
GSI	FSI	OSR	TVW surface potential	GR surface potential	Communal space potential	Q1	Q, cc
0.11	0.95	0.94	26.75%	100%	11625 m2	54.75 m3	70.67 m3

Demand	Q1			Q, climate change		
Green technologies potential	GR Potential	TVW Potential	CW Potential	GR Potential	TVW Potential	CW Potential
Residents	2.14 (CBS 2016)					
In-between unit						
Collective neighbourhood						

Discussion

Archetype: Row

WRS Integration Potential

Grey technologies

Considering that the Row is likely to house a small family, not the national average of 2.14 people (CBS 2016), we can assume there would be around three to five residents. As previously researched, simulation studies have demonstrated that total storage tank required per capita decreases with increasing occupancy once households are greater than three people (Liu et al. 2010). Therefore, not only would this archetype afford a relatively bigger share of private space for TTS compared to apartment-like units, they would be able to minimise their total water storage as private entities. This means that all the micro-scale grey technologies are viable for the row archetype and preference for varying maintenance levels and electricity consumption is up to the user.

Within a row unit, we can assume that there is ample space to place micro-scale LGW technologies. Considering the residential count of typically three or more within one unit, the Aqualoop300 or Hydraloop300 would be the smallest option to implement and can fit into the toolshed. Both have available customer support, and particularly the Hydraloop is incredibly user-friendly with minimal maintenance required, an advantage considering the hectic-ness of family-life. Upscaling the Hydraloop to meet climate-change peak factors is difficult and would require replacing the Hydraloop300 unit with a new Hydraloop600 unit. This can seem an excessive waste since an entire Hydraloop unit would need to be disposed of, or if possible sold to another potential customer/returned to the company. The Aqualoop on the other hand would simply require an additional cartridge to increase cleaning capacity and switching out the bioreactor and green water tanks to bigger sizes. Planning of tank sizes also mean tank capacity can be initially chosen for two membrane cartridges although one membrane cartridge is intended for usage. Furthermore, both units can be hooked up to an external rainwater collection tank and utilise that rain water when there is insufficient LGW.

Water storage-wise, the Row unit as an individual entity is able to construct sufficient subsurface water storage within their backyards, without compromising the recreational value their backyard offers. Utilising bioreactor-based technologies, however, requires visible surface space. This can be appropriated in their tool shed, or extension area on the ground floor. Furthermore, with the large amount of backyard available, bioreactor-based technologies can be housed in their own individual shed if the individual entity is willing to sacrifice that space. Although scalability can appear to be an advantage, WSE was found to be maximised at a treatment capacity of around 200 to 350 L/day with greater green water tanks not affecting the WSE (Liu et al. 2010). Therefore, the Row archetype does not need to worry about having to increase their private green water tank sizes once treatment capacity reaches that, which is already a suitable amount for family of four to five.

Hybrid systems and seasonal dynamics

Considering the steeper roof slopes present in the row archetype, RWH warrants further investigation. In the literature, it is suggested that RWH, specifically in the Netherlands, will require robust water treatment and frequent analyses to guarantee consistent purification (Hofman-Caris et al. 2018). Thereby, on a decentralised level costs would be relatively high (Hofman-Caris et al. 2018). As such, it was suggested that collecting stormwater runoff in addition to rain would fulfill drinking water needs for an average family living below that roof, especially in a dense urban setting (Hofman-Caris et al. 2018). However, the fact remains that to prevent problems caused by extreme showers due to climate change, rainwater would need to be collected and retained to prevent pluvial flooding and subsequent damage-related costs in cities (Hofman-Caris et al. 2018).

As a comparison, Table XX compares RWH yield between an individual Row unit and collective Row, with the latter sub-conceptualised with collective GR as well. The RWH numbers utilised median rainfall projected from the SSP2-4.5 scenario that averaged historical and projected rainfall values between 2015 to 2100 (CCKP 2022). The only RWH category assumes a runoff coefficient of a sloped roof (0.8) while the GR scenario assumes a runoff coefficient of a flat green roof (0.3). These numbers do not include the first flush diversion, which is recommended for RWH. It is a simple mechanism that bypasses the first 2 mm of rainfall as this portion of water contacting roof surface tends to have the highest concentration of pollutants (Hofman-Caris et al. 2018). Furthermore, derived values are comparable to Hofman-Caris et al.'s study on a 60 m2 Dutch roof (2018).

Collective with only RWH during wet season and LGW during dry season

The collective with only RWH assumes active function during the wet season and LGW recycling during the rest of the year. This also assumes that as a neighbourhood, storage is possible by creating a surface storage area/pond at selected areas. This pond can also double as passive filtration with an appropriate selection of macrophytes. Such a decision is due to the fact that urban lakes are particularly endangered to pollutants due to its close proximity to human activities and thereby rubbish that degrades water quality (Puri et al. 2015). So, it is interesting to passively filter the water with floating wetland treatments that are low maintenance. There is also a very high load of nutrients and organic matter that catalyses eutrophication (Puri et al. 2015). This is of concern since summers will become hotter, creating conditions of higher productivity for these algae blooms. Considering that aquatic organisms require a stable pH within an optimal range, pH should be frequently monitored. Consideration should be given to the Row's roof material to determine whether it is safe or whether coating will be necessary (Lawson et al. 2009).

From Table 6, it is evident that RWH during an average rainy day would fulfill a large portion of total water demand, both on as an individual entity, fulfilling 55 to 73%, and collective neighbourhood, fulfilling 70 to 94%. However, as a collective neighbourhood, the highest WSE achieved from RWH during a climate-change peak is a cool ~74%. In comparison, the WSE of LGW during the dry season would achieve 45% augmentation from the centralised system in Q1 but for the climate-change peak, it would only achieve 16% if treatment capacity is not increased as well. If it is increased by ~30%, then the WSE would remain at 45%. Therefore, it demonstrates that actions taken today need to consider scalability because the WSE can be dramatically reduced during times with climate-change peak demand, evident in Table 7. Furthermore, it remains unclear whether it is technically easier to scale up a larger intervention instead of single row units individually scaling up.

On a critical note, although ~86 m3 can be collected on an average rainy day, this is but an arithmetic derivative from dividing the total sum of rainfall with the average amount of rainy days in a year within the Netherlands. Therefore, it is unrealistic to assume that sufficient rain water can be collected on a given day to satisfy the idea of direct rainwater treatment, especially with the first flush mechanism. Imagine, on a day with minimal rainfall, the first flush mechanism may completely neutralise any rainwater yield.

In order to increase the flexibility of the water system, instead of focussing on scaling up LGW treatment, we should also consider that the excess stormwater run-off accumulated in the pond can be treated into useable water. The exact quantity of run-off that would remain has not been calculated in this thesis. If higher resilience is desired, it is important to note that replacing grey technologies for LGW processing with green technologies would increase the Row archetype's climate-adaptation, providing additional benefits, such as year-round insulation or passive air filtration.

Collective with GR

The collective with GR assumes that during the wet season, there would be RWH for only steep roofs unsuitable for GR and GR on flat roofs that are from the extension or tool shed. Note that in this case, there would be limited space for an infiltration pond by the back since the tool shed is in use, so shared storage may need to overlap roads. However, as an individual row unit, we assume that it is not worthwhile to install a GR for treatment purposes so calculations are withheld. In such a case, we can see that the WSE from rain alone during the wet season is quite high for three person households with daily peak demand at 94% (Table 8). In this case, the GR would provide limited additional insulation benefits since no one is living in the tool shed. However, this assumes that all the rain can be collected and stored long-term somewhere in the neighbourhood. Communal storage will have to be negotiated

	Roof surface area (m2)	Annual Yield (m3/year)	Rainy day avg. (m3/day)
Row Unit, only RWH	78.69	50.03	0.37
Collective, only RWH	18506.55	11765	85.88
Collective, with GR	RWH: 15997.2	10196.47	74.43
	GR: 2509.35	599.79	4.38
	Total	10796.26	78.81

Table 6: RWH yield in Row archetype

WSE (%) for avg. rainy day, valid for 137 days out of a year					
Roof type		**RWH only**		**with GR**	
Residents		3	4	3	4
Row unit (no ext.)	Q1	73.02	54.8	-	-
	Q, cc	57.1	42.82	-	-
Collective neighbourhood	Q1	94.17	70.63	86.42	65.81
	Q, cc	73.57	55.18	67.51	50.63

Table 7: WSE of RWH in Row archetype

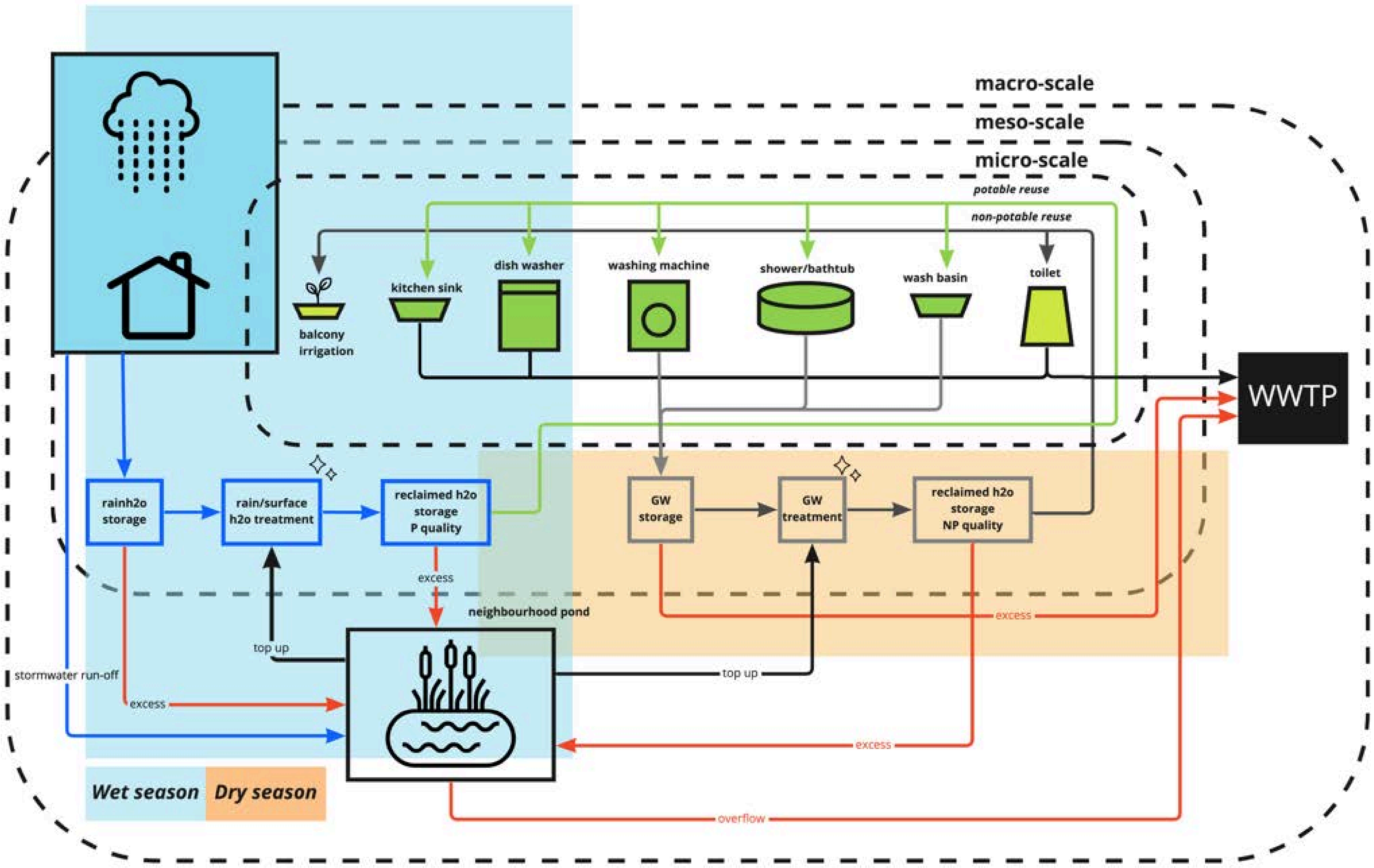
but it is unknown how such negotiations will pick and divide whose private property. In such a scenario, we can either pause LGW reuse during the wet season or continue operation, so, this will render relevant LGW technologies installed dormant for half the year, which may cause other technical issues. However, it was demonstrated in Zapater-Pereya et al.'s study (2016) that rain decreased the HRT of LGW going through the system but effluent quality remained safe.

Collective with only RWH and CW

In this case, GR and TVW are dismissed. Instead, the high potential for creating communal space can be reappropriated to creating a compact CW and even surface water storage as a buffer. Increasing the flexibility of the water system in the Row archetype can be achieved through increasing the period of time LGW is reclaimed beyond simply the dry season.

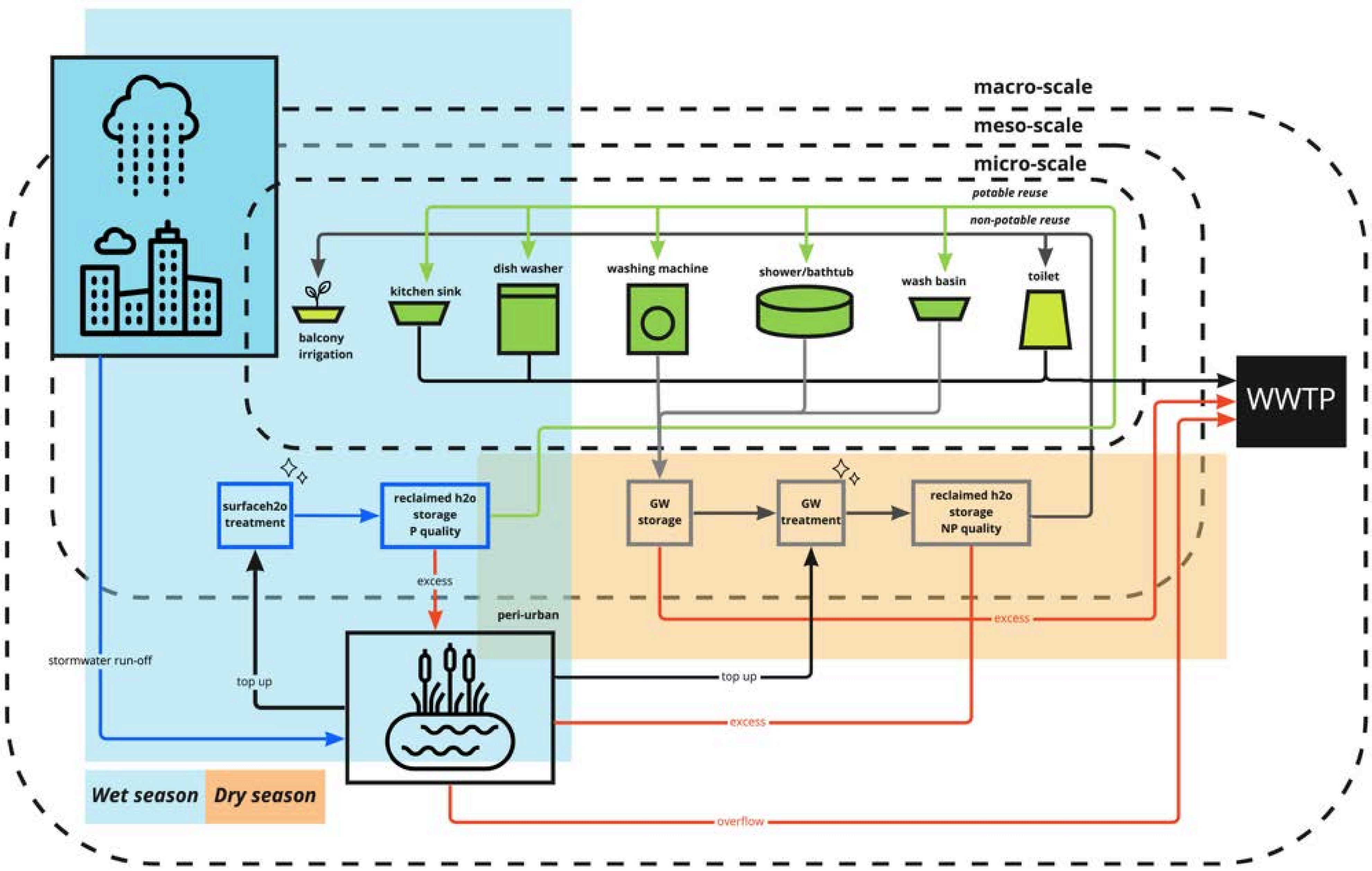
	Days of year	WSE		If LGW scaled
		Q1	Q,cc	Q,cc
RWH	137	94%	74%	74%
LGW	228	45%	16%	45%
	Total, year	64%	38%	56%

Table 8: Total WSE for collective RWH



Archetype: Row
Collective Neighbourhood

Figure 29: Water system schematic for Row archetype's collective hybrid scenario



Archetype: In-Between
Collective Neighbourhood

Figure 30: Water system schematic for In-Between archetype's collective hybrid scenario

Archetype: In-Between

WRS Integration Potential

Grey technologies

In the In-between archetype, space is scarce and therefore more valuable and faces competition. Even subsurface space. As such, the average unit size of 60 m2 would be something that the average citizen may not like to compromise with complex large gizmos that may cause odour or noise. Furthermore, considering the average citizen living in the inner city is more likely to have busier lives considering the proximity to cultural activities and entertainment, it is important that the grey technology also be low maintenance. Therefore, the Hydraloop 300 with its user-friendliness, available customer service, low space occupation and low energy consumption is preferred. It is not loud nor smells and design-wise looks like a second fridge you would never open. However, in the future, if commercialised into a product, the FFBM and GDMBRs are also desirable though the maintenance is slightly higher. With an average household occupancy of 2.14 people, the Hydraloop 300's capacity is suitable for climate-change-enhanced influx.

Hybrid systems and seasonal dynamics

The In-between archetype's geographical location within the inner city insinuates a massive amount of impermeable surfaces. These surfaces will contribute to higher surface runoff, less natural filtration, and reduced ground water recharge (LeFrançois 2015). Furthermore, the water will carry human litter with it, leading pollutants, sediment, and possibly top soil to water bodies (LeFrançois 2015). Therefore the quality of runoff is most likely lower than in peri-urban or rural areas, rendering it more costly and intensive for treatment. This is especially the case concerning emergent pollutants from PCPs as well.

Heavy rain in such environments, what is of great concern are hydrological peaks due to surface impermeability that cause flash pluvial flooding and subsequently, high economic costs. In such a situation, run-off is best attenuated by green spaces where no extra costs would be necessary to process the run-off for later. Yet, in this archetype, space is the most scarce. Therefore, if surface storage such as ponds were to be placed, overflow mechanisms must be in place that redirects the excess towards the WWTP for centralised treatment since terracing ponds for emergency overflows may not be a viable option with spatial limitations.

Furthermore, considering the higher concentration of pollutants, if a surface storage option were chosen, it would benefit to be designed as a floating wetland that can provide low-maintenance passive treatment. This is so considering that it has a higher possibility of catalysing algae blooms, disrupting the pond's chemistry and therefore health. The pond would also benefit from increased dynamics with a pump that prevents the pond from becoming stagnant. The last desirable case is to have a dead pond in the middle of the inner city. Additionally, water has a high specific heat capacity, meaning during warm summer nights, they still retain and radiate heat. Smaller ponds closer to residences would do best to be shaded by umbrella-like trees. This would provide a canopy that insulates the pond from absorbing too much heat.

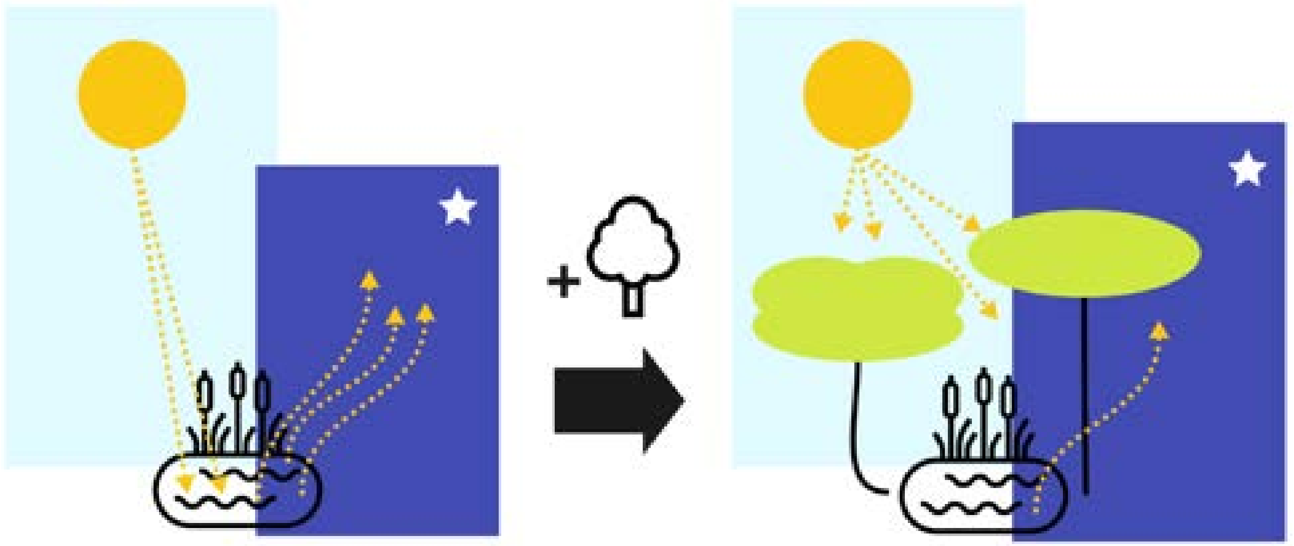


Figure 31: Preventing hot nights from surface storage in inner cities

This pond can become a seasonal buffer for emergency water if centralised water supply cannot keep up. The pond can also double as an infiltration pond if groundwater recharge is possible within the area. However, this should be approached with caution as we want to avoid the infiltration of emergent pollutants seeping into the groundwater.

Although overflows can be redirect to the centralised WWTP, smaller more macro-scale facilities can be created for the peri-urban area. Or instead of creating storage ponds within the inner-city itself, larger seasonal buffers can be located in the peri-urban area and provide for the inner-city. Both options will need to be fitted with more treatment intensive technologies in order to cope with these emergent pollutants, but this guarantees safer environmental discharge than if decentralised at the individual level.

Archetype: Dense

WRS Integration Potential

Grey technologies

The generic advice for grey technologies applicable to the Dense archetype's individual case is the same as the In-between archetype, considering that residents live in apartment units. However, with ample amounts of available space, individual grey technologies are not necessary at all. Instead, it is recommended that the residential building's water streams are separated and a communal treatment space negotiated. This would be reminiscent of the SMBR+UV case study. Although other treatment options would have less energy consumption, the high potential to harness alternative energy sources in this archetype also render its energy consumption less important.

Hybrid systems and seasonal dynamics

The Dense sample, in contrast to the In-between, is surrounded by non-built open space, indicated by its massive communal space potential that can be repurposed into both stormwater buffers that acts as a dry season emergency water supply and reclaimed LGW storage. This area does not need as extensive consideration concerning emergent pollutants since there is a low share of impermeable surfaces, therefore a low probability of pollutant concentrated waters. In fact, the green space already insinuates high stormwater attenuation, as the water saturates into the soil before evaporating after the rain event is over.

With this amount of space, low-impact interventions can thrive. A compact CW would be interesting in such an area, but would not help with insulating the building itself, which is desirable for future climate conditions. With such a massive amount of communal space potential, the dense archetype can also absorb excess overflow from the inner city. This would decrease conveyance needs to a centralised water plant. The landscape can be contoured with terraces to create more surface area and playful ways to increase the storage capacity of surface water storages. This is done by playing with elevation, of which construction rubble or debris can be used, creating layers of safety that overflow can flow into without flooding the area. This concept is very similar to the idea of flood plains. In the summertime, these areas can be repurposed into recreational areas, providing shade and cool spaces for the local biodiversity, people included.

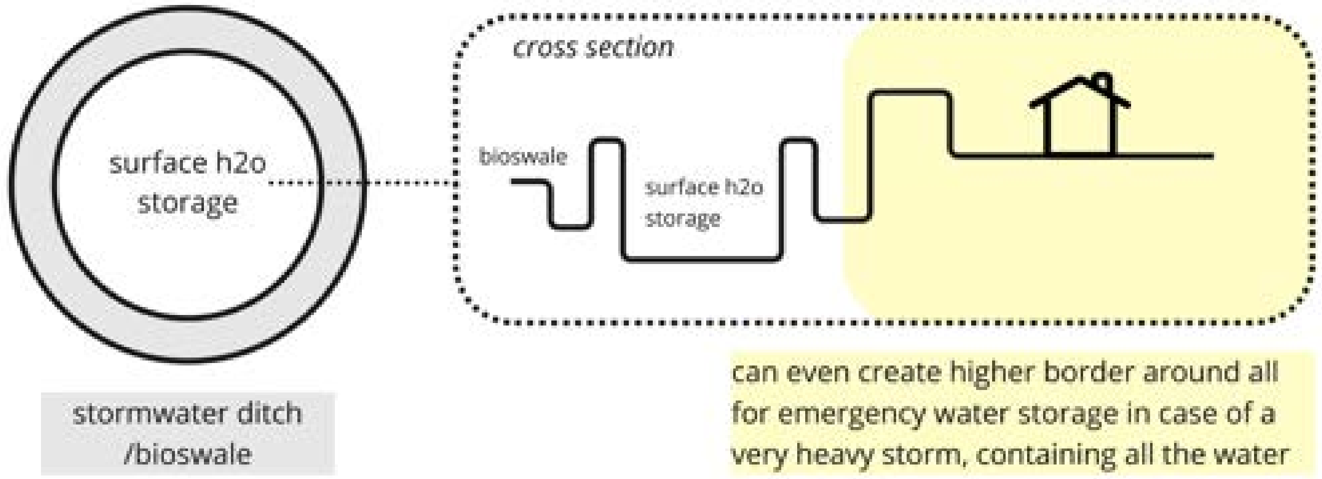


Figure 32: Playing with terracing to increase resilience and flexibility of water system

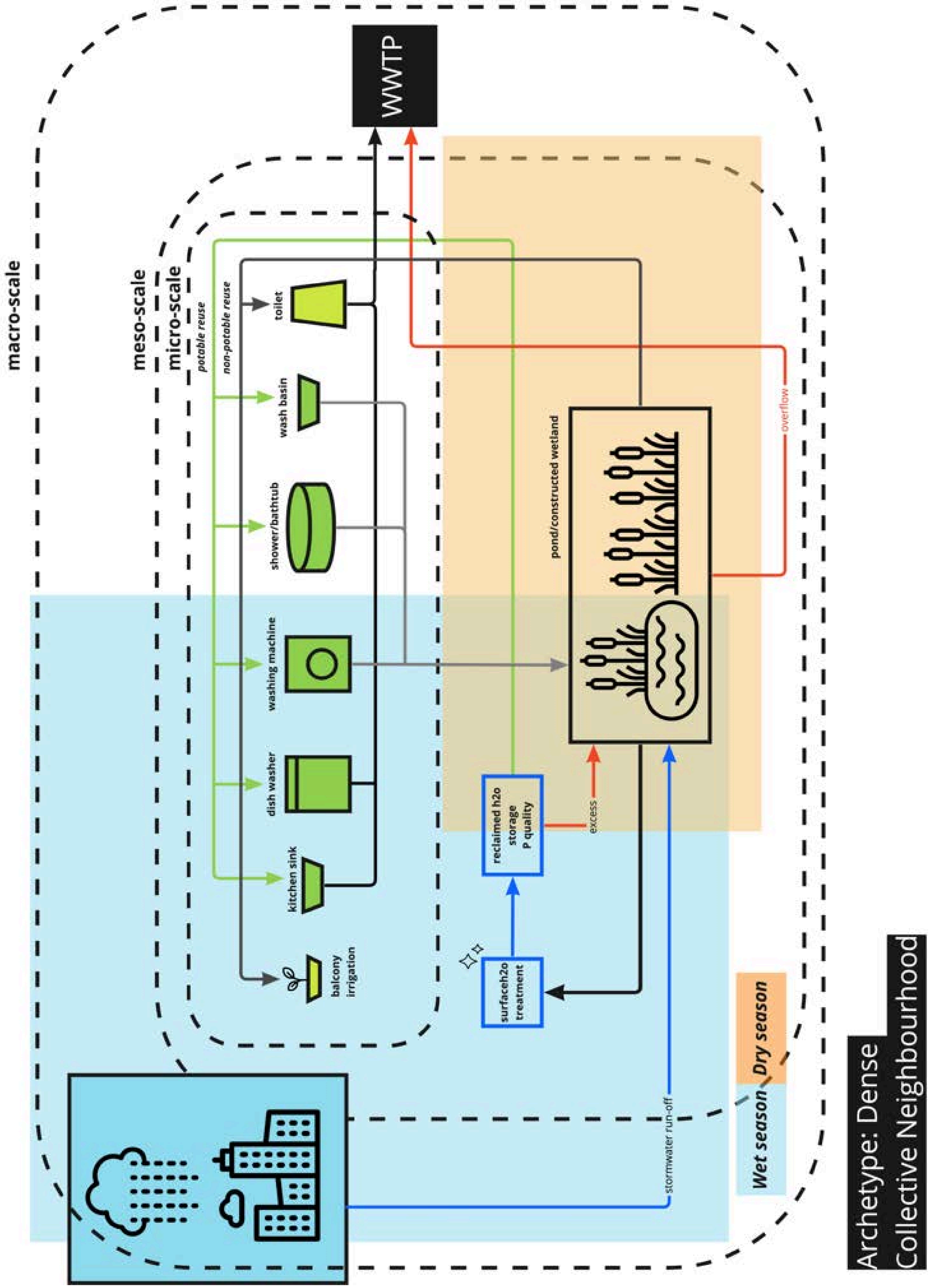


Figure 33: Water system schematic for Dense archetype's collective hybrid scenario

Conclusion

Archetype generalisations

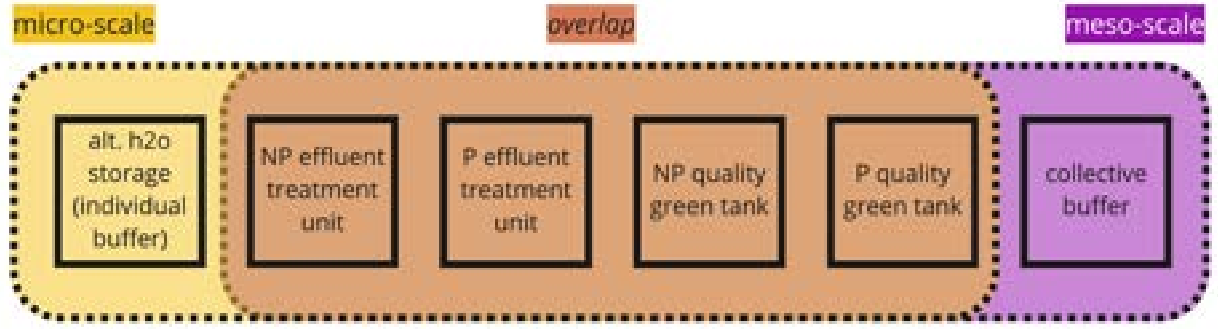


Figure 34: Basic elements for alternative water sources at micro to meso scale

It is evident from this thesis that although GW recycling is considered the least prioritised option of all alternative water sources to capitalise on, it is an interesting ingredient for increasing the flexibility of the centralised Dutch water system due to its constant availability and almost-real-time ability to meet fluxes in demand, due to the fact that it reuses the result of that demand (LGW). By rendering the LGW fit for NP quality, a WSE of 45% can be achieved. If further treated to P quality, through the means of an additional RO unit, It is plausible that 47% to 52% of residential water demand can be augmented, dependent on the retentate:permeate ratio. Such a choice would insinuate higher electricity consumption as well as higher frequency of cartridge replacements that may be wasteful in the longer run as well. LGW reuse on a decentralised scale, with its lack of standardisation and "yuck" factor, will need higher rates of public acceptance to become integrated into the social-technical system. However, it has been shown that experiences of water scarcity and small community practise can change one's mind.

Space-wise, it is clear that grey technologies are generally smaller than green technologies. Both would contribute to increasing the flexibility of the centralised water system due to their exploitation of an otherwise wasted resource. Yet, green technologies would increase the climate-resilience of a city, which will be necessary to cope with the increasingly extreme seasonal fluxes. It offers not only the capacity to purify water, but to insulate homes and filter the air from pollutants and noise. Its added value is also hard to measure, considering the calming effects that may improve a citizen's mental health.

However, size is a pressing issue if LGW is to be done on a micro-scale as individual entities. In order to achieve the same WSE of 45%, the individual's LGW reuse system would have to be scaled up by 29% to meet the climate-change-enhanced peak factor. In contrast, collective effort is able to reduce per capita TTS, as well as create larger seasonal buffers in areas where space can be afforded, which in this thesis appears to be the Dense archetype with its peri-urban-esque quality of spaciousness. Furthermore, the spatial qualities of an archetype can determine preferred seasonal dynamics that also exploit alternative water sources such as rain water, as demonstrated with the Row archetype.

From investigating the selected archetypes, it is evident that there are some generalisations that can be applied to other archetypes. In general the basic elements necessary to harvest alternative water sources in order to increase flexibility of the centralised water system can be summed into the following:

(1) Alternative water storage
(2) Alternative water treatment unit
(3) NP quality green tank
(4) P quality green tank
(5) Collective buffer

At the micro-scale it is evident that an individual or small residential unit will need to have space for untreated water storage, which doubles as their individual buffer. In this case, this buffer is defined as an intermediate storage of water for later processing. The alternative water treatment units and subsequent green tanks that follow must be separated by NP and P quality. This already demonstrates the additional space and piping needed for processing alternative water sources to potable water quality.

At the micro-scale, it is also evident that optimisation of the system is more necessary to save space and increase WSE. This is because even increasing treatment capacity and green tank volumes do not necessarily help with increasing WSE. Instead, it may waste unnecessary resources to treat the alternative water source when overflow occurs because buffering capacity is likely to be much less than collective buffers. Collective buffers increase the resilience of the urban drainage system and flexibility of the water supply system, as it offers a larger volume of back-up water, space for stormwater run-off, and longer storage durations if managed properly.

It is up to the discretion of the microclimate to determine whether the collective buffer will accept overflow of what quality. It is recommended that rain overflow should be collected, increasing the resilience of the area in general, as it prevents flash flooding and retains water without needing to transfer to another facility. However, for wastewater streams, raw wastewater should be redirected to the centralised WWTP, as discharging it into the environment without treatment exposes the surrounding environment to higher contaminants and that is why it is illegal. A way to circumvent this if there are fewer sources of alternative water and maximisation of wastewater streams is necessary to cope with fluctuations is to repurpose the shared buffer into a floating treatment plant, passively treatment the water at the same time. The treatment capacity of floating plants is dependent on incoming water influx and its spatial area, thereby HRT. So, pre-planning is necessary to account for the available space, incoming water streams and its subsequent treatment capacity. This is also an interesting idea in general, as stormwater is likely to carry a lot of pollutants from rubbish on the streets as well. A way to decrease the likelihood of cross contamination with run-off compared to the rain overflow in the shared pond is to create terraces of varying heights. Therefore, stormwater run-off can be separated from the main pond while still being detained. Although it may seep into the main pond, the passage is likely to include soil layers and macrophytes that simultaneously purify the water as well.

Future research

It is imperative to to reaffirm limitations of various other alternative water sources periodically. A fact is a nugget of information that is frozen in time and space, meanwhile changes are perpetual. For example, desalinisation has the possibility to have a zero carbon footprint if certain conditions are fulfilled (i.e renewable energy usage, proper brine control) (Pistochhi et al. 2020). If that is the case, then an abundant alternative water source becomes potentially physically and economically feasible, especially for the Western coast of the country. Ofcourse, such a situation does not mean allowing business-as-usual behaviour and lifestyle. Which is why the decentralisation of alternative water sources can offer a practical experience for people to change their perspective on their own lifestyles and perhaps even that can be reflected in their habits and vice versa if an individual is forced to changed habits to become compatible with the new hybrid water system.

Future research should look into creating water balances to analyse the interplay of alternative water sources and seasonal dynamics and determine with more accuracy and precision how much excess water from stormwater can be collected and how much deficit would occur during the seasons. Creating simulation models of the collective schematics would be able to provide further information on its feasibility and more accurate WSE. Finally, it is necessary to eventually figure out the cost and potential business models that encourage and facilitate the adoption of innovative technologies

References

Articles

1. Kajko-Mattsson, M., Karim, R., & Mirjamdotter, A. (2011). Essential components of e-maintenance. International Journal of Performability Engineering, 7(6), 555
2. 3D BAG. (2022). Overview. Accessed on April 20 2022. Available at: https://docs.3dbag.nl/en/
3. Abdel-Kader, A. M. (2013). Studying the efficiency of grey water treatment by using rotating biological contactors system. Journal of King Saud University - Engineering Sciences, 25(2), 89–95. https://doi.org/https://doi.org/10.1016/j.jksues.2012.05.003
4. Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape and Urban Planning, 100(4), 341–343. https://doi.org/https://doi.org/10.1016/j.landurbplan.2011.02.021
5. Aithal, P. S. and Aithal, Shubhrajyotsna, Opportunities & Challenges for Green Technology in 21st Century (September 8, 2016). International Journal of Current Research and Modern Education (IJCRME), 1(1), 818-828, (2016), ISSN (Online): 2455-5428,, Available at SSRN: https://ssrn.com/abstract=2837272
6. Aizstrauta, D., Ginters, E., & Eroles, M.-A. P. (2015). Applying Theory of Diffusion of Innovations to Evaluate Technology Acceptance and Sustainability. Procedia Computer Science, 43, 69–77. https://doi.org/https://doi.org/10.1016/j.procs.2014.12.010
7. Albergamo, V., Blankert, B., Van Der Meer, W. G. J., De Voogt, P., & Cornelissen, E. R. (2020). Removal of polar organic micropollutants by mixed-matrix reverse osmosis membranes. Desalination, 479, 114337.
8. Amorim, C. A., & Moura, A. do N. (2021). Ecological impacts of freshwater algal blooms on water quality, plankton biodiversity, structure, and ecosystem functioning. Science of The Total Environment, 758, 143605. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.143605
9. Amorim, C. A., & Moura, A. do N. (2021). Ecological impacts of freshwater algal blooms on water quality, plankton biodiversity, structure, and ecosystem functioning. Science of The Total Environment, 758, 143605. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.143605
10. Anda, M. (2017). Decentralized water and energy infrastructure: integration into compact urban form. In J-H. Bay, & S. Lehmann (Eds.), Growing Compact: Urban Form, Density and Sustainability Taylor and Francis. https://books.google.nl/books?hl=en&lr=&id=qEwrDwAAQBAJ&oi=fnd&pg=PT182&dq=info:yt29IbHV4BcJ:scholar.google.com&ots=Ml5mAvj6Lv&sig=XAy-xccN3Of3WaAGqM6XQYu5Bek&redir_esc=y#v=onepage&q&f=false
11. Assayed, A., Chenoweth, J., & Pedley, S. (2014). Drawer compacted sand filter: A new and innovative method for on-site grey water treatment. Environmental Technology (United Kingdom), 35(19), 2435–2446. https://doi.org/10.1080/09593330.2014.909886
12. Auvinen, H., Havran, I., Hubau, L., Vanseveren, L., Gebhardt, W., Linnemann, V., ... & Rousseau, D. P. (2017). Removal of pharmaceuticals by a pilot aerated sub-surface flow constructed wetland treating municipal and hospital wastewater. Ecological Engineering, 100, 157-164
13. Bamberg, S. (2013). Changing environmentally harmful behaviors: A stage model of self-regulated behavioral change. Journal of Environmental Psychology, 34, 151-159.
14. Bani-Melhem, K., Al-Qodah, Z., Al-Shannag, M., Qasaimeh, A., Rasool Qtaishat, M., & Alkasrawi, M. (2015). On the performance of real grey water treatment using a submerged membrane bioreactor system. Journal of Membrane Science, 476, 40–49. https://doi.org/https://doi.org/10.1016/j.memsci.2014.11.010
15. Banti, D. C., Tsangas, M., Samaras, P., & Zorpas, A. (2020). LCA of a membrane bioreactor compared to activated sludge system for municipal wastewater treatment. Membranes, 10(12), 1–15. https://doi.org/10.3390/membranes10120421
16. Barth, M., Masson, T., Fritsche, I., Fielding, K., & Smith, J. R. (2021). Collective responses to global challenges: The social psychology of pro-environmental action. Journal of Environmental Psychology, 74, 101562. https://doi.org/https://doi.org/10.1016/j.jenvp.2021.101562
17. Bell, S., Allen, A., Hofmann, P., & Teh, T. H. (Eds.). (2016). Urban water trajectories (Vol. 6). Springer.
18. Bernados, B. (2018), Reverse Osmosis for Direct Potable Reuse in California. Journal - American Water Works Association, 110: 28-36. https://doi.org/10.5942/jawwa.2018.110.0006
19. Biljecki, F., Ledoux, H., & Stoter, J. (2016). An improved LOD specification for 3D building models. Computers, Environment and Urban Systems, 59, 25–37. https://doi.org/https://doi.org/10.1016/j.compenvurbsys.2016.04.005
20. Binz, C., Harris-Lovett, S., Kiparsky, M., Sedlak, D. L., & Truffer, B. (2016). The thorny road to technology legitimation — Institutional work for potable water reuse in California. Technological Forecasting and Social Change, 103, 249–263. https://doi.org/10.1016/j.techfore.2015.10.005
21. Boddu, V., Paul, T., Page, M.A., Byl, C., Ward, L., & Ruan, J. (2016). Gray water recycle: Effect of pretreatment technologies on low pressure reverse osmosis treatment. Journal of environmental chemical engineering, 4, 4435-4443.
22. Bonnélye, V., Guey, L., & Del Castillo, J. (2008). UF/MF as RO pre-treatment: the real benefit. Desalination, 222(1), 59–65. https://doi.org/https://doi.org/10.1016/j.desal.2007.01.129
23. Boretti, A., & Rosa, L. (2019). Reassessing the projections of the world water development report. NPJ Clean Water, 2(1), 15. https://doi.org/10.1038/s41545-019-0039-9

24. Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and urban planning, 97(3), 147-155.
25. Brooks, B.W., Lazorchak, J.M., Howard, M.D., Johnson, M.-V.V., Morton, S.L., Perkins, D.A., Reavie, E.D., Scott, G.I., Smith, S.A. and Steevens, J.A. (2016), Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems?. Environ Toxicol Chem, 35: 6-13. https://doi.org/10.1002/etc.3220
26. Brooks, B.W., Lazorchak, J.M., Howard, M.D., Johnson, M.-V.V., Morton, S.L., Perkins, D.A., Reavie, E.D., Scott, G.I., Smith, S.A. and Steevens, J.A. (2016), Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems?. Environ Toxicol Chem, 35: 6-13. https://doi.org/10.1002/etc.3220
27. Brouwer S, van Aalderen N, Koop SHA (2021) Assessing tap water awareness: The development of an empirically-based framework. PLoS ONE 16(10): e0259233. https://doi.org/10.1371/journal.pone.0259233
28. Bui, X. T., Nguyen, V. T., Nguyen, D. D., Sthiannopkao, S., & Lin, C. (2017). Improvement of septic tank effluent and green coverage by shallow bed wetland roof system. International Biodeterioration & Biodegradation, 124, 138-145.
29. Bulkeley, H. (2013). Cities and climate change. Routledge.
30. Bunch, M., Morrison, K. E., Parkes, M. W., & Venema, H. D. (2011). Ecology and society: Promoting health and well-being by managing for social-ecological resilience: The potential of integrating ecohealth and water resources management approaches. Ecology and Society, 16(1), 6. doi:10.5751/ES- 03803-160106
31. Bundschuh, J., Kaczmarczyk, M., Ghaffour, N., & Tomaszewska, B. (2021). State-of-the-art of renewable energy sources used in water desalination: Present and future prospects. Desalination, 508, 115035. https://doi.org/https://doi.org/10.1016/j.desal.2021.115035
32. Byrne, J., & Jinjun, Y. (2009). Can urban greenspace combat climate change? Towards a subtropical cities research agenda. Australian Planner, 46(4), 36-43
33. Capodaglio, A. G., Ghilardi, P., & Boguniewicz-Zablocka, J. (2016). New paradigms in urban water management for conservation and sustainability. Water Practice and Technology, 11(1), 176–186. https://doi.org/10.2166/wpt.2016.022
34. Caroline J. Uittenbroek, Heleen L. P. Mees, Dries L. T. Hegger & Peter P. J. Driessen (2019) The design of public participation: who participates, when and how? Insights in climate adaptation planning from the Netherlands, Journal of Environmental Planning and Management, 62:14, 2529-2547, DOI: 10.1080/09640568.2019.1569503
35. Castellar, J. A. C., Torrens, A., Buttiglieri, G., Monclús, H., Arias, C. A., Carvalho, P. N., Galvao, A., & Comas, J. (2022). Nature-based solutions coupled with advanced technologies: An opportunity for decentralized water reuse in cities. Journal of Cleaner Production, 340, 130660. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130660
36. CBS (2022). Households used more water in 2020, companies less. Available at: https://www.cbs.nl/en-gb/news/2022/12/households-used-more-water-in-2020-companies-less
37. CBS (2022). Households used more water in 2020, companies less. Available at: https://www.cbs.nl/en-gb/news/2022/12/households-used-more-water-in-2020-companies-less
38. CBS. 2016. Small and relatively expensive housing in Amsterdam. Available at: https://www.cbs.nl/en-gb/news/2016/14/small-and-relatively-expensive-housing-in-amsterdam#:~:text=These%20are%20figures%20released%20by,in%20the%20Netherlands%20Housing%20Survey.&text=Amsterdam%20has%20the%20smallest%20houses,average%20is%2067%20m2.
39. Chen, Z., Ngo, H. H., Guo, W., Wang, X. C., Miechel, C., Corby, N., & O'Halloran, K. (2013). Analysis of social attitude to the new end use of recycled water for household laundry in Australia by the regression models. Journal of Environmental Management, 126, 79–84
40. Cheung, C. T., Mui, K. W., & Wong, L. T. (2013). Energy efficiency of elevated water supply tanks for high-rise buildings. Applied Energy, 103, 685–691. https://doi.org/https://doi.org/10.1016/j.apenergy.2012.10.041
41. Churchman, A. 1999. Disentangling the concept of density. Journal of Planning Literature, 13(4), pp. 389-411.
City of New York, 1990. Zoning handbook.

42. Climate Change Knowledge Portal (2022). Climate Data Projections, the Netherlands. Accessed in July 10, 2022. Available at: https://climateknowledgeportal.worldbank.org/country/netherlands/climate-data-projections
43. Coelho, B., & Andrade-Campos, A. (2014). Efficiency achievement in water supply systems—A review. Renewable and Sustainable Energy Reviews, 30, 59-84
44. Corinne Ong (2021) Capitalising on water soft paths: new futures for urban communities, Local Environment, 26:7, 872-892, DOI: 10.1080/13549839.2021.1931073
45. Coutts, C. (2016). Green infrastructure and public health. Abingdon, UK; New York, NY: Routledge
46. Covarrubias, A. (2010). Lending for electric power in sub-saharan Africa. Available from: wbln0018.worldbank.org/oed/oeddoclib.nsf/3ff836dc39b23cef85256885007b956b/58d5511f6e77e2498525681800610d04?
47. Cunillera-Montcusí, D., Beklioğlu, M., Cañedo-Argüelles, M., Jeppesen, E., Ptáčník, R., Amorim, C.A., Arnott, S.E., Berger, S.A., Brucet, S., Dugan, H.A., Gerhard, M., Horváth, Z., Langenheder, S., Nejstgaard, J.C., Reinikainen, M., Striebel, M., Urrutia-Cordero, P., Vad, C.F., Zadereev, E., & Matias, M.G. (2022). Freshwater salinisation: a research agenda for a saltier world. Trends in ecology & evolution.
48. Dai, L., van Rijswick, H., Driessen, P., & Keessen, A. (2017). Governance of the sponge city programme in China with Wuhan as a case study. International Journal of Water Resources Development. doi: 10.1080/07900627.2017.1373637
49. Dakos, V., Matthews, B., Hendry, A. P., Levine, J., Loeuille, N., Norberg, J., Nosil, P., Scheffer, M., & De Meester, L. (2019). Ecosystem tipping points in an evolving world. Nature Ecology & Evolution, 3(3), 355–362. https://doi.org/10.1038/s41559-019-0797-2
50. de Haan, F. J., Rogers, B. C., Frantzeskaki, N., & Brown, R. R. (2015). Transitions through a lens of urban water. Environmental Innovation and Societal Transitions, 15, 1–10. https://doi.org/10.1016/j.eist.2014.11.005
51. de Oliveira, T. M., Benatti, C. T., & Tavares, C. R. G. (2020). Pilot system of microfiltration and reverse osmosis membranes fogreywater reuse. Desalination and Water Treatment, 201, 13–19. https://doi.org/10.5004/dwt.2020.26020
52. Dixon, A., Butler, D., & Fewkes, A. (1999). Water saving potential of domestic water reuse systems using greywater and rainwater in combination. Water Science and Technology, 39(5), 25–32. doi:10.2166/wst.1999.0218
53. Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). Multi-criteria analysis: a manual.
54. Dominguez, S., Laso, J., Margallo, M., Aldaco, R., Rivero, M. J., Irabien, Á., & Ortiz, I. (2018). LCA of greywater management within a water circular economy restorative thinking framework. Science of The Total Environment, 621, 1047–1056. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.10.122
55. Du Plessis, C., & Brandon, P. (2015). An ecological worldview as basis for a regenerative sustainability paradigm for the built environment. Journal of Cleaner Production, 109, 53–61. https://doi.org/10.1016/j.jclepro.2014.09.098
56. Dunmade, I. (2002). Indicators of sustainability: assessing the suitability of a foreign technology for a developing economy. Technology in Society, 24(4), 461–471. https://doi.org/https://doi.org/10.1016/S0160-791X(02)00036-2
57. Emmanuel, R., & Loconsole, A. (2015). Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region, UK. Landscape and Urban Planning, 138, 71-86
58. Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (Eds.). (2012). Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press
59. Fielding, K. S., Dolnicar, S., & Schultz, T. (2019). Public acceptance of recycled water. International Journal of Water Resources Development, 35(4), 551–586. https://doi.org/10.1080/07900627.2017.1419125
60. Fleming, B. (2016). Lost in translation: The authorship and argu- mentation of resilience theory. Landscape Journal, 35(1), 23–36. doi:10.3368/lj.35.1.23
61. Fountoulakis, M. S., Markakis, N., Petousi, I., & Manios, T. (2016). Single house on-site grey water treatment using a submerged membrane bioreactor for toilet flushing. Science of The Total Environment, 551–552, 706–711. https://doi.org/https://doi.org/10.1016/j.scitotenv.2016.02.057
62. Francesch-Huidobro, M., Dabrowski, M., Tai, Y., Chan, F., & Stead, D. (2016). Governance challenges of flood-prone delta cities: Integrating flood risk management and climate change in spatial planning. Progress in Planning, 10, 1-27. doi:10.1016/j.progress.2015.1
63. Franco-Torres, M., Rogers, B. C., & Harder, R. (2021). Articulating the new urban water paradigm. Critical Reviews in Environmental Science and Technology, 51(23), 2777-2823
64. Friedler, E., Kovalio, R., & Ben-Zvi, A. (2006). Comparative study of the microbial quality of greywater treated by three on-site treatment systems. Environmental technology, 27(6), 653-663
65. Friedrich, J., Poganietz, W., & Lehn, H. (2020). Life-cycle assessment of system alternatives for the Water-Energy-Waste Nexus in the urban building stock. Resources Conservation and Recycling, 158, 104808.
66. Gaffin, S., Rosenzweig, C. & Kong, A. Adapting to climate change through urban green infrastructure. Nature Clim Change 2, 704 (2012). https://doi.org/10.1038/nclimate1685
67. Galar, D. (2014). Context-driven Maintenance: an eMaintenance approach. Management Systems in Production Engineering, (3 (15)), 112-120
68. Garrison, N., & Hobbs, K. (2011). Rooftops to Rivers II: Green strategies for controlling stormwater and combined sewer overflows. Natural Resources Defense Council, New York, NY, 1-134
69. Gil, J. A., Túa, L., Rueda, A., Montaño, B., Rodríguez, M., & Prats, D. (2010). Monitoring and analysis of the energy cost of an MBR. Desalination, 250(3), 997–1001. https://doi.org/https://doi.org/10.1016/j.desal.2009.09.089
70. Global Commission on Economy and Climate (GCEC). (2016) The sustainable infrastructure imperative: Financing for better growth and development. Retrieved Nov 15, 2021, from http://newclimateeconomy.report/2016/wp-content/uploads/sites/4/2014/08/NCE_2016Report.pdf

71. Godschalk, D. R. (2003). Urban hazard mitigation: Creating resilient cities. Natural Hazards Review, 4(3), 136–143. doi:10.1061/(ASCE)1527-6988(2003)4:3(136)
72. Gonzales, P., & Ajami, N. K. (2017). An integrative regional resilience framework for the changing urban water paradigm. Sustainable Cities and Society, 30(Supplement C), 128–138. https://doi.org/10.1016/j.scs.2017.01.012
73. Government.nl (2022). Addresses and Buildings Key Register (BAG). Accessed on May 30 2022. Available at: https://business.gov.nl/regulation/addresses-and-buildings-key-geo-register/
74. Gray, T. (2016). Issues in green infrastructure: Operations and maintenance lessons and coastal research needs. Hauppage, NY: Nova.
75. Hagan, Susannah. 2000. Cities of field: Cyberspace and urban space. In Architecture, city, environment. Proceedings of PLEA 2000, ed. Steemers Koen and Simos Yannas, 348-52. London: James & James.
76. Hamingerova, M., Borunsky, L., & Beckmann, M. (2015). Membrane technologies for water and wastewater treatment on the European and Indian market. Techview Report of Fraunhofer Center for International Management and Knowledge Economy. Fraunhofer IMW, Leipzig, Germany
77. Hartley, K., Tortajada, C., & Biswas, A. K. (2019). A formal model concerning policy strategies to build public acceptance of potable water reuse. Journal of Environmental Management, 250, 109505. https://doi.org/https://doi.org/10.1016/j.jenvman.2019.109505
78. Havermans, O. (2022, May 23). 'Zekerheid dat er altijd drinkwater is staat onder druk' Trouw. https://www.trouw.nl/duurzaamheid-natuur/zekerheid-dat-er-altijd-drinkwater-is-staat-onder-druk~b2d40e3e/
79. Hofman-Caris, R., Bertelkamp, C., de Waal, L., Brand, T., & Aa, R. (2018). Rainwater harvesting in the Netherlands: useful or not? November 2018, 61–67.
80. Hofman-Caris, R., Bertelkamp, C., de Waal, L., van den Brand, T., Hofman, J., van der Aa, R., & van der Hoek, J. P. (2019). Rainwater Harvesting for Drinking Water Production: A Sustainable and Cost-Effective Solution in The Netherlands? In Water (Vol. 11, Issue 3). https://doi.org/10.3390/w11030511
81. Hofman, J. & Paalman, M. (2014). Rainwater harvesting, a sustainable solution for urban climate adaptation? KWR. Report BTO 2014.042. Available at: https://edepot.wur.nl/345625
82. Holloway, R. W., Miller-Robbie, L., Patel, M., Stokes, J. R., Munakata-Marr, J., Dadakis, J., & Cath, T. Y. (2016). Life-cycle assessment of two potable water reuse technologies: MF/RO/UV–AOP treatment and hybrid osmotic membrane bioreactors. Journal of Membrane Science, 507, 165–178. https://doi.org/https://doi.org/10.1016/j.memsci.2016.01.045
83. Hoofs, J. (2022, July 8). 'WML stopt tijdelijk het halen van drinkwater uit de Maas' 1Limburg.
84. Hooimeijer, F.L., Lafleur, F., & Trinh, T. (2017). Drawing the subsurface: an integrative design approach. Procedia Engineering, 209, 61-74.
85. Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Science of The Total Environment, 409(19), 3578–3594. https://doi.org/https://doi.org/10.1016/j.scitotenv.2011.06.022
86. Jabornig, S., & Favero, E. (2013). Single household greywater treatment with a moving bed biofilm membrane reactor (MBBMR). Journal of Membrane Science, 446, 277–285. https://doi.org/https://doi.org/10.1016/j.memsci.2013.06.049
87. Jabornig, S., & Favero, E. (2013). Single household greywater treatment with a moving bed biofilm membrane reactor (MBBMR). Journal of Membrane Science, 446, 277-285.
88. James Horne, Cecilia Tortajada & Larry Harrington (2018) Achieving the Sustainable Development Goals: improving water services in cities affected by extreme weather events, International Journal of Water Resources Development, 34:4, 475-489, DOI: 10.1080/07900627.2018.1464902
89. Jenssen, P.D. & Vråle, L. (2003). Greywater treatment in combined biofilter/constructed wetlands in cold climate. In:P C. Werner et al. (eds.) Ecosan — closing the loop. Proc. 2nd int. symp. Ecological sanitation, Lübeck Apr. 7-11. 2003, GTZ, Germany, pp: 875-881.
90. Jeong, H., Broesicke, O. A., Drew, B., & Crittenden, J. C. (2018). Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. Journal of Cleaner Production, 174, 333–342. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.10.193
91. Johansson, N., Roth, E., & Reim, W. (2019). Smart and Sustainable eMaintenance: Capabilities for Digitalization of Maintenance. Sustainability, 11(13), 3553. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su11133553
92. Jugert, P., Greenaway, K. H., Barth, M., Büchner, R., Eisentraut, S., & Fritsche, I. (2016). Collective efficacy increases pro-environmental intentions through increasing self-efficacy. Journal of Environmental Psychology, 48, 12-23
93. Keeney, R. L., Raiffa, H., & Meyer, R. F. (1993). Decisions with multiple objectives: preferences and value trade-offs. Cambridge university press.
94. Kumar, N. U., & Martin, A. (2014). Co-generation of drinking water and domestic hot water using solar thermal integrated membrane distillation system. Energy Procedia, 61, 2666-2669
95. Kumar, V., & Shah, M. P. (2021). 1 - Advanced oxidation processes for complex wastewater treatment (M. P. B. T.-A. O. P. for E. T. P. Shah (ed.); pp. 1–31). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-821011-6.00001-3
96. Lakho, F. H., Le, H. Q., Van Kerkhove, F., Igodt, W., Depuydt, V., Desloover, J., Rousseau, D. P. L., & Van Hulle, S. W. H. (2020). Water treatment and re-use at temporary events using a mobile constructed wetland and drinking water production system. Science of The Total Environment, 737, 139630. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.139630
97. Lakho, F. H., Qureshi, A., Novelli, L. D. D., Depuydt, V., Depreeuw, T., Van Hulle, S. W. H., & Rousseau, D. P. L. (2022). Performance of a green wall (Total Value WallTM) at high greywater loading rates and Life Cycle Impact Assessment. Science of the Total Environment, 821, 153470. https://doi.org/10.1016/j.scitotenv.2022.153470
98. Lakho, F. H., Vergote, J., Ihsan-Ul-Haq Khan, H., Depuydt, V., Depreeuw, T., Van Hulle, S. W. H., & Rousseau, D. P. L. (2021). Total value wall: Full scale demonstration of a green wall for grey water treatment and recycling. Journal of Environmental Management, 298, 113489. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113489
99. Lau, J. T., & Mah, D. (2018). Green wall for retention of stormwater. Pertanika Journal of Science and Technology, 26, 283–298.
100. Le-Clech, P., Chen, V., & Fane, T. A. (2006). Fouling in membrane bioreactors used in wastewater treatment. Journal of membrane science, 284(1-2), 17-53.
101. Lefrançois, Camille B.. (2015). Designing Effective Stormwater Management Policies - The Role of the Urban Forest and Impervious Cover in Vancouver, B.C.. 10.14288/1.0300042.
102. Lefrançois, Camille B.. (2015). Designing Effective Stormwater Management Policies - The Role of the Urban Forest and Impervious Cover in Vancouver, B.C.. 10.14288/1.0300042.
103. Leigh, N., & Lee, H. (2019). Sustainable and Resilient Urban Water Systems: The Role of Decentralization and Planning. Sustainability, 11(3), 918. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su11030918
104. Leiva, E., Rodríguez, C., Sánchez, R., & Serrano, J. (2021). Light or Dark GW for Water Reuse? Economic Assessment of On-Site GW Treatment Systems in Rural Areas. Water.
105. Leong, J. Y. C., Oh, K. S., Poh, P. E., & Chong, M. N. (2017). Prospects of hybrid rainwater-greywater decentralised system for water recycling and reuse: A review. Journal of Cleaner Production, 142, 3014–3027. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.10.167
106. Li, C., Liu, M., Hu, Y., Zhou, R., Wu, W., & Huang, N. (2021). Evaluating the runoff storage supply-demand structure of green infrastructure for urban flood management. Journal of Cleaner Production, 280, 124420. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124420
107. Li, F., (2009). Treatment of household GW for non-potable reuses. PhD thesis, Hamburg University of Technology, 2009.
108. Li, F., Gulyas, H., Wichmann, K., & Otterpohl, R. (2009). Treatment of household grey water with a UF membrane filtration system. Desalination and Water Treatment, 5(1–3), 275–282. https://doi.org/10.5004/dwt.2009.550
109. Li, F., Wichmann, K., & Otterpohl, R. (2009). Review of the technological approaches for grey water treatment and reuses. Science of the total environment, 407(11), 3439-3449.
110. Li, Q., Beier, L. J., Tan, J., Brown, C., Lian, B., Zhong, W., Wang, Y., Ji, C., Dai, P., Li, T., Le Clech, P., Tyagi, H., Liu, X., Leslie, G., & Taylor, R. A. (2019). An integrated, solar-driven membrane distillation system for water purification and energy generation. Applied Energy, 237(August 2018), 534–548. https://doi.org/10.1016/j.apenergy.2018.12.069
111. Liao, X., Wishard, M.J. (2021). Nature-based solutions in China: Financing "sponge cities" for integrated urban flood management. World Bank Blogs. Available at: https://blogs.worldbank.org/eastasiapacific/nature-based-solutions-china-financing-sponge-cities-integrated-urban-flood
112. Liping Dai, Carel Dieperink, Susanne Wuijts & Marleen van Rijswick (2022) Assessing the soundness of water governance: lessons learned from applying the 10 Building Blocks Approach, Water International, 47:4, 610-631, DOI: 10.1080/02508060.2022.2048487
113. Liping Dai, Rebecca Wörner & Helena F. M. W. van Rijswick (2018) Rainproof cities in the Netherlands: approaches in Dutch water governance to climate-adaptive urban planning, International Journal of Water Resources Development, 34:4, 652-674, DOI: 10.1080/07900627.2017.1372273
114. Liu, Lijiao, Junjun Cao, Mehran Ali, Jiaxin Zhang, and Zhaolong Wang. "Impact of green roof plant species on domestic wastewater treatment." Environmental advances 4 (2021): 100059
115. López-Ruiz, S., Moya-Fernández, P. J., García-Rubio, M. A., & González-Gómez, F. (2021). Acceptance of direct potable water reuse for domestic purposes: evidence from southern Spain. International Journal of Water Resources Development, 37(5), 772-792
116. Ma, Y., Jiang, Y., & Swallow, S. (2020). China's sponge city development for urban water resilience and sustainability: A policy discussion. Science of The Total Environment, 729, 139078. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.139078
117. Marlow, D. R., Moglia, M., Cook, S., & Beale, D. J. (2013). Towards sustainable urban water management: A critical reassessment. Water Research, 47(20), 7150–7161. https://doi.org/https://doi.org/10.1016/j.watres.2013.07.046
118. Masmoudi Jabri, K., Nolde, E., Ciroth, A., & Bousselmi, L. (2020). Life cycle assessment of a decentralized greywater treatment alternative for non-potable reuse application. International Journal of Environmental Science and Technology, 17(1), 433–444. https://doi.org/10.1007/s13762-019-02511-3
119. Masmoudi Jabri, K., Nolde, E.L., Ciroth, A., & Bousselmi, L. (2019). Life cycle assessment of a

decentralized greywater treatment alternative for non-potable reuse application. International Journal of Environmental Science and Technology, 17, 433-444.
120. Meneses, M., Pasqualino, J. C., & Castells, F. (2010). Environmental assessment of urban wastewater reuse: Treatment alternatives and applications. Chemosphere, 81(2), 266-272
121. Meneses, M., Pasqualino, J. C., & Castells, F. (2010). Environmental assessment of urban wastewater reuse: Treatment alternatives and applications. Chemosphere, 81(2), 266–272. https://doi.org/https://doi.org/10.1016/j.chemosphere.2010.05.053
122. Mensink, J., & van der Hoeven, F. (2017). Density, compact urban form and sustainability in the Netherlands. In J-H. Bay, & S. Lehmann (Eds.), Growing Compact: Urban Form, Density and Sustainability Taylor and Francis.
123. Merz, C., Scheumann, R., El Hamouri, B., & Kraume, M. (2007). Membrane bioreactor technology for the treatment of greywater from a sports and leisure club. Desalination, 215(1), 37–43. https://doi.org/https://doi.org/10.1016/j.desal.2006.10.026
124. Millennium Ecosystem Assessment, (2005). Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
125. Mondria, M. (2020). How does a WADI work? Bachelor's Thesis. University of Twente. Available at: http://essay.utwente.nl/82472/1/Mondria_BA_EEMCS.pdf
126. Moya-Fernández, P. J., López-Ruiz, S., Guardiola, J., & González-Gómez, F. (2021). Determinants of the acceptance of domestic use of recycled water by use type. Sustainable Production and Consumption, 27, 575–586. doi:10.1016/j.spc.2021.01.026
127. Mukherjee, M., & Jensen, O. (2020). Making water reuse safe: A comparative analysis of the development of regulation and technology uptake in the US and Australia. Safety Science, 121, 5–14. https://doi.org/https://doi.org/10.1016/j.ssci.2019.08.039
128. Müller, T. M., Leise, P., Lorenz, I.-S., Altherr, L. C., & Pelz, P. F. (2021). Optimization and validation of pumping system design and operation for water supply in high-rise buildings. Optimization and Engineering, 22(2), 643–686. https://doi.org/10.1007/s11081-020-09553-4
129. Muurtuin (2022) Toepassing. Accessed on April 20 2022. Available at: https://www.muurtuin.be/toepassing/
130. Nagel, R. (2015), Making Direct Potable Reuse a Reality. Journal - American Water Works Association, 107: 76-82. https://doi.org/10.5942/jawwa.2015.107.0103
131. Nath, V., Kumar, R., Agrawal, R., Gautam, A., & Sharma, V. (2012). Green behaviors of Indian consumers. International journal of research in management, Economics and Commerce, 2(11), 488-498.
132. National Research Council. (2012). Water reuse: Potential for expanding the nation's water supply through reuse of municipal wastewater. National Academies Press.
133. Nault, J., & Papa, F. (2015). Lifecycle assessment of a water distribution system pump. Journal of Water Resources Planning and Management, 141(12), A4015004
134. Nguyen, V.-T., Bui, X.-T., Nguyen, H.-A., Lin, C., Nguyen, H.-H., Vo, T.-D.-H., Tran, L.-L., Nguyen, T.-B., Bui, M.-H., Nguyen, D.-T., Nguyen, D.-D., & Chang, S. W. (2021). Influence of plant types, bed media and feeding patterns on wastewater treatment performance of wetland roofs. Journal of Water Process Engineering, 40, 101972. https://doi.org/https://doi.org/10.1016/j.jwpe.2021.101972
135. Nolde, E. (1996). Wasserrecycling in 4-Sterne Hotel. Wasserwirtschaft Wassertechnik, 6, 39-41
136. Nolde, E. (2000). Greywater reuse systems for toilet flushing in multi-storey buildings – over ten years experience in Berlin. Urban Water, 1(4), 275–284. https://doi.org/https://doi.org/10.1016/S1462-0758(00)00023-6
137. Novotny, V. (2020). Integrated sustainable urban water, energy, and solids management: Achieving triple net-zero adverse impact goals and resiliency of future communities. John Wiley & Sons.
138. Ntengwe, F. W. (2004). The impact of consumer awareness of water sector issues on willingness to pay and cost recovery in Zambia. Physics and Chemistry of the Earth, Parts A/B/C, 29(15-18), 1301-1308
139. Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., ... & Rowe, B. (2007). Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience, 57(10), 823-833
140. Pasqualino, J.C., Meneses, M. and Castells, F. (2011), Life Cycle Assessment of Urban Wastewater Reclamation and Reuse Alternatives. Journal of Industrial Ecology, 15: 49-63. https://doi.org/10.1111/j.1530-9290.2010.00293.x
141. Pauw, P., De Louw, P., & Essink, G. (2012). Groundwater salinisation in the Wadden Sea area of the Netherlands: Quantifying the effects of climate change, sea-level rise and anthropogenic interferences. Netherlands Journal of Geosciences - Geologie En Mijnbouw, 91(3), 373-383. doi:10.1017/S0016774600000500
142. Peacock, B. (1996). Energy and cost required to lift or pressurize water. Available at: https://cetulare.ucanr.edu/files/82040.pdf
143. Pham, T. T. N., Ngo, H. H., Guo, W., Dang, H. P. D., Mainali, B., Johnston, A., & Listowski, A. (2011). Responses of community to the possible use of recycled water for washing machines: A case study in Sydney, Australia. Resources, Conservation and Recycling, 55(5), 535–540. doi:10.1016/j.resconrec.2011.01.004
144. Pistocchi, A., Bleninger, T., Breyer, C., Caldera, U., Dorati, C., Ganora, D., Millán, M. M., Paton, C., Poullis, D., Herrero, F. S., Sapiano, M., Semiat, R., Sommariva, C., Yuece, S., & Zaragoza, G. (2020). Can seawater desalination be a win-win fix to our water cycle? Water Research, 182, 115906. https://doi.org/https://doi.org/10.1016/j.watres.2020.115906
145. Puri, P., Yenkie, M.K., Rana, D., Meshram, S., & Awale, L.S. (2015). Surface water (Futala Lake) quality and its pollution load in terms of water quality index (WQI). Advances in Applied Science Research, 6, 15-26.
146. Raluy, R. G., Schwantes, R., Subiela, V. J., Peñate, B., Melián, G., & Betancort, J. R. (2012). Operational experience of a solar membrane distillation demonstration plant in Pozo Izquierdo-Gran Canaria Island (Spain). Desalination, 290, 1–13. https://doi.org/https://doi.org/10.1016/j.desal.2012.01.003
147. Revi, A., Satterthwaite, D. E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B., Pelling, M., ... & Genova, R. C. (2017). Urban areas.
148. Rijkswaterstaat (2019). Water management in the Netherlands. Available at: https://www.helpdeskwater.nl/publish/pages/165190/rij_8475_watermanagement_en_dv_1.pdf
149. Rogers, E. M. (1962). Diffusion of innovations. New York: Free Press of Glencoe.
150. Rozin, P., Haddad, B., Nemeroff, C., & Slovic, P. (2015). Psychological aspects of the rejection of recycled water: Contamination, purification and disgust. Judgement and Decision Making, 10(1), 50–63
151. Şahin, N. İ., & Manioğlu, G. (2019). Water conservation through rainwater harvesting using different building forms in different climatic regions. Sustainable Cities and Society, 44, 367–377. https://doi.org/https://doi.org/10.1016/j.scs.2018.10.010
152. Said, I. A., Chomiak, T. R., He, Z., & Li, Q. (2020). Low-cost high-efficiency solar membrane distillation for treatment of oil produced waters. Separation and Purification Technology, 250, 117170. https://doi.org/https://doi.org/10.1016/j.seppur.2020.117170
153. Saidi, A., Masmoudi, K., Nolde, E., El Amrani, B., & Amraoui, F. (2017). Organic matter degradation in a greywater recycling system using a multistage moving bed biofilm reactor (MBBR). Water Science and Technology, 76(12), 3328-3339
154. Salomon, E., Preston, J. L., & Tannenbaum, M. B. (2017). Climate change helplessness and the (de) moralization of individual energy behavior. Journal of Experimental Psychology: Applied, 23(1), 15
155. Sapkota, M., Arora, M., Malano, H., Moglia, M., Sharma, A., George, B., & Pamminger, F. (2014). An Overview of Hybrid Water Supply Systems in the Context of Urban Water Management: Challenges and Opportunities. Water, 7(12), 153–174. MDPI AG. Retrieved from http://dx.doi.org/10.3390/w7010153
156. Sarkar, P., Sharma, B., & Malik, U. (2014). Energy generation from grey water in high raised buildings: The case of India. Renewable Energy, 69, 284–289. https://doi.org/https://doi.org/10.1016/j.renene.2014.03.046
157. Scholes, R. C., Stiegler, A. N., Anderson, C. M., & Sedlak, D. L. (2021). Enabling Water Reuse by Treatment of Reverse Osmosis Concentrate: The Promise of Constructed Wetlands. ACS Environmental Au, 1(1), 7–17. https://doi.org/10.1021/acsenvironau.1c00013
158. Schramm, E.; Felmeden, J. Towards more resilient water infrastructures. In Resilient Cities 2; Springer: Berlin, Germany, 2012; pp. 177–186

159. Seth M. Munson, Sasha C. Reed, Josep Peñuelas, Nathan G. McDowell, & Osvaldo E. Sala. (2018). Ecosystem thresholds, tipping points, and critical transitions. The New Phytologist, 218(4), 1315–1317. https://www.jstor.org/stable/90021529
160. Shaleen Miller (2020) Greenspace After a Disaster: The Need to Close the Gap With Recovery for Greater Resilience, Journal of the American Planning Association, 86:3, 339-348, DOI: 10.1080/01944363.2020.1730223
161. Singh, V., Kaur, A., Ghawana, T., & Gupta, N. (2018). Feasibility Study of Treatment Technologies for GW to Enhance Water Security.
162. Stec, A. (2018). Rainwater harvesting and greywater recycling as alternative water resources: a survey of public opinion.
163. Stoeten, V. (2022). A systematic approach to characterise consecutive events in the Netherlands: from extremely dry to extremely wet (Unpublished master's dissertation). Delft University of Technology, Delft, the Netherlands.
164. Tamboli, A., Joseph, L., Vadnere, U., & Xu, X. (2008, March). Tall buildings: sustainable design opportunities. In Proc. of the CTBUH 8th World Congress (pp. 3-5).
165. Tang, C. Y., Yang, Z., Guo, H., Wen, J. J., Nghiem, L. D., & Cornelissen, E. (2018). Potable Water Reuse through Advanced Membrane Technology. Environmental Science & Technology, 52(18), 10215–10223. https://doi.org/10.1021/acs.est.8b00562
166. Tayara, A., Shanableh, A., Atieh, M.A., Abdallah, M., Battacharjee, S., Mustafa, A., & Bardan, M. (2021). Feasibility and impact of greywater recycling in four types of buildings in Sharjah, United Arab Emirates. IOP Conference Series: Earth and Environmental Science, 725.
167. Tchobanoglous, G., Cotruvo, J., Crook, J., McDonald, E., Olivieri, A., Salveson, A., & Trussell, R. S. (2015). Framework for direct potable reuse. WateReuse Research Foundation, 14-20
168. Thanh, B. X., Hai Van, P. T., Tin, N. T., Hien, V. T. D., Dan, N. P., & Koottatep, T. (2014). Performance of wetland roof with Melampodium paludosum treating septic tank effluent. Desalination and Water Treatment, 52(4-6), 1070-1076

169. Tyler, S., & Moench, M. (2012). A framework for urban climate resilience. Climate and Development, 4(4), 311–326. https://doi.org/10.1080/17565529.2012.745389
170. UKWIR, 2018, The National Chemical Investigations Programme 2015-2020, London
171. UN-WATER. (2018). Annual report 2017. UN-Water Technical Advisory Unit
172. van den Brink, M., Huismans, Y., Blaas, M., & Zwolsman, G. (2019). Climate Change Induced Salinization of Drinking Water Inlets along a Tidal Branch of the Rhine River: Impact Assessment and an Adaptive Strategy for Water Resources Management. Climate, 7(4), 49. https://doi.org/10.3390/cli7040049
173. Van Der Bruggen, B., Vandecasteele, C., Van Gestel, T., Doyen, W. and Leysen, R. (2003), A review of pressure-driven membrane processes in wastewater treatment and drinking water production. Environ. Prog., 22: 46-56. https://doi.org/10.1002/ep.670220116
174. Van der Krogt, W., Becker, B., Boisgontier, H. (2022). Low river discharge of the Meuse. RIWA-Meuse & Deltares. Available at: https://www.riwa-maas.org/wp-content/uploads/2022/06/IDF2857-RIWA-MAAS-Low-River-Discharge-of-the-Meuse-Rapport-digitaal.pdf
175. van Dijk, M. P., & Liang, X. (2012). Case study brief – Beijing, managing water for the eco city of the future (Final Report Annex). SWITCH–Managing Water for the City of the Future. UNESCO-IHE
176. Van Zomeren, M., Postmes, T., & Spears, R. (2008). Toward an integrative social identity model of collective action: a quantitative research synthesis of three socio-psychological perspectives. Psychological bulletin, 134(4), 504.
177. Van, Phan Thi Hai, Nguyen Thanh Tin, Vo Thi Dieu Hien, Thai Minh Quan, Bui Xuan Thanh, Vo Thanh Hang, Dinh Quoc Tuc et al. "Nutrient removal by different plants in wetland roof systems treating domestic wastewater." Desalination and Water Treatment 54, no. 4-5 (2015): 1344-1352
178. Vitalis, S., Labetski, A., Peters, R. (2022) 3D Building Metrics. Github. Accessed on April 20 2022. Available at: https://github.com/tudelft3d/3d-building-metrics
179. Vonk, E., Cirkel, D. G., & Blokker, M. (2019). Estimating peak daily water demand under different climate change and vacation scenarios. Water, 11(9), 1874.
180. Water Supplies Department. (2015). Technical specifications on greywater reuse and rainwater harvesting. Government of Hong Kong. Available at: https://www.wsd.gov.hk/filemanager/en/content_1459/technical_spec_grey_water_reuse_rainwater_harvest.pdf
181. Wheeler, Stephen. M. 2002. Constructing sustainable development/safeguarding our common future: Rethinking sustainable development. Journal of the American Planning Association 68 (1): 110-11.
182. Wilf, M., & Aerts, P. (2010). The Guidebook to Membrane Technology for Wastewater Reclamation: Wastewater Treatment, Pollutants, Membrane Filtration, Membrane Bioreactors, Reverse Osmosis, Fouling, UV Oxidation, Process Control, Implementation, Economics, Commercial Plants Design. Balaban Desalination Publications
183. Winward, G. P., Avery, L. M., Frazer-Williams, R., Pidou, M., Jeffrey, P., Stephenson, T., & Jefferson, B. (2008). A study of the microbial quality of grey water and an evaluation of treatment technologies for reuse. Ecological Engineering, 32(2), 187–197. https://doi.org/https://doi.org/10.1016/j.ecoleng.2007.11.001
184. Witte, J.-P., Zaadnoordijk, W., & Buyse, J. (2019). Forensic Hydrology Reveals Why Groundwater Tables in The Province of Noord Brabant (The Netherlands) Dropped More Than Expected. Water, 11(3), 478. https://doi.org/10.3390/w11030478
185. Wong, L. T., & Mui, K. W. (2007). Modeling water consumption and flow rates for flushing water systems in high-rise residential buildings in Hong Kong. Building and Environment, 42(5), 2024-2034
186. Wu, S., Carvalho, P. N., Müller, J. A., Manoj, V. R., & Dong, R. (2016). Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators. Science of the total environment, 541, 8-22
187. Xiao, T., Dou, P., Wang, J., Song, J., Wang, Y., Li, X.-M., & He, T. (2018). Concentrating greywater using hollow fiber thin film composite forward osmosis membranes: Fouling and process optimization. Chemical Engineering Science, 190, 140–148. doi:10.1016/j.ces.2018.06.028
188. Yadav, P., Ismail, N., Essalhi, M., Tysklind, M., Athanassiadis, D., & Tavajohi, N. (2021). Assessment of the environmental impact of polymeric membrane production. Journal of Membrane Science, 622, 118987. https://doi.org/https://doi.org/10.1016/j.memsci.2020.118987
189. Yu, J. T., Bouwer, E. J., & Coelhan, M. (2006). Occurrence and biodegradability studies of selected pharmaceuticals and personal care products in sewage effluent. Agricultural Water Management, 86(1), 72–80. https://doi.org/https://doi.org/10.1016/j.agwat.2006.06.015
190. Yun-Cai Wang, Jia-Ke Shen & Wei-Ning Xiang (2018) Ecosystem service of green infrastructure for adaptation to urban growth: function and configuration, Ecosystem Health and Sustainability, 4:5, 132-143, DOI: 10.1080/20964129.2018.1474721
191. Zapater-Pereyra, M., Lavrnić, S., van Dien, F., van Bruggen, J. J. A., & Lens, P. N. L. (2016). Constructed wetroofs: A novel approach for the treatment and reuse of domestic wastewater. Ecological Engineering, 94, 545–554. https://doi.org/https://doi.org/10.1016/j.ecoleng.2016.05.052
192. Zehnsdorf, A., Willebrand, K. C. U., Trabitzsch, R., Knechtel, S., Blumberg, M., & Müller, R. A. (2019). Wetland Roofs as an Attractive Option for Decentralized Water Management and Air Conditioning Enhancement in Growing Cities—A Review. Water, 11(9), 1845. MDPI AG. Retrieved from http://dx.doi.org/10.3390/w11091845
193. Zhang, X., Xia, S., Zhao, R., & Wang, H. (2019). Effect of temperature on opportunistic pathogen gene markers and microbial communities in long-term stored roof-harvested rainwater. Environmental Research, 108917. doi:10.1016/j.envres.2019.108917
194. Zhang, Z., Meerow, S., Newell, J. P., & Lindquist, M. (2019). Enhancing landscape connectivity through multifunctional green infrastructure corridor modeling and design. Urban Forestry & Urban Greening, 38, 305–317. https://doi.org/https://doi.org/10.1016/j.ufug.2018.10.014
195. Zhou, Y., Li, R., Guo, B., Zhang, L., Zou, X., Xia, S., & Liu, Y. (2020). Greywater treatment using an oxygen-based membrane biofilm reactor: Formation of dynamic multifunctional biofilm for organics and nitrogen removal. Chemical Engineering Journal, 386, 123989

Images

HydroGroup (2022). Membrane Filtration Process. Retrieved from https://www.hydrogroup.biz/areas-of-use/water-treatment/membrane-processes.html

Mar, W. (2021). Recirculating Shower Schematic. Retrieved from https://wilsonmar.github.io/water-conservation/

Aldris, B., Farhoud, N. (2020). MBBR Bioreactor. Retrieved from: Wastewater treatment efficiency of an experimental MBBR system under different influent concentrations. DYSONA - Applied Science, 1(1), 20-28. doi: 10.30493/das.2020.103717.

Aventia (2022). Hydraloop in house (above) and schematic (below). Retrieved from https://aventia.com.mx/aqualoop

Hydraloop (2022). Hydraloops placed in homes. Retrieved from https://www.hydraloop.com/technical

Biomatrix Water Solutions (2022). Active Island Reactor technolgy application in urban waterway. Retrieved from http://www.biomatrixwater.com/active-island-reactors/

iSpring (2022). iSpring RO500-BN Tankless RO Filtration System 2:1 Pure to Drain ratio. Retrieved from https://www.amazon.com/dp/B07WK457JX/ref=emc_b_5_t?th=1

Appendix

Calculating treatment process units

known variables from case studies

Calculating from SMBR + UV				
Per capia volume	=	Q	x	HRT
HRT	=	16 hours (Najmi et al. 2020)		

Calculating from TVW				
Area per capita	=	Q	/	surface HLR

Per capita Volume	=	Area per capita	x	Thickness/Depth

Calculating from Hydraloop, Aqualoop						
Unit Volume	=	Width	x	Length	x	Height

Per capita scaling factor	=	Q	/	volumetric HLR

Unit Volume	x	Per capita scaling factor	=	Per capita Volume

Calculating from Compact CW				
Per capita Volume	=	Area / P.E.	x	Thickness/Depth

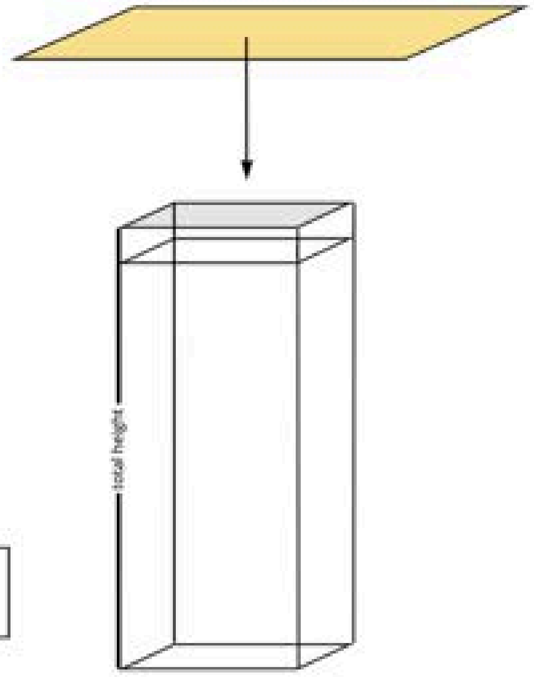
Calculating from GR				
Area per capita	=	Q	/	surface HLR

Per capita Volume	=	Area per capita	x	Thickness/Depth

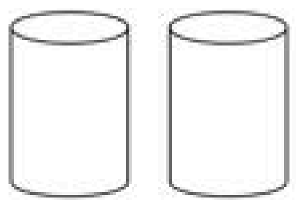
Calculating from DCSF				
Area per capita	=	surface HLR	/	Q

Area per capita	/	6 drawers	=	Area/capita /drawer

Area/capita /drawer	x	total height	=	Per capita volume



Calculating from FFBM, GDMBRs				
Per capita scaling factor	=	Q	/	volumetric HLR



(	Max tank capacity	x	Per capita scaling factor	)	2 tanks	=	Per capita Volume

Pumping system considerations

A particular concern about wastewater recycling via green infrastructure is its application in taller structures. As seen in Fig.XX, a conventional GW reuse system in a multi-storey residential building would consist of three subsystems: pipes that enable the collection of raw GW, pipes that convey raw GW for treatment then pumped to a storage tank, usually on the roof of the building itself, and finally pipes that distribute the treated GW to each unit, often gravitationally (Juan, Chen & Lin 2016). Integrating the green infrastructure means considering pumping energy involved in the building itself. Pumping is required to provide sufficient pressure to overcome the operating pressure of the water system to move the water at a desirable flow rate. We can expect in high-rise structures, booster stations, that enable the provision of water for every floor, especially in higher pressure zones (Müller et al. 2020). This is so as the water pressure head at government water mains do not typically have sufficient pressure tor each the topmost applicances in high-rise buildings, requiring boosters station (Wong & Mui 2007).

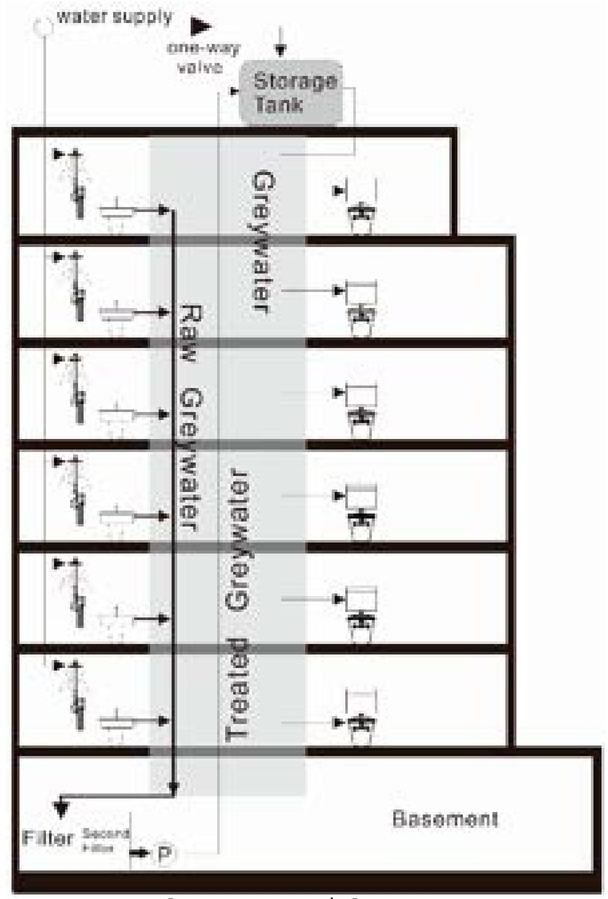


Figure. XX: Conventional GW reuse system in multi-storey residential building, taken from Juan, Chen & Lin (2016)

In a study assessing GW reuse for four types of buildings: high rise, hotel, school, and house of worship, it was found that the electricity consumption for capital and operating costs of its installation in high rise buildings were the same as a school (Adel Tayara et al. 2021). Which is counterintuitive considering the the higher you would have to pump water, the more power it would require according to physics. The energy requirement increases with every unit the water is lifted. For example, pumping water up one meter to meet the maximum flow of a Dutch house would cost 3.82 kW and to pump water up ten meters, it would cost 38.2 kW.

https://ocw.tudelft.nl/course-readings/design-drinking-water-distribution-networks/

Conventionally, booster systems consist of a set of parallel pumps installed in the basement and of a single-stranded pipe system that supplies each unique floor or several floors grouped into zones of the same pressure (Altherr et al. 2019). The reason for this layout is its fail-proofness, where if one pump fails, the water supply can be continued with parallel pumps and the piping costs are lowest (Altherr et al. 2019). The booster system can be optimised for the building layout and to minimise operating costs in the future, as 70% of a pump system's life cycle cost is its electricity consumption (Nault & Papa 2015).

In response, conventional booster systems are increasingly being challenged to consider decentralised layouts, opening up a significant potential for energy savings (Coelho & Andrade-Compos 2014). In a study by Altherr et al. (2019), three alternative booster system pipe layouts were compared to the conventional basement booster system, in order to compare the energy savings with each increasing zone. The layouts are visualised in Fig. XXX.

They concluded that increasing the number of pressure zones in a building enhances the potential energy savings. All alternatives have almost equal savings, however, the decentralised layout performed best, yielding the highest energy savings of up to 40% and total cost savings of around 35% (Altherr et al. 2019). This is not the only method to increase the energy efficiency of high-rise water supply systems. Considering that the energy efficiency of an average high-rise up to 300 m is ~0.25, it can be improved to 0.37 via water storage tank relocations to one tank per floor or adding one intermediate tank in-between the roof water tank (Cheung, Miu & Wong 2013).

Furthermore, there are other factors to consider in the design such as pipe diameter, pump type etc. (Altherr et al. 2019). In a survey evaluating the energy efficiency of elevated water tanks in high-rises (Cheung, Mui & Wong 2013), they measured the daily pumping energy required for water supply distribution in several high-rises. In table xx, it seems the daily pumping energy does not correlate to

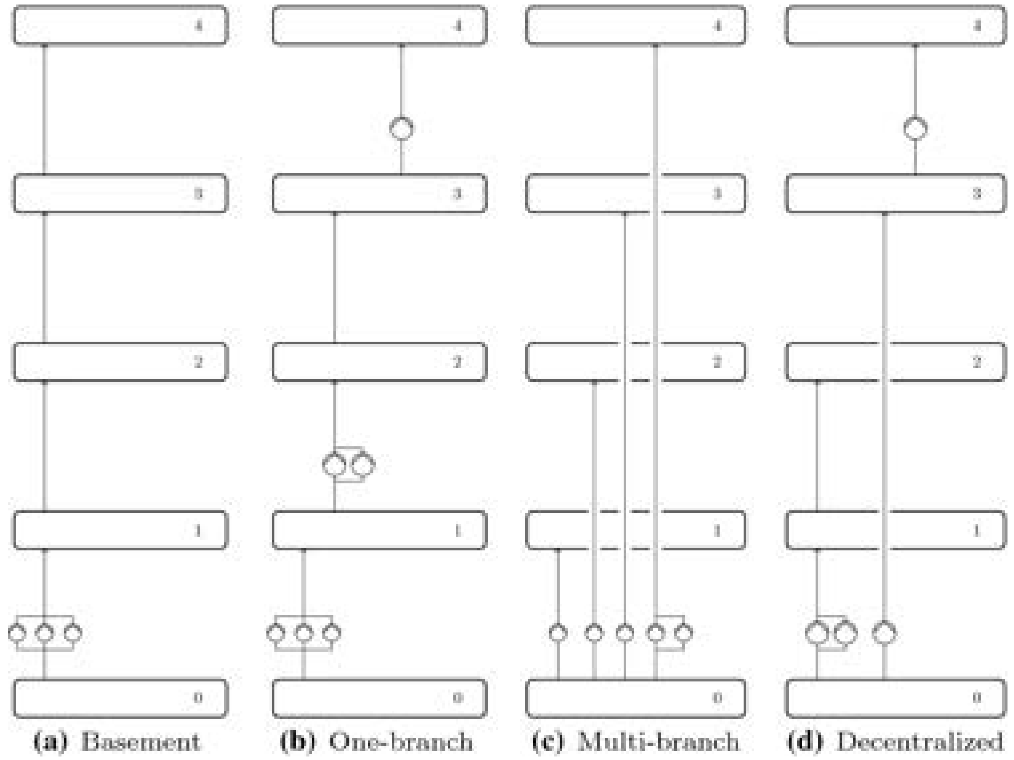


Figure. XX: Pipe layouts for four pressure zones, taken from Altherr et al. (2019)

the height of the high-rises. In fact, it may be more correlated with the amount of units per storey, as the highest value is attributed to a 36-storey building with 18 units/storey. Another building with an additional ten stories but with 10 units/storey consumed ~65% less pumping energy.

SCWs on roofs are designed with gradual slopes to facilitate the movement of water. Water can be fed

Stories	Units/Storey	Daily Pumping Energy (MJ)
25	15	345
36	18	1422
40	10	379
46	10	500

Table XX: Extracted values from Cheung, Mui & Wong's study (2013)

into the system intermittently or continuously, though intermittent feeding is usually more energy efficient and even increases the water-saving efficiency of the GW reuse system by 4% (Liu et al. 2010). So, additional energy would be required to pump the raw GW from lower floors up to the green roof, doubling the amount of work as it doubles the distance raw GW needs to travel for treatment. As for green walls, we can argue for a design of which higher floors gravitationally feed their raw GW into the green wall, this double work would still apply.

On the other hand, a pilot-scale study was able to harness energy through micro/pic hydro turbines at the groundfloor from GW while it flows down through high-rise buildings, utilising a Pelton turbine with an efficiency of 0.75 (Sarkar, Sharma & Malik 2014). The harnessed energy increases by almost double with each ten-floor interval increase, as observable in Table XX. An interesting note is that the minimum height of a collection tank for reasonable

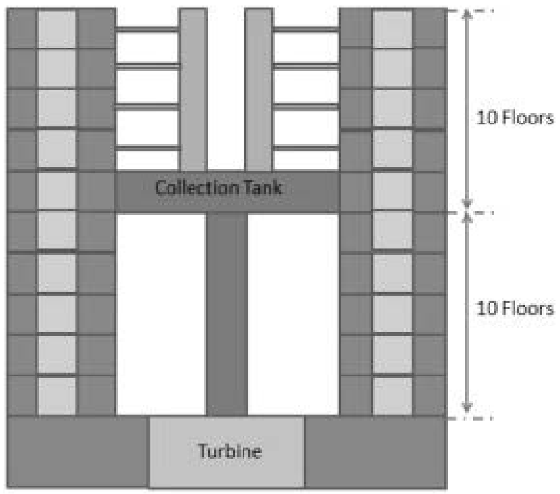


Figure XX: Proposed design from Sarkar, Sharma & Malik's study (2014)

power generation is about 30 m or 10 floors. The 6.85 kWh generated is equivalent to the amount of energy necessary to run a 6 kW water pump for an hour (Sarkar, Sharma & Malik 2014). The reason for the difference in number of floors and head heights is observable in Fig.XX, where the number of floors indicate the space in between where GW can be collected and flow down, generating electricity from the turbine. Ultimately, such a system can pay off within 7.68 years unless subsidised or mass manufactured in the future (Sarkar, Sharma & Malik 2014).

In consideration, the high potential for optimisation is good news considering the additional required energy for green infrastructure's water conveyance, as Dutch cities are likely to expand vertically through building on top of existing infrastructure. So, applying the decentralised layout would facilitate the connection of newer structures to the existing booster system and planning processes have ample opportunity to redesign water storage tank relocations for newer segments of buildings, optimising the overall energy efficiency of its water supply distribution system.

# of Floors	Head (m)	Energy (kWh)
20	30	6.85
30	43.4	15
40	58.17	28

Table XX: Extracted values from Sarkar, Sharma, & Malik's study (2014)