D1.8 Greenfield implementation in Filton Airfield

Deliverable D1.8

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Executive Summary

Urbanisation exacerbates health, environmental and climate-related issues, while at the same time using more natural resources. Recovering water-embedded resources including water, energy, nutrients and other valuable materials is a crucial opportunity for regions or countries to shift from a linear to a circular economy. In this regard, a radical redesign of water services and increasing reuse opportunities in a circular economy has become an urgent and important task to turn urban environments into green infrastructure and fast track achieving significant socio-economic benefits and making resource efficient.

The NextGen project aims to explore and demonstrate opportunities for water, energy and materials reuse for benefit of the urban, industrial and agricultural sectors. The findings will provide a more practical and sustainable solution to water in a circular economy through the demonstration of novel technologies and addressing business and governance challenges.

Filton Airfield (United Kingdom) is the case to be developed as a showcase by demonstrating the feasibility of circular solutions supporting a circular economy transition in the water sector. NextGen activities involved closing the water, energy and materials cycles to improve urban resource management. Thus, the NextGen circular solutions are applied to the greenfield implementation in Filton Airfield which will be developed as an attractive and sustainable area. Implementing circular solutions in practice requires a clear overview of benefits and challenges to identify opportunities for greater resource recovery efficiency.

Therefore, the below table presents an overview of the NextGen actions performed in the Filton Airfield case; related tasks, technologies/approaches and quantifiable results obtained from tasks.

Overview of NextGen tasks and quantifiable results for each task in Filton Airfield.

Task	Subtask	Technology/Approach	Quantifiable results
1.2 Closing the water cycle	1.2.7 Integrating alternative water sources at district level at Filton Airfield	Alternative water sources at district level: rainwater harvesting and greywater reuse	Toilet flushing and public irrigation: 10 - 75% of water savings
1.3 Closing the energy cycle	1.3.1 Local heat and energy recovery from wastewater	Feasibility study: low-grade heat recovery potential at district level	Domestic heating (space or water heating on-site reuse): 7.8 - 38% of energy savings
1.4 Closing the materials cycle	1.4.9 Integrated recovery and use of nutrients at district level	Feasibility study: nitrogen and phosphorus recovery and local reuse at district level	Impact of wastewater flow rate on nutrient concentrations in wastewater (on-site recovery): 53% of decrease in flowrate increase in N and P concentration in wastewater (53% and 31%, respectively)

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Sub-Task 1.2.7 Integrating alternative water sources at district level at Filton Airfield (Chapter 3)

As an urban water management solution, a feasibility assessment of rainwater harvesting (RWH) from the rooftop of the residential buildings and commercial YTL Arena for non-potable purposes, including washing machine, toilet flushing, irrigation and the combined use of toilet flushing and irrigation, depending on scenarios. The RWH systems of these applications were demonstrated using hydraulic and economic indicators – water savings efficiency (WSE), stormwater capture efficiency (SCE), cost-saving potential and unit product water cost. Five RWH scenarios were assessed. Four scenarios involved the RWH system for residential water applications while one scenario involved the RWH system for commercial water applications.

For the residential applications, two RWH scenarios were first considered – centralised and decentralised RWH systems. The harvested rainwater was used for non-potable purposes, i.e., washing machine and toilet flushing. It was found that the decentralized system had greater WSE at 47% compared to only 35% for the centralized system. Results showed that the amount of harvesting rainfall became a limiting factor at high tank volumes leading to upper limits of WSE at 45% for the centralised RWH system while at 70% for the decentralized RWH system. In addition, when the harvesting rainwater was used only for toilet flushing, the maximum WSE was 44%. The optimum tank size determined for a passive RWH system was 100 m^3. Within this scenario, this tank size gave a WSE of 38% and an SCE of 88%. Furthermore, within the extended scope of the study, the harvesting rainwater was assumed to be used for dishwasher, washing machine and toilet flushing. With more demand for the harvested rainwater (i.e., a medium-scale RWH system), the results highlighted the potential for a medium-scale system and showed that a larger system can recover capital costs and showed a net economic benefit.

However, the long return on investment periods remained a significant limitation to the adoption of these types of systems. The last RWH scenario demonstrated a large roof (30,000 m^2) RWH system in the YTL Arena (a commercial building) by conducting hydraulic and economic assessments. Three water demand scenarios, toilet flushing, irrigation and combined use, were considered. The hydraulic assessment results suggested that a storage capacity ranging from 400 to 1,000 m^3 would be enough for rainwater reuse scenarios considered in this application. From the economic aspect, the RWH system with a rainwater storage capacity of between 100 and 600 m^3 was more economically feasible as it showed high cost-saving potential. Furthermore, the unit water cost varied from 0.37 to 0.40 £/m^3 depending on the water demand, showing lower than the mains water cost (0.40 £/m^3). Consequently, the RWH system with a capacity between 400 and 600 m^3 can be the most favourable range under the given conditions.

A decentralised hybrid rainwater harvesting (RWH) and greywater reuse (GWR) system was further assessed for use in residential and commercial buildings. Within the scope of this study, stochastic water demand profiles and urban water cycle simulations at a block scale, taking possible RWH and GWR options for non-potable purposes, were conducted to quantitatively assess urban harvesting potential indicators (water demand minimization, urban resource reuse, and wastewater discharge minimization). When the RWH was implemented, the water demand minimization potential varied from 62% to 71%. Meanwhile, the combined use of RWH and GWR yielded even better results in terms of water demand minimization, peaking at 78% due to the additional supply from GWR. The combination also reduced wastewater discharge potential from 100% to 54% and consequently improves self-sustainability potential from 0 with no recycling, to 44% with only GWR, and to 100% with the combined use of RWH and GWR. Overall, this scenario-based urban water management study can provide insights into the applicability of urban water resource harvesting and its assessment approaches in existing and new development areas.

Sub-Task 1.3.1 Local heat and energy recovery from wastewater (Chapter 4)

Domestic wastewater has been recognised as a renewable heat source as it contains a relatively high amount of thermal energy, originating from hot water use at homes. Wastewater after discharging into a sewer network system will have an elevated temperature (20-30 °C). Since it is low-grade heat, it cannot be transported over long distances. The Filton Airfield Development offers potentially great opportunities for heat recovery from the sewer network and local reuse. Thus, the feasibility of local heat recovery from wastewater was demonstrated by simulating the heat balance (demand and supply) of the Filton sewer system.

There were two scenarios for demonstrating heat recovery potential and its reuse: (1) residential area consisting of conventional houses and (2) residential area consisting of so-called ecohouses (i.e., houses with water saving appliances). Three different changes in water temperature occurring due to a heat recovery system were considered: 0.5, 2 and 3 °C. Thus, the impact of the water use option in houses on energy recovery potential was assessed. As a result, it was confirmed that housing units generating a large amount of wastewater (i.e., conventional houses) held significant potential for energy recovery. Using historical energy demand data, the total energy demand for the study area was assumed to be 463,300 kWh/y and followed by 293,800 kWh/y for space heating and 101,700 kWh/y for water heating.

Energy recovery from wastewater discharge where the sewage is cooled by 0.5, 2 and 3 degrees, theoretically can recover 6,465, 25,860 and 38,790 kWh/y for the conventional house scenario, and 2,915, 11,660 and 17,490 kWh/y for the ecohouse scenario. The total heat recovery potential is highly dependent on wastewater flow rates. This study provides practical insight into the applicability of local heat recovery and its reuse in Filton Airfield. However, further investigation and development on simulating wastewater profiles, flow rates and temperature via reliable data collection and monitoring and heat storage are required to balance heat availability and demand. In addition, the effect of a scale of development area (e.g., densified housing plan and completion of development) should be implemented.

Sub-Task 1.4.9 Integrated recovery and use of nutrients at district level (Chapter 5)

Filton Airfield is set to become the best use of the largest area of greenfield land, and a new sewer design will be used that transports at higher density (lower water volume) which can enhance valuable nutrient recovery efficiency. Therefore, the feasibility of local recovery of nutrients from wastewater and local application as a fertilizer in the green spaces in the Filton area was investigated using a stochastic household wastewater discharge model. Thus, water demand and discharge profile analysis were conducted using the integrated method that consists of three simulation phases in the analysis, the spatial and temporal demand and discharge pattern analysis using SIMDEUM® and SIMDEUM WW®, and the sewer network input and output flows and nutrient quality analysis using SWMM (described in Chapter 2).

Two water consumption scenarios were considered: conventional houses with normal water use appliances and ecohouse with water-saving appliances. In ecohouse, water-saving toilets, water-saving shower heads and waterless washing machines were utilised. As a result, the total volume of wastewater into the sewer network was reduced by as much as 28.7% with an average reduction of 18.2% for the morning period (6:30 am – 9:30 am). Both morning and evening periods had flow reductions although the morning period often had the largest decrease in wastewater volume using the water-saving appliances.

In response to the change in the wastewater volume, the phosphorous concentration in the wastewater increased by as much as 36.6% using water-saving appliances and increased by an average of 27.9% over the morning period. The approach demonstrated in this study allowed assess the effect of variations of wastewater volume discharged into the sewer network system. The results highlighted that due to the increased nutrient concentrations from the use of a separated network and water-saving appliances, nutrient recovery would be more efficient, which is necessary for a more sustainable future, especially when natural resources such as phosphorus are becoming extremely depleted in the natural world. Although the application on a case study in Filton Airfield demonstrated the suitability of the suggested method as well as the promising potential of nutrient recovery, and the role it can play to reach sustainable circular economy targets, a more detailed spatial and temporal model prediction of the nutrient recovery is still required as it will allow for a more precise prediction of the feasibility of nutrient recovery and reuse in urban areas and thus the selection of the most suitable nutrient recovery technology for the Filton case.

Chapters 6 and 7 further addressed existing and emerging policy and regulatory frameworks, including barriers, challenges, opportunities, financial options and upscaling and future implementations to improve the social acceptability of circular solutions. Public and social acceptance is still a critical barrier to the successful introduction and implementation of NextGen approaches and technologies to recover and reuse urban resources. Understanding key findings from this Filton case study (this deliverable 1.8) provides useful input to the type of expert information people are likely to know. However, a range of policy and regulation options needs to be considered to promote greater support for NextGen solutions within the Filton Airfield development schemes. We examined barriers and challenges that impact circular water systems and services. Since NextGen circular solutions demonstrated in Filton Airfield are district level, the study focused on aspects of policy and regulation for circularity on a small, decentralised scale and their incorporation into planning and building frameworks and explored possible financing options for circular solutions. The findings highlighted the role of laws and government policy in implementing NextGen circular solutions. In this context, the adoption and uptake of decentralised circular solutions require new forms of innovative support that can work within the existing regulatory frameworks. It was found that although the UK has its set of permits, risk assessments, and authorisation requirements and protocols for circular-water solutions, implementing decentralised circular solutions for water continues to be challenged by local regulations and building-related regulations specific to smaller-scale installations and the cost-benefit gap.

However, barriers and challenges identified from this study provide an opportunity of establishing new and revised policies and regulations to improve the viability of NextGen technologies and approaches. This study thus concluded with recommendations to further integrate and implement circular solutions through urban planning and building:

(1) Determination of reclaimed water use purpose – it is crucial to evaluate technical requirements to control and monitor water quality and thus avoid additional costs to achieve high water quality requirements.

(2) There is a need for more experimental research that helps identify which variables affect the implementation of NextGen technologies and approaches. This also includes the context, application (product quality and risk management), and scale (system). Thus, the research findings can be applied to improve policy, guidelines, processes, and protocols for circular water reuse.

(3) Since a pricing concern is related to greater acceptance of circular solutions, the assessment of life-cycle cost-benefits and risks for socio-economic profiles should be conducted. Thus, the findings will be used to create financial incentives that should be implemented to support circular technology uptake in the built environment.

(4) For upscaling and future implementations of NextGen solutions, understanding how design and plan can address end-users concerns is critical. Thus, social participation and collaboration platforms play a vital role to provide a coherent justification and knowledge of the environmental, economic, and social benefits and impacts. This will support engagement activities demonstrated in Filton Airfield, by outlining ambitions beyond the NextGen project and findings that can be fed into the current design codes/Building regulations.

Chapter 8 finally concludes with recommendations for future research. Conducting a risk analysis is crucial to address potential risks affecting the commercialisation of secondary products (i.e., treated wastewater reuse). Through this assessment, public and social acceptance of the use of treated wastewater can be increased. In addition, there is a need for more simulation and experimental research that helps establish ways or mechanisms that would foster strengthening trust. Such experimental research on demonstrating urban water, energy and nutrient recovery potential at a large scale can help develop new sustainability indicators that can reduce barriers to fast and direct decisions. Finally, this deliverable recommends developing a new roadmap that can be used for the small-, medium- and large-scale NextGen solution process design and system analysis and application at other sites.

Acronyms

ATES	Aquifer thermal energy storage
BOD	Aquifer thermal energy storage
CAPEX	Capital expense
CE	Circular economy
COD	Chemical oxygen demand
COP	Coefficient of performance
CSO	Combined sewer overflows
DMI	Demand minimisation index
DS	Dry solids
FAO	Food and Agriculture Organization
FC	Filter coefficient
GHG	Greenhouse gas
GW	Greywater
GWH	Greywater harvesting
GWR	Greywater reuse
HFMC	Hollow fibre membrane contactor
HT	High temperature
IEX	Ion exchange
KPI	Key performance indicator
KS test	Kolmogorov-Smirnov test
LCA	Life cycle assessment
LCC	Life cycle cost
LPM	Litre per minute
NF	Nanofiltration
NPV	Net present value
OPEX	Operational expense
PBP	Payback period
PCI	Precipitation concentration index
PE	Population equivalent
REI	Resource exported index
RO	Reverse osmosis
ROI	Return-on-investment period
RW	Rainwater
RWH	Rainwater harvesting
SCE	Storm capture efficiency
SPI	Standard precipitation index
SSI	Self-sufficiency index
SSW	Surface water system
SWMM	Storm water management model
TDS	Total dissolved solids
TH	Total hardness

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TKN	Total kjeldahl nitrogen
TP	Total phosphorous
UV	Ultraviolet
UWC	Unit water cost
UWOT	Urban water optioneering tool
WOI	Wastewater output index
WSA	Water saving appliance
WSE	Water savings efficiency
WW	Wastewater
WWHR	Wastewater heat recovery
WWTP	Wastewater treatment plant
YAS	Yield after spillage
YBS	Yield before spillage

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CHAPTER 1

Deliverable D1.8

1. Introduction

Globally, around 80% of all wastewater is released back into the environment where it creates health, environmental and climate-related issues (IWA, 2018). Urbanisation further exacerbates these challenges with an increase in wastewater production and discharge, while at the same time using more natural resources.

In the context of greenfield implementation, designing and planning sustainable water services and systems and increasing reuse opportunities in a circular economy is an important task to turn wastewater into wealth and fast track achieving significant socio-economic benefit while at the same time making it resource efficient and climate resilient. Thus, recovering water-embedded resources including water, energy, nutrients and other valuable materials is a crucial opportunity for regions or countries to shift from a linear to a circular economy. This will contribute to filling the gap between increased natural resource demand and supply shortage. NextGen has therefore built up its circular economy system on the next generation of water systems and services to increase the availability of water, reduce energy consumption and recover other valuable resources.

In the frame of closing the water cycle, there are many water reuse strategies that have been commenced to address issues, including (i) high operating and maintenance costs of nutrients removal (e.g., nitrogen and phosphorus) from the wastewater effluent to mitigate negative environmental impacts (e.g., eco-toxicity due to eutrophication), (ii) accelerated urbanization and (iii) climate change (e.g., heavy rainfall and drought) (Voulvoulis, 2018). Therefore, rainwater and treated wastewater reuse and valuable resource recovery (i.e., thermal energy and nutrients) from wastewater would become a new generation of validated, progressive solutions to address these challenges.

Reuse of rainwater and wastewater is very common and has been implemented using a wide range of technologies from small to medium/large scales for non-potable purposes. However, most energy recovery practices have been primarily demonstrated at the large scale with a conventional anaerobic digestion system while recovery of nutrients (i.e., nitrogen, N and phosphorous, P) by source separation has shown to be feasible at a small scale application (Diaz-Elsayed et al., 2019). In this context, there is a need of a practical approach for their design and scale, prior to the choice of resource recovery technologies and economic evaluation. In other words, a more detailed spatial and temporal model prediction of urban resource recovery potential is required as it will allow for a more precise prediction of the feasibility of urban resource recovery and reuse in urban areas.

Filton Airfield has been developed as a showcase and demonstrated a scenario-based simulation and analysis approach to evaluate potential of urban resource recovery (water, energy and nutrients) and thus providing quantitative results, including water saving potential, energy saving potential and recoverable nutrient concentrations. This report therefore aims to provide understanding and awareness underpinned by the utilization of a more reliable simulation approach to water-embedded resource recovery in the Filton area. It also aims to explore business and governance challenges that can enhance UK's ability to have a resilient urban resource management strategy and thus greenfield implementation.

The findings in this report are expected to be used to transform water-wise communities. This report also provide evidence to prove the applied concepts for closing the water, energy and nutrients.

1.1. Report structure

This deliverable 1.8 consists of eight chapters with the introduction and report structure in the Introduction. In addition, the Introduction provides the status of the Filton Airfield development and the specific NextGen tasks. Further, Table 1.1 presents a brief description of the approaches for closing water, energy and materials, Chapter 3, 4 and 5 (Work package 1, WP1).

Table 1.1. Three main tasks to demonstrate the feasibility of the water, energy and materials cycles in the water sector in Filton Airfield.

Chapter #	Feasibility study	Related Deliverable*
3. Closing the water cycle	Alternative water sources at district level	D1.3 New approaches and best practices for closing the water cycle
4. Closing the energy cycle	Heat recovery from wastewater and local reuse	D1.4 New approaches and best practices for closing the energy cycle in the water sector
5. Closing the materials cycle	Nutrients recovery potential at district level	D1.5 New approaches and best practices for closing materials cycle in the water sector

*Deliverables will be accessible via the Water Europe Marketplace at the case study section: https://mp.watereurope.eu/l/CaseStudy/

Chapters 6 and 7 concentrate on regulatory aspects for urban resource recovery and reuse (challenges, opportunities and cost and incentives) to implement circular solutions in either existing or new housing developments for operators/planners of resource reuse schemes. The major findings from the tasks and recommendations for future research and implementation of circular solutions are presented in Chapter 8.

It has to be noted here that NextGen will deliver technological, economic and environmental impact assessments and business and governance solutions for water in the circular economy in 10 demonstration cases across Europe including the Filton Airfield demonstration case in the UK. Thus, other deliverables that emphasize on the technical demonstrations of closing the water, energy and materials cycles (WP1), but activities related to economic and environmental assessment and design systems (WP2), stakeholder engagement (WP3) and policy and governance challenges (WP4) can be found via the Water Europe Marketplace (https://mp.watereurope.eu/l/CaseStudy/).

1.2. Filton Airfield Development

Filton Airfield is a landmark, prime regional greenfield redevelopment opportunity. The site lies within the South Gloucestershire Council administrative area in UK. It is at the heart of the wider mixed-use area of Bristol’s North Fringe, including employment, manufacturing, retail, residential and recreational uses. The majority of the site comprises the former operational airfield, including the Airfield's former terminal buildings, fire station, helipad, storage buildings and the older WWII service shed. As shown in Figure 1.1, the principal existing feature of the Airfield site is the main runway, which runs in an east-west direction. The runway is 2,467 m in length and 91 m wide and is constructed in concrete with adjacent surface water drainage. In addition to the main runway, there are the remnants of a crosswind runway which runs in a north-south direction.

The Filton Airfield masterplan proposes to form a new mixed-use neighbourhood. A new suburb to be named Brabazon, will comprise 141.79 ha (350.35 acres) for 2675 new homes and 25 ha (62 acres) of commercial space, as well as new schools, recreation spaces and health facilities in Bristol's northern fringe (Figure 1.1). In addition, it includes a nursery facility, retail space, a 120-bedroom hotel, a secondary and two primary schools, safeguarded land for a railway station, community facilities and provides a setting for the Aero heritage museum to celebrate the area's aviation history. There are also informal and formal open spaces, new road accesses and associated infrastructure. The specific land use plan is described in Table 1.2.

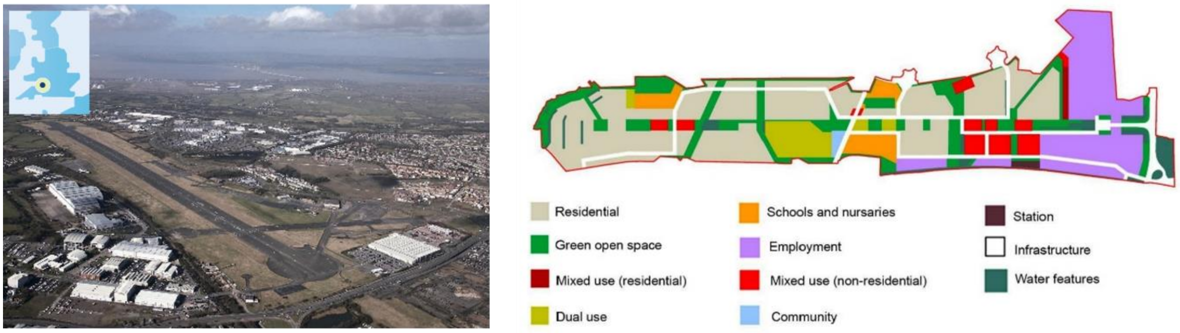

Figure 1.1. Location of Filton Airfield and Filton Airfield master plan.

Table 1.2. Filton Airfield land use plan (YTL, 2021).

Land use	Area (ha)	Area (acres)
Total residential area	54.3	134.18
Total mixed use (commercial and residential)	2.10	5.19
Residential extra care	0.69	1.7
Employment	24.95	61.65
Other non-residential uses	17.10	42.25
Open space	27.49	62.92
Infrastructure/Highways	15.16	37.46
Total application site	141.79	350.35

1.3. NextGen objectives

A masterplan for the site development is available, but further development and exploration of ideas for sustainable development are required. Urban greening strategies need to be demonstrated in new cities to support sustainable urban planning and development. An integrated local recovery and reuse of water, energy and nutrients is one of the promising solutions and can provide multiple and complementary benefits to the public.

The aim of the NextGen project is to demonstrate and evaluate the application of circular economy to a Filton Airfield development case study where the area will be a showcase in urban development for the UK. The aim of this project translates into the following set of objectives as described in Figure 1.2 and Table 1.3.

Water: Demonstrating the feasibility of urban water resource management
Energy: Demonstrating the feasibility of thermal energy recovery from the sewer system and local reuse
Materials: Demonstrating the feasibility of nutrient recovery potential

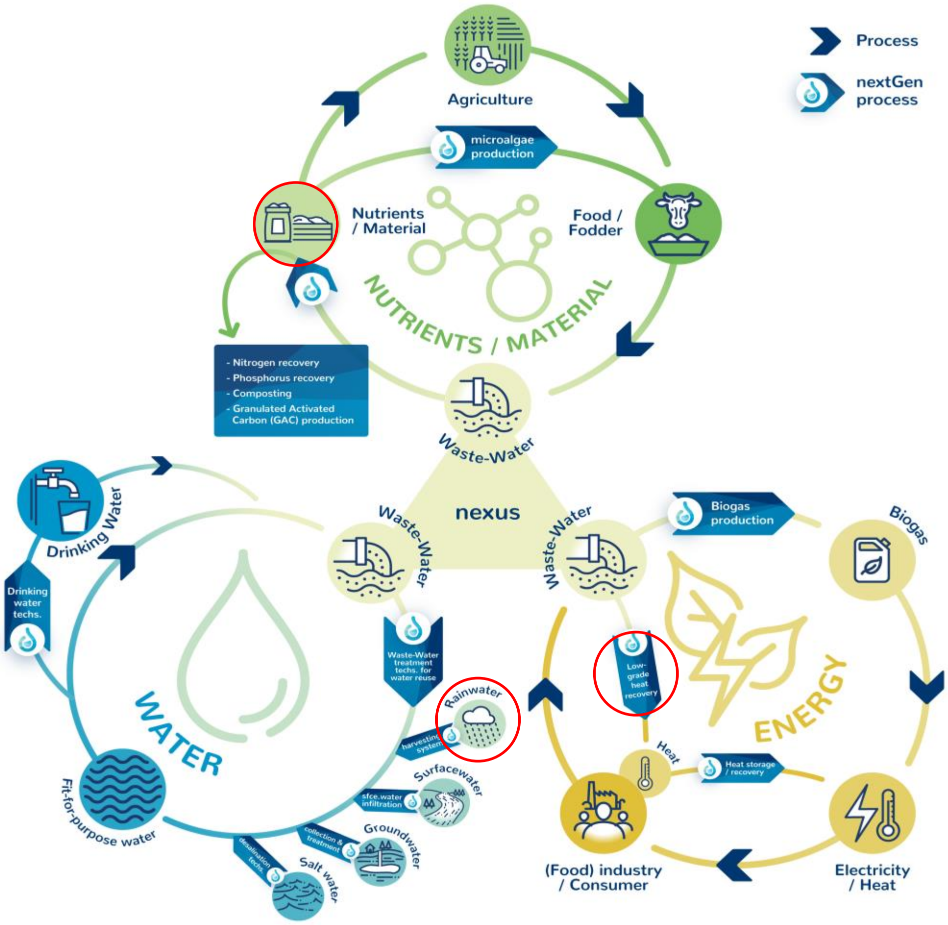

Figure 1.2. Positioning of Filton Airfield in the circular economy. The red circles indicate the technologies assessed in the Filton case study.

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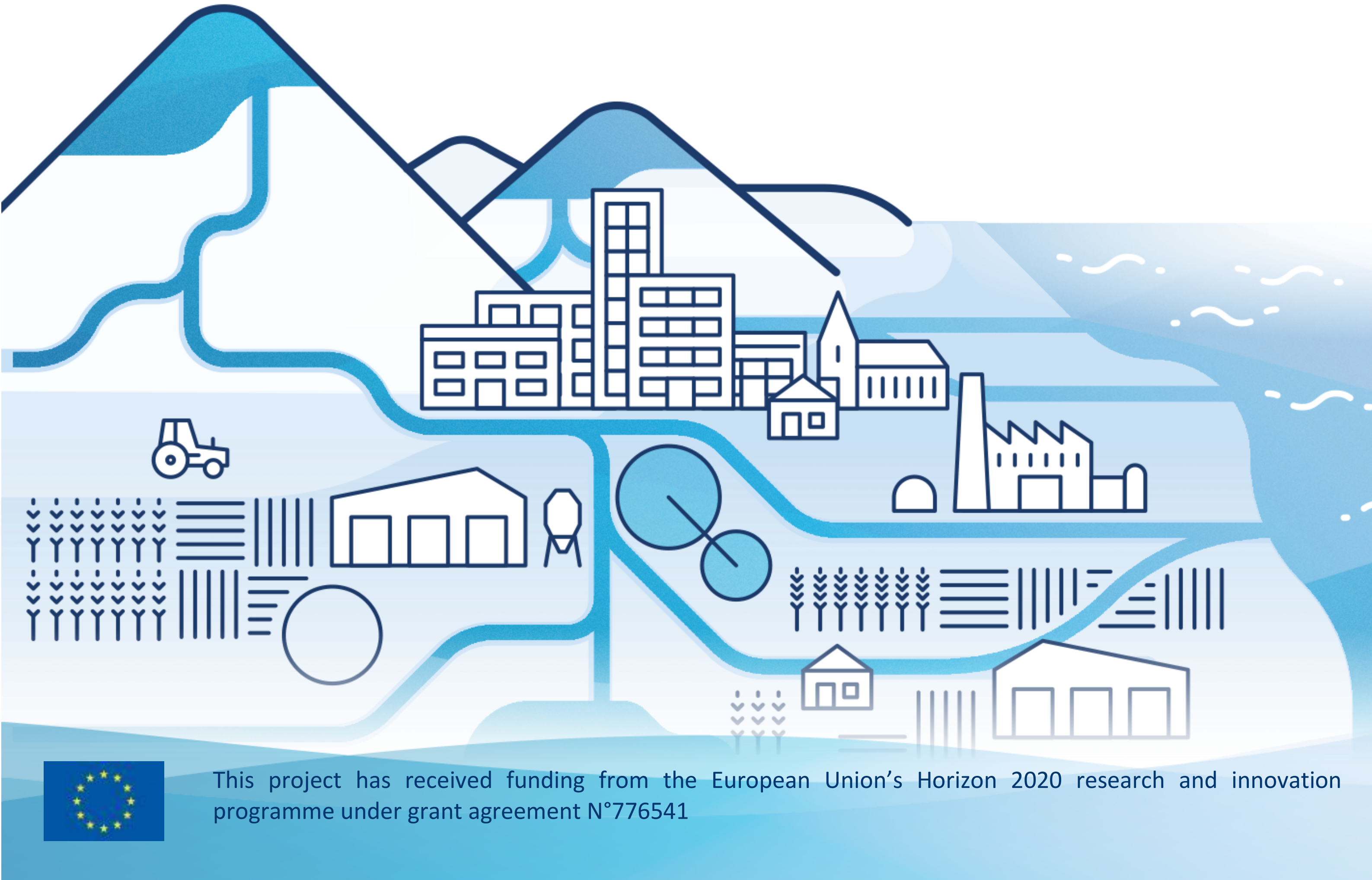
Table 1.3. Description of NextGen tasks and objectives.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
# 9 Filton Airfield Location: A former airfield in South Gloucestershire, north of Bristol	Sub-Task 1.2.7 Integrating alternative water sources at district level at Filton Airfield	- A former airfield in South Gloucestershire, north of Bristol, UK - YTL Developments will develop this former airfield into an attractive and sustainable area	- Decentralized solutions for increased circularity in new housing districts	TRL 7 → 9	50-600 m^3 storage capacity for residential and commercial buildings	Urban water resource reuse for non-potable uses (on-site reuse)
	Sub-Task 1.3.1 Local heat and energy recovery from wastewater			TRL 9	113 housing units	Domestic heating - space or water heating (on-site reuse)
	Sub-Task 1.4.9: Integrated recovery and use of nutrients at district level			TRL 9	113 housing units	Nutrient recovery potential - nutrient concentrations in wastewater

CHAPTER 2

Deliverable D1.8



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2. Methodology

2.1. Introduction

In this deliverable, a series of theoretical, experimental and scenario-based investigations were conducted. In particular, the experimental investigation was carried out to analyse the quality of fresh rainwater samples collected across Filton Airfield.

Feasibility of water, energy and nutrient recovery and reuse at district level was investigated through theoretical simulation and scenario-based approaches. For the feasibility study, water demand and discharge profiles, including flowrate, nutrient concentrations (i.e., nitrogen and phosphorus) and temperature were obtained using specific analysis tools - Simulation of Water Demand, End-Use Model" (SIMDEUM), SIMulation of water Demand, an End-Use Model Wastewater (SIMDEUM WW) and Storm Water Management Model (SWMM).

With the aid of urban water cycle analysis results, an urban assessment tool, namely Urban Water Optioneering Tool (UWOT), was used to assess and compare different urban water management options. The results obtained from the UWOT simulation were used to assess urban harvesting potential using demand minimisation index, wastewater output index, self-sufficiency index and resource exported index (Agudelo-Vera et al., 2012; Leusbrock et al., 2015).

This chapter describes the general approaches that were applied within the Filton case study, including the experimental procedure used for rainwater quality analysis and the overview of the simulations. More specific details can be found in their respective chapters.

2.2. Study area - Filton Airfield eastern infrastructure

Figure 2.1 shows the location of the study area. This study only considered the east side of the Filton Airfield site as information on design and planning of the east side was available at the time of the study. The east side includes apartments and free-standing housing units named ‘Hangar District’. In addition, there is only one commercial application as illustrated in Figure 2.1. There exists the three-bay Brabazon Hangar, which was built in 1946. This will be transformed into a premier live entertainment venue with a capacity about 17,080 visitors, named as YTL Arena (YTL, 2021). The total roof area of the arena is about 30,000 m^2: 8500 m^2 (East), 13,000 m^2 (Centre) and 8500 m^2 (West). The feasibility of urban water resource recovery and reuse was investigated by considering residential and commercial buildings while that of energy and nutrient recovery from wastewater was carried out by considering only residential buildings (i.e., Hangar District). Details of different residential and commercial application scenarios are described in their respective chapters.

Figure 2.1. Filton Airfield eastern infrastructure development: residential area "The Hangar District" and commercial "YTL Arena".

2.3. Rainwater quality analysis

Rainwater samples collected directly from atmospheric precipitation were analysed. There were five different sampling points (SP1-SP5) across the Filton Airfield (n = 25 samples). As shown in Figure 2.2, SP1 is located at the northwest of the Filton Road. SP2 and SP5 are located at the right side and the front of the east wing of the YTL Arena (YA), respectively. SP3 and SP4 are located at the behind of the west wing (near the used tanks) and the centre of the YA, respectively.

At this location, there is a local road with moderate traffic, with its distance from the YA varying between 0.5 km and 2 km. In addition, commercial and residential areas are located to the east, northeast and northwest of the YA, Figure 2.2 (a). In addition, a sewage treatment plant and light industrial areas are located less than 10 km from the study area, but these are not shown in the figure. Figure 2.2 (b) shows prevailing winds in this area are from the southwest. It has to be noted here that the wind direction data during the sampling period were obtained from at weather station located 2.3 km from the Filton site (Underground, 2020).

Weekly collection of rainwater samples conducted, and the samples were kept in the cold room at 4 °C prior to analysis. pH, electrical conductivity (EC, µS/cm), total dissolved solids (TDS, mg/L) were measured on site using a pH/EC/TDS meter Hanna Instruments™ HI9812-5, while samples were sent to Wessex Water Scientific Centre to analyse the other selected physiochemical and microbiological parameters according to the Standard Methods ISO 17025 (UKAS, 2020) as described in Table 2.1. The physicochemical parameters analysed are turbidity (NTU), chemical oxygen demand (COD) and biochemical oxygen demand (BOD). In

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addition, nutrients, major ions and metals including total hardness, calcium hardness, magnesium hardness, alkalinity (HCO_3^-), ammonia (NH_4^-), nitrite (NO_2^-), nitrate (NO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), fluoride (F^-), calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn), copper (Cu), chromium (Cr), cadmium (Cd), nickel (Ni), zinc (Zn), and lead (Pb), were determined using different methods described in Table 2.1. Microbiology parameter (i.e., *E.Coli*) was analysed by membrane filtration method. Tap water was also analysed for the same parameters to compare the quality of both rainwater and tap water.

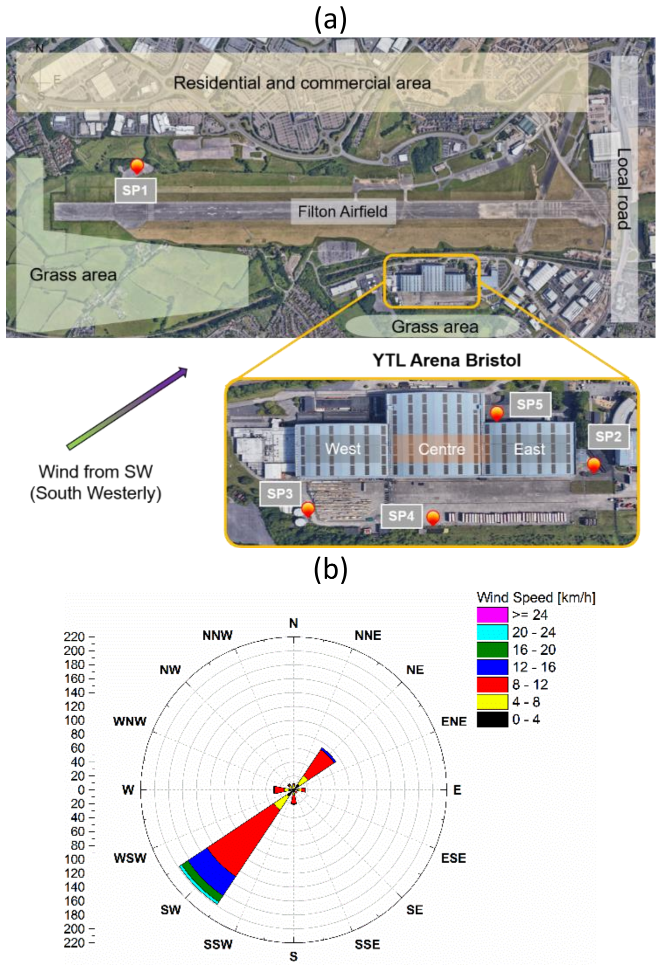


Figure 2.2. (a) Characteristics of the Filton Airfield area. Sampling points - SP1: at the end of the Filton Airfield, close to green area, SP2: the right side of the east wing of the arena, open area, SP3: at the behind of the west wing of the arena and near the used tanks, SP4: the behind of the arena, close to green area, and SP5: the front of the east wing, surrounded by small buildings) and (b) Wind direction data from Little Stoke Weather station (Distance from the arena: 2.3 km).

Table 2.1. Physiochemical and microbiological analysis methods (UKAS, 2020).

Parameter	Method No.	Techniques used
Physiochemical parameters		
pH	-	pH/EC/TDS meter Hanna Instruments™ HI9812-5
Conductivity at 25 °C	-	pH/EC/TDS meter Hanna Instruments™ HI9812-5
Turbidity	3:404	Turbidity meter; nephelometric method (Hach 2100N Turbidimeter)
Alkalinity ($CaCO_3$)	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Total dissolved solids, TDS	-	pH/EC/TDS meter Hanna Instruments™ HI9812-5
Biochemical oxygen demand	2:702	Incubation at 20 °C
Chemical oxygen demand	2:703	Acid Dichromate - Colorimetric
Total hardness ($CaCO_3$)	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Ca. Hardness	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Mg. Hardness	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Nutrients, major ions and metals		
Chloride, Cl	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Nitrite, NO_2	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Nitrate, NO_3	-	Calculation
Ammonium, NH_4	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Sulphate, SO_4	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Fluoride, F	3:408	Ion Selective Electrode
Calcium, Ca	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Potassium, K	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Magnesium, Mg	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Sodium, Na	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Iron, Fe	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Manganese, Mn	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Copper, Cu	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Chromium, Cr	2:302	Inductively Coupled Plasma - Mass Spectroscopy
Cadmium, Cd	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Nickel, Ni	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Zinc, Zn	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Lead, Pb	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Microbiological parameters		
E.Coli	3:301	Membrane filtration

2.4. Simulation procedure

Figure 2.3 shows an overview of the simulation procedure. Data from the UK Time Use Survey, UK household occupancy statistics, and survey of UK appliance ownership (penetration) were required to generate water demand profiles for households in SIMDEUM. SIMDEUM WW was then used to create a stochastic wastewater discharge element based on appliance-specific discharge parameters such as nutrient loads in the wastewater. These patterns were then incorporated into the SWMM software by editing MATLAB codes behind SIMDEUM which produced file types that could be inputted into the SWMM programme. For a feasibility study on urban water recovery and reuse, SIMDEUM, SIMDEUM WW and UWOT were used while for a feasibility study on energy and nutrient recovery potential, SIMDEUM, SIMDEUM WW and SWMM were used. Details for each tool are presented in the following sections.

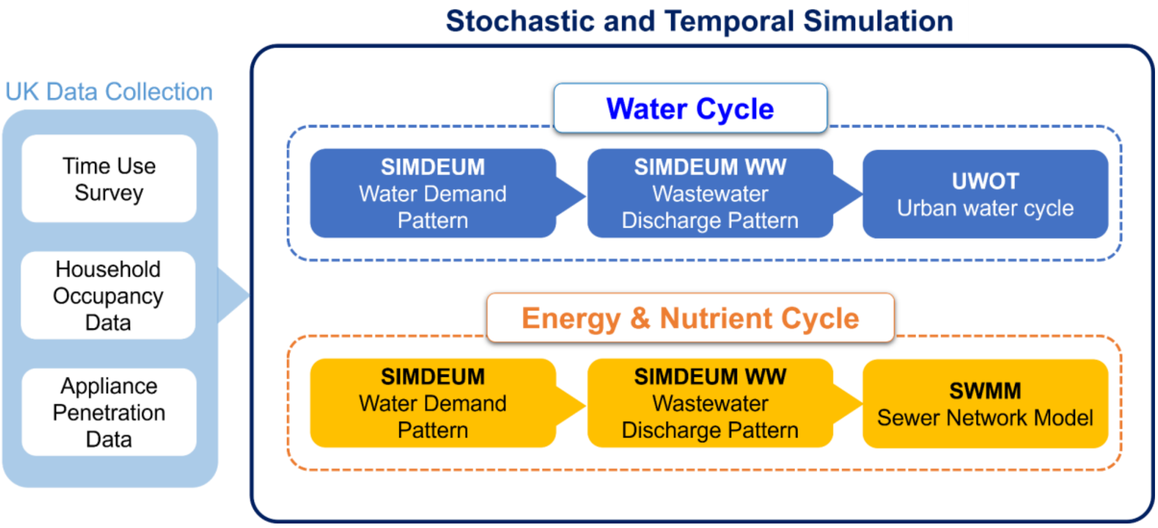


Figure 2.3. Overview of simulation procedure.

2.4.1. Water demand simulation

A potable water demand model entitled SIMDEUM® or "SIMulation of water Demand, an End-Use Model" developed by the KWR Water Research Institute (Blokker, 2010) was used. SIMDEUM is a stochastic end-use simulation with a small temporal and spatial level and generates water use patterns in both residential and commercial buildings based on water using devices, and consumer activities.

This study estimated water demand within the commercial YA building (i.e., toilet flushing and hand basin usage) using the default data Blokker et al. (2017) within SIMDEUM with the following assumptions: (i) an equal proportion of men and women; (ii) for hand basins, 2 L/use as a frequency of two times per day; and (iii) annual operation of 365 days (Hills et al., 2001). Although this study has not considered the effect of seasonal weather changes on water demand, this calibration nevertheless provides highly reliable results on water use profiles in houses within the study area. There were **three calibration steps** before running the SIMDEUM simulation, and details are as follows.

First, a calibration within SIMDEUM was conducted using the UK's official household occupancy statistics (Statistics, 2020) and the UK time use survey (Gershuny, 2017) by replacing the default Dutch data. Using the UK household occupancy statistics, the proportion of each household's occupancy (one, two, or family) for each house type was identified and thus used as input data within the model (Table 2.2). In addition, using the UK time use survey, how people spend their time with different age groups (eight years and over) was illustrated and summarised in Figure 2.4 and Table 2.3, respectively.

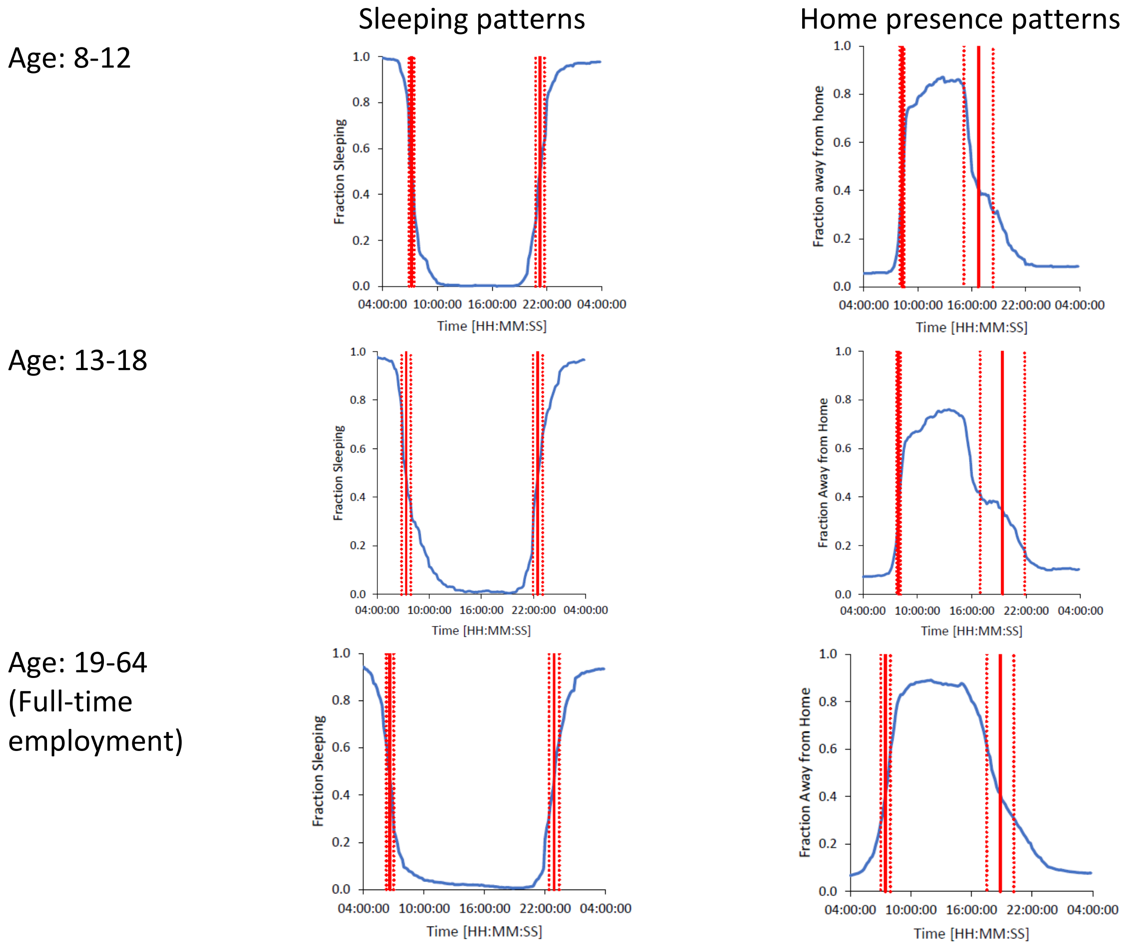
This replaced the default input of the Dutch time budget within SIMDEUM®. This was then used to simulate average weekday and weekend diurnal patterns in the UK. Finally, each house type utilizes different water use appliances. For example, two-bedroom house has two bathrooms, so we considered the use of two toilets, two freestanding showers and one bathtub for this household type. Such information for each house type was set in SIMDEUM.

Therefore, SIMDEUM could provide water demand patterns for each household type depending on the number of occupancy and bedrooms as presented in Table 2.4.

For the purposes of assessing the viability of energy and nutrient recovery (Chapter 4 and Chapter 5), stochastic modelling of discharge has an advantage over continuous models in that it may highlight where irregularities in wastewater flowrate may undermine performance of recovery equipment. For example, if there was only one house with a single occupant discharging into a system, whatever the average flowrate might be across a 24-hour period the modal flowrate would presumably be 0 LPM.

Table 2.2. Average household occupancy for each household type in the UK used for the SIMDEUM® simulation (Statistics, 2020).

	1-person households	2-person households	Family households
1-bedroom	69.5%	24.8%	5.7%
2-bedroom	36.6%	40.1%	23.3%
3-bedroom	21.0%	35.6%	43.4%
4-bedroom	11.1%	33.7%	55.2%



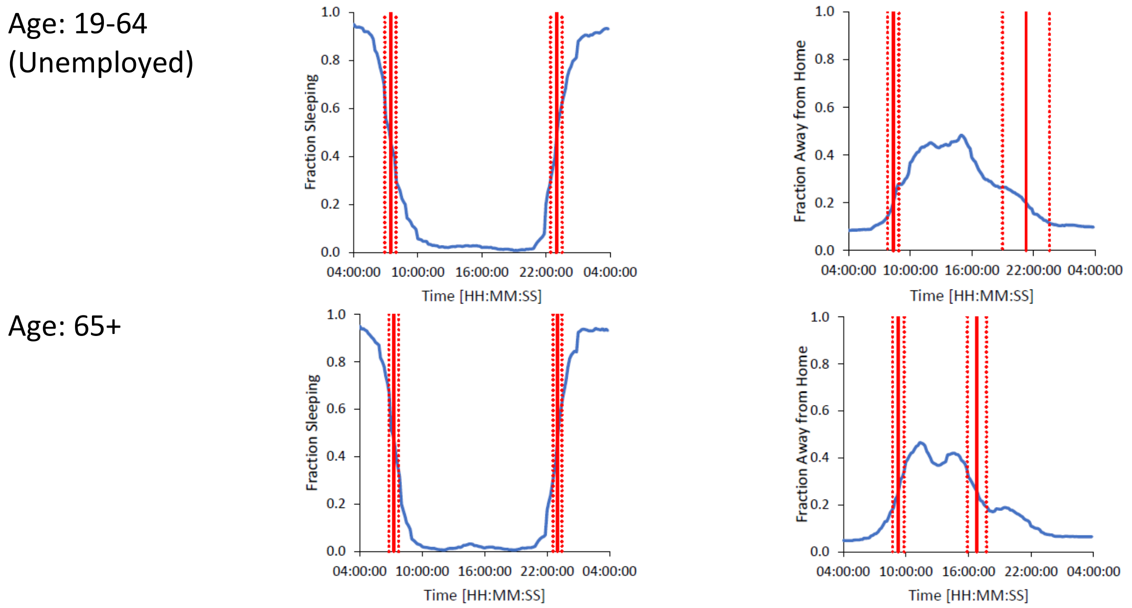


Figure 2.4 Diurnal patterns. The dashed red line indicates the method for calculating the standard deviation around the time of getting up and sleep. Values obtained from this figure were summarized in Table 2.3 and used for SIMDEUM simulation.

Table 2.3. Time budget data for the UK used for the SIMDEUM® simulation (Gershuny, 2017).

		Time of getting up		Time of leaving the house		Duration of no presence at home		Duration of sleeping	
		Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD
Child 8-12	Week	7:11	0:30	8:20	0:40	8:00	1:00	9:56	0:30
	Weekend	7:57	1:00	9:35	1:00	8:50	1:30	10:24	1:30
Teen 13-18	Week	7:17	0:50	8:02	0:45	8:38	1:30	8:46	0:50
	Weekend	9:10	0:50	10:35	0:45	9:17	1:30	10:12	1:00
Working adult 19-64	Week	6:31	0:30	7:44	0:30	9:32	1:15	7:34	0:30
	Weekend	6:58	1:15	8:01	1:00	10:54	2:00	7:50	1:00
Home adult 19-64	Week	7:22	0:30	8:45	1:30	9:46	1:30	8:20	0:50
	Weekend	7:59	0:50	9:52	1:30	8:48	2:00	8:51	1:00
Senior 65+	Week	7:15	0:45	9:17	1:00	7:32	1:30	8:15	1:00
	Weekend	7:35	1:10	9:35	1:00	7:48	2:30	8:32	1:20
Total	Week	6:59	1:00	8:09	0:50	9:48	1:10	8:07	0:50
	Weekend	7:55	1:30	9:31	1:30	9:29	2:00	8:57	1:30

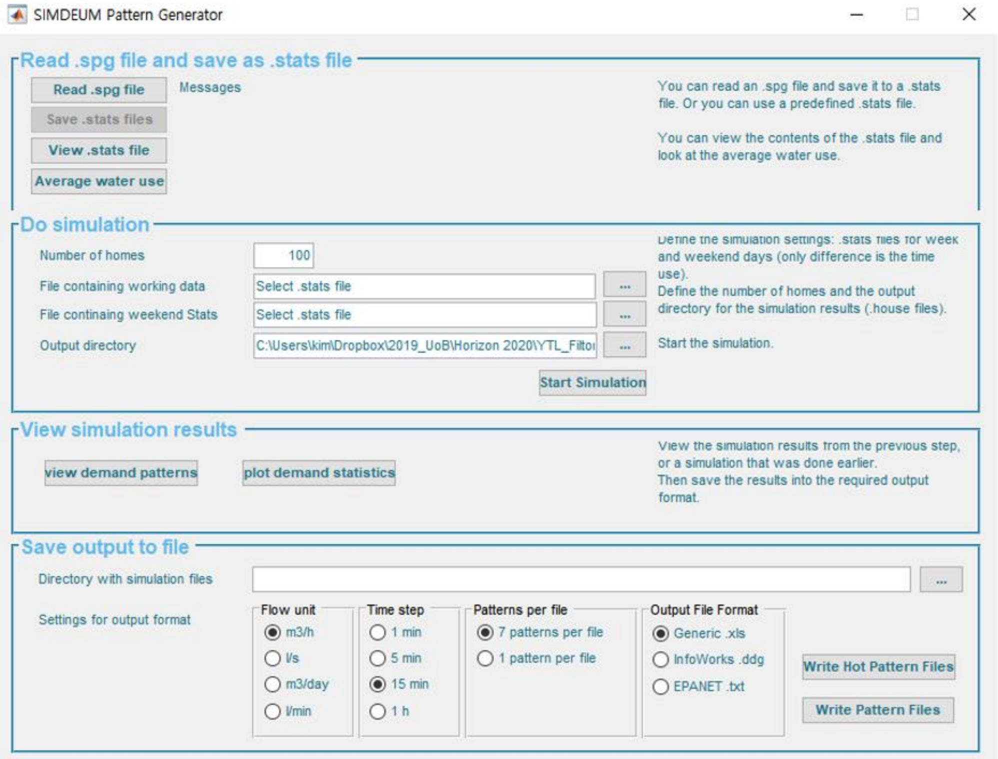
Avg.: Average, SD: Standard Deviation

Table 2.4. Average household occupancy for house with given number of bedrooms ± standard deviation.

	1 Bedroom	2 Bedrooms	3 Bedrooms	4 Bedrooms
Average household occupancy	1.31 ± 0.59	1.86 ± 0.90	2.45 ± 1.20	2.88 ± 1.30

The SIMDEUM pattern generator (SPG) tool was supplied by Watershare and the calibration for this pattern generator is described in the following section. The SPG tool is coded in MATLAB to provide a user-friendly interface without editing information within the code script of the programme, which can be seen in Figure 2.5.

The SPG works firstly by reading an .spg file which is user-produced in the Watershare tool and then saving the information in the .spg file as a week.stats file and a weekend.stats file, as can be seen under the “Read .spg file and save as .stats file” header of Figure 2.5. These .stats files can then be used to run a simulation of the water demand patterns which can then be plotted as time series graphs (Figure 2.7).



You can read an .spg file and save it to a .stats file. Or you can use a predefined .stats file.

You can view the contents of the .stats file and look at the average water use.

Number of homes: 100
File containing working data: Select .stats file
File continaing weekend Stats: Select .stats file
Output directory: C:\Users\kim\Dropbox\2019_UoB\Horizon 2020\YTL_Filto

Define the simulation settings: .stats files for week and weekend days (only difference is the time use).
Define the number of homes and the output directory for the simulation results (.house files).

Start the simulation.

View the simulation results from the previous step, or a simulation that was done earlier.
Then save the results into the required output format.

Directory with simulation files:

Settings for output format

Flow unit: ● m3/h ○ l/s ○ m3/day ○ l/min
Time step: ○ 1 min ○ 5 min ● 15 min ○ 1 h
Patterns per file: ● 7 patterns per file ○ 1 pattern per file
Output File Format: ● Generic .xls ○ InfoWorks .ddg ○ EPANET .txt

Figure 2.5. SIMDEUM Pattern Generator (SPG) User-Friendly Interface.

Once all 3 sections of the Watershare Tool had been completed, the data could be saved and exported into an .spg file type. If necessary, these .spg files could be opened in a notepad app as .txt files and be easily manipulated.

Using the downloadable SPG from the Watershare Tool, the .spg files could be read and saved as .stats files as shown in Figure 5.1. Using the SPG interface it was possible to view the household statistics information of the .stats files. This information on household statistics is summarised in Figure 2.6 for a 2-bedroom house type. The distribution of single, two person and family households are defined in the middle of Figure 2.6 and the other parameters including age, gender and labour division are shown around the edge.

Using this household occupancy information as well as the time use data, together with the water consumption information for each appliance, SPG was able to run a simulation and produce discharge profiles for each house type (Figure 2.7).

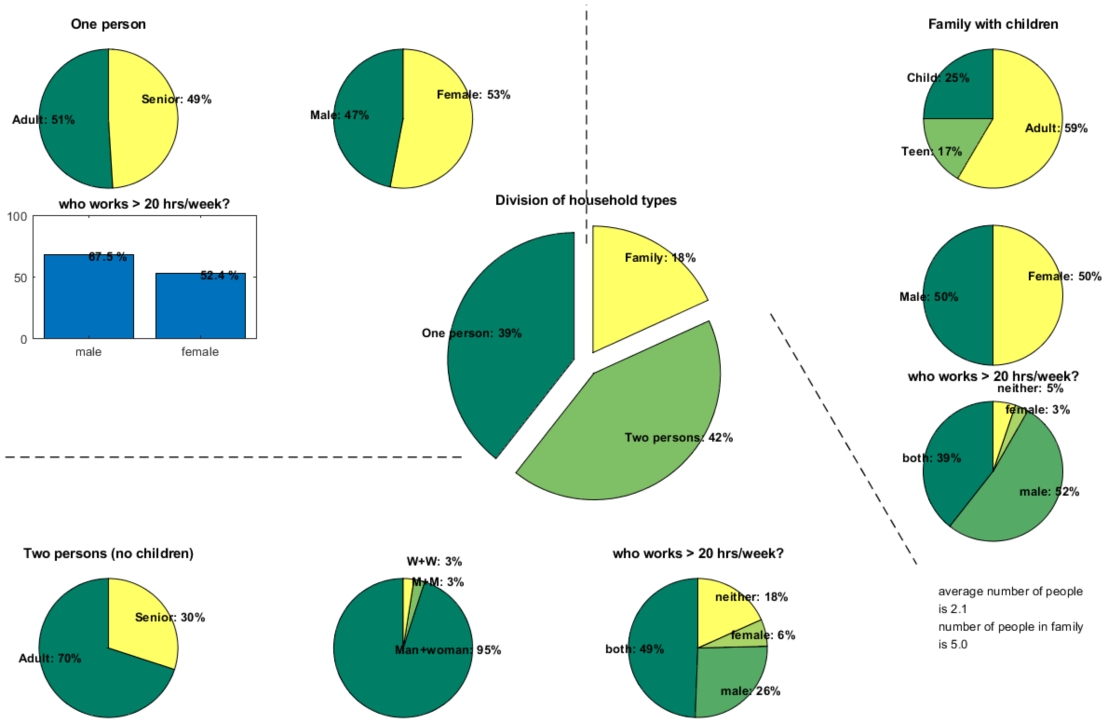


Figure 2.6. Household statistics data – an example of two-bedroom house.

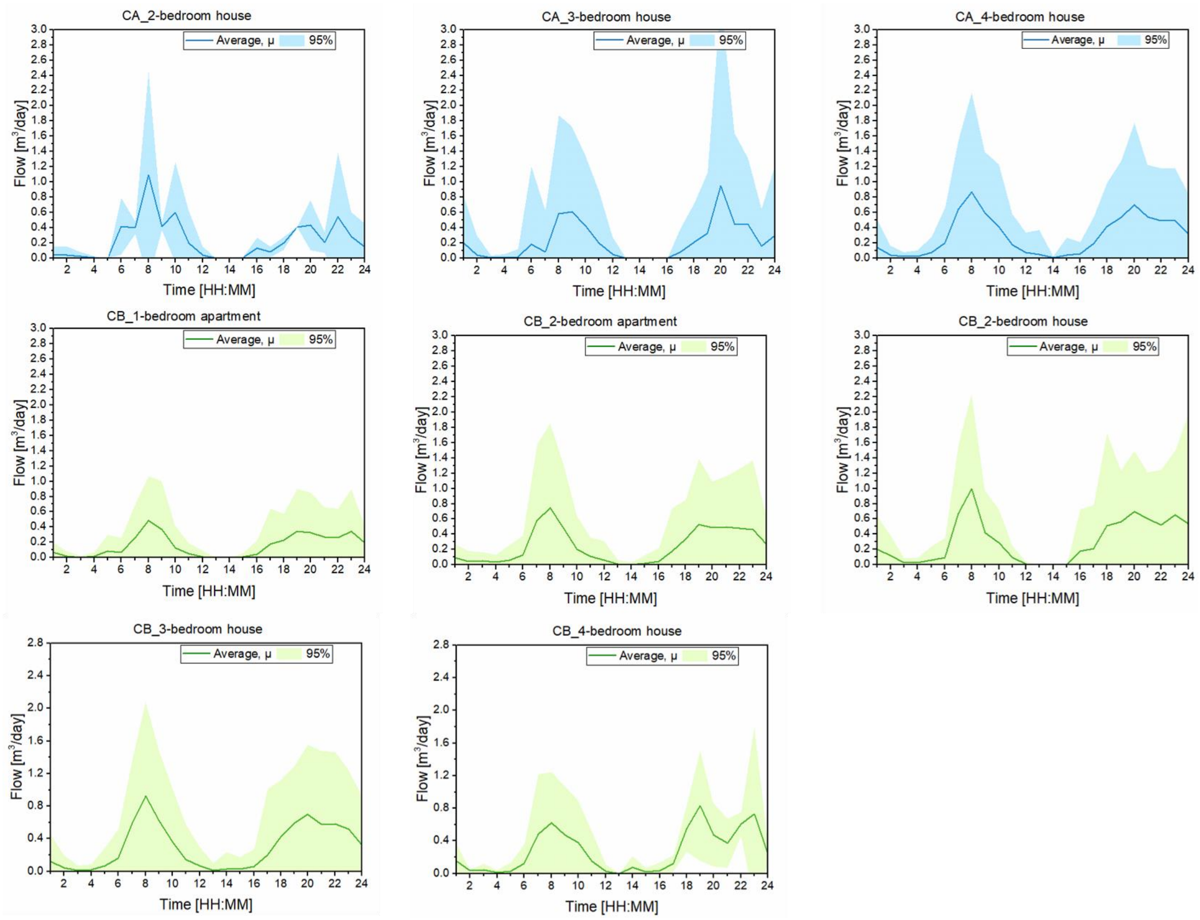


Figure 2.7. SIMDEUM simulations for each household types in catchments A and B.

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2.4.2. Wastewater discharge profiles

SIMDEUM WW is an extension of SIMDEUM and was used to assign appliance-specific wastewater quality profiles to each wastewater discharge. Certain appliances have similar demand and discharge patterns, for example, the shower running to the drain, however, other appliances such as a toilet or washing machine may discharge much faster than they are filled. By using SIMDEUM and SIMDEUM WW together it is possible to produce probabilistic discharge pulse flows into the sewer network. Unlike for the SPG, however, there has been no user-friendly interface built for the SIMDEUM WW programme, meaning these wastewater quality profiles were developed within the MATLAB code of SIMDEUM WW to produce time series .dat files to be integrated into SWMM. A separate time series file was required for each parameter, i.e., time series files for each house type and each nutrient, Nitrates (N) and Phosphates (P). Separate time series files were also needed for the water-saving appliances situations. The water saving appliances were water-saving shower heads and water saving toilets.

Time steps of 1 minute were used and the simulations were conducted over a 5-day period, the weekdays. The SWMM software could then produce a time series at the outfall of the network showing the cumulative flow and concentrations collected from the network over the simulated period.

2.4.3. Urban water cycle model

An urban assessment tool, namely the Urban Water Optioneering Tool (UWOT), is a model that optimizes the development of sustainable strategies for urban water cycle management (Makropoulos et al., 2008). UWOT produces various urban cycle metrics, including urban water flows (non-potable and potable water demand, wastewater production and stormwater volume) and water treatment technologies (treated greywater and rainwater) (Makropoulos et al., 2008; Rozos et al., 2013; Rozos et al., 2010).

Stored within the UWOT “technology library” is a variety of household items which have assigned water consumption and frequency of use parameters which correspond to different water-saving options for each item (i.e., showers items have multiple “brands” which offer different water-saving parameters). While the stored database offers a user-friendly operation, the parameters stored within the database may need to be verified and modified according to more up-to-date data. For the UWOT to make use of the database information, users are required to input 3 data measurements:

1. A time series of rainfall information that will be used to set up the rainwater harvesting scheme and to aid in the urban runoff from the area using permeability. For this timeseries, it is necessary to have access to primary rainfall data and set up possible forecasts as to the variation the Brabazon development can expect.

2. A timeseries of occupancy demonstrating the population expectations over an extended period of time. This is important information when identifying possible season trends in

population expectancy. For the Brabazon development, it is expected that there will not be a significant seasonal variation in population numbers.

3. A timeseries of the number of households. This information accounts for the influence of urban growth. For the Brabazon development, the entire project is expected to occur over more than 10 years, with housing areas being completed in stages. This can be seen as a form of urbanization and thus the rate at which the development expands falls under this timeseries.

In an assessment of water recycling technology, the UWOT has been used to prove the benefit of rainwater harvesting technology by reducing the drinking water demand in households (harvested rainwater can be used for non-potable uses which saves the use of drinking water) (Rozos et al., 2012). The effective modelling of these technology alternatives proves that the UWOT is successful in the simulation of integrated water management schemes, hence proving the tools suitability to the Brabazon development.

2.4.4. Sewer network model

The EPA storm water management model (SWMM) is primarily used to determine the impact of wet weather events on the urban water cycle with special consideration for combined sewer systems where wet weather events can create flooding events.

Using the files produced from SIMDEUM WW, each house has a node which can be matched to a specific time series, e.g., a time series of flow rates and temperature or a time series of nutrient concentrations. SWMM runs the wastewater quality model alongside the hydraulic model to produce realistic patterns. The concentration at every node is calculated for every time step, following the conservation of mass. It was assumed that the nodes are well mixed and there is no deposition or accumulation along the system. Dispersion along the conduits is also assumed to be negligible in SWMM and pollutants move through the conduits at a constant velocity. The SWMM simulation can then be run and the time series that results at the outfall for the 5-day period can be exported to Excel.

For the purposes of a modelling a closed gravity sewer the network consists of inflow nodes, junction nodes, outfalls, and channels. At inflow nodes wastewater is added to the network as described by a time series. At junction nodes flows are combined and are proceed onwards as a perfectly mixed plug. The outfall is simply the last node in the network where wastewater is removed. Channels carry wastewater along their length between nodes according to the Manning Equation 2.1 given below:

$$F = \frac{1.49}{n_M} AR^{2/3}S^{1/2}$$

Equation 2.1

where F is the flow rate, n_M is the Manning roughness coefficient for the channel material, A is the cross-sectional area of flow through the channel, R is the hydraulic radius of channel, and S is the slope of the channel. Hydraulic radius is described by Equation 2.2 below:

$$R = A/P_w$$ Equation 2.2

where P_w is the wetted perimeter of the conduit.

SWMM does not track dispersion, treating the network as a series of plug flows. This results in higher peak flowrates with periods of no flow that would not be encountered in actual sewers.

While SWMM does account for atmospheric temperature when determining inflows due to snow melt or losses due to evaporation, it does not natively track the temperature of wastewater itself. However, as SWMM does track pollutant concentrations in wastewater a simple model of wastewater temperature could be created by treating it as a material pollutant in an otherwise homogenous flow. SWMM ignores diffusion of pollutants, instead treating them as a slug.

In a simple case of two flows (F_1, F_2) with different temperatures (T_1, T_2) mixing at a junction node (as illustrated in Figure 2.8), the temperature of wastewater leaving that junction node (T_3) would be described by Equation 2.3 below

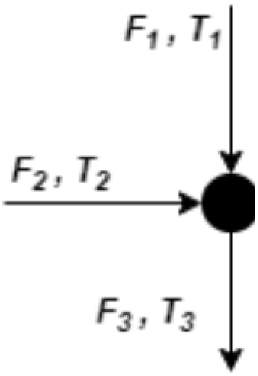

Figure 2.8. Example of mixing flow at junction.

$$T_3 = \frac{T_1F_1 + T_2F_2}{F_1 + F_2}$$ Equation 2.3

In general, this takes the form shown below in Equation 2.4 for a confluence of *n* pipes.

$$T_{mix} = \frac{T_1F_1 + T_2F_2 + \cdots + T_nF_n}{\sum F_n}$$ Equation 2.4

where T_{mix} is the temperature of the resultant flow.

Pollutants can be removed from any node in the network using a treatment function which takes the form of an equation describing either the outlet concentration or removal fraction from that node. Depth of wastewater, flowrate, surface area, simulation time step, and hydraulic residence time at the node are all valid variables for removal expressions.

The sewer network for the housing residential area shown in Figure 2.9 (Chapter 4 and Chapter 5). For this residential development, a separated sewer network was developed, meaning it excludes storm water. The sewer network is a gravity driven system with the outfall being the lowest point of the network and the furthest house from the outfall being the highest point. There are inflow junctions from each house or apartment block and all nodes are connected by conduits.

From the outfall the wastewater may be taken to a water treatment plant. The pipe network containing all junctions, nodes, conduits, and outfall can be seen in Figure 2.9. Figure 2.9 shows a map of the sewer network, with the network outfall (discharge to a wastewater treatment plant, WWTP) marked by an inverted triangle. By reading the map of the sewer network it was established that the path of flow through the sewer network to the network outfall was no more than 250 m for any node, and the maximum direct distance between the outfall and a network node was 168 m. This satisfies the proximity requirements for WWHR suggested by (Ali et al., 2019), making the site suitable for assessment.

The vertical pipes shown in Figure 2.10 demonstrate manhole locations from street level to the sewer pipes along the network. Each conduit was assigned a roughness factor of 0.01 and the conduits were all circular closed. The highest point of the network at 64.15 m and is the inflow from the 3-bedroom house, whilst the outfall is the lowest point at 58.665 m giving an overall elevation change of -5.485 m. Each node shown in Figure 2.10 could contain inflow from one or more houses in the network.

Figure 2.9. Map of the residential development with overlaid sewer network (SWMM).

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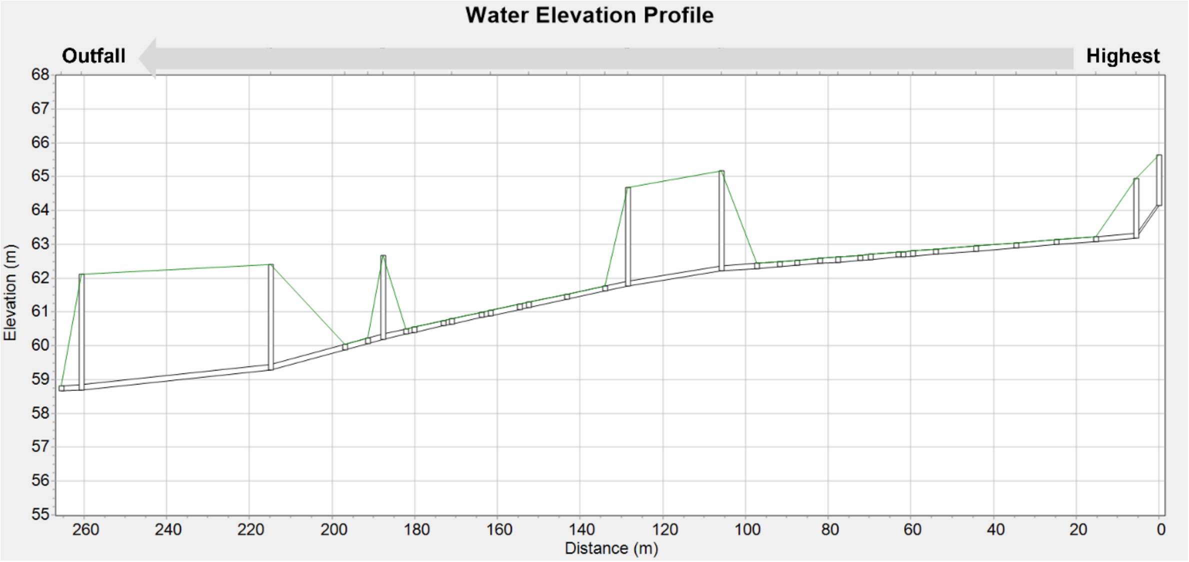

Figure 2.10. Cross sectional view of the sewer network from highest to outfall (lowest) point (SWMM).

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CHAPTER 3

Deliverable D1.8

Sub-Task 1.2.7 Integrating alternative water sources at district level at Filton Airfield

This chapter was published as:

1. Mackenzie, B., *Is rainwater harvesting a feasible water supply for Filton Airfield, Bristol*. MEng Research Project, University of Bath, 2020.
2. Ezekiel, J., *Dynamic modelling of a rainwater harvesting system for the YTL Development at Filton Airfield*. MEng Research Project, University of Bath, 2020.
3. Hubertus, L., *Rainwater harvesting system feasibility study for medium-scale urban developments – the Brabazon Development case study*. Master Research Project, University of Bath, 2020.
4. Kim, J.E. et al., *Optimal storage sizing for indoor arena rainwater harvesting: Hydraulic simulation and economic assessment.* Journal of Environmental Management, 2021. 280: p. 111847.
5. Kim, J.E. et al., *Evaluation of harvesting urban water resources for sustainable water management: Case study in Filton Airfield, UK.* Journal of Environmental Management, 2022. 322: p. 116049.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

3. Closing the Water Cycle

The study site covers the development of Filton Airfield eastern infrastructure where includes residential and commercial land uses. We focussed on this first phase of the development with the intention that the results and findings from the research providing a useful business case for YTL Developments in the future phases of the development. The development plan involves different blue-green infrastructure elements. In this study, the main reasons for including blue-green infrastructure on-site are to demonstrate alternative water resources and evaluate sustainable urban water management strategies: (i) rainwater harvesting system and (ii) hybrid rainwater-greywater harvesting system.

3.1. Rainwater harvesting system

3.1.1. Introduction

Rainwater harvesting (RWH) has been recognised as an effective management method. RWH can provide benefits, including a supply of non-drinking water for end uses such as toilet flushing, washing machines, washing cars and watering gardens. This can reduce a building's clean water demand and water bills (Campisano et al., 2017). Rainwater collected from roof runoff is the most common type of RWH system as it requires minimum treatment and only consists of a collection area, a conveyance system and a storage tank (Ward, 2007). Several scales of RWH systems operate in the UK, ranging from individual houses to commercial buildings for different non-potable water purposes (Fewkes, 2012).

The existing studies on the simulation-based optimization of a rainwater harvesting system and cases implemented in the UK have offered some solutions to determine the optimum storage capacity for rainwater harvesting at residential or commercial buildings by taking into account optimizing variables, including cost, reliability, water saving efficiency, green roofs irrigation and runoff capture (An et al., 2015; Bocanegra-Martínez et al., 2014; Okoye et al., 2015; Ruso et al., 2019; Sample et al., 2014; Ward et al., 2012). However, it is often difficult to validate a global optimum for any conclusions and any applications as identifying an optimal storage size for a RWH system is highly depends on water demands, seasonal conditions, economics and infrastructure at a given geographic area (Alim et al., 2019; Semaan et al., 2020).

Besides, in the UK, there has been a wider implementation of rainwater harvesting at commercial scales due to their financial benefit (Campisano et al., 2017), there is limited information for closing the implementation and investment gap in the rainwater reuse. Therefore, there is still a need to demonstrate practical ways to increase the applicability and cost-benefit of a rainwater harvesting system.

This section 3.1 reports a feasibility study of a RWH system in an indoor arena and residential area via daily water balance simulations and economic analysis approaches. Rainwater harvesting scenarios therefore include centralised and decentralised rainwater supply systems with different rainfall catchment scenarios.

3.1.2. Methods

3.1.2.1. Rainwater catchment and water demand scenarios

Table 3.1 presents detailed information on scenarios for collecting rainwater from rooftops of residential and commercial buildings. The centralised system involves a rainwater harvesting system with a single rainwater storage tank while the decentralised system involves multiple rainwater harvesting systems with multiple rainwater storage tanks which each system is connected to a small number of houses. Collected rainwater is used for non-potable purposes, including dishwasher, washing machine, irrigation and toilet flushing, depending on scenarios (Table 3.1).

As the early stage of the Brabazon development design plan, a total of 278 housing units were planned, but there was little information on the percentage of apartments and housings. So, a mean catchment area of 65 m^2 per unit was initially assumed. For S-1, a group of 23 houses was considered for the decentralized system with a roof surface of 1,495 m^2. Whereas S-2 considered a centralized rainwater system that collects rainfall from a roof of the central hangar 13,000 m^2. It was assumed that the collected water is used for non-potable uses, including washing machine and toilet flushing. Thus, the annual demand for the decentralized (S-1) and centralized (S-2) systems amounted to 1,275 m^3 and 15,412 m^3, respectively. Although S-3 also considered a centralised rainwater collection from the roof of the central hangar (13,000 m^2), water demand in this scenario differs from S-1 and S-2, considering only toilet flushing. Thus, the yearly demand without the washing machine was 12,652 m^3.

Scenario 4 (S-4) further demonstrated a centralised rainwater collection from a group of 278 houses. During the second stage of the Brabazon development design plan, although it was intended to include 1- and 2-bedroom apartments as well as 2-, 3-, 4- and 5-bedroom houses, the exact details of the breakdown of the number of each unit type were not available (September 2020). However, this information provided an indication of the potential roof surface collection area. An estimation for the floor space for each of the unit types was the starting point for the estimate of potential collection surface areas.

Table 3.2 thus shows a summary of the estimated breakdown of the number of each of the different unit types with an estimate of roof collection surface areas for each unit type. It has to be noted here that apartment buildings consist of 34 units per floor (x17 1-bedroom units, and x17 2-bedroom units). Thus, the total collectable surface area is limited to the total surface area of these 34 units. The catchment area for S-4 assumed to be 16,530 m^2. In this scenario, an upper and lower limit to the input data for the supply and demand characteristics was employed to obtain a performance range which will include the likely performance of the system. This approach also has the added benefit of incorporating a measure of sensitivity to changes in the supply and demand information. To achieve the upper and lower limit for the system's performance, variations in the supply and demand input characteristics were simulated. The lower limit combines the highest demand and lowest rainwater supply (referred to as the worst case), while the upper limit combines the lowest demand with the highest rainwater supply (referred to as the best case). Table 6 indicates the best and worst cases.

Scenarios 1-4 used the collected rainwater for only domestic purposes while S-5 assumed to use the collected rainwater for commercial uses, including toilet flushing within YTL Arena and irrigation for both Filton golf course and Brabazon park as described in Table 3.3. In this scenario, the entire roof of the YTL Arena (30,000 m^2) was assumed to be the catchment area for the centralised rainwater harvesting system.

Table 3.1. Rooftop rainwater harvesting scenarios for Filton Airfield (WM= …, WC=toilet flushing, etc.

Scenario (S)	Supply system	Catchment	Roof area (m^2)	Water reuse (non-potable)
S-1	Decentralized system	Roof of a group of 23 houses, 65 m^2/unit	1,495	WM, WC
S-2	Centralised system	Central roof area of YTL Arena	10,000	WM, WC
S-3	Centralised system	Central roof area of YTL Arena	10,000	WC
S-4	Centralised system	278 houses	16,530	DW, WM, WC
S-5	Centralised system	Entire roof area of YTL Arena	30,000	WC, IR

Table 3.2. Estimated unit number and roof surface area used for scenario 4.

Residential unit type	Bedroom type	Assumed quantity	Unit roof surface area (m^2/unit)	Roof surface area estimate (m^2)
Apartment	1	68	50	850
	2	68	75	1,275
Houses	2	36	100	3,600
	3	36	130	4,680
	4	35	80	2,800
	5	35	95	3,325
Total	-	278	-	16,530

Table 3.3. Water demand scenarios and values used for scenario 5.

Scenario			Unit	Value
Single use	YTL Arena (YA) toilet flushing (TF_{YA})	Visitors (TF_{YA1}, TF_{YA2}, TF_{YA3}, TF_{YA4})	Person/day	2,000, 5,000, 10,000, 20,000
		Toilet	L/flush	6
		Urinal	L/flush	3.6
		Frequency	Flush/capita/day	2
	Irrigation (IR_{BP} & IR_{FG})	Brabazon Park (BP) (IR_{BP1} & IR_{BP2})	ha	6 and 12
		Filton Golf Course (FG) (IR_{FG1} & IR_{FG2})	ha	23 and 46
		Frequency (May–October)	Irrigation/week	1
		Water use	L/m^2/day	5
Combined use	50%TF + 50%IR and 70%TF + 30%IR			

For S-5, there were sub-scenarios for water reuse applications. Figure 3.1 and Table 3.4 show the water demand scenarios and values used for four different water use scenarios: (a) toilet

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flushing (WC) within the YTL Arena (YA), (b) irrigation (IR) for the Brabazon Park (BP), (c) the Filton Golf Course (FG) and (d) a combination of toilet flushing and irrigation (WC+IR).

Figure 3.1. Location of water reuse applications, YTL Arena, Brabazon park and Filton golf course.

Table 3.4. Demand characteristics for each scenario.

Scenario (S)		Water reuse (non-potable)		Water demand (m^3/year)
S-1		WM, WC	23 houses per RWH system	1,275
S-2		WM, WC	278 houses	15,412
S-3		WC	278 houses	12,652
S-4	Best case	DW, WM, WC	278 houses	9,787
	Worst case			39,463
S-5	TF_{YA1}	WC	YTL Arena (YA)	8,030
	TF_{YA2}			19,710
	TF_{YA3}			39,420
	TF_{YA4}			78,840
	IR_{BP1}	IR	Filton golf course (FG) and Brabazon park (BP)	55,115
	IR_{BP2}			110,230
	IR_{FG1}			211,700
	IR_{FG2}			423,035
	$50\%TF_{YA4} + 50\%IR_{BP2}$	WC+IR	YA, FG and BP	94,535
	$70\%TF_{YA4} + 30\%IR_{BP2}$			88,330
	$50\%TF_{YA4} + 50\%IR_{FG2}$			182,135
	$70\%TF_{YA4} + 30\%IR_{FG2}$			251,120

For toilet flushing demand within the YA (S5), four different capacities were assumed to be met every functional day. An equal proportion of males and females was considered. For toilet use, half the males used urinals and the other half used toilet bowls. Toilet bowls were assumed to use 6 litres per flush, while the urinals used 3.6 litres per flush (Hills et al., 2002; Zadeh et al., 2013). The annual operation days was assumed to be 365 (Hills et al., 2001). An irrigation plan was assumed to be in operation when there is no rain from May to October for BP and FG. The volume of irrigation water was assumed to be 5 litres per square meter per day (Matos et al., 2013; Roebuck et al., 2011). Equations 4.1 and 4.2 to determine the water demand for each application are as follows (Matos et al., 2013):

Water demand for toilet flushing

$$D_{WC} = V_{WC} \times F_{WC} \times N$$

Equation 3.1

where D_{WC} is the total demand for toilet flushing (m^3), V_{WC} is the volume of water used per flush (m^3), F_{WC} is the frequency of toilet use/flush (-) and N is the number of people using the toilet (-).

Water demand for irrigation

$$D_{IR} = V_{IR} * F_{IR} * IA \quad \text{Equation 3.2}$$

where D_{IR} is the total demand for irrigation (m^3/day), V_{IR} is the consumption unit per irrigation area (m^3/m^2), F_{IR} is the frequency of irrigation (day^{-1}) and IA is the irrigation area (m^2).

3.1.2.2. Rainfall data

As described in Table 3.5, scenarios 1-3 used the same rainfall data with a time series covering an 11-year. Whereas, S-4 and S-5 used different historical rainfall data, 10-year and 53-year, respectively. Detailed rainfall analysis conducted for each scenario are addressed in the following sections.

Table 3.5. Description of collected rainfall data used for each scenario.

Scenario (S)	Historical rainfall data	Rainfall analysis
S-1	11-year, 1st January 2008 - 31st December 2018	Rainfall data was used to generate synthetic rainfall data
S-2		
S-3		
S-4	10-year, 16th September 2010 - 1st October 2020	Correlation coefficients was evaluated to select the most reliable weather station
S-5	53-year, 1st January 1968 - 31st December 2020	The precipitation concentration index (PCI) and standard precipitation index (SPI) values were analysed to confirm the climatic regimes (dry, normal and wet years) using long-term period rainfall data

Synthetic rainfall data generation - Scenarios 1, 2 and 3

Throughout the preliminary stages of development, a placeholder approximation was used for daily rainfall, represented by the variable X, which was normally distributed around a mean of 10 mm. Once generated, X was appended to an array containing the previously generated values. Consequently, the tank volume model was run using this array of values to simulate rainfall. This approach to rainfall simulation was taken to ensure the tank volume model functioned as intended – once this was established, a more sophisticated and real-world approach to rainfall simulation was taken. A time series containing an 11-year-long set of daily rainfall values in the Bristol region for approximately 4000 consecutive days from the 1 of January 2008 until the 31 of December 2018 was used as an input to replace the rudimentary placeholder approximation described above. This approach allowed for the demonstration of the tank volume model with real-world, region-specific rainfall data.

Given that the RWH systems in urban settings are beginning to form part of a more holistic, decentralized approach to urban stormwater management systems, it is important to consider resilience and long-term applicability when optimizing design parameters (Valdez et al., 2016). Consequently, proposed RWH systems must be designed with the capacity to withstand and manage extreme events. Given the typical operational lifetime of a RWH system, an extreme event that occurs once in 30 years should be accounted for (Ghimire et al., 2019). An 11-year-long historical set should not be used to simulate a once-in-30-year event due to the limitations of extrapolating a data set beyond a reasonable scope. Hence probabilistic modelling must be employed.

Weather events can be simulated by either deterministic or stochastic models. The word "stochastic" implies the presence of a random variable, e.g., stochastic variation is a variation in which at least one of the elements is a variate and a stochastic process is one wherein the system incorporates an element of randomness as opposed to a deterministic system. In a deterministic model, the values for the dependent variables of the system are entirely determined by the parameters of the model. In contrast, stochastic, or probabilistic, models include randomness in such a way that the outputs of the model take the form of probability distributions rather than discrete values (Rey, 2015). Rainfall is a complex phenomenon driven by multiple physical mechanisms acting at multiple spatial-temporal scales; thus, deterministic modelling holds limited practical value for the purpose of rainfall simulation (Hingray et al., 2005). More specifically, Hingray et al. (2005), through an analysis of seven disaggregation models, showed that classic deterministic models lead to a significant underestimation of some important rainfall statistics such as variation coefficient and extremes of 10-min rainfall amounts.

Stochastic models have been the standard for several decades where the model outcomes are non-discretised (Rey, 2015). Instead, they are probability distributions, or density functions, which represent the inherent statistical properties of a phenomenon. Koutsoyiannis et al. (1996) demonstrated the efficacy of such models at simulating rainfall by showing there to be no substantial difference in behaviour between a synthetic and historic rainfall time series. Kurothe et al. (1997) provides evidence to show that the intensity of daily rainfall levels is distributed exponentially if only wet days (days with rainfall) are considered. To allow for the modelling approach described by the flowchart in Figure 3.2, two assumptions were made. Firstly, daily rainfall levels were assumed to be exponentially distributed for wet days only. Secondly, the probability of a day without rainfall occurring is equal to the total number of 'dry days' divided by the total number of days in the time series. For the 11-year-long set of daily rainfall values this probability was found to be 0.47. With these two modelling assumptions, synthetic rainfall time series could be generated using the simulation steps described below.

Firstly, the 11-year-long set of daily rainfall values (2008-2018) was manipulated by omitting all dry days from the data set to only include days with non-zero rainfall levels. The Kolmogorov-Smirnov test (KS test) is a distribution-fitting algorithm that quantifies the extent to which a dataset adheres to an empirical distribution. The K-S test outputs the location and scale parameters for the probability distribution which most closely matches the dataset as well as the p-value which indicates the probability that this pattern was due to a random sampling error. After the application of the KS test (distribution fit), the inherent statistical properties of the historical time series are represented by a probability (continuous) distribution using the location and scale parameters. Subsequently, a Monte Carlo simulation can be applied to yield different sets of rainfall data or ‘paths’ of this stochastic process through iteration with a set of random variables or ‘state space’ modelled based on the probability distribution produced in the previous step.

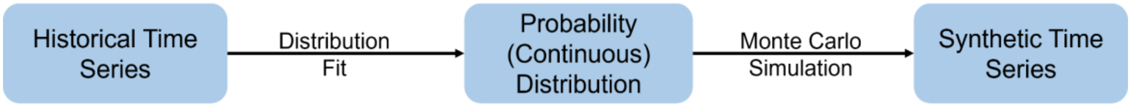


Figure 3.2. Flowchart displaying the process for generating synthetic rainfall data from a historical time series.

The efficacy of the distribution-fitting and Monte Carlo simulations were analysed to ensure that the inputs to the tank volume model were consistent with typical rainfall patterns of the North Bristol region which encompasses Filton Airfield. Rainfall events, patterns and behaviours may be described by a plethora of metrics. Within the context of this enquiry as it relates to the applicability of RWH systems to a development at Filton Airfield, five key metrics were identified as necessary components of a thorough comparison of synthetic and historical rainfall data. These metrics are the distribution of rainfall event intensity, total annual rainfall, peak annual rainfall, seasonality, and periodicity. This analysis is comprised of a comparative analysis of rainfall data from between 2008 and 2018 with a year-long synthetic time series.

The distribution of rainfall events was assessed through a side-by-side, qualitative comparison of Figure 3.3 (a) and (b). Both time series appear to be distributed exponentially – this is expected since the synthetic time series displayed in Figure 3.3 (a) reflects the inherent statistical properties of the historical time series in Figure 3.3 (b). Given the assumption that rainfall levels for wet days are exponentially distributed, the KS test may be applied to yield the p-value which was used to quantify the validity of this assumption. The KS test yields a p-value of 0.027; thus, the probability that this pattern was due to a random sampling error is sufficiently low. The KS test provided location and scale parameters of 0.254 and 3.85 respectively. These parameters describe an exponential distribution with the best-possible fit to the historical data, i.e., the distribution in Figure 3.3 (b) is the best-possible representation of the inherent statistical properties of the historical data insofar as it can be assumed that the historical data is distributed exponentially. This assumption is valid due to the p-value from the KS test, and consequently the synthetic time series accurately reflects the distribution of rainfall event intensity. Annual rainfall averaged 706 mm per year with a peak of 1135 mm in 2012 and a low of 585 mm in 2010 over the 11-year period from 2008 to 2019. This year-on-year variability is not apparent in the synthetic time series since each set is based off the same probability distribution – it is only the random nature of the input variables that results in variance. The overall average of mean annual rainfall for a set of ten synthetic time series was 729 mm which is within ± 2.5% of the real-world figure. As expected, there was little year-on-year variance with a peak of 743 mm and a low of 717 mm. The similarities in mean annual rainfall between historic and synthetic data demonstrate the general accuracy of the simulation, however, the lack of exceptionally wet years in the synthetic data (due to the low year-on-year variance) limit the applicability of such data. RWH system parameters need to be optimized with both typical and high-rainfall years since this will have a direct effect on flood attenuation performance – the main cost saving benefit of RWH systems. Peak annual rainfall is the amount of rainfall experienced on the wettest day of a calendar year.

(a) (b)

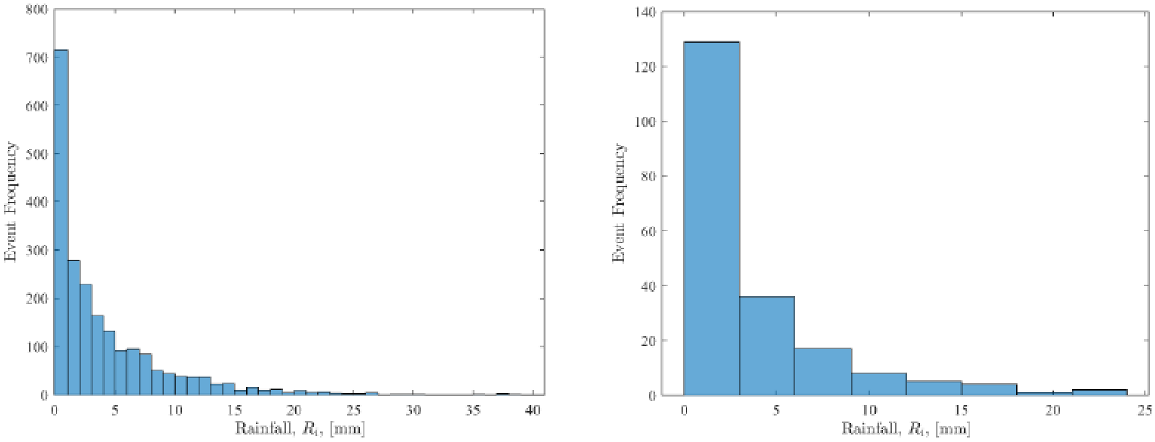
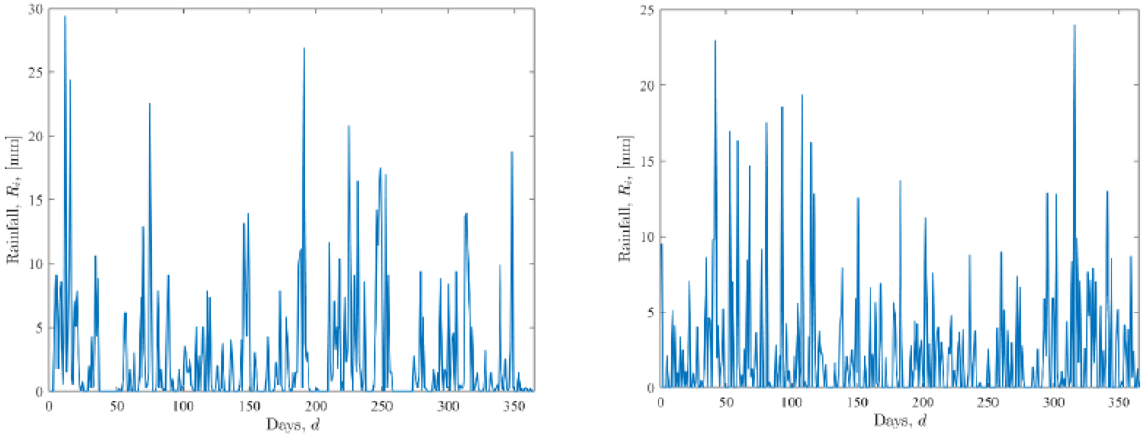


Figure 3.3. (a) Histogram displaying the distribution of daily rainfall levels – excluding dry days – for Bristol from 1st January 2008 to 31st December 2018 and (b) Histogram displaying the distribution of daily rainfall levels – excluding dry days – for a yearlong period that was generated stochastically based on the time series presented in Figure 3.3 (a).

In the synthetic time series, the peak annual rainfall was 24.1 mm and 29.5 mm for the historical as shown in Figure 3.4 (a) and (b) respectively. The peak annual rainfall for each of the other years was analysed to ensure this discrepancy was not due to an abnormal year. From this, it was found that as a mean, peak annual rainfall in the historic time series was 24% greater than in the synthetic time series. Although the historical data may be closely approximated by an exponential distribution, it is not a perfect fit. This is the cause of discrepancies between peak annual rainfall values in historic and synthetic time series. This discrepancy was more pronounced when looking at extreme rainfall events. I.e., the rainfall values of common events are within ± 5% of each other for historic and synthetic time series, however, for extreme events this difference is significant since the adherence to exponentiality decreases as events become less frequent. The histogram of rainfall events in Figure 3.4 (b) shows this deviation from exponentiality at high rainfall values (greater than 15 mm). For this reason, a fitted exponential distribution will be unable to produce synthetics time series with similar peak annual rainfall values.


(a)

(b)

Figure 3.4. (a) Daily rainfall levels for Bristol from 1st January 2018 to 31st December 2018 and (b) Daily rainfall levels for a year-long period that were generated stochastically based on a time series of rainfall values from 2008 to 2018.

Seasonal variance is a key characteristic of rainfall that affects the distribution of wet and dry months throughout the year. Figure 3.5 (a) contains the mean monthly rainfall from 2008 until 2019 and exhibits seasonal variance with significantly wetter months from September to

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January and drier months from February to August. Although this data is specific to the Bristol region, this reduction in rainfall during the summer period is consistent with national rainfall data. Figure 3.5 (b) shows the mean monthly rainfall for data produced by the simulation which does not account for seasonal variance and as a result, month-on-month variance does not exceed ± 3.5% from a mean of 66.8 mm.

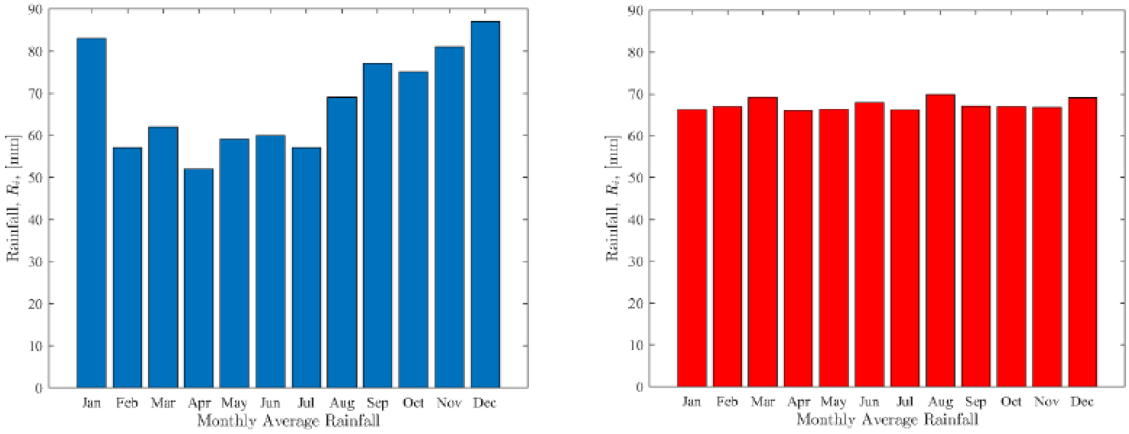
(a) (b)

Figure 3.5. (a) Monthly average rainfall for the Bristol region from 2008 to 2019 and (b) Monthly average rainfall for synthetic rainfall data produced by the simulation (11-year aggregates).

Thus, the simulation underestimates monthly rainfall totals from September to January and overestimates these totals from February to August. This limitation has significant implications for the optimization of RWH system parameters – namely, it may lead to an underestimation of the overall tank volume since parameters optimized using the synthetic data (found in Figure 3.3 (b) and Figure 3.4 (b)) do not account for the high-rainfall months from September to January. I.e., RWH systems that are optimized for an inflow from 66.8 mm of rainfall per month will likely be unable to manage greater inflows caused by the effect of seasonality on rainfall. As a metric, the periodicity of rainfall has important implications for the design and optimization of RWH systems, specifically the impact of periodicity on the reliability of storage systems (Afzal et al., 2016). As stated earlier in this report, the periodicity of rainfall is not accounted for due to an assumption made during modelling – specifically that a rainfall event has a 47% chance to occur on any given day. The longest annual dry periods were 18 days and 7 days for the 2018 data and the synthetic data displayed in Figure 3.4 (a) and (b) respectively.

Moreover, inspection of these graphs shows dry periods to be more sustained and frequent in the historical rainfall data compared to the synthetic data. This stark difference is a result of the modelling assumption mentioned prior as the probability of rainfall on any given day is function of complex meteorological conditions and not a constant value of 47%. Since the simulation cannot accurately model dry periods, the RWH model will have a steadier influx of rainwater when operated using synthetic data. This feature will result in the artificial inflation of RWH system reliability as the RWH tank is less likely to be empty. When operated with historical data, dry periods have a far more prominent effect on the dynamics of the tank water level, with a higher likelihood for an empty tank, necessitating mains water usage and consequently reducing performance. This difference in tank volume behaviour for historic and synthetic rainfall data is demonstrated in Figure 3.6 (a) and (b) which report the tank volume over a monthlong period for both historical and stochastic rainfall data with the centralized RWH system.

Evidently the tank volume in Figure 3.6 (b) does not accurately simulate the tank volume based on real-world data because of the rainfall simulation method. Without accounting for periodicity, rainfall levels from the simulation are highly erratic and therefore so is the tank volume. Considering all the above, historical rainfall data is best suited for RWH parameter optimization due to the limitations of the rainfall simulation at replicating the inherent statistical properties of the historical data.

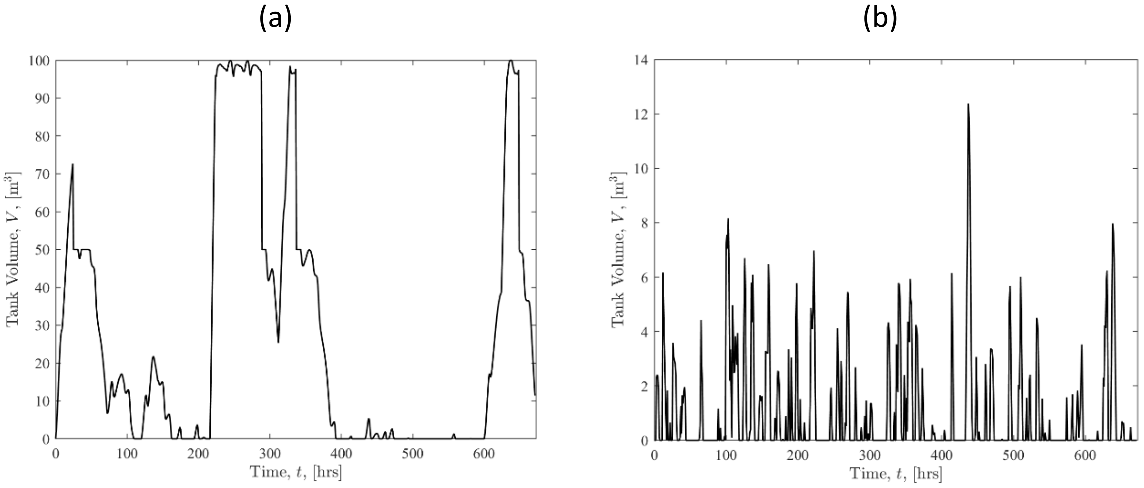

Figure 3.6. (a) Variance of tank volume for a month-long period with rainfall data from October 2018 with an hourly temporal scale and (b) Variance of tank volume for a month-long period with synthetic rainfall data with an hourly temporal scale.

In summary, although probabilistic modelling encompasses possible extreme rainfall events not within the scope of an 11-year-long data set, the synthetic data was inaccurate since the periodicity and seasonality of rainfall were not taken into account. RWH tank parameters were optimized with rainfall data from 2018 which is a typical year with mean annual rainfall of 706 mm, within 2% of the mean. Subsequently, the optimized system was stress-tested using rainfall data from November 2009 (the wettest year of the available historical data, mean annual rainfall of 1,135 mm) to assess the resilience of the optimized system to adverse conditions.

Selection of weather station - Scenario 4

The forecasted rainfall in the area is the principal factor in calculating the amount of water the system can harvest. This factor requires the use of a historical rainfall dataset. The University of Bath operates a weather station (now referred to as UOB1) that is located at the Filton site and has a complete hourly rainfall dataset from 16 September 2019. This station represents the most accurate rainfall recordings for the Filton site, but the use of this data is limited due to the short reporting period. By using rainfall datasets from weather stations surrounding the Filton site, it is possible to extend the UOB1 dataset to cover a 10-year period between 16 September 2010 and 1 October 2020. Although the extended dataset will not be an exact representation of the historical Filton rainfall, it will represent an acceptably accurate estimate for this period.

Figure 3.7 shows a summary of the nearby weather stations and their respective reporting periods. The IBRISTOL25, IBRISTOL137, IBRIST53 and IBRIST73 weather stations are all excluded from this study due to their short reporting period. However, the IBRISTOL3 and IBRISTOL29 stations have acceptable reporting periods for use in this study. Rainfall data is obtained from Weather Underground (Underground, 2020) for each of the IBRISTOL3 and IBRISTOL29 stations. To distinguish between these weather stations, Pearson's correlation (or correlation coefficient) is used to compare the readings from the 2 stations for the period between 16 September 2019 and 25 June 2020 to the readings taken by the UOB1 station.

The correlation coefficient that is closest to a value of 1.0 represents a dataset that most accurately replicates the UOB1 station. The results from the correlation coefficient calculation can be found in Figure 3.8.

Both weather stations present correlation coefficients above 0.86 which indicates that each of the stations presents a suitable dataset for the use in this project. Even though the IBRISTOL3 station shows the lower correlation coefficient (0.86 compared to 0.89 for IBRISTOL29), the IBRISTOL3 station is chosen as the representative dataset for the period September 2010 to September 2019 as this station is the closest weather station to the Filton site.

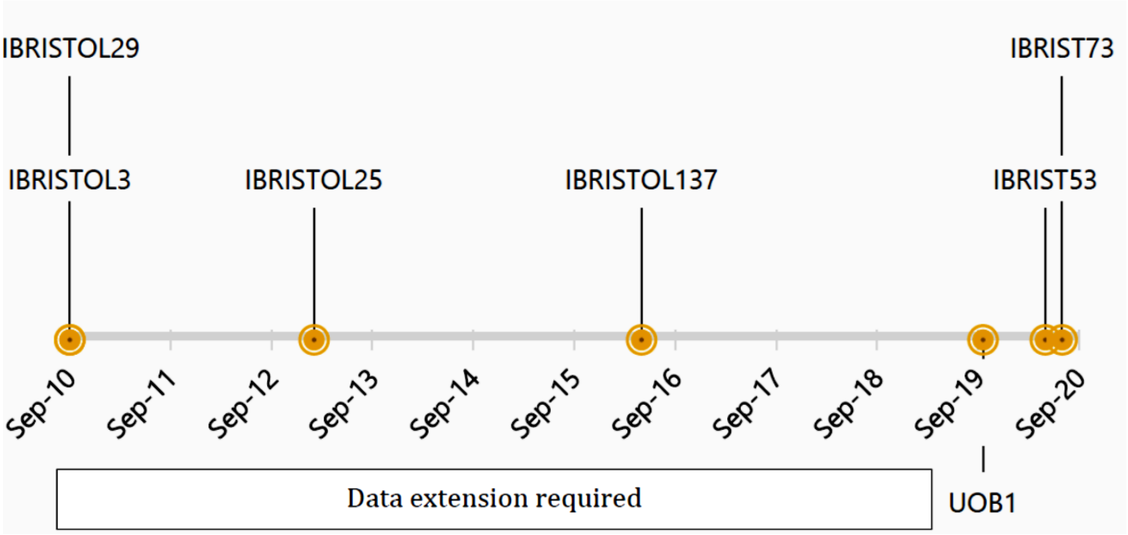

Figure 3.7. Weather station reporting period timeline (16 September 2019 – 25 June 2020).

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(a)

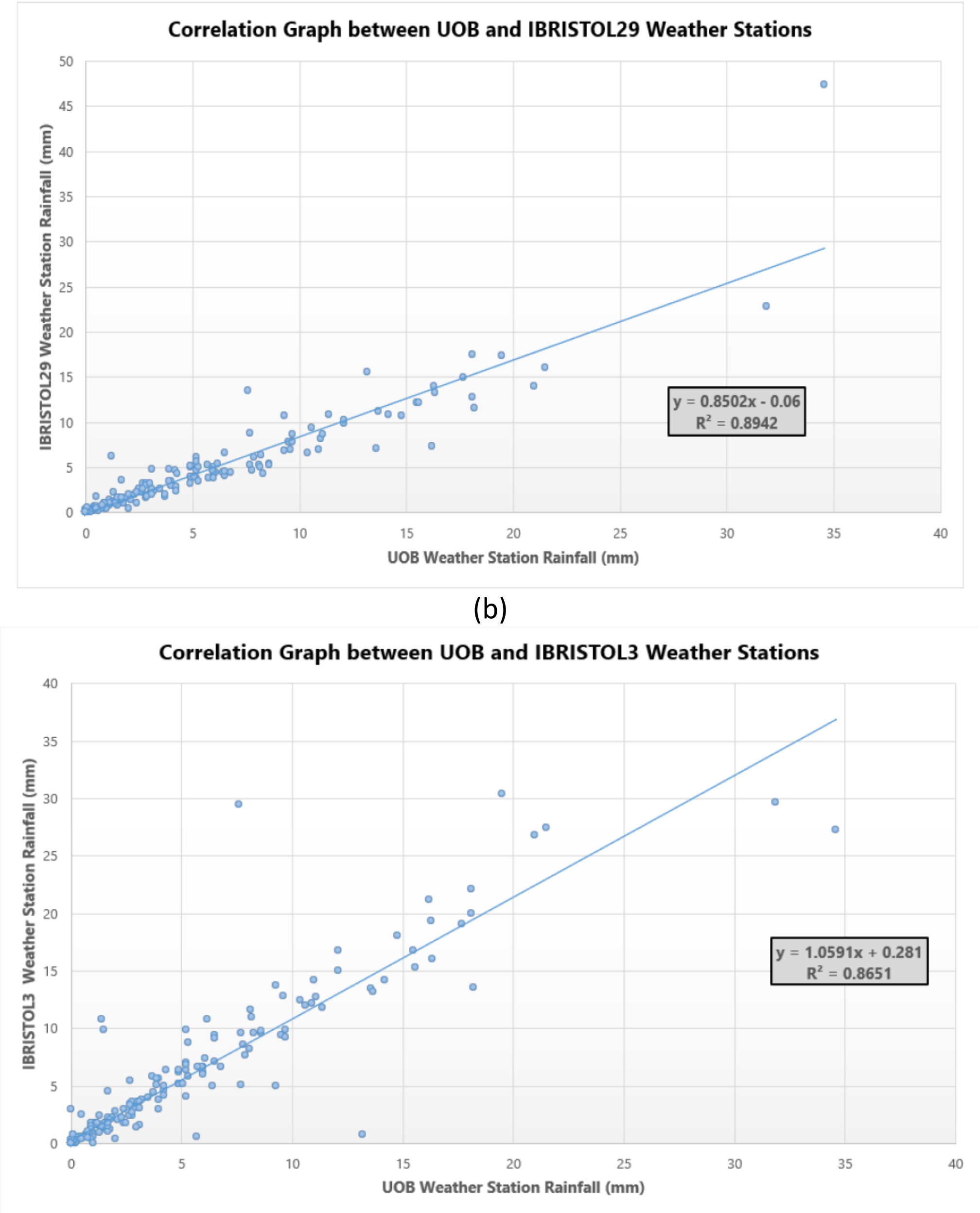

Figure 3.8. Correlation coefficient between UOB1 and (a) IBRISTOL29 and IBRISTOL3.

Rainfall trend analysis - Scenario 5

Historical daily rainfall data from 1 January 1968 to 31 December 2018 was used. The annual average rainfall amount is 811 mm, and the annual average rainy days is 128 days. Two years (2000 and 2012) received significant precipitation of 1,112 and 1,125 mm, respectively, while in 1973 and 2010 the average annual rainfall was 569 and 584 mm, respectively. These results correspond to the annual rainy days. The years 2000 and 2012 counted 159 and 162 rainy days, respectively, while for 1973 and 2010 there were 97 and 113 rainy days, respectively. Figure 3.9 displays the seasonal variability of precipitation in Filton Airfield between 1968 and 2018. The average monthly rainfall for the entire period is 67.6 mm. Rainfall in six months shows similar or higher rates than the average rainfall, indicating that the wet period starts in August and lasts for six months (August–January). The precipitation rates between February and July are lower than the average rainfall. This information suggests that the dry period is from February to July.

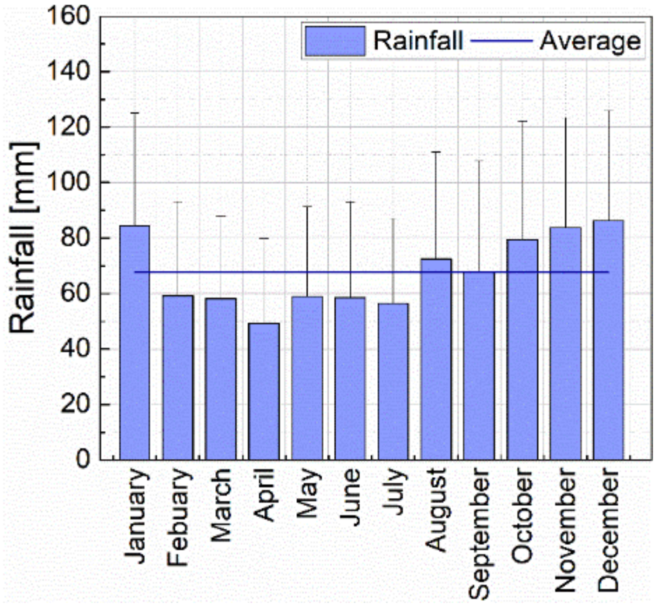

Figure 3.9. Monthly average rainfall variations in Filton Airfield.

The precipitation concentration index (PCI) and standard precipitation index (SPI) values were further analysed to confirm the climatic regimes (dry, normal and wet years). The PCI proposed Oliver (1980) was used to evaluate the fluctuation in rainfall amounts based on the monthly precipitation of 50 years. The SPI can provide a better understanding of qualifying rainfall variability over the selected period. From historical rainfall data and the analysed PCI and SPI values, three different years were selected to represent dry year, average year and wet year. PCI values can be classified according to four different distributions: (a) PCI values below 10 represent a uniform precipitation distribution throughout the period, (b) values between 11 and 15 indicate a moderate distribution, (c) values from 16 to 20 denote an irregular concentration of precipitation and (d) and values above 20 correspond to a strong irregular variability in precipitation (Oliver, 1980).

$$\mathrm{PCI} = 100 \;\times \sum_{n=1}^{12} \frac{{X_n}^2}{R^2} \qquad \text{Equation 3.3}$$

where X_n represents the monthly precipitation (mm) of month n, and R denotes the annual rainfall data (mm).

In addition, the daily rainfall data were used to calculate the SPI, hence the classification of the precipitation regimes. According to McKee et al. (1993), calculated SPI values constitute seven precipitation regimes: extremely wet (>2.0), very wet (1.5 to 1.99), moderately wet (1.0 to 1.49), near normal (−0.99 to 0.99), moderately dry (−1.49 to −1.0), severely dry (−1.99 to −1.5) and extremely dry (<−2.0).

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$$\mathrm{SPI} = \frac{X_p - X_m}{\sigma}$$

Equation 3.4

where X_p is the seasonal precipitation (mm) of n years, X_m is the seasonal mean of n years (mm) and σ is the standard deviation.

The PCI and SPI values were analysed to confirm the climatic regimes (dry, normal and wet years). Figure 3.10 shows that the PCI values ranged from a minimum value of 9.3 to a maximum value of 13. Notably, the PCI value did not exceed 16 for Filton Airfield. This result indicates Filton Airfield's homogeneous rainfall distribution with moderate seasonality.

Furthermore, as shown in Figure 3.10, the SPI values remained between –0.6 and 0.7 (near normal and moderately wet), indicating that Filton Airfield tends to have maintained its moist conditions, which would be more beneficial for RWH even during the dry season. Throughout the historical period considered in this study, the highest and lowest SPI values were observed in 1973 and 2012 (–0.59 and 0.69, respectively). In addition, the SPI value for 1982 was –0.003, which is close to the average SPI value of 0. Therefore, 1973, 1982 and 2012 were selected for dry, normal and wet years, respectively. This study conducted the analysis of the economic impacts of rainfall patterns on the RWH system using the rainfall data of those three years (Section 3.1.2.5). Overall, Filton Airfield has shown a moderate rainfall trend for the last 50 years, suggesting that the impacts of rainfall changes on the performance of the RWH system would be less significant than those of the water demand scenarios.

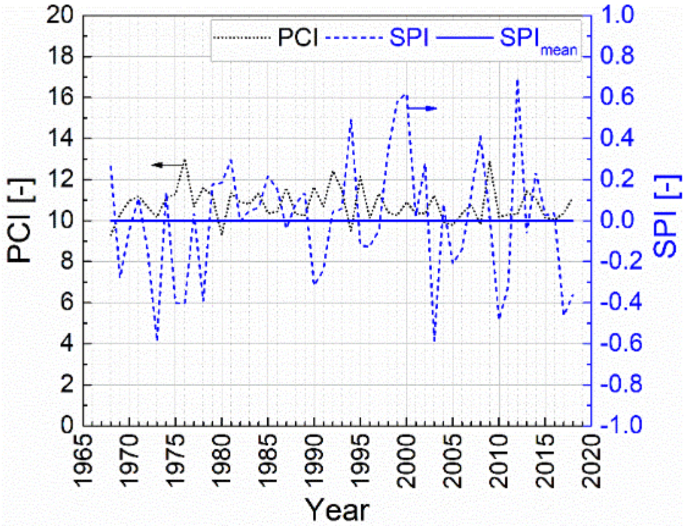


Figure 3.10. Variations of the precipitation concentration index (PCI) and standard precipitation index (SPI).

3.1.2.3. Hydraulic performance analysis

For the hydraulic analysis of the RWH system for residential and commercial buildings, a spreadsheet-based daily water balance model was developed based on the yield after spillage (YAS) and yield before spillage (YBS) models developed by Jenkins et al. (1978). The YAS and YBS models were used for scenarios 1, 2 and 3 while scenario 5 used only YAS model. In addition, only scenario 4 conducted rainwater cycle simulations using UWOT.

YAS and YBS models - Scenarios 1, 2, 3 and 5

Figure 3.11 show the YAS and YBS models that represent extreme of a modelling assumption relating to when harvested rainwater is used.

Starting with the YAS model, firstly, the total inflow into the tank is added to the stored volume at the previous time step. Secondly, the water volume that exceeds tank capacity (i.e., spillage) is calculated and subtracted. Finally, yield, is then accounted for, providing the stored volume at the current timestep. This is represented below by Equation 3.5 and Equation 3.6 (Fewkes et al., 2000).

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} \end{cases} \qquad \text{Equation 3.5}$$

$$V_t = \min \begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases} \qquad \text{Equation 3.6}$$

In both models, yield equates to demand insofar as the demand does not exceed the stored tank volume. In the case where demand exceeds stored tank volume (i.e., the tank is fully drained), water from the mains is used to ensure demand is fully met. The YBS model follows the same computations as the YAS model except that yield is accounted for before excess rainwater is spilled. This is represented below by Equation 3.7 and Equation 3.8 (Fewkes et al., 2000).

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} + Q_t \end{cases} \qquad \text{Equation 3.7}$$

$$V_t = \min \begin{cases} V_{t-1} + Q_t - Y_t \\ S \end{cases} \qquad \text{Equation 3.8}$$

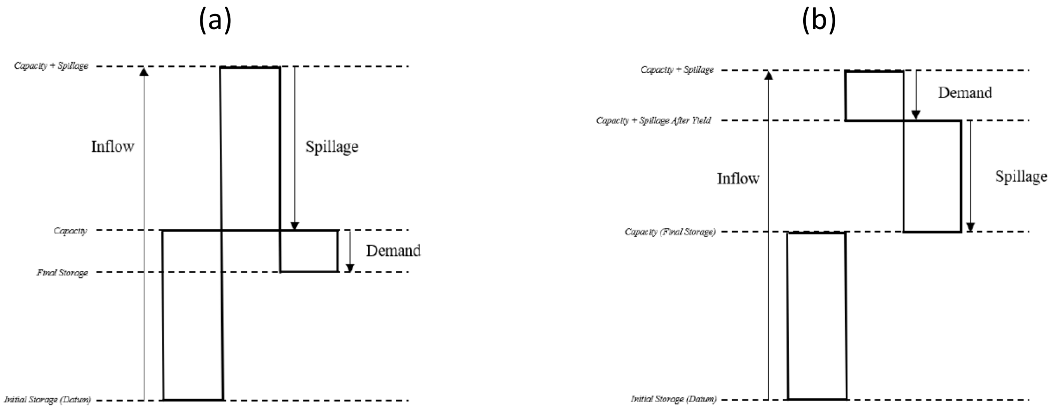


Figure 3.11. (a) YAS behavioural model with arrows denoting inflows and outflows to the tank and (b) YBS behavioural model with arrows denoting inflows and outflows to the tank.

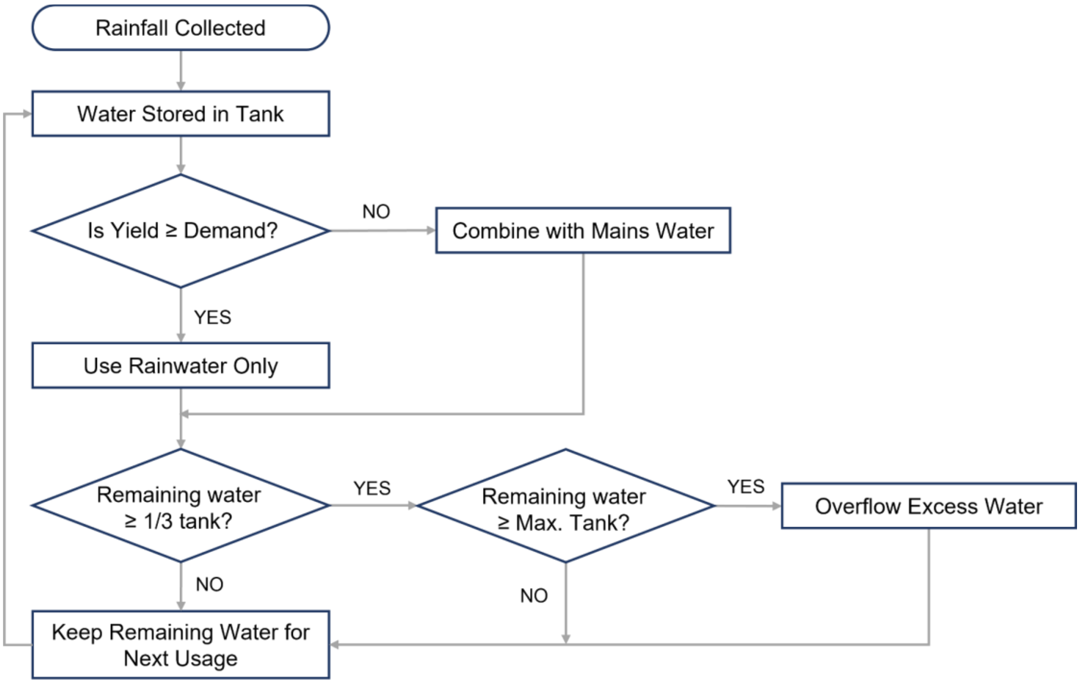


Figure 3.12. Flowchart displaying the computations executed at each timestep of the model.

Figure 3.13 presents key parameters and variables used to model rainwater harvesting (RWH) systems. Rainfall (R_t) represents the rainfall incident on the catchment surface. Harvested rainwater (Q_t) represents the volume of rainwater harvested from the catchment area. Volume (V_t) represents the volume of harvested rainwater stored within the tank. Yield (Y_t) represents the volume of harvested rainwater (stored within the tank) that is used to satisfy demand. Mains (M_t) represents the volume of water (supplied by the mains network) needed to meet demand if yield is insufficient. Demand (D_t) represents the volume of water supplied to household appliances which is met by either yield, mains or some combination of the two. Spillage (O_t) represents the volume of harvested rainwater diverted to a drainage network due to zero spare storage within the tank. For all the above variables, t is the time step of the model where each time step is separated by a constant time interval.

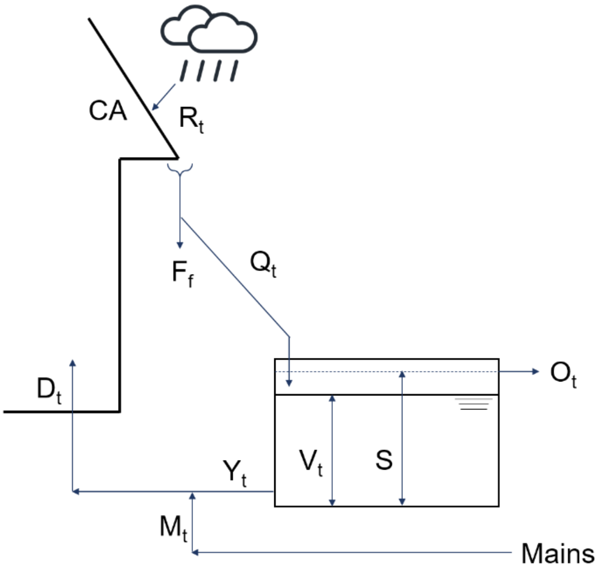
The roof of the building collects the precipitation which then flows into the rest of the system via guttering and downpipes. After being flushed and filtered from contaminants such as bacteria, the water enters a storage tank. Here, the water can be extracted when needed for the non-potable water demand of the house. If the tank overfills, excess water is spilt into the surroundings or existing stormwater drainage. If the tank cannot provide enough rainwater to meet demand, potable water will be withdrawn from the mains, ring the resident will always have access to immediate water. Although commercial and large-scale applications of RWH will have much larger variables, the process remains the same.

The key parameters of RWH design that can significantly affect the performance are the tank volume and the catchment area. Catchment area can be less flexible as it is often limited to roof space, but the economic benefits and performance of the system is highly dependent on the tank volume. Larger tank volumes will retain larger amounts of rainfall, meeting more of the non-potable water demand and further reducing stormwater run-off. However, too large and the capital and operating costs will affect the economics of the system. Similarly, a small volume will greatly reduce costs but inhibit the performance.

Inflow to the tank was calculated with Equation 3.9, where RC is the runoff coefficient and *CA* is the total area of the catchment surface. Runoff coefficient is a dimensionless factor that is used to convert the rainfall amounts to runoff. It represents the integrated effect of catchment losses. Consideration must be given to the type of surface, slope, degree of saturation and rainfall intensity when specifying the runoff coefficient for a given surface (Alim et al., 2019). The recommended runoff value for typical urban roofing used to determine the volumetric inflow is 0.95 (ASCE, 1996). The filter coefficient (FC) attempts to account for rainwater lost over the filter as harvested rainwater moves from the catchment area to the storage tank and was considered to be 0.9 (Ward et al., 2010a). It is assumed that the tank is covered, thus loses due to evaporation are negligible. The general balance for a RWH system is described by Equation 3.10.

$$Q_t = RC \cdot FC \cdot R_t \cdot CA \qquad \text{Equation 3.9}$$

$$V_t = V_{t-1} + Q_t - S_t - Y_t \qquad \text{Equation 3.10}$$



R_t	Rainfall (mm) during time interval, t
Y_t	Yield from store (m^3) during time interval, t
D_t	Demand (m^3) during time interval, t
V_t	Volume in store (m^3) during time interval, t
V_{t-1}	Volume of water in storage tank (m^3) on the previous time
Q_t	Rainwater run-off (m^3) during time interval, t
M_t	Volume of water from the mains supply (m^3)
S	Storage capacity (m^3)
O_t	Overflow (m^3)
F_f	First Flush volume (mm)
CA	Catchment area (m^2)

Figure 3.13. General configuration of a rainwater harvesting system.

UWOT - Scenario 4

The urban water cycle simulation is set up in such a way that the harvested rainwater is treated, stored and then distributed to meet the non-potable water demand from the residential and commercial units, depending on scenarios. Where the supply of rainwater fails to meet this non-potable water demand, a "make-up water" stream will initiate and make up the deficit. The make-up water stream is a potable water stream provided by the drinking water distribution network. In the case where the harvested rainwater exceeds the storage capacity, the spillwater stream will leave the system via the stormwater network. This simple urban water cycle is shown in Figure 3.14 and represents a simplified model of the simulated urban water cycle for the first phase of the Brabazon Development.

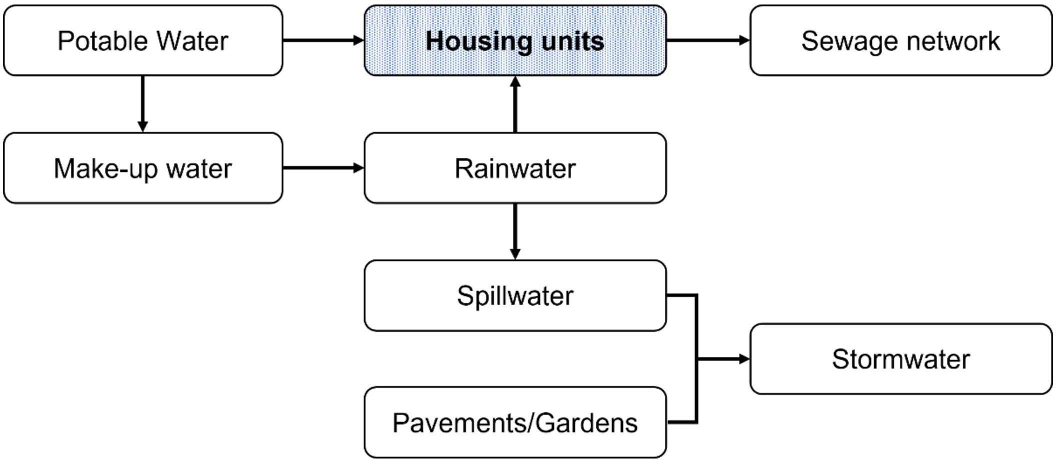


Figure 3.14. Simplified urban water cycle model.

3.1.2.4. Performance indicator analysis

Water savings efficiency (WSE) is the percentage of non-potable demand that is met by harvested rainwater. Water savings efficiency quantifies the water conservation performance of RWH systems (Haque et al., 2016; Wallace et al., 2015). Water savings efficiency tends towards 100% when harvested rainwater can fully satisfy demand and it is defined according to Equation 3.11.

$$WSE, \% = \frac{\sum Y_t}{\sum D_t} \times 100\% \qquad \text{Equation 3.11}$$

Stormwater capture efficiency (SCE) is the percentage of stormwater generated from the catchment which is used to satisfy non-potable water demand (Zhang et al., 2013). In essence, the stormwater capture efficiency is identical to the water savings efficiency expect for spillage; storm capture accounts for spillage whilst water savings does not and thus it can be used to assess the effect of the RWH system on downstream drainage networks. It quantifies the runoff reduction performance and may be calculated through use of Equation 3.12 (Zhang et al., 2020).

$$SCE, \% = \frac{\sum Y_t}{\varphi A \sum H_t / 1000} \times 100\% \qquad \text{Equation 3.12}$$

Campisano et al. (2014) define retention efficiency (E_R) according to Equation 3.13 which evaluates the volumetric retention performance of the tank. The loss factor (L_F), a new indicator based on the retention efficiency is defined according to Equation 3.14. Instead of retention, the loss factor measures spillage from the tank (due to overfill and the setpoint) relative to the total volume of harvested rainwater. The loss factor tends towards 100% when the sum of overflow discharges (O_t) tends towards the total volume of harvested rainwater. This is commonly the case in systems with small tanks and reduced demand. Table 3.6 presents a summary of performance indicators for each scenario. Scenarios 4 and 5 were selected to further conduct economic analysis of RWH systems, and the method is described in the following Section 3.1.2.5.

$$E_R, \% = [1 - \frac{\sum O_t}{\sum \varphi A \frac{H_t}{1000}}] \times 100 \qquad \text{Equation 3.13}$$

$$L_F, \% = [\frac{\sum O_t}{\sum A \cdot H_t}] \times 100 \qquad \text{Equation 3.14}$$

Table 3.6. Summary of RWH performance indicators used for each scenario.

Scenario (S)	Water reuse (non-potable)		Assessment indicators
S-1	WM, WC	23 houses per RWH system	Water saving efficiency (WSE), Stormwater capture efficiency (SCE), Loss factor (L_f)
S-2	WM, WC	278 houses	
S-3	WC	278 houses	Water saving efficiency (WSE), Stormwater capture efficiency (SCE),
S-4	DW, WM, WC	278 houses	Water saving efficiency (WSE) Economic analysis
S-5	WC	YTL Arena (YA)	Water saving efficiency (WSE) Economic analysis

3.1.2.5. Economic analysis

RWH system for residential building - Scenario 4

As a preliminary study, scenario 4 includes economic assessment in terms of the return-on-investment period (ROI). The results from the best- and worst-case scenario then define the upper and lower limit to the RWH systems performance range from a net economic perspective.

The calculation of the return-on-investment period uses the net present value method which compares the cost of implementing, operating and maintaining the system with the potential benefit of the system. Equation 3 is the net present value formula with the necessary component description. This calculation is done from a net cost and benefit perspective. This means the calculation will determine the ROI and NPV for the system considering the net expenses and benefits to society. The analysis section of this report considers these results in the context of the development owner, homeowner, and authorities.

The discount rate for the economic assessment is chosen as 30 years. The expected lifespan of the storage tank is about 30 years. Since the storage tank makes up a significant portion of the capital expense for the system, after 30 years the system may require an additional capital input. Therefore, measuring the feasibility up to 30 years will indicate the potential benefit for

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

the implementation of the system. The discount rate is chosen as 5% as is common in existing literature (Domènech et al., 2011; Roebuck et al., 2011).

Medium-scale rainwater harvesting systems are relatively unexplored in literature. One of the most significant limitations to the feasibility of these systems is that there is very little information available about the economic performance of these larger systems. The smaller-scale domestic systems show that the high capital expenses are infrequently recovered by the savings from the system. However, the principle of economies of scale, which suggest that there are improved economic benefits with an increasing scale of output from the system.

Capital and operational costs

The starting point for estimating the capital cost of the system is the small-scale domestic systems. A collection of quotes in the UK involving the purchasing of an underground tank, a pump, a filter unit, an electronic management unit and the excavation and installation costs for systems ranging between 1.2 m^3 and 15 m^3 provide the starting point for the estimation of the system's capital costs (Roebuck et al., 2011). The results for these systems are summarized in Table 3.7. By extrapolating the capital costs for these systems, an estimated capital cost of the 430 m^3 system for the first phase of the Brabazon Development can be approximated to £72,662.

Table 3.7. Capital cost extrapolation using capital and installation costs of small-scale RWH systems (Roebuck et al., 2011).

System Size (m^3)	Capital and installation cost (£)	Reference/Method of estimation
1.2	2,500	Roebuck et al. (2011)
3	3,200-3,400	
4	3,500	
5	3,400-4,000	
7	4,000	
11	3,800-4,100	
13	4,500	
15	5,500	
430	**72,662**	**Linear extrapolation**

As a second means of estimation, this result is compared to a study for a multistorey building in Spain (Domènech et al., 2011). The results for this research show that a 50 m^3 concrete tank with the pump, filter unit, and pipelines is estimated to cost approximately €19,000 (using 2011 exchange rates approximates to £16,530). Extrapolating this result shows an estimated system price for the 430 m^3 system to be £142,158.

Although these results show significantly different capital costs for the respective systems, for the purpose of this research, they serve as acceptable upper and lower limits to the feasibility of the system at the Brabazon Development. Hence, the capital costs that are used in the calculation of the economic feasibility of the system is £70,000, £100,000 and £130,000.

The lack of information available regarding operating and maintenance costs highlight the significance of the literature gap for larger rainwater harvesting systems. However, an operating and maintenance cost of 5% of the initial capital investment is commonly employed and is used in the economic assessment for the Brabazon Development (Domènech et al., 2011; Roebuck et al., 2011). The nature of the percentage means these operating and maintenance costs will vary with the upper and lower limit to the capital costs.

Although this assumption-based method is less accurate than obtaining actual maintenance cost and completing the full specifications of the system, the purpose of this research is not the full design of the rainwater harvesting system. Thus, the estimated operating and maintenance costs are suitable in determining the feasibility of the system.

Sensitivity analysis

It has already been discussed that the economic benefit considered in this economic assessment is limited to the savings associated with the substitution of the rainwater for the treated drinking water in meeting the non-potable water demand. As a result, these savings can be estimated by multiplying the volume of rainwater that is “consumed” in the residential units by the future price of treated water.

The price of water is expected to vary over the 30-year assessment period. The nature of this variation is dependent on many factors which may increase or decrease the cost of water. Thus, for the estimation of the potential savings, 3 future prices of water are considered: the current price of £1.2669/m^3 (BristolWater, 2021); a 1% per annum decreasing water price and then a 1% per annum increasing water price.

The exclusion of the economic savings of the reduced size of the storm water system and the reduced flood mitigation measures do limit the economic feasibility of the system. It is expected that these benefits will improve the feasibility of the system.

RWH system for a large commercial building - Scenario 5

Capital and operational costs

The scope of the economic analysis was extended for scenario 5. Since RWH for a large commercial building is more economically favourable, it is crucial to evaluate and determine optimal rainwater tank size using financial scenarios. Life cycle costing (LCC) is an economic analysis technique for the evaluation of the financial feasibility of a system over its life span (Farreny et al., 2011; Nnaji et al., 2020). LCC is defined as the sum of the capital and the total operational expenses over the lifetime of the project (CAPEX and OPEX). CAPEX includes the investment and installation costs, including storage tank, filter, pump, a data logging unit, delivery and labour while OPEX includes the operation costs (i.e., water and energy costs), routine and infrequent maintenance and replacement costs. It has to be acknowledged that the specific system components and associated costs for this study were adopted from both RainCycle tool, which focuses on UK use (Roebuck et al., 2007) and previous studies (Roebuck et al., 2011; Słyś et al., 2020; Wang et al., 2015).

The net present value (NPV, £) was calculated by the sum of present values (PV) of the cost over the project life-time (Christian Amos et al., 2016; Umapathi et al., 2019). PV is a well-known and accepted financial term for calculating the present-day of an amount of money that is received at a future date (Linares et al., 2016). The annualised OPEX cost was then determined using capital amortisation (Christian Amos et al., 2016; Kim et al., 2017). The final unit water cost per m^3 of rainwater and mains water is the sum of capital cost and annualised expenditure cost. Therefore, the optimal tank size was assumed to correspond to the maximum value of savings over the project time (£) and the minimum value of total water cost per cubic metre of water supplied (£/m^3). The prices of drinking water and sewage considered in this study were based on the non-household services with a fixed cost. Equations and input parameters used for economic calculations are presented in Table 3.8 and Table 3.9 respectively.

Table 3.8. Equations used for analysing cost in scenarios 4 and 5.

Equations		Reference
$\boldsymbol{Present\ value\ (PV)\ =\ C\frac{1-(1+i)^{-n}}{i}}$	*Equation 3.15*	Abas et al. (2019); Christian Amos et al. (2016); Kim et al. (2017); Linares et al. (2016)
$\boldsymbol{Net\ present\ value\ (NPV) = \sum_{t=1}^{n}\frac{PV_t}{(1+i)^t}}$	*Equation 3.16*	
$\boldsymbol{Annualised\ OPEX\ cost\ (A, \text{£}/y) = NPV \times \frac{i(1+i)^n}{(1+i)^n - 1}}$	*Equation 3.17*	
$\boldsymbol{Final\ unit\ water\ cost\ \left({}^{\text{£}}/_{m^3}\right) = \frac{CAPEX + A}{D}}$ where *C* is the cost in GBP, *n* is the project period in year, *i* is the discount rate, *t* is the time in years and *D*: annual water demand, m^3/y.	*Equation 3.18*	

Table 3.9. Input parameters for the economic evaluation of the RWH system.

Parameter		Unit	Value	Reference
Discount rate		%	5	Roebuck et al. (2011)
Water tariff		£/m^3	1.05	BristolWater (2021)
Sewage		£/m^3	1.59	YTLGroup (2020)
Energy tariff		£/kWh	0.125	UK average price*
System life span		years	50	Lani et al. (2018)
CAPEX– construction and installation	Tank (50-year life span)	£/m^3	372.5	(Roebuck et al., 2007); Roebuck et al. (2011); Wang et al. (2015)
OPEX– maintenance and replacement	Inspection, reporting and information management	year	2	
	Roof washing, cleaning inflow filters	year	2	
	Tank inspection and disinfection	year	1	
	Intermittent system maintenance (system flush, debris/sediment removal from tank)	year	3	
	Pump replacement	year	10	
	Minor fittings replacement	year	10	
	Filter replacement	year	15	

*https://www.ukpower.co.uk/home_energy/tariffs–per–unit–kwh

Sensitivity analysis

The main variables in determining financial performances of the RWH system are rainfall variations (i.e., dry, wet and normal), mains water tariffs (i.e., the predicted cost) and discount rates (Lani et al., 2018; Zhang et al., 2018). A sensitivity analysis was conducted to evaluate the effects of these factors on the economic feasibility of the RWH system in terms of unit water costs with variations of the storage sizes. The optimal storage capacity was determined based on the unit water cost being lower than the mains-only supply water for the same water demand scenarios.

Water and sewage tariffs were assumed to increase by 1.8% and 0.8% per year, respectively (Roebuck et al., 2011). Thus, the predicted water for the next 10 and 20 years would be 2.9 £/m^3 and 3.3 £/m^3, respectively. Based on this estimation, the water price ranged from 1 to 3 £/m^3. In addition, three different years were selected to represent dry, wet and normal years based on the SPI analysis results. According to the LCC approach, a discount rate of 5% was taken as the baseline (Table 3.9). Since specific guidance on the selection of appropriate discount rates for the adaptation of the RWH system was unavailable, three possibilities of 5%, 10%, and 15% used in previous studies were adopted for this study (Matos et al., 2015; Nnaji et al., 2020; Roebuck et al., 2011). In this regard, the payback period, which is the time required to recover the capital investment, was estimated by considering water tariffs (2 and 3 £/m^3) and discount rates (5%, 10% and 15%).

3.1.3. Results and discussion

3.1.3.1. Rainfall quality analysis

Figure 3.15 presents the results of the following parameters: pH, conductivity, turbidity, total dissolved solids (TDS), total hardness, calcium, sodium, and *E.Coli*. Moderate or marginal differences are observed among sampling points. The physiochemical and microbial characteristics of all raw rainwater samples can be found in Table 1 in Appendix.

Rainwater showed the pH range from 7.0 to 8.2, with a mean of 7.52, indicating rainwater of a neutral to alkaline nature. This is mainly because of basic components such as calcium and magnesium being present in the soil dust (Kulshrestha et al., 2003) and no accumulation of such acidic compounds in the rainwater due to the limited concentrations of nitrates and sulphates in the atmosphere (Table 2 in Appendix).

Elsewhere, conductivity ranged between 8 and 62 µS/cm with an average of 25 µS/cm, representing a quality much lower than that of irrigation and drinking water (700 and 400 µS/cm, respectively). In addition, concentrations of both turbidity (0.09-0.6 NTU) and TDS (4.2-60 mg/L) satisfied the irrigation and drinking standard levels (<5 NTU for turbidity and 500 mg/L for TDS). Meanwhile, total hardness (TH) values showed the much lower values than the standard values of 460-500 mg/L $CaCO_3$. Overall, these results indicate that the free-fall rainwater in Filton area is clean and soft (Al-Khashman et al., 2017).

Furthermore, the effect of the marine environment on rainwater quality was also investigated. Table 3.10 shows the ratios of Cl, Ca, K and Mg to Na, and compared to seawater ratios. All ratios were found to be higher than the seawater ratios. In addition, the non-sea salt fractions for Cl, Ca, K and Mg shows 95.7%, 95.5%, 91.7% and 28%, respectively, indicating that most components in the rainwater here are established by local contributions. The enrichment factor values further confirm that these components originated from non-marine sources, such as natural and anthropogenic activities across the site (Herut et al., 2000; Kulshrestha et al., 2003).

E. coli (between 20 and 400 cfc/100 ml) was observed lower than the irrigation water standards (< 1000 cfc/100 ml), but higher than the drinking water standards (0 cfc/100 ml). This indicates that rainwater collected directly from the atmosphere here appears to be applicable for a wide range of non-potable purposes, but not for potable purposes without additional treatment. All rainwater samples showed low content of metals (Fe, Mn, Cu, Cr, Cd, Ni, Zn and Pb) and they met the recommended limit for irrigation and drinking water (Table B.1 in Appendix B). It has to be noted here that the main objective of the quality analysis was to understand the environment in Filton. Further analysis of factors that influence harvested rainwater quality such as catchment materials, location, seasonality, and pollutant concentrations need to be further investigated.

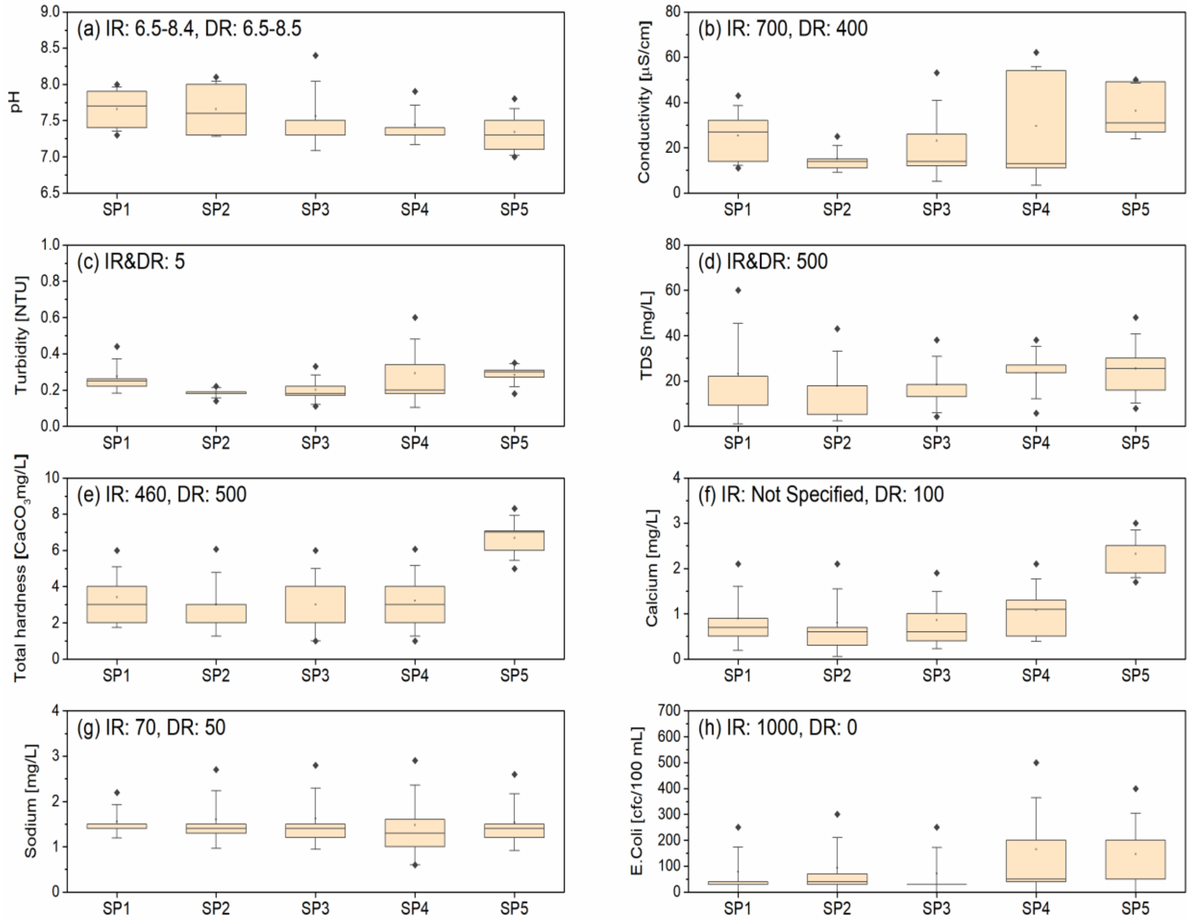


Figure 3.15. Physio-chemical and microbial characteristics of free-fall rainwater collected from Filton Airfield. (a) pH, (b) conductivity, (c) turbidity, (d) total dissolved solids (TDS), (e) total hardness, (f) calcium, (g) sodium and (h) E. Coli. Five samples for each SP (n = 25 samples). IR: Irrigation water standards, DR: Drinking water standards.

Table 3.10. Evaluation of marine contributions via comparison of seawater ratios with rainwater components.

	Cl/Na	Ca/Na	K/Na	Mg/Na
Seawater ratios*	0.12	0.04	0.03	0.12
Ratios in rainwater	2.79	0.85	0.36	0.17
Sea salt fraction %	4.3%	4.5%	8.3%	71.9%
Non-sea salt fraction %	95.7%	95.5%	91.7%	28.1%
Enrichment factor**	23.2	21.2	12.0	1.4

*Sea water composition ratios obtained from Kulshrestha et al. (2003)

**Enrichment factor = Ratios in rainwater/Seawater ratios

3.1.3.2. *Hydraulic performance analysis*

Scenarios 1 and 2 - residential application

Scenarios 1 and 2 utilized optimization of parameters*,* storage fraction (S_f), which is a dimensionless parameter that allows for equitable comparison of the centralized and decentralized system. S_f is defined by Equation 3.19 which relates storage capacity (S), catchment area and mean annual rainfall (R_t) – in this case t denotes a year-long period (Campisano et al., 2012b).

$$S_f = \frac{\mathrm{S}}{A \cdot R_t} \times 100\% \qquad \text{Equation 3.19}$$

The optimization approach for tank size involved variance of the storage fraction with the three performance indicators listed in Table 3.6: water savings efficiency (WSE), storm capture efficiency (SCE) and loss factor (L_F). Both YAS and YBS algorithms were analysed. For each of these indicators, there is a trade-off between system performance and increased storage fraction, i.e., rising costs. Simulations for the decentralised RWH systems (scenario 1) were conducted producing data that related storage fraction with WSE, SCE and L_F as presented in Figure 3.16 (a), (b) and (c), respectively.

To ensure consistency in the optimization approach the setpoint was kept at 90% of the total tank volume in order to prevent it from being a limiting factor at the expense of flood attenuation performance. Since it is a dimensionless quantity, the storage fraction allows for comparison of performance indicators despite a difference in tank size.

Figure 3.16 (a) shows the WSE, approaching a limit of 72%. For storage fractions in the range 0.001 to 0.01, WSE increases sharply since tank volume is the limiting factor. In this range, small increases in storage fraction led to a large reduction of spillage volume throughout the year period as instances where the tank is full decreases. At some point, in the region where S_f = 0.01, the limited volume of harvested rainwater begins to dominate the relationship between S_f and WSE. Further increases in tank size cause minor reductions of spillage as few rainfall events can fill up the total capacity of the tank. With a S_f of 0.0075, a water savings efficiency of 36% is achieved. In addtion, SCE approaches an upper limit of 90% as S_f is increased (Figure 3.16 (b)) while initially, L_F decreases sharply and eventually approaches 7% with a storage fraction of 0.06 (Figure 3.16 (c)).

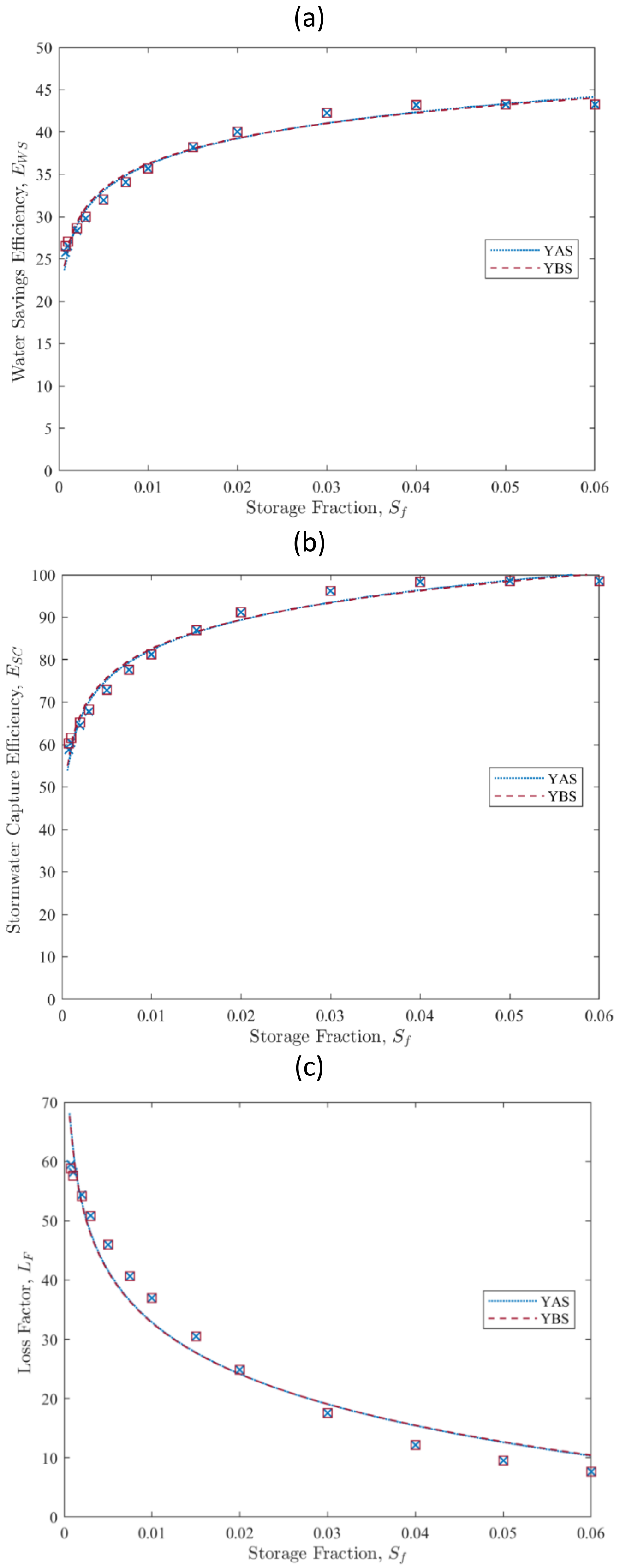


Figure 3.16. The variance of storage fraction with (a) water savings efficiency and (b) stormwater capture efficiency and (c) loss factor for a decentralized system (Scenario 1).

Figure 3.17 (a), (b) and (c) show simulation results of the centralised RWH system (scenario 2) relating storage fraction with WSE, SCE and L_F, respectively. During the beginning of the optimization process, the setpoint was kept at 90% of the total tank volume in order to prevent it from being a limiting factor at the expense of flood attenuation performance. Figure 3.17 (a) shows WSE reaching a maximum of 45%. Despite sharp increases in WSE for low S_f values, there are diminishing returns for performance gains as S_f is increased further. For the centralized system, an S_f of 0.05 equates to a tank with a capacity of 356 m^3. Although such a system is beyond financial and even physical possibility, it demonstrates that tank size is not the limiting factor for further improvements in WSE. There are two possible reasons for this; firstly, the insufficient supply of rainwater to the system relative to the expected demand; and secondly, a low setpoint causing large spillage volumes and therefore necessitating top-up from the mains to meet demand. Given that a setpoint of 90% was used for these initial simulations, the diminishing performance increases are likely due to the insufficient supply of rainwater, not tank sizing.

SCE data reported in Figure 3.17 (b) provides more evidence showing that diminishing performance increases are due to a lack of available rainwater. An SCE of 91% is reached with an S_f of 0.02, meaning that 91% of all harvested rainwater is used to satisfy demand whereas only 9% leaves the system as spillage. Although the SCE is high, the corresponding water savings efficiency is only 40%; consequently 60% of demand is met by the mains supply at considerable expense.

In the centralised system, an S_f of 0.02 equates to a tank of volume 143 m^3. A centralised system at the Brabazon Hangar has the greatest potential to accommodate a single large tank, however it is unlikely to yield a good return on investment if the supply of rainwater is insufficient. As emphasized throughout this result, the two most significant benefits of RWH systems are the non-potable water savings and flood attenuation. With a tank of volume 143 m^3, the reduced strain on the urban water system is beneficial with only 601 m^3 of spillage for 6769 m^3 of harvested rainwater over a year-long period; despite this, satisfying only 40% of non-potable demand is likely to be insufficient. Figure 3.17 (c) shows the ability of this centralized system to retain harvested rainwater with very low loss factors across a wide range of storage fractions even reaching 0% at an S_f of 0.05. Increased spillage drives the L_F and although low loss factors are preferential, spillage is only detrimental at times when the downstream drainage network is overwhelmed.

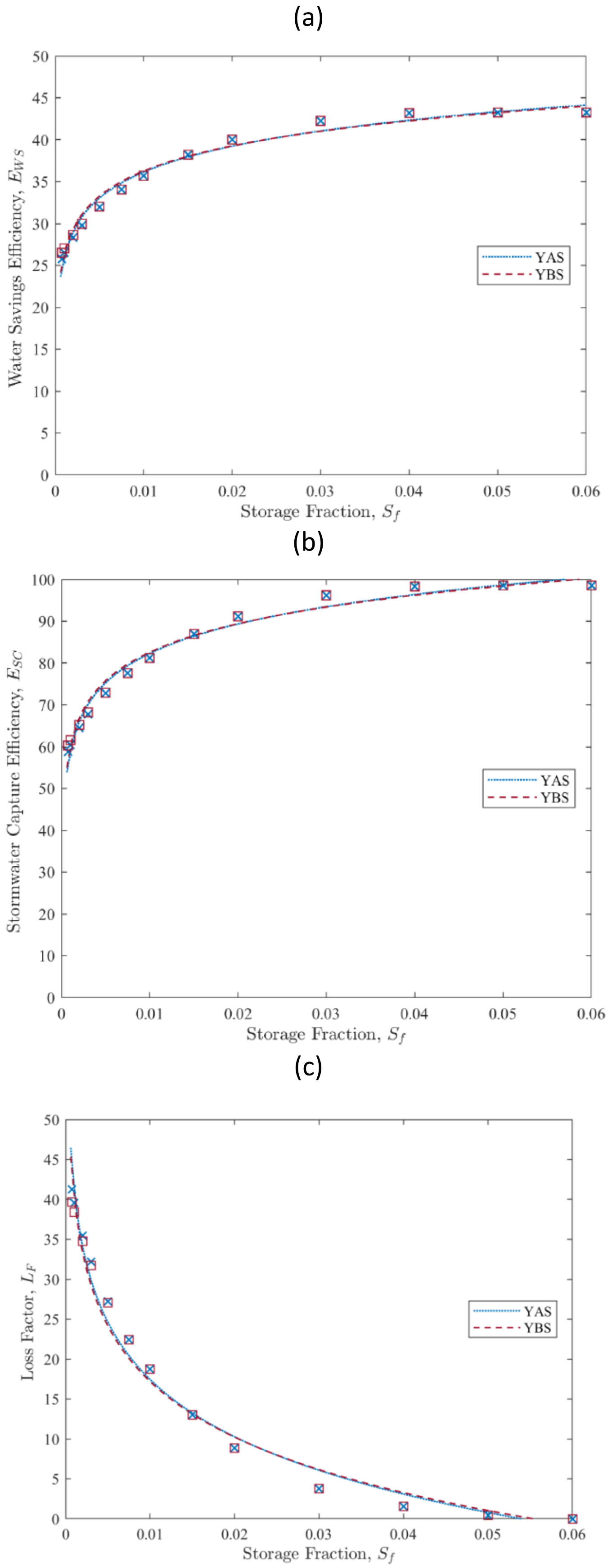


Figure 3.17. The variance of storage fraction with (a) water savings efficiency, (b) stormwater capture efficiency and (c) loss factor for a centralized system (Scenario 2).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

Results reported in Figure 3.17 show that the YAS and YBS algorithms produce results that are almost identical. There is some difference in performance at low storage fractions (between 0.0001 and 0.0025) where the model using the YBS algorithm yields a greater WSE and a greater SCE; however, the differences in WSE, SCE and L_F are 5% at most and decrease to 0% as S_f reaches 0.005.

Generally, the results produced by models using YAS and YBS algorithms are significantly different at low tank volumes; a YAS model will give a conservative estimate of performance whilst a YBS model will give a liberal estimate (Ward et al., 2010b). However, as the temporal resolution of rainfall and demand data increases the difference between YAS and YBS performance decreases. In the YBS algorithm, yield may be drawn from the spillage volume – this assumes that the spillage volume at each timestep is available to satisfy yield insofar as it occurs within the same timestep. This is a questionable assumption as in real-world systems, harvested rainwater will leave the system as spillage instantaneously if the tank is full. The validity of this assumption is poor for data with a large timestep as the spillage volume has longer to accumulate; thus, it has greater potential to be used as yield. At smaller timesteps this potential is reduced and therefore the difference between the tank levels at the end of each timestep (due to the YAS and YBS models) is lessened. In this instance, daily rainfall levels for 2018 are being used in conjunction with hourly water demand volumes. To address the mismatch in temporal scale, the model averages the daily rainfall values equally across 24-hour long segments. By artificially reducing the timestep of the rainfall data by a factor of 1/24 to correspond to the hourly demand data, the difference between the tank levels (due to the YAS and YBS algorithms) at the end of each timestep is greatly reduced. At an hourly temporal scale, the models perform similarly as evidenced in Figure 3.17.

To show the effect of an increased temporal scale on performance, Figure 3.18 reports the water savings efficiency for YAS and YBS models using daily demand and rainfall data. At low storage fractions (small tank volumes) the YBS model clearly outperforms the YAS model with a water savings efficiency of 52.8% compared to 32.4% at a storage fraction of 0.15×10^{-3}. This 20.4% performance difference is significant and equates to water savings of 3144 m^2 over the course of a year. Despite this saving, YAS performance sharply increases between storage fractions of 0.15×10^{-3} and 0.5×10^{-3}, eventually matching YBS performance at $S_f = 0.75 \times10^{-3}$. Over this range there is an increased likelihood that the tank is full – this has a more adverse effect on a YAS system since the spillage volume is completely lost whereas a YBS system can recoup some of the spillage volume as yield. Beyond $S_f = 0.75 \times10^{-3}$ this effect diminishes as tank size increases and thus the likelihood of a full tank is reduced which reduces the propensity of large and frequent spillage volumes.

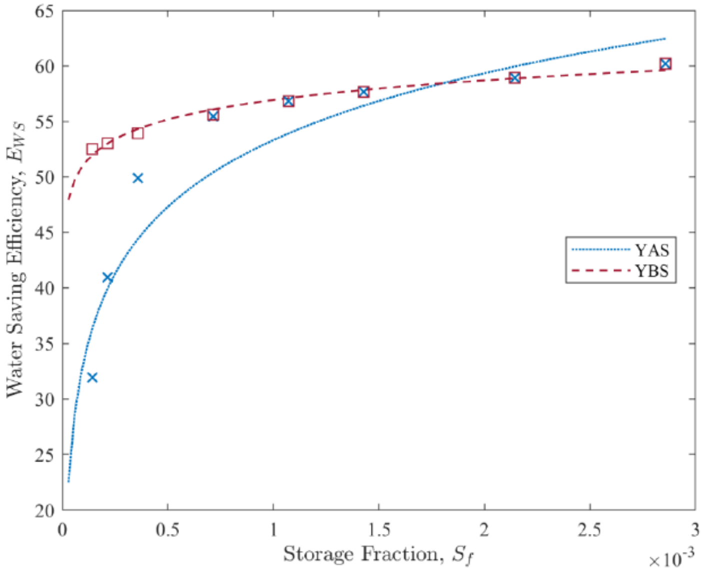


Figure 3.18. The variance of storage fraction with water savings efficiency for daily rainfall and demand data highlighting the effect of time step on YAS and YBS performance. The relationships between S_f and WSE for the YAS and YBS models are approximated by logarithmic functions with R^2 values of 0.88 and 0.97 respectively.

Scenario 3 - residential application

Although scenario 3 refers to the centralised system with a roof of the central YTL Arena, like scenario 2, the effect of storage fraction (S_f) on WSE and SCE was analysed for only toilet flushing purpose (Figure 3.19).

As expected, all indicators increased with tank size. When demand consisted of only a toilet, the maximum WSE that could be achieved if all rainfall was utilized was 53.47%. For a storage fraction of 0.002 (14.14 m^3), WSE was close to maximum with 53.42% (Figure 3.19 (a)). This is due to only 9.66 m^3 of water being spilt from the tank over the year. A storage fraction of 0.0015 (10.6 m^3) showed little change with a WS efficiency between 53.14% and 52.85%. It is when a fraction of 0.001 (7.07 m^3) is used that WSE begins to quickly drop. Efficiency falls to between 51.69% and 50.71%. Whilst this may not seem significant, this is a loss of between 217000 and 340000 L when compared to a fraction of 0.002. Any lower than 0.001 and the efficiency drops significantly, ruling out a tank size of below 7 m^3. For SCE as shown in Figure 3.19 (b), a fraction of 0.001 also seemed to be the point at which the indicator begins to drop substantially. The SCE values dropped between 3.2% and 5%. This means a tank size of 7.07 m^3 could prevent up to 335 m^3 less rainwater reaching the stormwater drainage every year.

The optimum tank size, using the above performance indicators, lies between 7 m^3 and 10 m^3. Any higher than 10 m^3, the extra capital and operating costs of a larger storage tank will yield little benefit to the efficiency and reliability of the system. Smaller than 7 m^3, the performance will drastically decrease, and accuracy of results will become uncertain due to YAS and YBS differences. Using rainfall data from the stochastic model will therefore lie around 9 m^3.

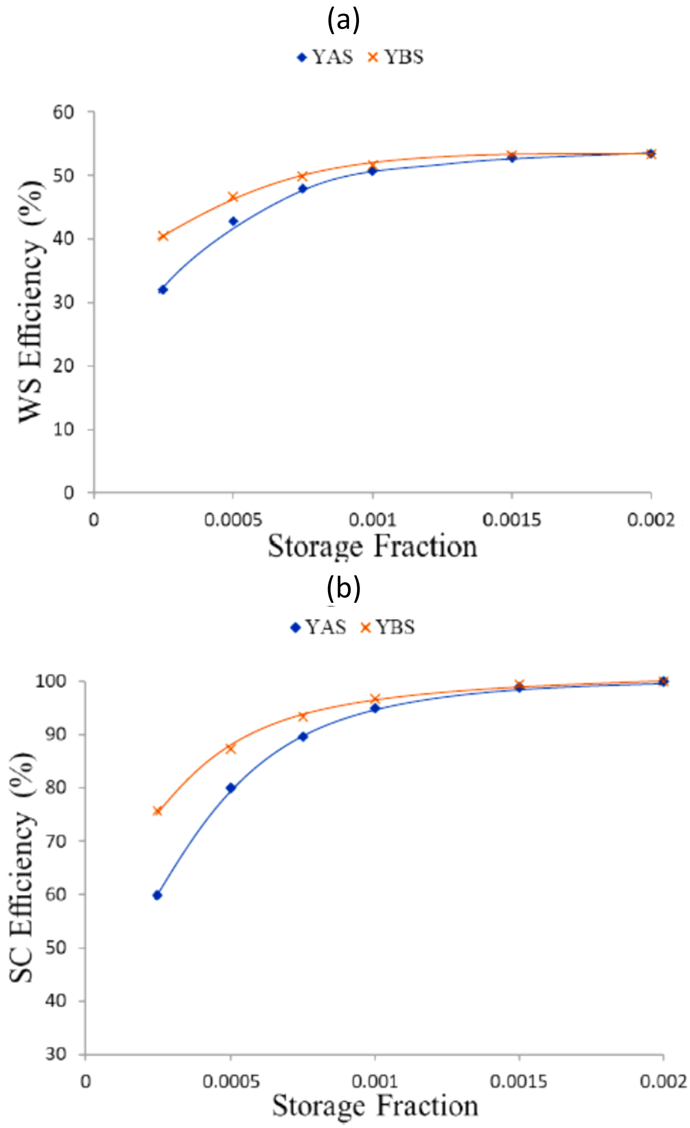


Figure 3.19. Performance indicators against storage fraction and water reuse only for toilet flushing within 278 housings (a) water savings efficiency and (b) stormwater capture efficiency (Scenario 3).

Scenarios 4 - residential application "UWOT" simulation

The results from the simulations are presented according to the best- and worst-case scenarios. The important water balance quantities that need to be extracted from the simulations are the potable water demand, the non-potable water demand, the total collectable rainwater, the make-up water, the spillwater, the garden and pavement runoff and the total stormwater. Additionally, an important quantity is the number of failures of the rainwater storage tank. A failure is defined as any day in which the stored rainwater equals a value of zero (i.e., When the full non-potable water demand is met by the drinking water network). This number of failures helps to highlight the storage tank sizing issues. Included in Table 3.11 and Table 3.12 are the summary results for the potable and non-potable water demand as well as the collectable rainwater for the best and worst cases respectively. The remaining quantities for the make-up water, stormwater, runoff from gardens and pavements and spill water are presented in Table 3.13.

Table 3.11. Best case scenario simulation results.

Bedroom type	Potable demand (m^3/year)	Non-potable demand (m^3/year)	Total collectable rainwater (m^3/year)
Apartments	7,007.9	2,856.3	1,887.9
2 Bed	2,473.4	1,008.1	2,947.1
3 Bed	3,710.1	1,512.2	3,844.1
4 Bed	4,809.3	1,960.2	2,292.2
5 Bed	6,011.7	2,450.2	2,740.7
Total	24,012.3	9,787.0	13,711.9

Table 3.12. Worst case scenario simulation results.

Bedroom type	Potable demand (m^3/year)	Non-potable demand (m^3/year)	Total collectable rainwater (m^3/year)
Apartments	35,720.8	21,641.1	1,073.0
2 Bed	4,727.8	2,864.3	1,694.2
3 Bed	6,303.7	3,819.0	2,192.5
4 Bed	7,660.7	4,641.2	1,317.7
5 Bed	10,725.0	6,497.6	1,550.3
Total	65,138.0	39,463.1	7,827.8

Table 3.13. Additional featured results from simulations.

	Make-up Water (m^3/year)	Spillwater (m^3/year)	Runoff (m^3/year)	Stormwater (m^3/year)	Failures
Best Case	1,106.1	5,000.3	3,432.8	8,433.1	512.0
Worst Case	31,644.7	9.4	3,432.8	3,442.2	3,569.0

Non-potable demand vs rainwater supply

The rainwater harvesting system shows the potential to be able to entirely meet the non-potable demand under the best-case scenario but fails in the worst-case scenario. Figure 3.20 shows a simple summary of the total non-potable demand, spillwater, collected rainwater and available rainwater. These categories highlight the systems' ability to meet the non-potable water demand for the system. The available rainwater for use, which is representative of the spillwater quantity subtracted from the total collected rainwater, sits at approximately 8,700 m^3/year whereas the non-potable water demand sits at approximately 9,800 m^3/year. This shows that the rainwater harvesting system in the best-case scenario is only capable of meeting 89% of the non-potable water demand. However, the 5,000 m^3/year spillage stream represents the amount of water that the system "wastes" each year and indicates that the system could be optimized to increase the available rainwater and meet the non-potable water demand.

The worst-case scenario shows significantly less feasibility. Figure 3.21 shows the total non-potable demand, spillwater, collected rainwater and available rainwater for the worst-case scenario. The system shows a significant increase in the non-potable water demand, resulting from the significant increase in population size and consumption category. The small spillage stream is a result of the reduced collected rainwater stream and the increased demand which draws water from the storage tank.

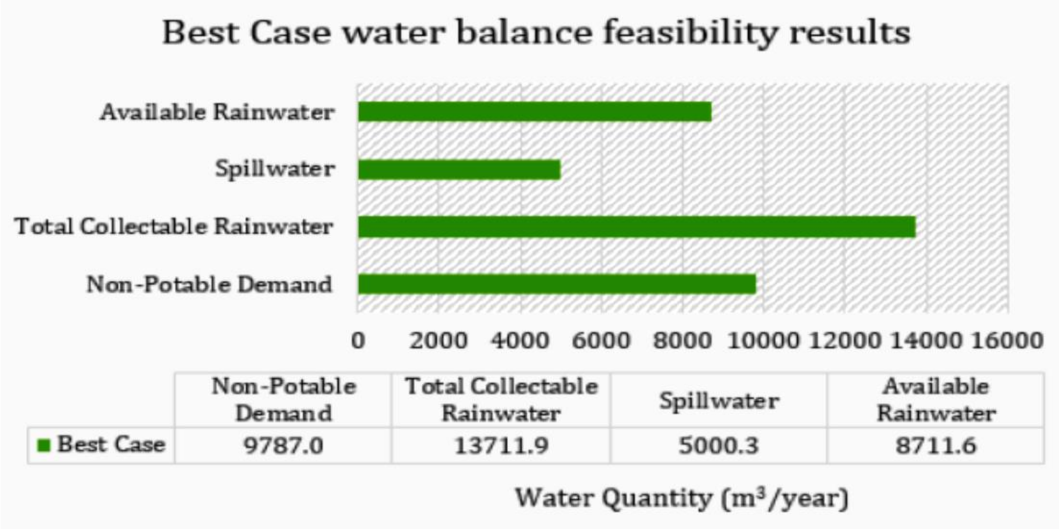


Figure 3.20. Best-case scenario feasibility results.

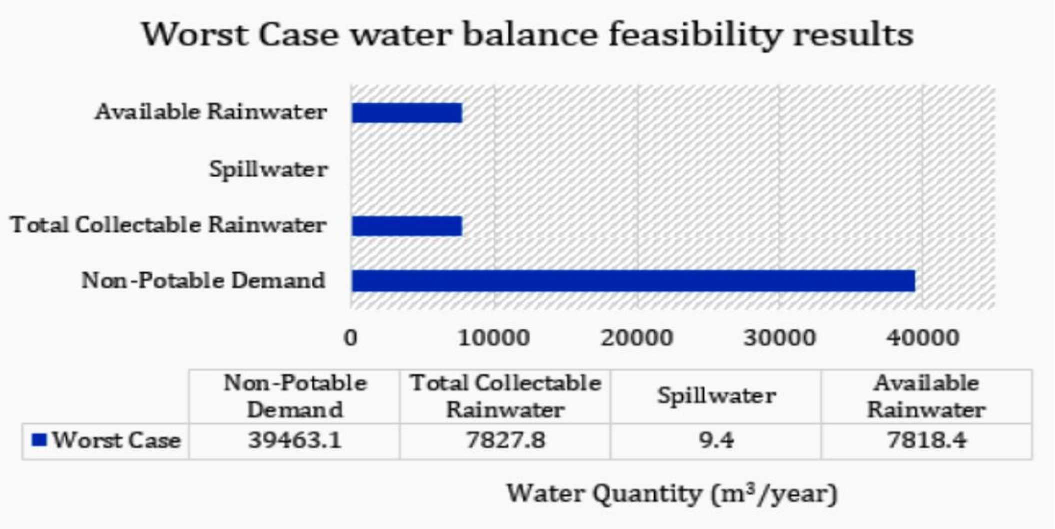


Figure 3.21. Worst-case scenario feasibility results.

As a general indicative range for the performance of the system, these results adequately express the potential for the system. With a dedicated focus on maximising the rainwater supply, the feasibility of the system is still largely determined by the population the system services and their water consumption. The first phase of the development will show a non-potable water demand of between 9,800 m^3/year and 39,500 m^3/year and can expect to collect between 7,800 m^3/year and 13,700 m^3/year. This shows that the variability in the demand from the system outweighs the supply of rainwater and thus it is unlikely the system will be able to meet the non-potable water demand with harvested rainwater.
One important result to highlight is the influence that the density of population has on the feasibility of the system.

Figure 3.22 and Figure 3.23 show a comparison between the non-potable water demand and the collectable rainwater quantity for both the best- and worst-case scenarios, broken down into the different residential unit types. For the best-case scenario, each of the 2-, 3-, 4- and 5-bedroom housing units have collection surface areas which collect more rainwater than would be required to meet the non-potable water demand. The apartment units are the only residential unit type which does not collect enough rainfall to be able to meet the non-potable water demand. The worst case shows that none of the unit types are able to collect enough water to meet the non-potable water demand. However, considering the best-case rainwater collection (which is achievable as this can be integrated into the building designs at a planning stage) and the worst case non-potable water demand, the supplied rainwater would be sufficient in meeting a total of 35% of the non-potable water demand for the zone.

Table 3.14 shows a comparison of the best possible rainwater collection scenario against the worst possible non-potable water demand scenario. The 2- and 3-bedroom units collect enough water to completely meet the non-potable water demand (103% and 101% respectively), with the 4- and 5-bedrooom units having the non-potable water demand 49% and 42% met by the supply of rainwater.

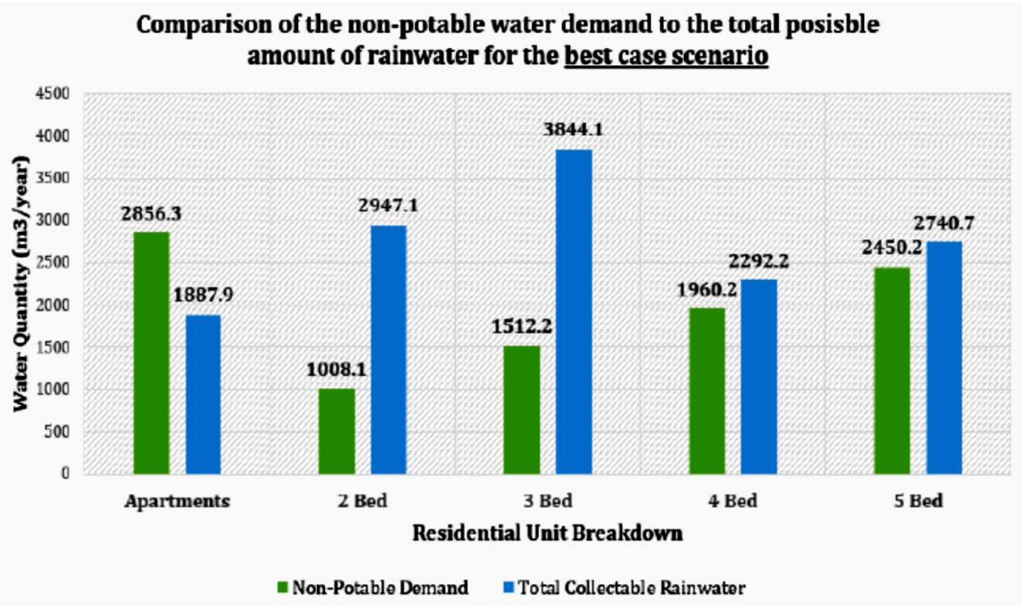


Figure 3.22. Breakdown of the non-potable water demand and the collectable rainwater by residential unit type for the best case.

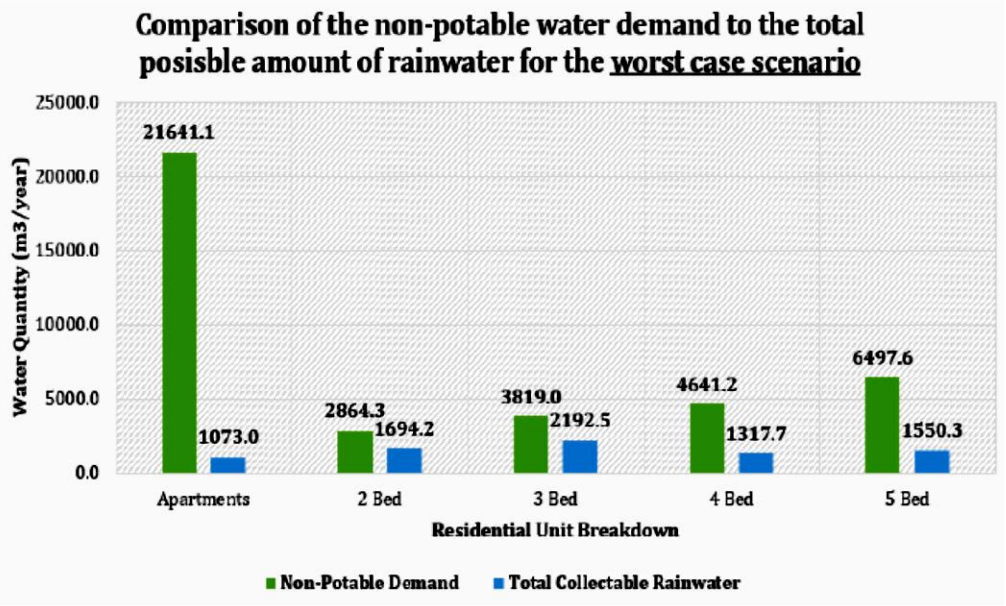


Figure 3.23. Breakdown of the non-potable water demand and the collectable rainwater by residential unit type for the worst case.

Table 3.14. Summary of the best-case rainwater supply and the worst case non-potable water demand.

	Apartments	2 Bed	3 Bed	4 Bed	5 Bed	Total
Best case supply	1,887.9	2,947.1	3,844.1	2,292.2	2,740.7	13,711.9
Worst case non-potable demand	21,641.1	2,864.3	3,819.0	4,641.2	6,497.6	39,463.1
Change %	9%	103%	101%	49%	42%	35%

The system's inability to completely meet the non-potable water demand, even under the best-case scenario, shows that the economic performance from the system is governed by the amount of rainwater collected. There is addedd benefit to the reduction of the non-potable water demand from the home-owners perspective, however this is not realised in the improved economic performance of the system.

Treated water consumption reduction

The total reduction in treated water consumption through the substitution of harvested rainwater is represented by the total harvestable rainwater, less the spillwater stream. This quantity is used in the economic assessment for the system. Table 3.15 shows the total potable water reduction as a result of the rainwater harvesting system for each of the best and worst cases. The best case shows a reduction in treated drinking water by 8711.6 m^3/year, which is an 89% reduction, whereas the worst case shows a reduction of 7818.4 m^3/year, which is a 19.8% reduction.

Table 3.15. Total treated water reduction with the rainwater harvesting system implemented.

	Non-Potable Demand (m^3/year)	Harvested Rainwater (m^3/year)	Spillwater (m^3/year)	Treated Water Reduction (m^3/year)	% Treated Water Reduction
Best case	9787.0	13711.9	5000.3	8711.6	89.0%
Worst case	39463.1	7827.8	9.4	7818.4	19.8%

Storage facility suitability

The system feasibility is largely determined by the suitability of the storage facilities. For this system, an estimated 430 m^3 tank was used as the storage facilities with a starting volume of 0 m^3. Table 3.16 offers some indication of the suitability of the storage tank. In the best-case scenario, which is set up to maximise the amount of collectable rainwater, the spillwater quantity of 5,000 m^3/year shows that the tank is significantly too small. Considering the total collectable rainwater each year approximates to 13,700 m^3, the system loses 36.4% of the collectable rainwater. The 512 system failures (meaning 512 days out of the 3,864-day simulation period – 13.3%) confirms that the smaller demand quantity from the residential units results in a lower quantity of water removal. For the worst-case scenario, the system shows a significant reduction in spill water, but a significant increase in system failures. The large increase in water demand from the residential area draws more water from the system. To compound the infeasibility of this scenario, the reduced rainwater collection surface area and the reduced runoff percentage results in less water being supplied to the storage tank.

The 3,569 failures system is a clear indication of the infeasibility of this case by highlighting the influence that home-owner consumption has on the system feasibility.

The large spillwater quantity in the best-case scenario suggests an increase in the storage tank volume will improve the system feasibility. However, the most notable determinant of the system feasibility can be tracked back to the demand from the residential unit. In order to optimise the system, collaboration between homeowners to limit the water consumption ratings is vital in promoting the system feasibility.

Table 3.16. Summary of spillwater and system failure.

	Spillwater	Failures
Best case	5000.3	512
Worst case	9.4	3569

Scenarios 5 - commercial application

Figure 3.24 (a) illustrates the impacts of the toilet flushing scenarios (TF_{YA1}, TF_{YA2}, TF_{YA3}, TF_{YA4}) on the WSE of the RWH system for the large YTL arena building with the storage capacity varying from 100 to 2,000 m^3. For toilet flushing (TF_{YA1}, 22 m^3/day), when the storage capacity exceeded 800 m^3, the WSE of the RWH system remained constant, with a WSE of 98.3%. However, for a tank of between 400 and 800 m^3, the WSE of the system was between 21.8% and 42% for TF_{YA3} and TF_{YA4} (108 - 216 m^3/day). However, for TF_{YA2} (54 m^3/day), when the storage size exceeded 1,800 m^3, the WSE of the RWH system was 79.8%.

For irrigation, the use of rainwater for different irrigation areas was assumed: 50% and 100% for the Brabazon Park (BP, IR_{BP1} and IR_{BP2}) and the Filton Golf course (FG, IR_{FG1} and IR_{FG2}). For a tank size of less than 800 m^3, the WSE of the system was varied from 12.7% to 42% for $IR_{BP1,}$ showing the most sensitive to the storage capacity and followed by IR_{BP2}, IR_{FG1} and IR_{FG2}. However, when the storage size exceeded 800 m^3, the WSE of the RWH system remained constant between 7.2% and 14.1%, depending on the water demand (580 - 1159 m^3/day) for IR_{FG1} and IR_{FG2} as shown in Figure 3.24 (b). Similarly, for IR_{BP1} and IR_{BP2} (151 - 302 m^3/day), the WSE of the RWH system for a tank 1,000 m^3 was between 25.7- 46.1%. However, when considering the tank's infinite capacity, the WSE was between 33.7% and 67.4%, depending on the water demand. Although a higher WSE was achievable from the system with a large storage tank, such a large capacity would increase the installation costs (Umapathi et al., 2019), hence 1,000 m^3 for the maximum tank size which maximises the WSE of the system for this application.

For the combined use of toilet flushing and the irrigation of BP (Figure 3.24 (c)), at a threshold value of 800 m^3, the WSE showed 24.1% and 25.6% for different ratios: 70:30 (242 m^3/day) and 50:50 (259 m^3/day), respectively, whereas, for the combined use of toilet flushing and the irrigation of the FG, the storage capacity exceeded 600 m^3, the WSE was varying between 11.8% and 14.7%, depending on the water demand (499 - 688 m^3/day). These results suggest that the WSE of the RWH system is highly influenced by the water demand scenarios. They further suggest that the threshold value ranged from 400 to 1,000 m^3, depending on the water demand scenarios. As a result, a storage capacity of between 400 and 1,000 m^3 can be perceived as the optimal size for all scenarios considered in this scenario.

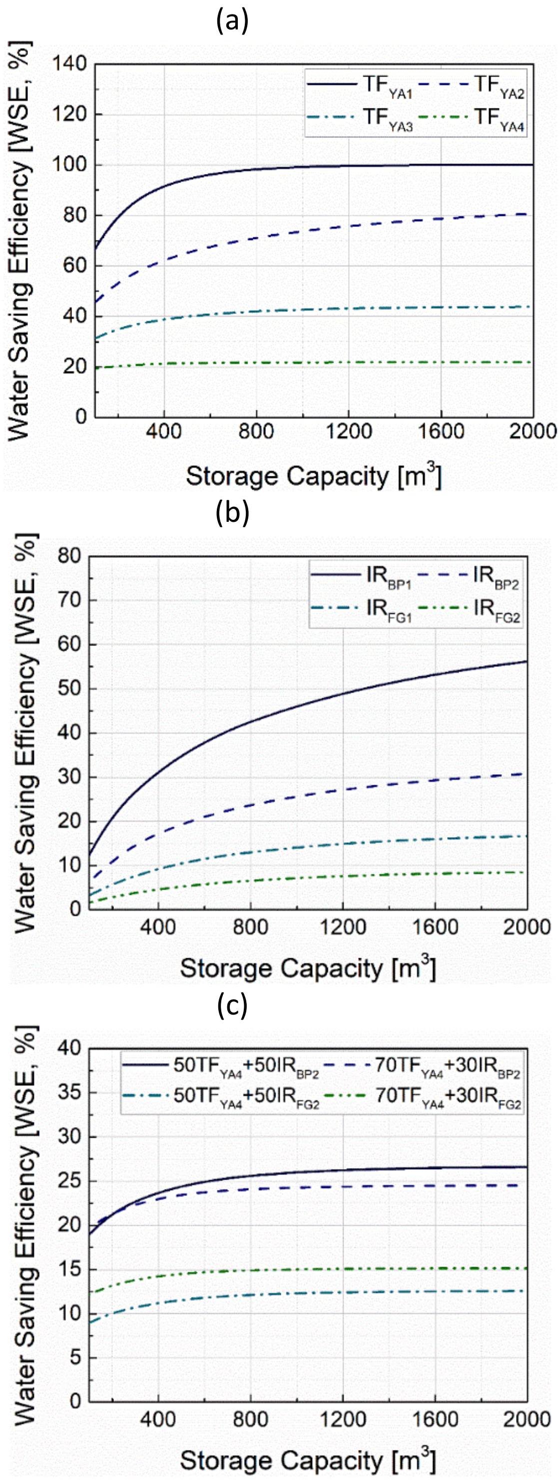


Figure 3.24. Variations of water saving efficiency values as a function of storage capacity for single and combined use scenarios (a) YA toilet flushing with varying numbers of visitors (b) irrigation: BP and FG and (c) combined use: YA toilet flushing + Irrigation.

The results in Figure 3.24 indicate that the WSE of the RWH system for this application can be enhanced by controlling the water demand scenarios, suggesting the importance of the water demand profile for the design and operational parameters of the RWH system. Larger rainwater storage volumes result in less overflow and more yield, hence a higher WSE of the RWH system. In contrast, smaller storage tanks limit the collection of rainwater, resulting in more overflow and less yield, hence a lower WSE of the RWH system. In this regard, the huge roof area of the arena requires a large storage tank, which could enhance the WSE of the RWH system and reduce the mains water consumption, albeit at higher capital and operational costs (Silva et al., 2015; Wang et al., 2015). In this analysis, the WSE of the RWH system with different water demand scenarios was evaluated using the historical rainfall data. These results affirm the significance of the water use profiles in the performance of the RWH system. However, changes in future rainfall patterns due to climate change need to be considered in the design and optimisation of the system, as the impacts of rainfall changes on the WSE of the RWH system are significant (Zhang et al., 2018).

3.1.3.3. Economic analysis

Scenarios 3 - residential application

To further optimize tank volume, more simulations were carried out with tank sizes within and slightly outside the stated optimum range. Table 3.17 shows the yield of each simulation, a useful value as it equals the volume of potable water saved over the year.

Table 3.17. Yield values for different tank sizes.

Tank Size	Without Washing Machine		With Washing Machine	
	YAS Yield (m^3)	YBS Yield (m^3)	YAS Yield (m^3)	YBS Yield (m^3)
71	4,530	5,094	4,810	5,547
90	4,864	5,344	5,188	5,783
110	5,155	5,560	5,500	5,963
130	5,413	5,760	5,757	6,135
150	5,616	5,933	5,942	6,275
170	5,815	6,073	6,118	6,393

According to a leaflet distributed by Bristol water, they will charge £1.2669 for a cubic metre of water in 2020/21 (BristolWater, 2021). As this is the price of water and not the cost to treat potable water, the financial savings calculated using this value will be more inflated than reality. This price will account for extra costs to Bristol water such as plumbing and pumping the water, which would also be a cost for the rainwater. However, finding an exact value for the cost difference between potable and rainwater proved difficult. Therefore, the standard price given by Bristol water was used in the analysis.

To assess the costs associated with an increase in tank volume, the price of large, galvanised steel water storage tanks from a nearby company (Tanks Direct) in Minehead, Somerset were used. Whilst the company provides specialised rainwater harvesting tanks and systems for domestic use, the tank capacities did not exceed 20 m^3. Operating costs were assumed to be negligible. The pumps and energy requirements would be the same regardless of tank size, due to the same volume of water being pumped out for demand. However, costs associated with the required space of each tank may increase the initial capital costs. The 72 m^3 tank occupied 23 m^2 whilst the 150 m^3 tank occupied 65.6 m^2. The storage tank prices are shown in Figure 3.25:

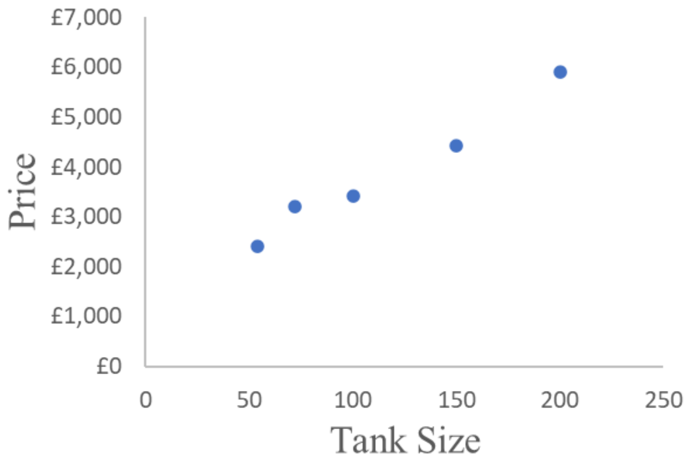


Figure 3.25. Price of five different tanks from Tanks Direct.

The price of each tank follows the same increase except the 72 m^3 tank. For a better analysis this price was changed using Excel's LINEST function, with both included in Table 3.18:

Table 3.18. Economic analysis results for different tank sizes.

Tank size (m^3)	Price	YAS Yield (m^3)	YBS Yield (m^3)	YBS Savings	YAS Savings	Maximum Difference	Minimum Difference
54	£2,414	4106.66	4841.00	£6,133	£5,203	£3,719	£2,788
72	£3,198	4550.01	5107.92	£6,471	£5,764	£3,273	£2,566
100	£3,408	5016.85	5460.46	£6,918	£6,356	£3,510	£2,948
150	£4,434	5615.70	5933.23	£7,517	£7,115	£3,083	£2,681
200	£5,892	6041.44	6265.96	£7,938	£7,654	£2,046	£1,762
72	£2,910	4550.01	5107.92	£6,471	£5,764	£3,561	£2,854

Dependant on which behavioural model used, the optimum tank size will be different. Using the conservative YAS model, the optimum peak in Figure 3.26 lies around the 100 m^3 mark. However, for a YBS model the optimum peak will lie further to the left of the chosen range. As a result, the optimum tank size will be chosen as 100 m^3.

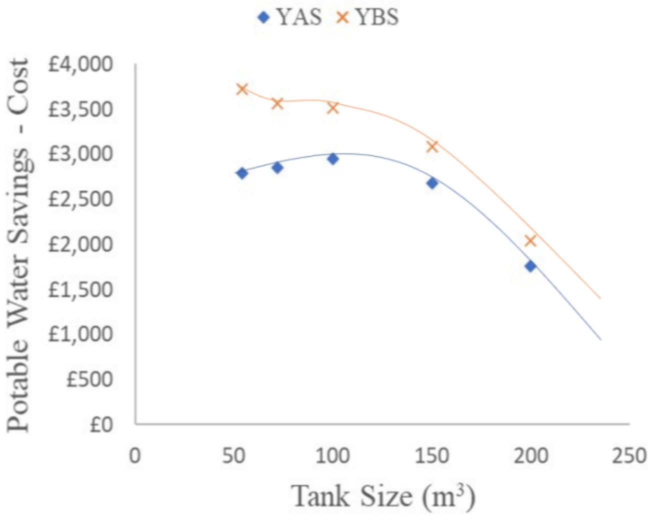


Figure 3.26. Potable water savings for different tank sizes.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Scenarios 4 - residential application

The economic assessment follows a similar sensitivity approach in that the capital, maintenance and operation costs are varied against varying future water prices in the economic benefit. Figure 3.27 shows variations of the net present value as a function of the timeline (2022-2055) for each scenario and Table 3.19 and Table 3.20 present a summary of the results obtained from Figure 3.27.

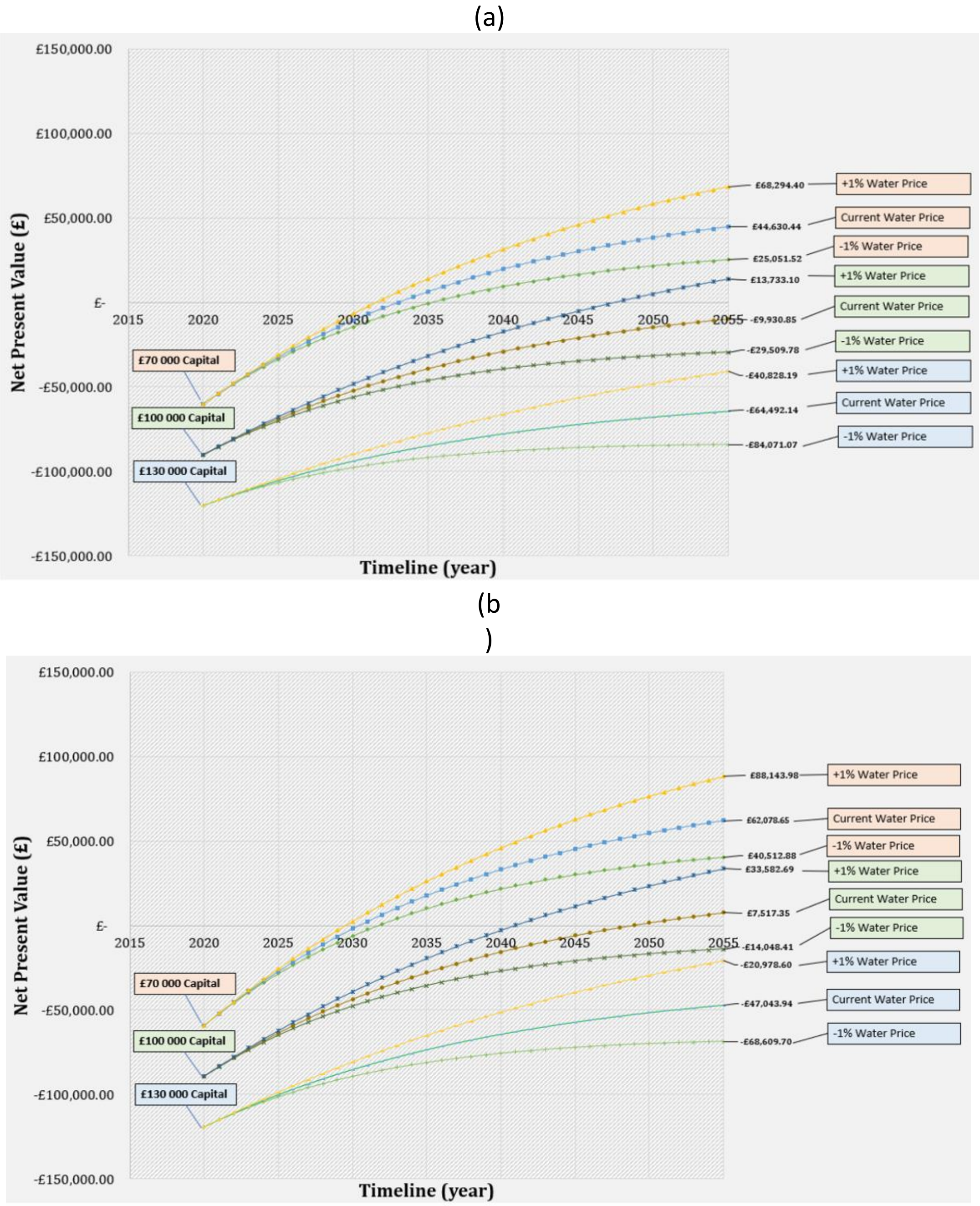


Figure 3.27. Return on investment period (a) worst case scenario and (b) best case scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 3.19. Return on Investment Periods for best- and worst-case scenarios.

Case		Return on investment period (years)		
		-1% Water price	Current*	+1% Water price
70k	Worst Case	16	14	12
	Best Case	12	11	10
100k	Worst Case	-	-	27
	Best Case	-	29	21
130k	Worst Case	-	-	-
	Best Case	-	-	-

*Current: £1.2669/m^3 (BristolWater, 2021).

Table 3.20. Net present value of total profit (+) and loss (-) for the best and worst case scenarios.

Case		NPV of total savings after 30 years (2050, £)		
		-1% Water price	Current	+1% Water price
70k	Worst Case	+21434.67	+38223.00	+58045.64
	Best Case	+36173.21	+54665.19	+76499.41
100k	Worst Case	-31624.01	-14835.68	+4986.97
	Best Case	-16885.46	+1606.51	+23440.73
130k	Worst Case	-84682.68	-67894.35	-48071.71
	Best Case	-69944.14	-51452.16	-29617.95

*Current: £1.2669/m^3 (BristolWater, 2021)

Under specific circumstances, the system can be economically feasible. However, the feasibility results presented in Table 3.19 and Table 3.20 take on a global perspective which does not consider the costs and benefits to the homeowner and development owner (in this case, YTL Developments). By separating the system economics into the homeowner and development owner perspectives, the system is unlikely to be implemented.

As expected, the feasibility of the rainwater harvesting system is highly dependent on the initial capital investment. Without a robust economic model that incorporates current commercial prices for the installation of the storage tank, pumps and the pipeline network, the economic assessment is significantly limited. However, the results from this economic assessment are aimed at providing an estimated range for the feasibility of the system. Using the best- and worst-case scenario water balance results and a range of potential capital, maintenance and operating costs, the economic potential for the system is adequately expressed.

The feasibility for this system also shows a dependency on the amount of rainwater collected. The demand of non-potable water is likely to exceed the available rainwater because the non-potable demand quantity varies between 9,787 m^3/year and 39,400 m^3/year, whereas the harvestable rainwater varies between 7800 m^3/year and 13,700 m^3/year. Thus, for the system economic benefit to be maximised, emphasis needs to be placed on maximising the possible collectable rainfall. By maximising the rainfall collection, the system is able to achieve the economic performance as expressed for the best-case scenario (potential savings after 30 years ranges between £1,600 and £76,000). However, this is under the strict condition that the capital expenses remain lower than £100,000. The system is shown to be economically unfavourable if the capital expenses exceed this threshold.

Additionally, the future price of water holds a key role in the economic feasibility. An increasing water price improves the potential savings that the system provides. With the threats of climate change and water scarcity in urban areas, the price of water will vary. The system benefits from an increase in water price which proves that the implementation of the rainwater harvesting into urban water management plans is an effective means of climate-proofing.

However, these economic feasibility results are expressed from a global, more holistic perspective. In reality, there are separate stakeholders that incur the cost from each the capital, maintenance and operations as well as a separate stakeholder benefitting from the savings from the substitution of rainwater for treated water. From the perspective of YTL Developments, their primary objective for the Brabazon Development is to make a profit on the sale of the residential units and the commercial office space. It is unlikely that YTL Developments will sell the residential and office space and then continue to maintain and cover the operating expenses for the rainwater harvesting system, especially considering that the economic benefit from the reduced water bill is to the advantage of the homeowner. Therefore, the system is unlikely to be implemented.

Scenarios 5 - commercial application

Cost saving potential and determination of rainwater storage size

In this analysis, an optimal size of the rainwater storage capacity of a RWH system in YTL Arena was determined. The cost-effectiveness of the RWH system with different application scenarios was evaluated in terms of the cost savings of over 50 years and the unit water cost as a function of tank size variations (100 - 2,000 m^3). Figure 3.28 shows the cost savings, which include the difference between the total costs of the mains-only supply system and the RWH system for three different applications scenarios, toilet flushing (a), irrigation (b) and a combined use (c). Positive values of cost savings correspond to a range of storage sizes, which make the RWH system economically feasible for the given scenarios.

Figure 3.28 (a) shows the changes in the cost savings of toilet flushing with different numbers of visitors, as the storage capacity of the RWH system increases. The cost savings of TF_{YA1} and TF_{YA2} (21.6 and 54.0 m^3/day, respectively) remained negative values regardless of the tank sizes, indicating that the systems for these water demand scenarios are economically unfeasible. However, the systems can become economically viable if the water demand grows higher than 54.0 m^3/day. For example, the cost savings of TF_{YA3} and TF_{YA4} were shown to be positive values at a tank size between 100 and 600 m^3. However, when the tank size goes beyond 600 m^3 the result shows that the RWH systems for these applications are no longer economically beneficial mainly due to the increase of the tank size thus capital cost. This indicates that for toilet flushing in the YA, RWH systems with a tank size between 100 and 600 m^3 would be economically feasible. As shown in Figure 3.28 (b), when the collected rainwater was only used for irrigation applications (BP and FG), the cost savings of the RWH system were shown to be negative values for all tank sizes although its variation was more sensitive to the tank sizes, less than 800 m^3. For irrigation scenarios, this study assumed that that irrigation activities occurred between May and October, discharging the excess runoff into a sewer drainage system. This practice increased the OPEX costs of the RWH systems, thus illustrating the negative values of cost savings regardless of the tank sizes.

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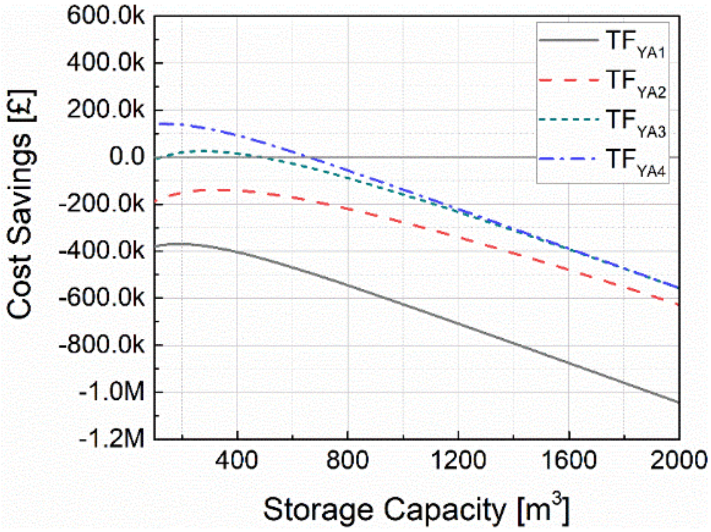
Figure 3.28 (c) displays the combined use of the RWH systems with different application ratios of toilet flushing to irrigation (50TF+50IR and 70TF+30IR). The cost savings across all four scenarios give positive values at a tank size between 100 and 600 m^3, while the values turn negative at above 600 m^3. This indicates that combined regular and irregular water applications could make the system more cost-effective, thus suggesting an optimal storage capacity of between 100 and 600 m^3 for the RWH system at the YA.

Furthermore, Figure 3.29 presents the unit rainwater costs for single and combined use scenarios ($TF_{YA3\&4}$, $50TF_{YA4}$ + $50IR_{BP2\&FG2}$, and $70TF_{YA4}$ + $30IR_{BP2\&FG2}$) with selected storage capacity variations from 100 to 1,000 m^3, which are based on the results obtained from Figure 6. The unit rainwater cost decreased gradually in tandem with an increase in the storage capacity, ranging from 100 to 200 m^3, depending on water demand scenarios. After that, the unit rainwater cost rapidly increased, exceeding that of the mains-only supply water cost. For example, at 700 m^3, the unit rainwater costs for across scenarios were between 0.42 and 0.45 £/m^3. From these results, it can be concluded that a storage capacity of between 100 and 600 m^3 would be enough for the RWH system in the YA to maintain the unit rainwater cost range from 0.37 to 0.40 £/m^3, depending on the costs of water use scenarios, which are equal to or lower than the mains-only supply water cost (0.40 £/m^3).

The results of the economic analysis conducted in this study suggest that there is a correlation between the total cost of a RWH system and the level of water consumption. This means that the water demand pattern dominates the overall economic performance of the RWH system (Ghimire et al., 2017; Hajani et al., 2014; Słyś et al., 2020; Ward, 2007). Considering hydraulic and economic performances, consequently, the use of the RWH system with a tank size between 400 and 600 m^3 for toilet flushing, coupled with the combination of toilet use and irrigation, can be the most favourable scenario under the conditions considered in this study.

(a)



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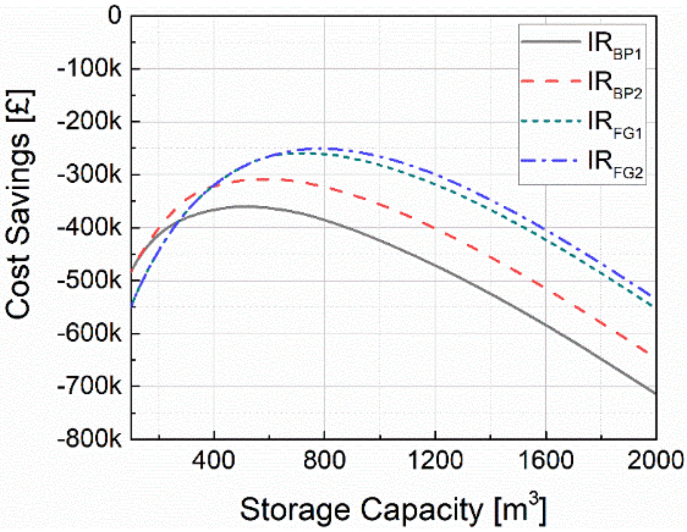

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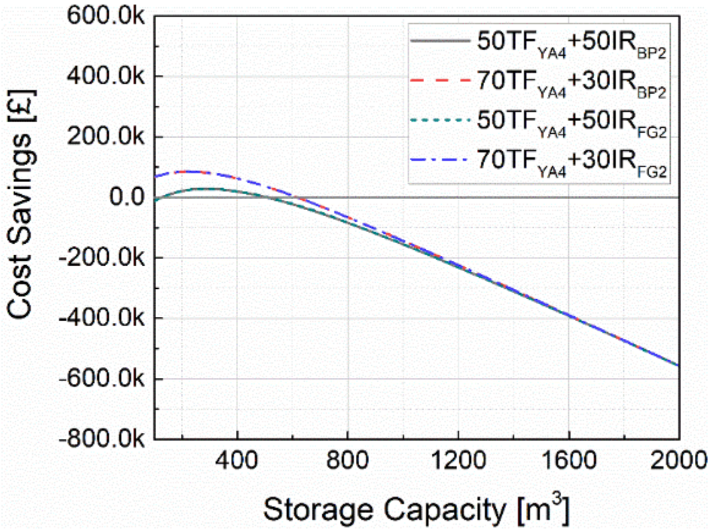


Figure 3.28. Cost savings as a function of storage capacity ranging from 100 to 2,000 m^3 (a) YA toilet flushing with different numbers of visitors, (b) irrigation of BP and FG and (c) combined use: YA toilet flushing + BP and FG.

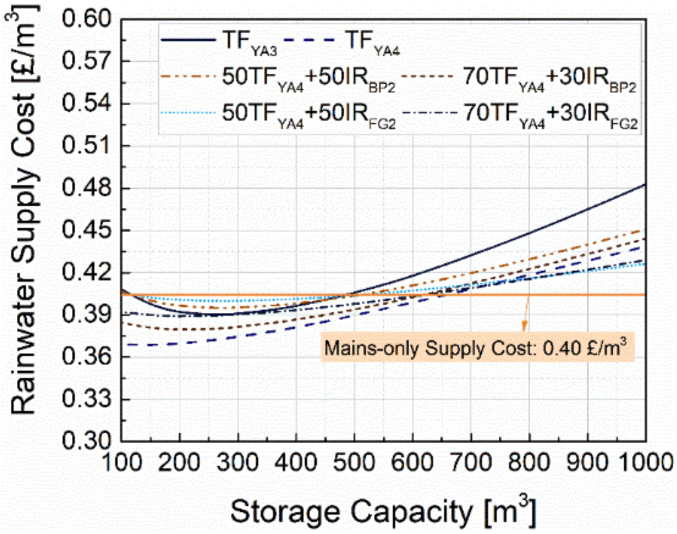


Figure 3.29. Harvested rainwater cost and mains-only supply cost as a function of storage capacity ranging from 100 to 1,000 m^3.

Sensitivity analysis

Water prices, rainfall conditions, and discount rates are the three major factors contributing to the economic viability of RWH systems (Amos et al., 2018). A sensitive analysis was performed to assess those parameters and identify ways to further reduce the unit cost of rainwater of the RWH system compared to the unit cost of mains-only supply. Based on the results obtained from the previous section, a storage tank of 600 m^3, which could maximise the WSE and maintain the unit rainwater cost lower than the mains-only supply cost calculated using a 5% discount rate and 1.05 £/m^3 water price, and three water application scenarios were chosen: toilet flushing (TF_{YA4}) and combined use of toilet flushing and irrigation ($50TF_{YA4} + 50IR_{BP2}$ and $50TF_{YA4} + 50IR_{FG2}$).

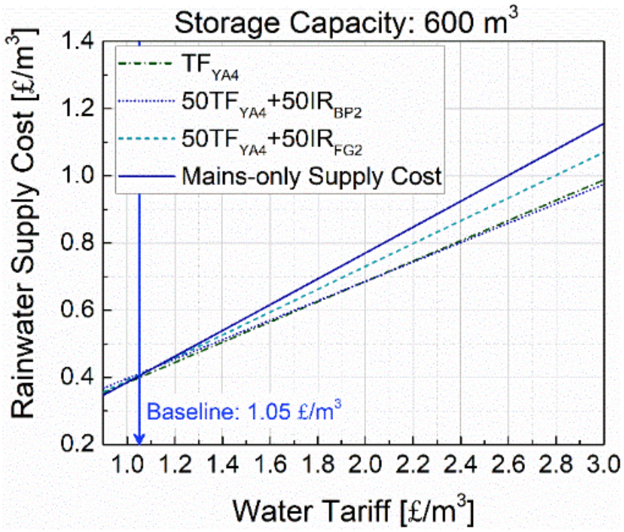
Figure 3.30 (a) shows the sensitivity analysis of changes in water tariffs ranging from 1 to 3 £/m^3. As the water tariffs increased from 1 to 3 £/m^3, the mains-only supply costs increased accordingly. The baseline value in this figure represents the water tariff of 1.05 £/m^3 (Table S4). The unit rainwater cost across all scenarios increased in tandem with an increase in water tariffs. At lower water price (<1.05 £/m^3, baseline), the unit rainwater cost of all scenarios was slightly higher than the mains water cost, while, at higher water price (>1.05 £/m^3, baseline), the unit rainwater cost remained below (0.39 - 1.07 £/m^3) the mains water cost (0.40 - 1.16 £/m^3) under the given conditions. The results confirm that the economic performance of RWH systems is sensitive to variations of mains water prices (Lani et al., 2018).

Furthermore, Figure 3.30 (b) shows how the change in the climate conditions (dry, normal and wet) affected the unit rainwater cost of each scenario. The SPI of 0 represents the average rainfall condition. When the SPI values were below average (i.e., dry conditions), the mains-only water cost (0.40 £/m^3) was lower than the unit cost of rainwater ranging from 0.42 to 0.44 £/m^3, depending on the water use scenarios and the higher mains water requirements. In contrast, when the SPI values turned positive (i.e., wet conditions), the unit rainwater costs of all scenarios ranged between 0.38 and 0.40 £/m^3, depending on the water demand scenarios. During the wet years, the maximum achievable savings ranged between 3.7% and 12.3%, depending on the scenarios. Despite no significant reduction in the unit rainwater costs, the results indicate that the duration of the wet period could play a crucial role in enhancing the economic performance of RWH systems, as reported in previous research (Imteaz et al., 2017; Zhang et al., 2018).

The impacts of changes in the discount rates (0% - 15%) on the unit water costs of RWH systems are shown in Figure 3.30 (c). The unit rainwater costs across all scenarios were higher than the unit cost of mains water (0.40 £/m^3) at the discount rate of below 5.5% which was lower than the mains water cost at the discount rate of above 5.5%. For toilet flushing, for example, the unit water cost was 0.94 £/m^3 at a 0% discount rate, while it was 0.21 £/m^3 at a 15% discount rate, which suggests a 77.3% reduction. This indicates that the economic results of the RWH systems were highly influenced by discount rates. Although no clear idea exists to determine the exact discount rates of specific applications, generally, social discount rates for institutions (e.g., water utilities and private companies, 10% and 15%, respectively) should be lower than the rates considered for individuals (e.g., homeowners, 5%) (Roebuck et al., 2011; Voinov et al., 2007). This sensitivity analysis illustrates the potential for making the RWH system of the YA cost-effective by considering the discount rates between 5.5% and 15%.

Table 3.21 presents the payback period (PBP) of three selected scenarios considering two variables: the future water cost of 2 and 3 £/m^3 and the discount rates of 5%, 10% and 15%. Overall, no significant difference exists between water demand scenarios. For toilet flushing, when considering a future water price of 2 £/m^3, the PBP of the system is 19 and 35 years for 5% and 10% and above 50 years for 15%. However, when considering a future water price of 3 £/m^3, the PBP of the system is 10, 12 and 18 years for 5%, 10% and 15%, respectively. These results indicate that it is possible to achieve a shorter PBP at a lower discount rate. However, the water price increase could play a more significant role in the economic feasibility of the proposed RWH (Domènech et al., 2011; Khastagir et al., 2011). The results suggest that the RWH system of the YA could be economically feasible in the light of a discount rate of lower than 10% and a water price of higher than 2 £/m^3. For the purpose of implementing RWH systems in a sustainable way, there would be an opportunity to negotiate a lower tariff for both drinking water and sewage as charges for commercial buildings are directly correlated to the amounts of the used water and the discharged sewage, the higher the water use or the sewage discharge the lower the charges. This can result in the further improvement of the economic feasibility of the RWH of the YA.

(a)



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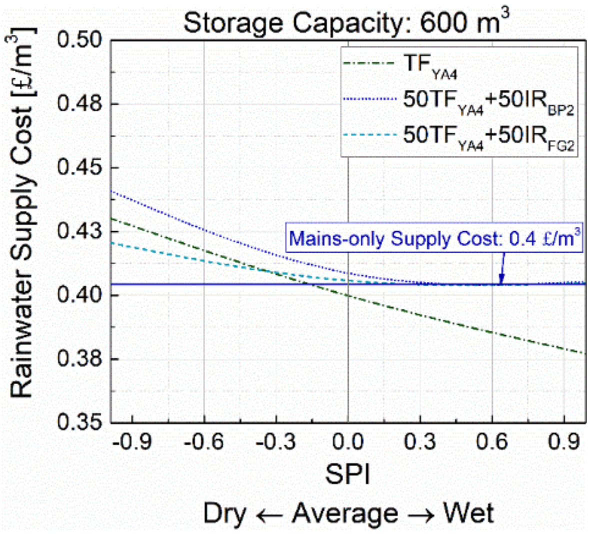

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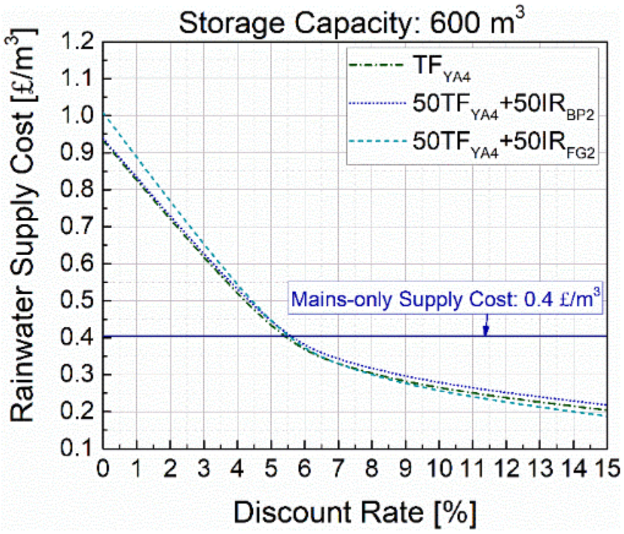

Figure 3.30. Sensitivity analysis of the rainwater cost as a function of variations of (a) water tariff (1–3 £/m^3) (b) rainfall (SPI values refer to dry, normal and wet conditions) and (c) discount rate (0%–15%), considering three different application options: toilet flushing for 20,000 people and combined use of toilet flushing and irrigation.

Table 3.21. Financial results of the RWH strategies for a 600 m^3 tank.

Scenario		TF_{YA4}	$50TF_{YA4}+50IR_{BP2}$	$50TF_{YA4}+50IR_{FG2}$
Water price = 2 £/m^3	PBP (years) at 5%	19	22	22
	PBP (years) at 10%	35	50	50
	PBP (years) at 15%	50	50	50
Water price = 3 £/m^3	PBP (years) at 5%	10	11	11
	PBP (years) at 10%	12	15	14
	PBP (years) at 15%	18	23	23

3.1.4. Conclusions

This study presented the results of a feasibility assessment of RWH from the rooftop of the residential buildings and YTL Arena in Filton Airfield for non-potable purposes, including water demand scenarios of washing machine, toilet flushing, irrigation and the combined use of toilet flushing and irrigation, depending on scenarios. The RWH systems of these applications were assessed using hydraulic and economic indicators. Main conclusions drawn from this study are as follows:

- **RWH for residential applications (Scenarios 1,2,3 and 4)**
  - Optimized storage fractions for the centralized and decentralized systems (0.01 and 0.0075) were a trade-off between the three performance indicators, tank volume and flood attenuation. These storage fractions equate to tank volumes of 71.2 m^3 (centralized, scenario 2) and 8.0 m^3 (decentralized, scenario 1). The decentralized system had greater water savings efficiency at 47.1% compared to only 35.7% for the centralized system. Data showed that the influx of harvested rainfall became a limiting factor at high tank volumes resulting in upper limits of 45% (centralized, scenario 2) and 70% (decentralized, scenario 1) for WSE. This effect was more detrimental for the centralized system which has higher annual demand per m^2 of catchment area at 1.53 m^3/m^2 compared to 0.85 m^3/m^2 for the decentralized system.

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  - In scenario 3, the maximum WSE that could have been achieved for the year 2018 was 43.56%. The optimum tank size determined for a passive RWH system was 100 m^3. Using a YBS model, this tank size gave a WSE of 38.1% and SCE of 87.5%. 100 m^3 was chosen by comparing the costs of different tanks within a range to the yield savings they produced.
  - In scenario 4, the rainwater system poses a suitable alternative water source to meet the non-potable water demand for a medium-scale urban development. From a holistic, global perspective, the system has been proven to be feasible, even under the worst case scenario, provided the capital costs or between £70,000 and £100,000. This RWH application highlights the potential for a medium-scale system and shows that larger systems are able to recover the capital costs and show a net economic benefit. However, the long return on investment periods remains a significant limitation to the adoption of these types of systems. The results from the simulations highlight the wider benefits of a rainwater harvesting system.

- **RWH for commercial applications (Scenario 5)**
  - When the storage capacity was between 400 and 1,000 m^3, the water saving efficiency of the system could be obtained between 7.2% and 98.3%, depending on the water demand considered in the scenario 5.
  - The results of the economic analysis further confirmed that the economic performance of the RWH systems in terms of cost savings and unit water cost was significantly influenced by water demand scenarios. Cost savings values of the RWH system for irrigation use requiring significant water consumption compared to toilet flushing and combined use scenarios remained negative, regardless of the tank size, which was not cost-effective. However, when the RWH system was used for toilet flushing and combined toilet flushing and irrigation, positive cost savings were observed at the tank between 100 and 600 m^3, indicating that the tank size of the given applications should be smaller than 600 m^3. To maintain the unit rainwater cost lower than the mains-only supply cost (0.40 £/m^3), the results showed that the storage capacity of between 100 and 600 m^3 would be enough for the implementation of RWH at the YA (0.37 - 0.40 £/m^3). Consequently, considering the WSE and economic analysis results, the use of the RWH system with a tank between 400 and 600 m^3 for toilet flushing, coupled with the combination of toilet use and irrigation, can be the most favourable scenario under the conditions considered in this study.
  - At the fixed tank size of 600 m^3, the sensitivity analysis results indicated that the RWH system with a 600 m^3 tank is cost-effective when the discount rate reaches 10% or when the water price is higher than 2 £/m^3. Furthermore, the impacts of rainfall changes on the unit rainwater costs illustrated the importance of designing the water use scenarios of RWH systems, as unexpected rainfall changes are one of the main constraining factors affecting the performance of RWH systems. Moreover, a 5% discount rate and a water price of 3 £/m^3 yielded the shortest PBP for all water demand scenarios between 10 and 11 years.

3.2. Hybrid rainwater-greywater system

3.2.1. Introduction

As alternative urban water sources or supply systems, rainwater harvesting (RWH) and greywater reuse (GWR) have been integrated in residential and commercial buildings (Dallman et al., 2021; Fox et al., 2009; Fulton, 2018; Hills et al., 2002; Kim et al., 2021; Marleni et al., 2012). Many studies into RWH and GWR have proved its technical feasibility and economic viability by considering unit water tariff, reliability, potable water saving efficiency, and stormwater attenuation and demonstrated their applicability for non-potable purposes such as toilet flushing, laundry, irrigation, car washing, and industrial cooling (Agudelo-Vera et al., 2013; Ali et al., 2020; An et al., 2015; Friedler et al., 2005; Gerolin et al., 2010; Imteaz et al., 2013; Kim et al., 2021; Liang et al., 2011; Meneses et al., 2010; Weber et al., 2007; Zadeh et al., 2013). A decentralised hybrid RWH and GWR system has become more promising to balance between discontinuous rainwater yield and continuous greywater production with a significant reduction of potable water consumption.

This section therefore focuses on the urban water harvesting potential for the Filton Airfield development by conducting a dynamic and stochastic demand simulation and extended scenario approach to assess a range of possible RWH and GWR options. This study ultimately prompts a rethink of urban planners and decision-makers to adapt urban assessment tools for either existing or new community development to outline a vision for sustainable urban water management.

3.2.2. Methods

3.2.2.1. Study scenarios

Urban water resource catchment scenarios include different building types including an entertainment venue, a free-standing house, and a mid-rise apartment building as illustrated in Figure 3.31. Table 3.22 further describes the specific building types and bedroom breakdown in catchments A and B (CA and CB). CA includes the roof surfaces of 54 houses while CB contains the roof surfaces of 52 houses and a mid-rise apartment consisting of 33 units. In addition, the YTL Arena (YA) is an entertainment centre with a capacity of 17,080 people and with one million visitors expected annually (Hills et al., 2002; YTL, 2021).

Figure 3.31. Location of housing plan phase 1 'the Hangar District' and YTL Arena. YTL Arena, Catchment A and Catchment B are rainwater catchment points (In catchments A and B, boxes with blue colour were considered for the study).

Table 3.22. Description of building units within the study area.

Catchment	Building type	Bedroom type	No. of units
YTL Arena (YA)	Commercial – entertainment/shopping centre	-	-
Catchment A (CA)	Residential – free-standing houses	2-bed	2
		3-bed	15
		4-bed	37
Catchment B (CB)	Residential – apartment[†]	1-bed	13
		2-bed	20
	Residential – free-standing houses	2-bed	6
		3-bed	43
		4-bed	3

Rainwater harvesting and greywater recycling for the provision of water for non-potable uses were evaluated in this study. The baseline was defined as business-as-usual (i.e., a conventional mains water supply system). As shown in Table 3.23 houses and apartments in CA and CB (residential - R1, R2 and R3), YA (commercial - C1), and combined residential and commercial buildings (RC1, RC2, and RC3) were inspected. Scenario RC1 shows the largest rooftop surface – 29,288 m^2 - followed by RC2 and RC3, at 21,356 m^2 and 20,932 m^2 due to the large roof surface of the YTL entertainment centre (13,000 m^2). Scenario C1 considers rainwater reuse for only toilet flushing. Details regarding the catchment area estimation for each scenario is shown in Table 3.24 and Table 3.25.

Table 3.23. Different scenarios for rooftop rainwater harvesting and catchment area.

	Scenario	Roof catchment	Catchment area (m^2)	Water use
Residential (R)	R1	CA+CB	16,288	WC & WM
	R2	CA	8,356	WC & WM
	R3	CB	7,932	WC & WM
	R4	CB_H	7,402	WC & WM
	R5	CB_A	530	WC & WM
Commercial (C)	C1	YA	13,000	WC
Residential & Commercial (RC)	RC1	YA+CA+CB	29,288	WC & WM
	RC2	YA+CA	21,356	WC & WM
	RC3	YA+CB	20,932	WC & WM

*CB_H refers to houses in catchment B, whereas CB_A refers to the apartment building in catchment B.
*WC: toilet flushing, WM: washing machine

Table 3.24. Apartment building information used to estimate the total roof surface.

Level	Estimated surface (No. of units per floor)						Total (m^2/floor)
	1-bedroom				2-bedroom		
	Type1	Type2	Type3	Type4	Type5	Type6	
Ground	49.3(1)		51.7(1)	52.2(1)			153
First		103.2(2)			73.7(1)	227.1(3)	404
Second		103.2(2)			73.7(1)	302.8(4)	480
Third		103.2(2)			73.7(1)	151.4(2)	328
Fourth		103.2(2)			73.7(1)	227.1(3)	404
Fifth		103.2(2)			147.4(2)	151.4(2)	402
Estimated total APT roof surface: 530 m^2							

*Total roof surface of 530 m^2 was estimated using the largest surface area of 480 m^2 and the calculation was carried out via https://www.calculator.net/roofing-calculator.html

Table 3.25. Estimated total roof surfaces for each catchment used for water balance analysis.

Catchment	Building type	Bedroom type	No. of units	Estimated roof surface, m^2/unit	Total roof surface, m^2
YTL Arena	Commercial	-	-	-	13,000
Catchment A	Houses	2-bed	2	111	8,356
		3-bed	15	124	
		4-bed	5/22/10	164/165/183	
Catchment B	Apartment[†]	1-bed	13	-	530
		2-bed	20		
	Houses	2-bed	3/2/1	102/104/111	7,402
		3-bed	5/3/16/19	124/124/138/159	
		4-bed	1/2	164/186	

[†]The apartment has different types of units with different surface areas, and each level has different number of units.

3.2.2.2. Rainfall data

Historical daily rainfall data from 1 January 1968 to 31 December 2020 were gained from Tanguy et al. (2019) and Underground (2020). The average annual precipitation over this period was 820 mm. The daily and average monthly and annual precipitation trends for the Filton site are presented in Figure 3.32.

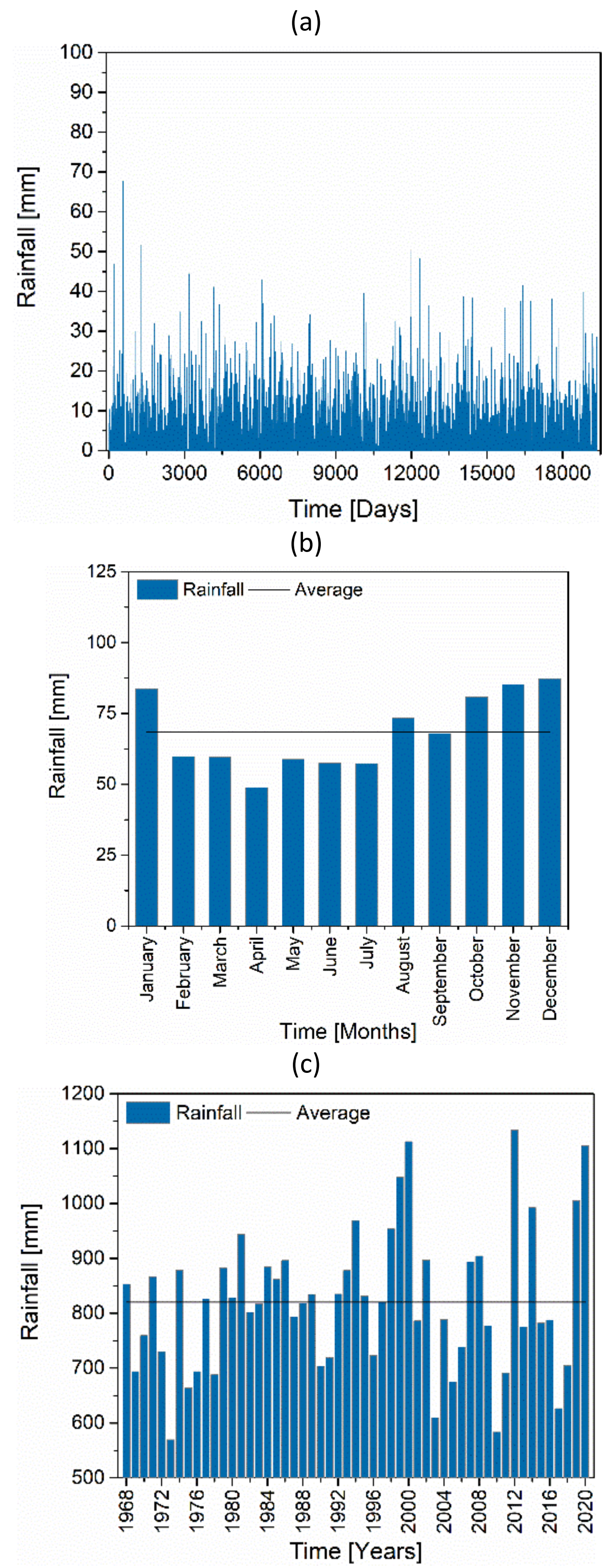

Figure 3.32. Historical rainfall data from 1 January 1968 to 31 December 2020 collected from the weather stations close to Filton Airfield (a) daily, (b) monthly and (c) yearly average rainfall variations.

3.2.2.3. Performance indicator analysis

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The yield after spillage (YAS) principle (Campisano et al., 2012a; Jenkins et al., 1978) was used to determine an optimal storage tank for rooftop RWH by assessing hydraulic and economic behaviours, including water saving efficiency (WSE, %), stormwater capture efficiency (SCE, %), total savings (£), and unit product water cost (£/m^3). The detailed YAS mass balance equations and WSE and SCE estimation used in this study can be found in

Table 3.26. During the YAS simulation, the tank capacity was varied between 1 and 2,000 m^3. This range was determined based on our previous study (Kim et al., 2021). The economic analysis includes the construction expense (CAPEX) and operational expense (OPEX) throughout the project's lifetime (Kim et al., 2018; Wang et al., 2015). The installation and operational costs were estimated using the cost information on storage installation and maintenance adopted from the RainCycle tool (Doncaster et al., 2012) and previous studies (Roebuck et al., 2011; Słyś et al., 2020; Wang et al., 2015). Equations and input variables utilised for financial evaluations are shown in

Table 3.26 and Table 3.27, respectively. Further details can be also found in (Kim et al., 2021).

This study used UWOT to assess the urban water cycle for each scenario with different water management options: RWH; GWR; and combined RWH and GWR.

Figure 3.33 indicates input parameters for SIMEUM and UWOT simulations. All indicators of urban harvesting potential assessment - demand minimisation index (DMI), wastewater output index (WOI), self-sufficiency index (SSI), and resource exported index (REI) - were calculated using equations presented in

Table 3.26 (Agudelo-Vera et al., 2012; Leusbrock et al., 2015). To evaluate the DMI, water-saving appliances for each scenario were selected, and input values for the conventional (baseline) and water-saving appliances selected within UWOT. The baseline represents the commercial and residential developments using conventional water supply, assuming there is no RWH and GWR. In addition, all water-related services (i.e., external water source and wastewater discharge) are provided using conventional water facilities. The water saving scenario is based on the same input data (number of housing units and households in the Filton development) but utilises water saving appliances at the household scale. This includes, for instance, dual flush toilets and low-flow shower system, which are the pre-set characteristics (Table 3.28).

In addition, Figure 3.34 describes the hybrid RWH and GWR system configurations considered in the current study. Configuration 1 (C1) is a hybrid system where rainwater and greywater are treated separately (Li et al., 2010; Zhang et al., 2010). The light greywater recycling scheme (i.e., wastewater produced from the baths, showers, and hand basins) was utilised as they are relatively clean compared to other wastewater from kitchen sinks, washing machines and toilets (Birks et al., 2007; Penn et al., 2013). Within UWOT, a greywater system of 60 m^3/day, consisting of filtration of coarse pollutants with 90% removal efficiency, followed by disinfection with UV was demonstrated (Makropoulos et al., 2008). The current study determined the capacity of the greywater system by assuming that the volume of wastewater discharged to a sewerage system is about 80% of the total water demand for the buildings (Assefa et al., 2018). Configuration 2 (C2) combines harvested rainwater, greywater, and mains water top-up into a single storage tank (de Gois et al., 2015; Dixon et al., 1999; Weissenbacher et al., 2009; Zhang et al., 2009). Although there was a concern about the quality of the final product, it was successfully controlled by a hybrid membrane process (Birks et al., 2004; Kim et al., 2007). Since an evaluation of treatment trains is beyond our current scope, this study assumed that the final product could meet the quality for end-users.

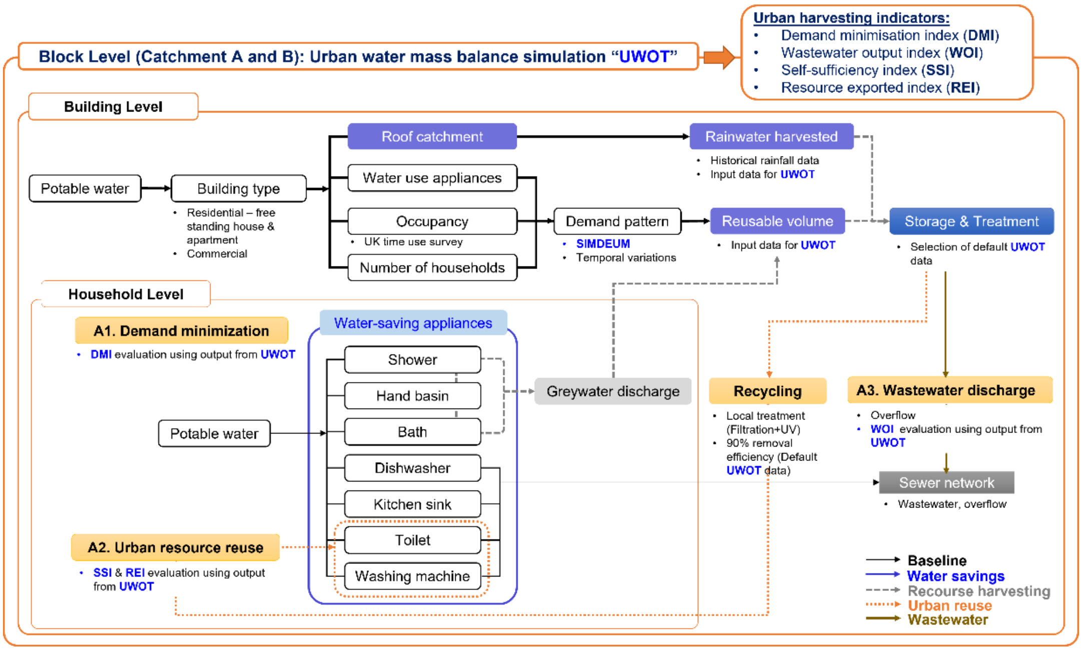

Figure 3.33. Urban water cycle showing urban water management strategies: demand minimization (A1), resource harvesting and reuse (A2), and wastewater discharge (A3). Note that wastewater stream is not in the scope of the current study.

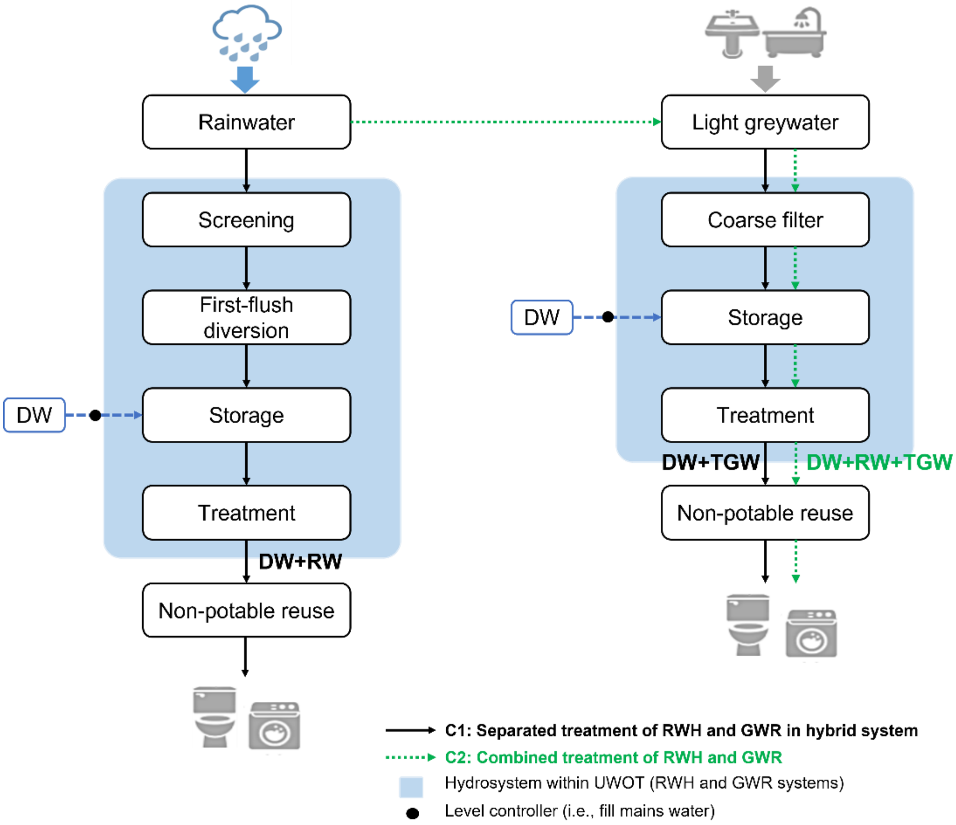

Figure 3.34. Hybrid rainwater and greywater system configurations considered in this study. DW – drinking water, TGW – Treated greywater, and RW – rainwater.

Table 3.26. Equations used for analysing water balance behaviours, water demands and cost in this study.

	Equation	Reference
Water balance simulation	$Y_t = \begin{cases} V_{t-1} + Q_t, & if\ V_{t-1} + Q_t \leq D_t \\ D_t, & if\ V_{t-1} + Q_t > D_t \end{cases}$ $V_t = \begin{cases} V_{t-1} + Q_t - Y_t, & if\ V_{t-1} + Q_t \leq S \\ S - Y_t, & if\ V_{t-1} + Q_t > S \end{cases}$ $O_t = \begin{cases} 0, & if\ V_{t-1} + Q_t \leq S \\ V_{t-1} + Q_t - S, & if\ V_{t-1} + Q_t > S \end{cases}$ $Q_t = (R_t - F_f) \times CA \times FC \times RC$	Sendanayke (2016)
	$WSE, \% = \frac{\sum Y_t}{\sum D_t} \times 100\% = \left(1 - \frac{\sum_t^T M_t}{\sum_t^T D_t}\right) \times 100$ $SCE, \% = \dfrac{\sum Y_t}{\varphi A \sum H_t / 1000} \times 100\%$ where Y_t is the rainwater yield, m^3; D_t is the water demand, m^3; ϕ is the runoff coefficient; A refers to the catchment area, m^2; H_t is the rainfall amount, mm; t is the time interval number. For the filter coefficient (FC) and roof runoff coefficient (RC) the values 0.9 and 0.85 were used respectively.	Kim et al. (2021)
Economic evaluation	$Present\ value\ (PV) = C\,\dfrac{1 - (1 + i)^{-n}}{i}$	Abas et al. (2019);

	$Net\ present\ value\ (NPV) = \sum_{t=1}^{n} \frac{PV_t}{(1+i)^t}$ $Annualised\ OPEX\ cost\ (A, £/y) = NPV \times \frac{i(1+i)^n}{(1+i)^n - 1}$ $Unit\ water\ cost\ (^{£}/_{m^3}) = \frac{CAPEX + A}{D}$ where *C* is the cost in GBP, *n* is the project period in year, i is the discount rate, *t* is the time in years and *D*: annual water demand, m^3/y.	Christian Amos et al. (2016); Kim et al. (2017); Linares et al. (2016)
Urban harvesting potential index	$DMI = \frac{Baseline\ demand - Minimized\ demand}{Baseline\ demand}$ $WOI = \frac{Exported\ waste}{Minimized\ demand}$ $SSI = \frac{Harvested\ resources - Exported\ resources}{Minimized\ demand}$ $REI = \frac{Exported\ resources}{Minimized\ demand}$	Agudelo-Vera et al. (2012), Leusbrock et al. (2015)

Table 3.27. Input parameters for the economic evaluation of the RWH system.

Parameter		Unit	Value	Reference
Discount rate		%	5	Roebuck et al. (2011)
Water tariff		£/m³	1.29	BristolWater (2021)
Sewage		£/m³	1.68	YTLGroup (2021)
Energy tariff		£/kWh	0.147	UK average price*
System life span		years	50	Lani et al. (2018)
CAPEX–construction and installation	Tank	£/m³	372.5	Roebuck et al. (2007); Roebuck et al. (2011); Wang et al. (2015)
OPEX–maintenance and replacement	Inspection, reporting and information management	year	2	
	Roof washing, cleaning inflow filters	year	2	
	Tank inspection and disinfection	year	1	
	Intermittent system maintenance (system flush, debris/sediment removal from tank)	year	3	
	Pump replacement	year	10	
	Minor fittings replacement	year	10	
	Filter replacement	year	15	

*https://www.ukpower.co.uk/home_energy/tariffs–per–unit–kwh

Table 3.28. Water consuming household appliances used in UWOT.

Water use appliance				Conventional	Water saving
Potable	Bath	BT	L/use	130	65
	Hand Basin	HB	L/use	2.1	1.7
	Shower	SH	L/use	60	35
	Kitchen sink	KS	L/use	2.1	1.7
	Dishwasher	DW	L/use	35	15
Non-potable	Washing machine	WM	L/use	60	35
	Toilet	WC	L/use	9	4

3.2.2.4. Sensitivity analysis

The changes in the urban water cycle and its resource harvesting potential are influenced by specific local conditions, including water supply-demand, resource availability, wastewater outputs, and climate conditions. The main variables considered in this study were rainfall variations (dry, wet, and normal) and urban density (i.e., different number of units for each catchment). A sensitivity analysis was carried out to evaluate the effects of selected variables on the urban water cycle by conducting urban harvesting potential assessment. To represent dry and wet conditions during the last 53 years, 1973 (569 mm) was selected for dry and 2012 (1125 mm) was selected for wet as shown in Figure 3.32. In addition, introducing a hypothetical development, the scenario in which the urban density doubles (i.e., CA - 108 units and CB - 170 units, Table 3.29) the current Filton development plan was investigated.

Table 3.29. Number of units for each catchment used for the sensitivity analysis.

Type	Bedroom	Standard plan		Densified plan	
		CA	CB	CA	CB
House	2 bed	2	6	4	12
	3 bed	15	43	30	86
	4 bed	37	3	74	6
Apartment	1 bed	None	13	None	26
	2 bed	None	20	None	40
Total		54	85	108	170

3.2.3. Results and discussion

3.2.3.1. Urban water quantitative analysis

Daily water demand patterns

Figure 3.35 shows the average and standard deviation of the water demand patterns for each catchment. As expected, the standard deviations are larger for the YA commercial building than for the residential buildings in CA and CB. Pertinently, water demand patterns in a commercial building highly depend on the number of visitors and events. With this in mind, the peak time for water demand in the YA is between 10 am and 6 pm, which obviously differs from residential buildings as shown in Figure 3.35 (b) and (c). As expected, Table 3.30 shows that the YA consumes a significant volume of water through toilet flushing and hand basins (91.8 m^3/day and 34 m^3/day, respectively).

In addition, compared to CB, CA shows a larger variation in terms of water demand patterns. This is associated with the variations of water demand patterns for each house type (2-, 3-, and 4-bedroom household) in the CA (Figure 3.35). The comparison of the stochastic demand patterns shows that they are significantly influenced by water use appliances, household size, and family composition rather than the number of occupancies or houses. Specifically, Table 3.30 represents that the water demand flow for a 4-bedroom house in CA is the highest (10.89 m^3/day, 129.6 L/pp/day), followed by a 3-bedroom (4.09 m^3/day, 132.1 L/pp/day), and a 2-bedroom (0.48 m^3/day, 119.4 L/pp/day). This is mainly attributable to the size of the household and thus the occupancy. For CB, the difference in water flows between apartments and households is significant, with 6.98 m^3/day (127.1 L/pp/day) for the apartment units and 15.64 m^3/day (131.4 L/pp/day) for the households. The main reason for this difference is the absence of baths in the apartment building units and the fact that the 1-bedroom apartment unit has only one bathroom. This highlights the importance of both the presence of water-based appliances installed in households and the users' water demand activities. These factors play a crucial role in being able to accurately estimate urban water harvesting potential (i.e., greywater production) in the study area.

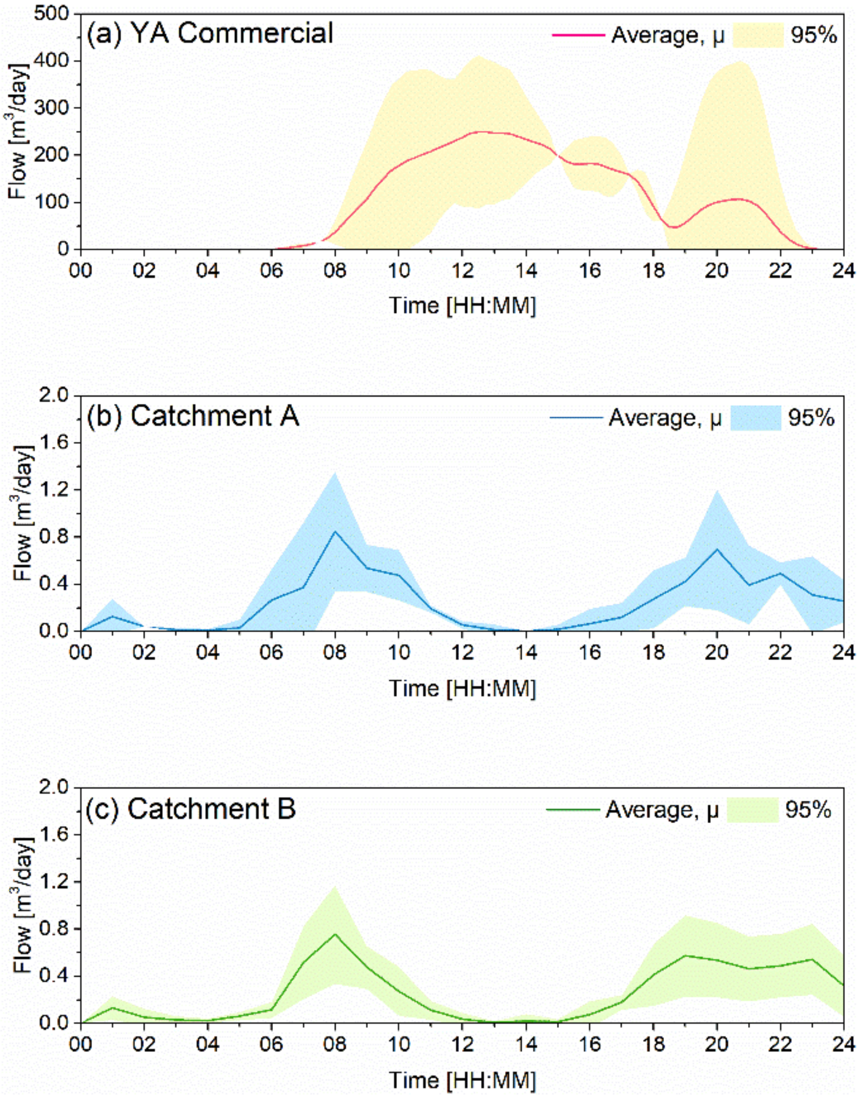

Figure 3.35. Hourly water demand flow - (a) YTL Arena (YA), (b) catchment A (CA), and (c) catchment B (CB) - obtained from SIMDEUM simulations.

Table 3.30. Water demand profiles for catchments, YTL Arena commercial building and catchments A and B (CA and CB) in the residential area.

Catchment		Type	WC+WM	BH+BT+SH	DW+KT+OT	Total (m^3/day)	Average (m^3/day/house)
YTL Arena		-	91.8 (WC)	-	34.0 (KT)	125.8	-
CA	House	2 bed	0.19	0.19	0.10	0.48	0.24
		3 bed	1.59	1.60	0.90	4.09	0.27
		4 bed	4.23	4.26	2.40	10.89	0.29
CB	Apartment	1 bed	0.88	0.89	0.28	2.05	0.16
		2 bed	2.12	2.14	0.67	4.93	0.25
	House	2 bed	0.73	0.73	0.41	1.87	0.31
		3 bed	5.02	5.06	2.85	12.94	0.30
		4 bed	0.32	0.32	0.19	0.83	0.28

*Total water consumption = Average water demand x Number of houses (shown in Table1).
*YTL arena - water use only for KT and WC.
*BH: Bath, BT: Bath tap, DW: Dishwasher, KT: Kitchen tap, OS: Outside tap, SH: Shower, WC: toilet flushing, WM: washing machine.
*Water consumption per capita per day (L/pp/day) is shown in Table 2 in Appendix.

Urban water management option assessment

This study evaluated urban water management options based on quantitative analysis of the water cycle in Filton using: (i) a hydraulic and economic assessment of RWH and (ii) urban water harvesting and its potential.

Rainwater harvesting

Figure 3.36 shows the hydraulic and economic performances of RWH with different rooftop catchment surfaces. From the results, the most reasonable storage size was determined for each scenario for toilet flushing and washing machine. Figure 3.36 (a) shows the WSE of RWH system as a function of a storage capacity ranging from 1 to 2,000 m^3. For residential scenarios (R1-R3), R2 shows constant WSE values (100%) when the storage capacity went above 200 m^3. Meanwhile, the WSE for R1 and R3 reaches 100% at the storage size of 750 m^3. This indicates that the maximum storage capacity to obtain the highest possible WSE for residential applications is 200 m^3, meaning that the WSE values range between 70% and 100% for R1-R3. For the YA (C1) with a roof area of 13,000 m^2, the WSE ranges between 18% and 23%, showing significantly lower WSE values than the residential buildings. This is mainly because C1 requires a large amount of water within the building despite its huge catchment surface area (Table 2) and thus suggesting that the optimal storage size for this commercial building application would be less than 200 m^3. This demonstrates that a high WSE can be achieved with RWH where tank sizes are larger and where water demand is lower (Ali et al., 2020). However, as the catchment surface expands, the WSE is mostly controlled by water requirements (Ali et al., 2020; Silva et al., 2015). For the combined applications (RC1-RC3), when the storage capacity became 400 m^3 the WSE maintained at between 31% and 43%, depending on the water usage pattern. Specifically, at 300 m^3 RC1 shows the highest WSE (39%) and followed by RC2 and RC3 (33% and 32%). The difference between RC2 and RC3 is determined by the amount of harvested rainwater in CA being higher due to its larger catchment area compared to CB. Consequently, a tank size of less than 300 m^3 would be the optimal size for this application.

Figure 3.36 (b) shows the SCE of RWH across all the scenarios for non-potable water purposes. A higher SCE is observed where the storage size is larger and where there is a greater demand for RWH. In the various catchments and demand scenarios, the SCE of RWH increases when the storage size is between 1 to 800 m^3. However, the SCE of all scenarios becomes uniform when the storage size is larger than 800 m^3. More specifically, for residential reuse scenarios, an RWH system with a tank size of 200 m^3 can achieve an SCE of 41% (R2), 50% (R1), and 98% (R3), depending on the water demand. When the size exceeded 200 m^3 it remained constant, representing that water demand and catchment area have a significant impact on the SCE variations. This indicates that the water level of the tank captured through the system is limited by storage size (Li et al., 2010).

Figure 3.36 (c) further indicates the optimum size of RWH using the unit rainwater costs across the scenarios. The unit water cost decreases gradually as the storage size increases. After that, the unit rainwater cost surpassing the mains-only supply water cost of 0.50 £/m^3. The minimum value of the unit water cost indicates the most economically viable storage size, which stays lower than 0.50 £/m^3. At 100 m^3, the unit rainwater cost for C1 is 0.43 £/m^3. However, for combined use, the unit water cost is shown to be the lowest at a storage size of 300 m^3 for RC1 and 200 m^3 for RC2 and RC3. Besides, scenarios R1-R3 show much higher unit costs than the mains water cost regardless of storage size. The high rainwater cost is mainly due to the lower water demand, which leads to less rainwater operation thereby lessening the financial benefits gleaned from rainwater reuse. These economic results emphasise the importance of the water demand profile, which dictates the financial impacts of RWH systems (Hajani et al., 2014; Pavolová et al., 2019). A summary of the results obtained from this analysis can be found in Table 4 in Appendix.

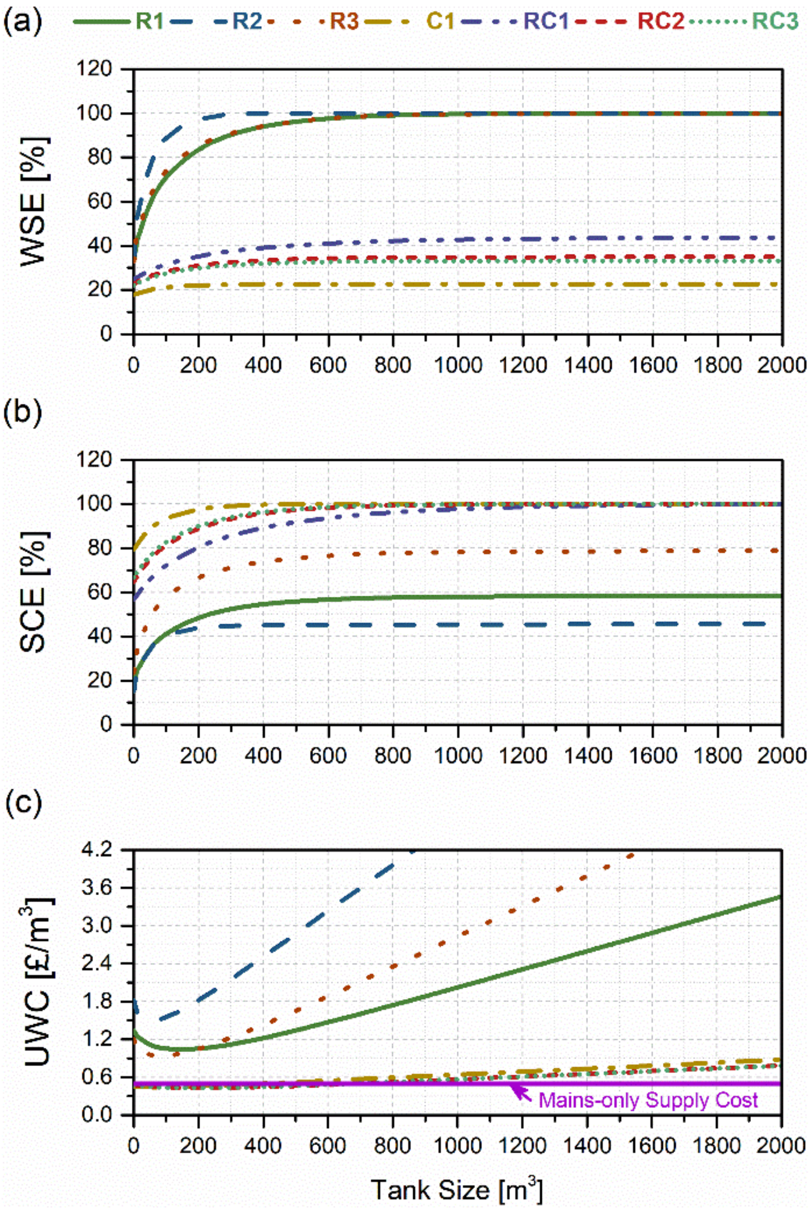

Figure 3.36. Effect of various storage capacity (1-2,000 m^3) on (a) water saving efficiency (WSE), (b) storm water capture efficiency (SCE), and (c) unit water cost (UWC). R: residential, C: commercial and RC: residential and commercial.

Urban water harvesting potential assessment

From the UWOT simulations, the quantities of water in the potable water, harvested rainwater, and reusable water were analysed. In Figure 3.37 (a), R1 consumes a water volume of 13257 m^3/year (128.7 L/pp/day), while water-saving appliances require 7896 m^3/year, thus representing a 40% reduction. In addition, for commercial and combined use, demand reduction sits at around 45%. For RC1, for example, the yearly baseline is 59299 m^3/year (143.5 L/pp/day) but with water-saving devices, it is 32758 m^3/year, thus representing a 45%

reduction. This water saving option is the most promising option as the water saving appliances have already been established and both the market and community are actively accepting them. However, since there is no recycling or reuse the WOI values are 100% for all options (i.e., all wastewater is discharged to a wastewater treatment plant), indicating a linear urban resource cycle (Leusbrock et al., 2015). Furthermore, the baseline provides information on the potential for wastewater discharge reduction for all scenarios. In Figure 3.37 (b), when considering GWR potential, the WOI and SSI values range from 56% to 60% and from 40% to 44%, respectively. This confirms that a recycling strategy simultaneously reduces wastewater outputs and improves urban sustainability.

In Figure 3.37 (c), for residential cases (R1-R3), harvesting rainwater from the roofs could improve both DMI and SSI ranging from 62% to 63% and from 97% to 99%, respectively. There is a marginal difference between scenarios. For cases with commercial only (C1) and the combined use for residential and commercial buildings (RC1-RC3), the DMI and the SSI are slightly higher than the results with residential use scenarios (R1-R3). The DMI values range between 73% and 76%, while the SSI values are between 95% and 98%, respectively. The difference between cases here is not significant. These results indicate that water demand profiles and the potential of harvested resources (rainwater in this case) are pivotal to the DMI and SSI values. This demonstrates that the implementation of RWH could make Filton more sustainable and self-sufficient.

However, the DMI and SSI results from Figure 3.37 (b) and (c) indicate that minimizing wastewater could be more beneficial with respect to improving self-sufficiency. In Figure 7 (c), the WOI values range between 133% and 265% due to overflow from the tank at a given storage capacity. In relation to this, scenarios R1-R3 show high REI values ranging between 31% and 103%. The REI values define the difference between resources harvested and water demand (Leusbrock et al., 2015). When the REI is higher than 0, there is a surplus due to higher rainwater harvesting but also lower water demand. Compared to other scenarios (C1 and RC1-RC3), rainwater reuse for residential buildings should be considered for other water-based activities such as car washing and irrigation, thus resulting in greater reduction in both REI and WOI. Figure 3.37 (d) includes the integration of RWH with greywater recycling. Moreover, harvesting and recycling two local resources result in the improvement of SSI values for all scenarios (≈100%). However, as expected, most scenarios show an increase in WOI and REI values. The WOI, in this case, range between 133% and 307%. Scenarios R1-R3 show higher REI values, ranging from 74% to 146%. Besides, RC1 increased from 0% to 10% when RWH with greywater recycling was integrated.

When the amount of the harvested rainwater and greywater for recycling is substantial, smaller storage tanks impede rainwater collection, resulting in more spillage and thus higher WOI (>100%). This highlights the importance of controlling both the overflow from the storage tank and the surplus from greywater recycling (Agudelo-Vera et al., 2013). Although using rainwater for drinking water application is still challenging due to it being cost-intensive and lacking in public acceptance, this would be an option to reduce the wastewater production caused by overflow and/or surplus. Therefore, controlling a storage capacity for harvesting and storing urban water resources for future recycling processes is crucial to ensure sustainable urban water management and better self-sufficiency in Filton.

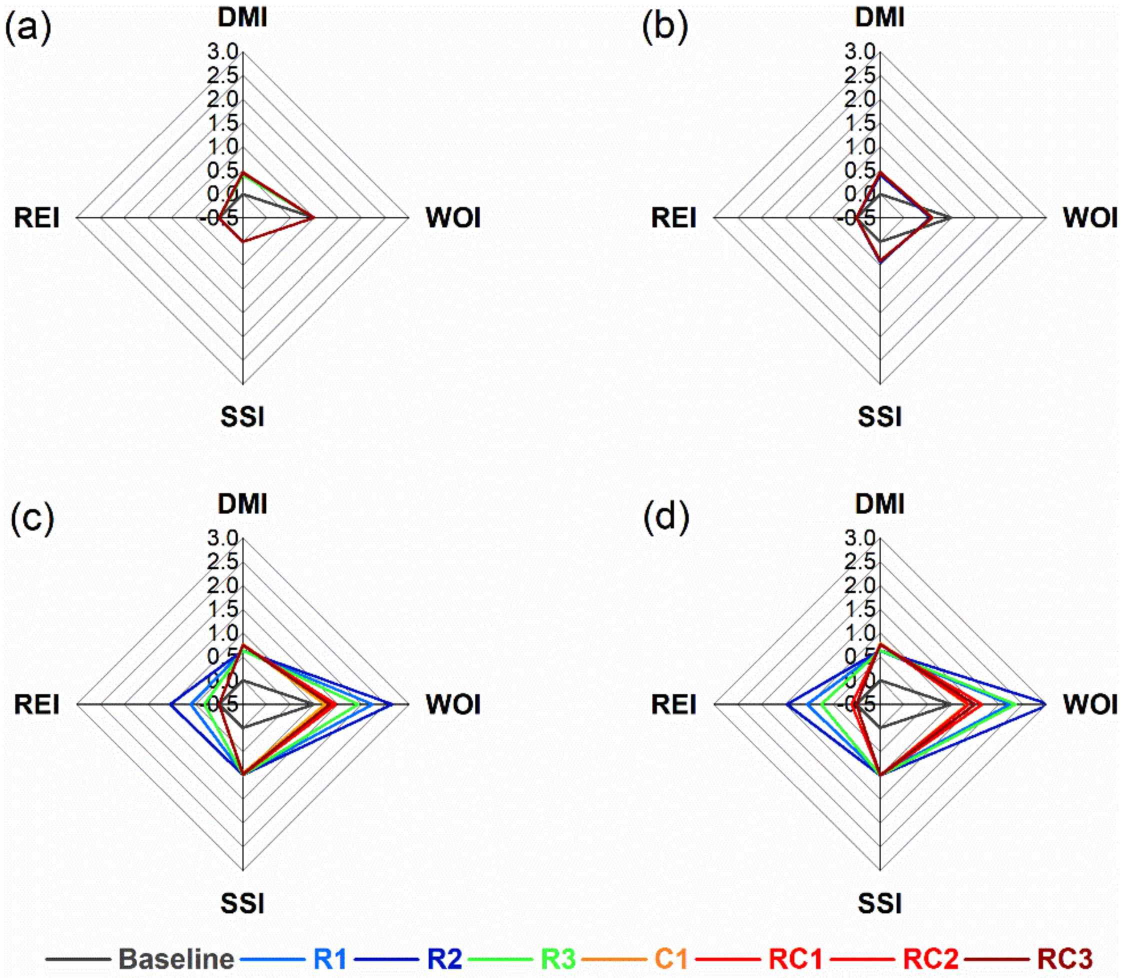

Figure 3.37. Visualisation of the evaluation results for the following sustainable strategies: (a) water savings; (b) wastewater minimization; (c) resource harvesting: rainwater; and (d) resource harvesting: rainwater and greywater using sustainability indexes - DMI: demand minimisation index; WOI: wastewater output index; SSI: self-sustainable index; and REI: resource export index.

Sensitivity analysis

A sensitivity analysis was conducted to assess the influence of different variables for selected scenarios, namely RC1 and R1. As shown in Table 3.31, a wet year leads to a much higher volume of harvested resources (RW+GW) at 44,951 m^3/day, compared to a dry year with 29,253 m^3/day. Likewise, for the densified plan, the harvested resources for RC1 are 32,689 m^3/year for a dry year and 48,387 m^3/year for a wet year. These differences are attributed to changes in water demand profiles and the quantity of local resources collected under the given scenario conditions. For both cases the quantity of water demand, resources harvested, and wastewater production increases with greater urban density. Using the results presented in Table 3.31, sustainable indexes were finally evaluated to assess the impacts of variables on urban harvesting potential.

Figure 3.38 shows the results of R1 (a and b) and RC1 (c and d). Overall, in both scenarios the maximum SSI values that can be achieved is 50% regardless of weather conditions and urban density. In terms of DMI, there were no changes with values for R1 constant at 40.4%. However, a slight decrease of 0.8% was observed when urban density increased for RC1, with 44.8% for the standard plan and 44% for the densified plan under the same weather conditions. Although the densified plan returns a lower DMI due to the increase in water

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demand, the drop is not significant for both R1 and RC1. This implies that DMI is more sensitive to the water user's behaviour and water-saving devices, rather than to the local conditions. However, WOI values are more sensitive to changes in precipitation than in population (standard and densified plan, Table 3.29). To illustrate this point, in wet conditions and under the standard plan, the WOI is extended further and reaches to 323% for R1 and 143% for RC1 (Figure 3.38 (b) and (d)). However, this value decreases when the urban density increases for both scenarios. As a result, WOI is more sensitive to rainfall but relatively less sensitivity to urban density. Although wastewater outputs and water demand increase in line with the population, a high SSI (≈100%) with low WOI (≈0%) would be achievable if the urban water cycle is balanced and managed by integrating RWH and GWR or even other local resources.

Table 3.31. Sensitivity analysis results for scenarios RC1 and R1 (Greywater + Rainwater)

			Baseline (Conv.)	Average Year	Standard Plan (S)		Densified Plan (D)	
					Dry Year	Wet Year	Dry Year	Wet Year
RC1	D	m^3/year	59,299	16,995	32,758	32,758	40,654	40,654
	Rh	m^3/year	0	29,787	29,253	44,951	32,689	48,387
	We	m^3/year	59,299	38,242	32,758	32,758	40,654	40,654
	Er	m^3/year	0	12,792	29,253	44,951	32,689	48,387
R1	D	m^3/year	13,257	7,896	7,896	7,896	15,792	15,792
	Rh	m^3/year	0	16,061	12,248	25,439	24,604	33,335
	We	m^3/year	13,257	17,639	16,761	25,491	25,010	33,740
	Er	m^3/year	0	8,165	4,352	17,543	8,812	17,543

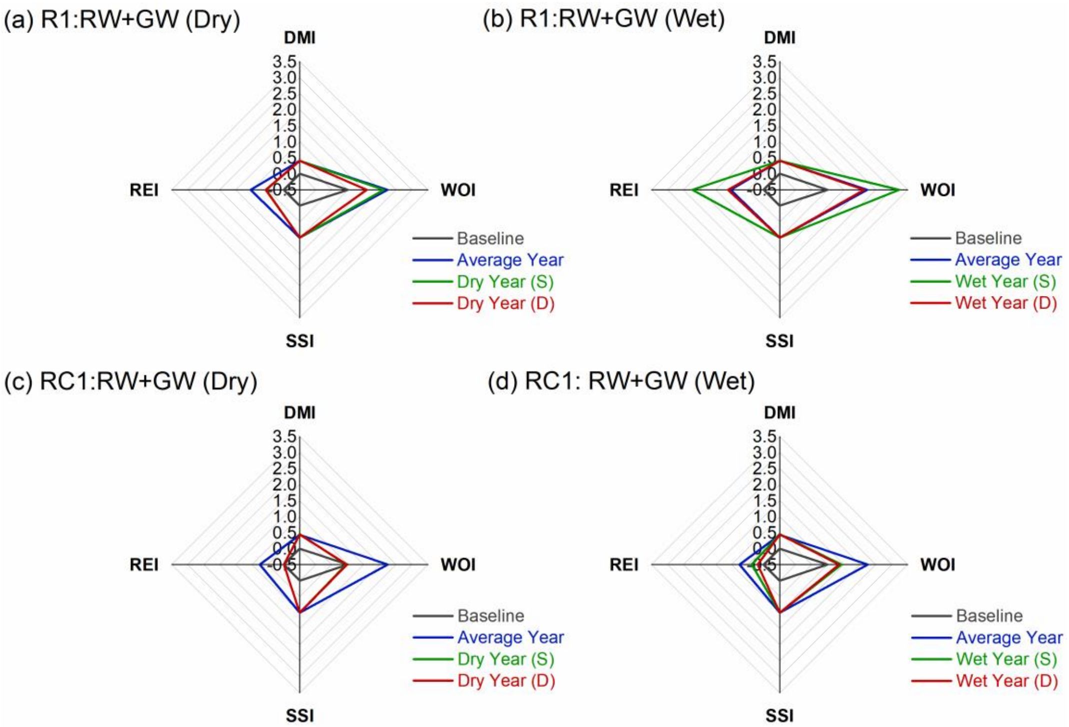

Figure 3.38. Sensitivity analysis - Effects of variations of climate conditions and population density on urban sustainability for the selected scenarios R1 and RC1. (a) and (b) refer to R1 with RWH and greywater recovery considering dry and wet conditions, respectively. (c) and (d) refer to RC1 with RWH and greywater recovery considering dry and wet conditions, respectively.

3.2.4. Conclusions

This study aimed to provide insights to improve urban resource management by integrating alternative water sources, including rainwater and greywater. The main findings to be drawn from the study are presented as follows:

- The physio-chemical and microbiological properties and metal content of bulk free-fall rainwater samples collected in the Filton site is acceptable for non-potable applications.
- The hydraulic and economic assessment showed that for residential applications (R1-R3), the storage size was between 50 and 100 m^3 while it was between 100 and 300 m^3 for commercial and combined uses (C1 and RC1-RC3).
- Under realistic variation in daily water demand patterns, demand minimization is the most promising strategy through which the external supply can be reduced. The results further confirmed the improvement of the DMI going from 0% to 78% and the WOI going from 100% to 56% due to additional water being supplied from the recycling of greywater.
- The combining greywater with rainfall showed the large potential of wastewater discharge (i.e., overflow from the storage system, WOI >>100%) if rainwater or greywater is not exported or if the storage size is limited. However, the WOI can be further improved by exporting the excess treated greywater to be applied for other non-potable uses such as car washing and irrigation.
- The sensitivity analysis showed that urban water harvesting and its sustainability are limited by greywater production and available rainfall. During a dry year, the water demand is greater, so the WOI is lower. Meanwhile, during a wet year, although higher urban density contributes to a significant reduction of wastewater output, the values are still similar to or higher than the results to have taken into account dry conditions with high density.
- The approaches of a stochastic end-use water demand profile simulation and the results obtained from urban harvesting potential assessment by integrating RWH and GWR for new residential developments can provide practical insights for decision-makers planning urban water harvesting in Filton Airfield and other places under development or that have a development plan.
- Although this research conducted a comprehensive scenario analysis on urban water management by considering water reuse for commercial and residential buildings in an area currently under development using more reliable and dynamic information, this study used default data within SIMDEUM due to the limitations of other specific input variables, including statistics on male or female, age, and hours worked, as well as the individual’s water usage habits (average number of toilet uses, average shower time, etc.).

CHAPTER 4

Deliverable D1.8

Sub-Task 1.3.1 Local heat and energy recovery from wastewater

This chapter was published as:

1. Evans-Gavhure, T.J., Modelling the potential of heat recovery from UK housing developments. MEng Research Project, University of Bath, 2021.

4. Closing the Energy Cycle

4.1. Low grade heat recovery potential

4.1.1. Introduction

In the UK 1.21 billion litres of domestic wastewater are discharged into sewers every day under dry flow conditions with an average temperature of 17.5 °C (Ali et al., 2019). Due to high the heat capacity of water, if 3 °C of cooling could be used for wastewater heat recovery (WWHR) it would be possible to generate 1.5 TWh of heat energy annually which would be 1.2% of total UK renewable energy generation in 2019 (ONS, 2021).

Due to the low grade of heat collected through WWHR, transforming it into electricity is not a viable option and it is instead used for heating. When collected outside of the home this energy is instead better used in a heat network/district heating which directly delivers hot water to a heat exchanger inside domestic buildings through a network of pipes (DBEIS, 2018). Due to the large percentage of domestic energy consumption which is used for heating the UK government does not believe that it will be able to meet its 2050 decarbonization target unless at least 18% of UK heat is distributed by heat networks from sources such as WWHR (DBEIS, 2018). To this end the UK government is providing £320m of investments and other incentives to support heat networks, making identifying locations at which WWHR may be implemented a priority.

There are already a number of commercially available WWHR systems that could be installed in gravity sewers (source – raw wastewater) and at a wastewater treatment plant (source – treated wastewater). WWHR installed in a sewer network fall into two broad categories: systems that line the walls of the sewer pipes and systems that pump filtered sewer water above ground into a separate heat exchanger unit (Nagpal et al., 2021). In the latter case there are additional costs involved in pumping and wastewater must be filtered before pumping to minimize blockages in the heat exchanger due to debris, but by having a more compact heat exchange unit in a more accessible location it is possible to clean the unit and minimize fouling.

In the Filton Airfield case, potential for recovering the heat from the sewers were explored. As sewer heat is low-grade energy, it cannot be transported over long distances, but could be re-used in the local area, for instance for heating of a swimming pool or a shopping centre. The Filton scheme, comprising mixed-use development will be well-placed to explore heat recovery options the size of the development will deliver sufficient energy to be used for space heating in schools or public buildings. Therefore, in the Filton Airfield case, a feasibility study of wastewater heat recovery potential was carried out and assessed its reuse for space heating and water heating via theoretical quantitative analysis (energy consumption reduction and energy bill savings). This study offers insights into the transferability of wastewater recovery and its local reuse in Filton Airfield.

4.1.2. Methods

4.1.2.1. *Study area description*

This study focused only on the sewage network of residential houses from the first stages of building of the Hangar District, consisting of 80 houses and an apartment block, namely the Navigator Building. These 80 houses can be broken down more specifically into 8 two-bed houses, 60 three-bed houses and 12 four-bed houses, and the apartment block is a mix of one and two bed apartments with a total of 33 apartments (Figure 4.1). Every house type was found to have one main bathroom, which contained an over-bath shower, a WC and a basin, as well as a separate WC. The wastewater from the kitchen of every house type came from a combination of the kitchen tap, dishwasher and a washing machine. The ensuites of each house type that had one were assumed to contain both a WC and a shower. All house types were also found to have an outdoor tap. The one and two-bed apartments did not have outdoor taps and only the two-bed apartments had ensuite bathrooms, with both having the same standard bathrooms as the house types. Both apartment types also contained the same kitchen appliances as the houses.

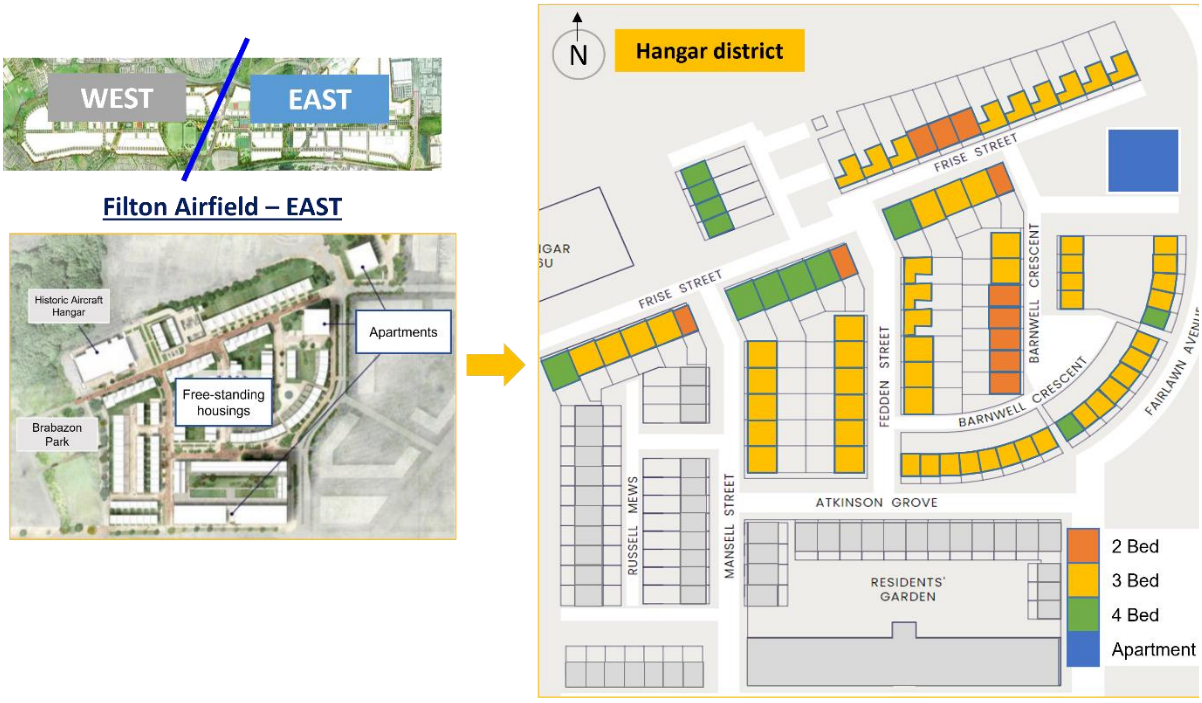

Figure 4.1. Map of the Hanger District development with different housing types adapted from YTL Developments Master plan. Housings with grey colour are not included for this study.

4.1.2.2. *Temperature data required for SIMDEUM*

Household wastewater discharge patterns and quality loading were generated using SIMDEUM WW®. The SIMDEUM WW can convert water demand patterns obtained from the SIMEUM® into wastewater discharges, including flow and temperature (Bailey et al., 2019; Bailey et al., 2020b). Through a review of relevant literature, appropriate input values for temperature used in this study are presented in Table 4.1.

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Table 4.1. Appliance-specific pollutant concentrations for improved SIMDEUMWW® (Bailey et al., 2020a; Bailey et al., 2020b).

Appliance	Temperature (°C)
Bath	36
Shower	35
Bathroom tap (BrTap)	40
Kitchen tap (Ktap)	40
Dishwasher (Dw)	35
Washing machine (Wm)	35, 35, 35, 45
Toilet (Wc)	20

4.1.2.3. Heat recovery potential

The potentially recoverable power (Q_{PR}) at a given time interval was estimated from the product of the wastewater flowrate (F_w), specific heat capacity and density of wastewater (c and ρ_{ww}), and the change in water temperature taking place due to the heat exchanger (ΔT_{HX}) as shown below in Equation 4.1.

$$Q_{PR} = F_W \cdot \mathrm{c} \cdot \Delta\, T_{HX} \cdot \rho_{WW}$$

Equation 4.1

The specific heat capacity was taken as 4.18 kJ kg^{-1} $°C^{-1}$ and the density of wastewater was assumed to be 1000 kg m^{-3} based on Funamizu et al. (2001), and the change in wastewater temperature due to heat exchange was the elevated temperature above 15.2°C capped to a maximum value of either 0.5°C to ensure no impact on downstream WWTPs, 2°C following the specifications given by Huber (2021), or 3°C as an optimistic best case scenario with current technology given by Ali et al. (2019). 15.2°C was chosen as the reference point as this was the value given by the Trust (2013) for the average main's water temperature in the UK and it is assumed that heat transfer from wastewater would be poor beneath this temperature.

4.1.3. Results and discussion

4.1.3.1. Discharge patterns

Figure 4.2 shows the flowrate at the network outfall. An average of 16,000 L was discharged into the network each day and the flowrate failed to meet the industry recommended 600 L/min (LPM). Figure 4.3 further shows the temperature of the wastewater in excess of 15.2 °C, temperature met target 55.6% of the time. The flow rates clearly showed periodic fluctuations. The minimum discharge appears after midnight while the maximum discharge occurs during the morning (Figure 4.2). The warm discharge starts to increase little before 6:00 am, reaching to maximum from 10:00 to noon (Figure 4.3). After midday, warm discharges drop, and no discharge occurs until late afternoon. This corresponds to the consumer's behaviour.

Stochastic flow and average wastewater temperatures could be quickly calculated at any node in the sewer network allowing for the comparison of multiple locations. These results allow a better approximation of continuous flow when the simulation output is averaged over multiple days and as the number of houses considered increases. By treating temperature as a material pollutant subject to exponential decay it is possible to model wastewater temperatures as being higher closer to their source, aiding comparison of different locations.

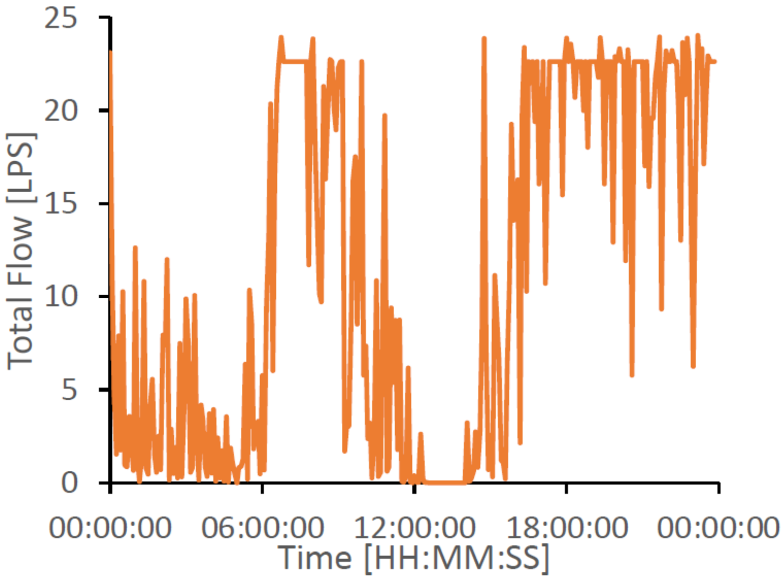

Figure 4.2 Total flowrate at the network outflow.

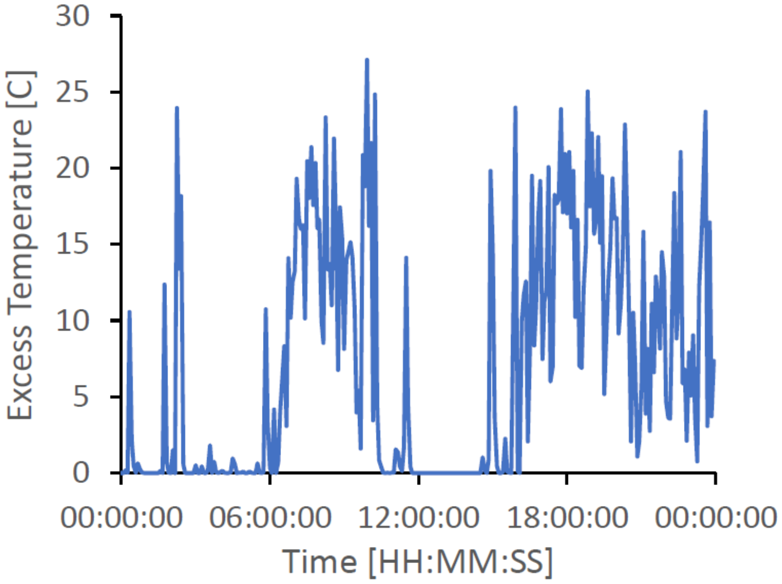

Figure 4.3 Temperature in excess of the average water mains temperature of 15.2 ℃ at the network outflow.

As many more appliances were added to households than were found present in any of the demo files packaged with the SIMDEUM software it was decided to investigate the impact of device frequency. This was done by creating new simulation data files, dividing the original appliance frequency of toilets, bathroom taps, and showers by the number of those appliances present in the house (i.e., 4, 4, and 3 respectively), and measuring the impact on flowrates and temperatures around node 1. on Figure 4.4. For bathroom taps the frequency of shaving was restored to “average” for each tap as otherwise the frequency of shaving would have been adjusted down by too much. This modification allowed for multiple showers to be in use at a single time, which could result in higher overall usage as each device has an

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independent minimum time between two uses (offset) but not to the same degree as multiple copies of an appliance would – importantly for the hydraulic model in general it allowed for higher peak discharge. Files for discharge patterns were selected to ensure that the same number of occupants (11) were present in both the original and reduced frequency scenario.

Figure 4.4 shows inflow at node 1. over a 24-hour period averaged over five days at the original appliance frequency and the reduced device frequency discussed earlier. Total inflow was found as shown in Table 4.2 below. As expected, the total inflow decreased with less use of devices, from 960 L to 638 L (33.5% reduction).

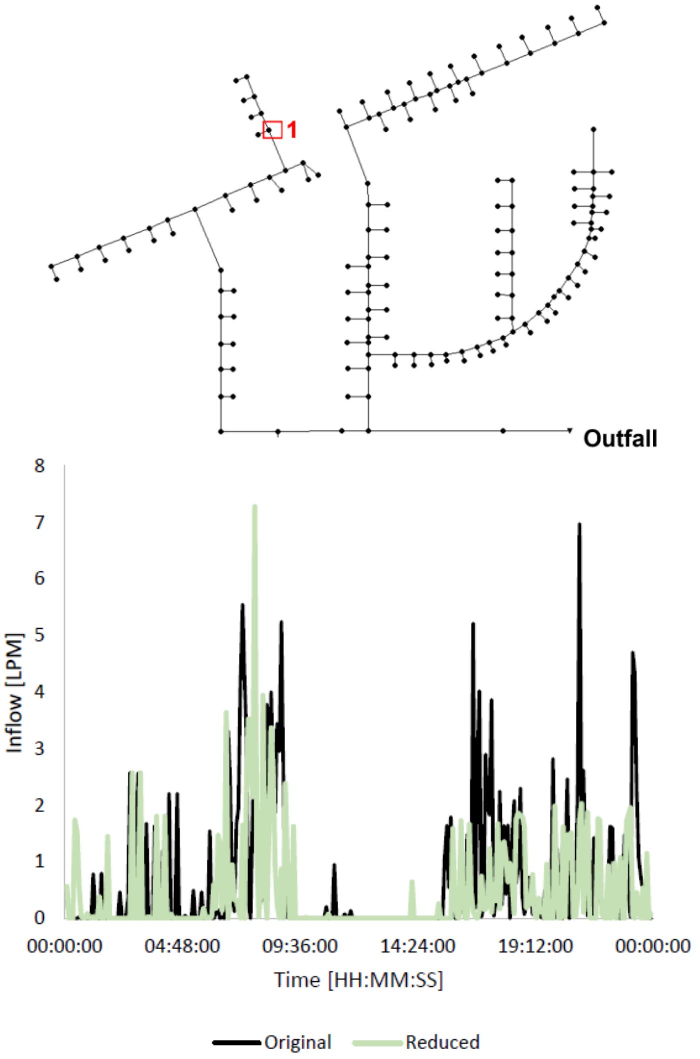

Figure 4.4 Inflow at node 1. averaged over five days with original and reduced appliance frequencies.

Table 4.2 Total inflow through Node 1. Over one day with original and reduced appliance frequencies.

Appliance Frequency	Total Inflow [L]	Total Inflow Per Person [L]
Conventional	960	87
Ecohouse (reduced frequency)	638	58

4.1.3.2. Recoverable heat potential

Figure 4.5 shows the maximum potential power recovery at the network outfall averaged over five days, under three assumptions of maximum cooling: 0.5, 2 and 3 °C.

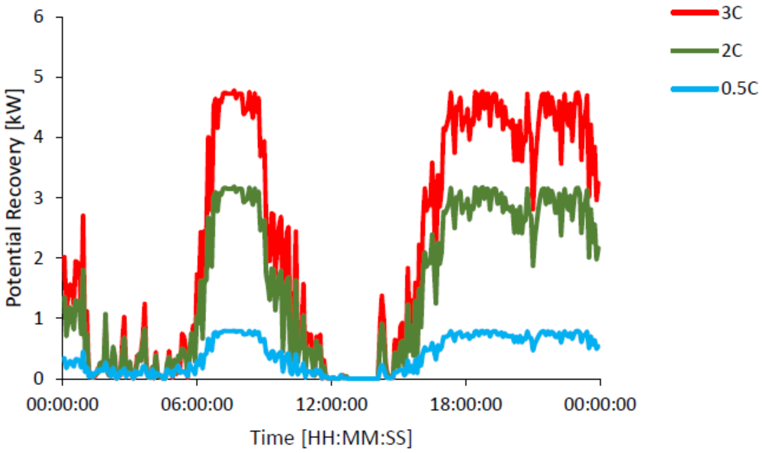

Figure 4.5 Potential recovered power at network outfall averaged over five days under three different assumptions of maximum useful cooling, 0.5, 2 and 3 °C.

The simulation produced satisfactory diurnal patterns that mirror results seen in sewers elsewhere: an initial peak following the morning followed by a lull due to people leaving their homes, followed by a more extended period of high flow in the evening. This can be seen in Figure 4.5 where heating demand precedes available power, although there is a base load not accounted for in this curve. Assuming an average occupancy of 2.4 for the 113 housing units modelled the total flow per person was approximately 60 L/day. When examining the node 1 (Figure 4.4). With a known number of upstream occupants, the average daily discharge was found to be 87 L/pp/day, which is 58% of the 150 L/pp/day UK average (Aquaterra, 2008). Reducing the appliance frequency of housing in proportion to the additional appliances led to an average 33.5% reduction in discharge to sewers, which suggests that the SIMDEUM model handles additional appliances well if they are of the same type.

Minimum flowrate for in-sewer WWHR systems not reached with maximum flowrates in the region of 24 LPM compared to the minimum of 600 LPM recommended by manufacturers, suggesting that any heat recovery station should be located further downstream. This is not surprising as Frank Oesterholt (2014) found that WWHR was not well suited for small housing projects of 50 homes and the first stage of the Brabazon development is not much larger. However, Hrabová et al. (2019) noted that in-sewer WWHR systems may be viable even on scales as small as 10 kW, which is only twice what was obtained at the network outfall under the assumption of 3°C during peak times. If the flowrates have been underestimated by a factor of 2-3 as discussed previously, a 10 kW WWHR system may be viable with adequate storage for heat recovered during peak times. Furthermore, as the heat recovery station can be sited within 500 m of the network outfall tested, this provides the possibility of including the region as part of a wider district heating system. In this context, the decentralised heat recovery unit demonstrated in Athens (NextGen case study in Greece, https://mp.watereurope.eu/d/CaseStudy/1) can be applied for heat recovery in Filton Airfield. For example, when treated wastewater after membrane bioreactor as a source of thermal energy, the system capacity ranged from 1 to 10 kW. In addition, the coefficient of performance of the heat recovery system for heating mode was between 4.0 and 5.83. For this application, it has been shown that the system has minimal biofouling risks. Therefore, the implemented heat recovery solution in Athens can effectively work in Filton Airfield, which can promote the spread and acceptance of thermal energy recovery solutions. Such thermal energy recovery solution can make possible the use of commercially available heat recovery system, which can accelerate the acceptance of the technology.

Table 4.5 further shows that the total energy demand for the study area was estimated to be 463,300 kWh/y and followed by 293,800 kWh/y for space heating and 101,700 kWh/y for water heating. Theoretically, if above daily discharge is cooled by 0.5, 2 and 3 degrees for heat recovery, for baseline (conventional house) it is possible to recover 6,465, 25,859 and 38,788 kWh/y and for ecohouse 2,915, 11,659, 17,488 kWh/y (
Table 4.6). Although there is a concern in relation to temperature drop below the legal limit (WWTP inlet ≥ 10 °C (Ali et al., 2019)) after more is extracted, it was assumed that the presence of a densely populated area downstream can keep temperature above the legal limit.

The results obtained from this study show that residential area with conventional houses could recover more energy due to higher wastewater discharges. For example, the total heat recovery potential is shown to be 7.85**%** and 3.54**%** for baseline and ecohouse, respectively. This indicates that the impact of wastewater flow rates is significant to recover thermal energy from wastewater. As shown in Figure 4.5, potential recovered heat at network outfall exhibits diurnal pattern like wastewater and temperature. When wastewater discharge flow is maximum so is the temperature and hence heat recovery potential, occurring in two peaks (early morning and late afternoon and evening). This periodic changes in recovered heat suggests that thermal energy storage should be considered at plan and design stage so that energy can be recovered and stored when it is available and collected for reuse from the storage when there is demand.

Table 4.3 Contribution of each activity consuming energy in a household unit to the total energy consumption (averaged from 1970 to 2020 in the UK using dataset obtained from Parker (2021)).

Energy use	% household energy contribution
Space heating	**62.1%**
Water heating	**22.0%**
Cooking	3.9%
Lighting	3.1%
Appliances	8.9%

Table 4.4 Baseline KPIs - Historical average energy consumption in Bristol, Southwest, UK (2005-2020) (BEIS, 2021).

	Mean (kWh/year/unit)		
Bedroom type	**Total**	**Space heating (62.1%)**	**Water heating (22.0%)**
1	3,100	2,000	700
2	3,700	2,300	900
3	4,200	2,700	1,000
4	5,300	3,300	1,200
Average	4,100	2,600	900

Table 4.5 NextGen KPIs - Estimated energy consumption and energy bill in Filton using historical energy consumption in Bristol, Southwest, UK (2005-2020) (BEIS, 2021).

Demand	Energy consumption (kWh/year)			Bill (£/year)		
	Total	Space heating	Water heating	Total	Space heating	Water heating
Total	463,300	293,800	101,700	83,950	53,237	18,428

*Southwest – 18.12 pence per kWh

Table 4.6 Estimation of theoretical heat recovery potential and energy savings under different NextGen scenarios.

		Units	Value
Scenario 1 – Conventional house			
Heat recovery potential		kWh/year @ 0.5 °C	6,465
		kWh/year @ 2 °C	25,859
		kWh/year @ 3 °C	38,788
Energy saving potential	Total saving	% @ 0.5 °C	**1.31**
		% @ 2 °C	**5.23**
		% @ 3 °C	**7.85**
	Space heating	% @ 0.5 °C	**2.20**
		% @ 2 °C	**8.80**
		% @ 3 °C	**13.20**
	Water heating	% @ 0.5 °C	**6.36**
		% @ 2 °C	**25.43**
		% @ 3 °C	**38.14**
Scenario 2 – Ecohouse			
Heat recovery potential		kWh/year @ 0.5 °C	2,915
		kWh/year @ 2 °C	11,659
		kWh/year @ 3 °C	17,488
Energy saving potential	Total saving	% @ 0.5 °C	**0.59**
		% @ 2 °C	**2.36**
		% @ 3 °C	**3.54**
	Space heating	% @ 0.5 °C	**0.99**
		% @ 2 °C	**3.97**
		% @ 3 °C	**5.95**
	Water heating	% @ 0.5 °C	**2.87**
		% @ 2 °C	**11.46**
		% @ 3 °C	**17.20**

4.1.3.3. Considerations for future work

Simulation accuracy - Data Collection

Much of the data used in this report will soon be able to be updated due to the 2021 census. Specifically, washing machine penetration and household occupancy can be updated shortly. Diurnal patterns for weekends can be found using the same dataset as was used to find weekday patterns and should be used to give a more accurate picture of flow patterns. There are still some discrepancies between the demographic groups used within the SIMDEUM and those in the data collected by ONS (2021) which might be useful to resolve, but these are a minor concern relating to the definition of children aged 17-21.

Simulation accuracy - SIMDEUM

Updating the frequency of appliance usage is a high priority as demonstrated by the four-household test case, but more research will be required to find how additional appliances change the frequency of use in real cases. As Blokker et al. (2017) advises, it would be wise to update other demand to match the British context as the system was calibrated around Dutch water usage. Currently there is an issue with how SIMDEUM handles washing machine cycles that start near the end of a simulated timespan, causing the simulation to fail. The likelihood of encountering this error increases with the number of days and houses simulated, which

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limits the tool’s ease of use. SIMDEUM does not generate single parent households or households made of more than two adults with no children, with single parent households accounting for 14.9% of family households (Statistics, 2020). SIMDEUM cannot switch between weekday and weekend demand patterns. Although it is possible to combine the output created by two different demand patterns there will be slight inconsistencies due to the randomly generated household composition so that a house that is simulated as having four occupants during the week would only have one at a weekend or vice versa.

Heat recovery technologies

Commercially available WWHR systems that could be installed in gravity sewers fall into two broad categories: systems that line the walls of the sewer pipes and systems that pump filtered sewer water above ground into a separate heat exchanger unit (Dürrenmatt et al., 2014). Figure 4.6 shows the basic units of these two kinds of WWHR system configurations.

In the latter case there are additional costs involved in pumping and wastewater must be filtered before pumping to minimize blockages in the heat exchanger due to debris, but by having a more compact heat exchange unit in a more accessible location it is possible to clean the unit and minimize fouling (Nagpal et al., 2021). There are three potential locations at which WWHR may be implemented in the residential context: inside individual households (in-drain), in the sewers those households discharge to (in-sewer), and in the wastewater treatment plants (WWTP) responsible for handling the effluent. Table 4.7 shows examples of WWHR systems using two wastewater sources – raw wastewater and treated wastewater. In-drain and in-sewer WWHR is advantageous in that it requires the smallest minimum capital investment and that it recovers energy where temperatures are both highest and closest to the point of demand, but it is limited by the intermittent nature of the wastewater flowrate that makes energy less likely to be available when needed without investment in storage capacity. While all WWHR must deal with high amounts of fouling, in-drain systems attached to cleaner units like showers may be less vulnerable and cleaned more regularly as part of household maintenance (Nagpal et al., 2021). Conversely, recovery at WWTP has a high and consistent flow of wastewater as well as better fouling characteristics due to the removal of biological material (Elías-Maxil et al., 2014) but suffers from being far away from domestic demand for energy and a lower average temperature of wastewater. In-sewer WWHR is predictably the intermediate position between in-drain and at WWTP, as summarized in Table 4.7.

Table 4.7. Examples of wastewater heat recovery applications

Source	Location	Arrangement	Heat pump capacity/COP	Purpose	Scale	References
Raw wastewater	Mülheim, Cologne, Germany	In-Sewer	150 kW	Heating	Pilot	(Perez et al., 2016)
	Wahn, Cologne, Germany	In-Sewer	200 kW	Heating	Pilot	(Perez et al., 2016)
	SinTec Technology Park, Singen, Germany	In-Sewer	200 kW + 243 kW/COP 3.5-3.9	Heating	Large	(Farman Ali et al., 2021)
	Lübeck, SchleswigHolstein, Germany	In-Sewer	147 kW	Heating	Small	(Farman Ali et al., 2021)
	Leverkusen, Germany	In-Sewer	170 kW	Heating + Cooling	Pilot	(Ali et al., 2019)
	Eco-district Nanterre, Paris, France	In-Sewer	2x400 kW/ COP 2.7	Heating + How water	Medium	(Dürrenmatt et al., 2014)
Treated wastewater	Postal office of Muelligen from Werdhoelzli STP Switzerland	Effluent at WWTP	5.5 MW	Heating + cooling, uses NH3, 65°C HW supply	Large	(Zogg, 2008)
	Whistler Athlete's Village, Canada	Effluent at WWTP	3.5 MW	Heating + cooling	Large	(Archer et al., 1997)
	Beijing Olympic Village, China	Effluent at WWTP	4x5.4 MW + 4x5.25 MW/COP 3.85	Heating + cooling	Large	(Shi et al., 2008)
	Suomenoja Espoo, Finland	Effluent at WWTP	2x20 MW + 2x30 MW/ COP 3.5	Heating + Hot water	Large	(Farman Ali et al., 2021)
	Katri Vala, Helsinki, Finland	Effluent at WWTP	3 × 30 MW + 2 × 30 MW, COP 3.5	Heating + cooling, uses R-134a, 88°C Hot water supply	Large	(Bailer et al., 2006)
	Kakola, Turku, Finland	Effluent at WWTP	2 × 10 MW + 2 × 30 MW, COP 3.3	Heating + cooling, uses R-134a, 78°C Hot water supply	Large	(Niemela et al., 2009)
	Ryaverket, Gothenburg, Sweden	Effluent at WWTP	2 × 50 MW + 2 × 30 MW, COP 3	Heating hot water	Large	(Farman Ali et al., 2021)
	Kalundborg, Denmark	Effluent at WWTP	10 MW, COP 3.6 to 4.0	Heating + HW, uses R-134a, 79°C hot water supply	Large	(Petersen et al., 2017)

In the frame of the Filton Airfield development, a decentralized and compact heat recovery system (i.e., in-sewer WWHR, a combination of a heat pump and heat exchanger) would be the best sustainable solution to increase self-energy efficiency. Within the NextGen project schemes, a commercially available heat recovery system (i.e., a hybrid heat pump and heat exchanger system) has been demonstrated at a pilot-scale in Athens, Greece (https://mp.watereurope.eu/d/CaseStudy/1). During the project, it has been successfully demonstrated and proved that

- ✓ Significant amount of thermal energy can be recovered from wastewater. More than 80% of the recovered energy can be used for heating and/or cooling while the remaining can be used for composting/nutrient recovery boosting.
- ✓ The system can be a decentralised solution which contributes to implementation of water, energy and nutrient circular economy.
- ✓ Although the system is sensitive to feed water quality, using highly treated wastewater (e.g., high quality effluent from membrane bioreactor) for energy recovery makes the process technically feasible and competitive.
- ✓ The demonstrated thermal energy recovery solution makes possible the use of commercially available heat pump equipment, which can accelerate the acceptability of the technology.

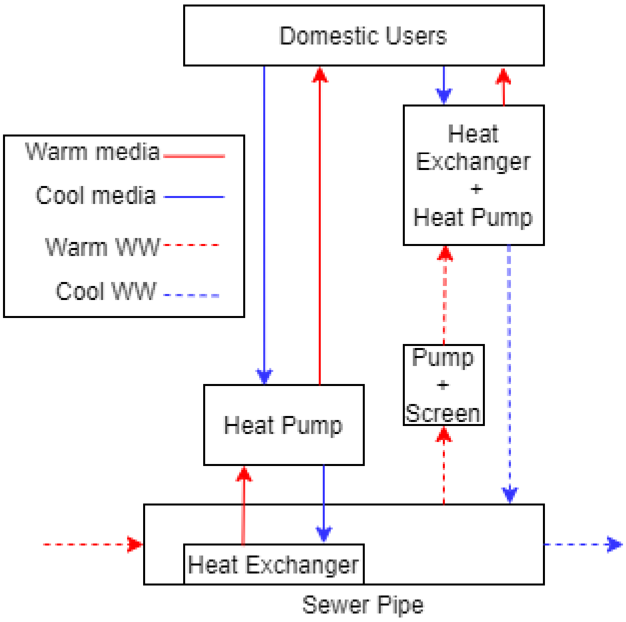

Figure 4.6. Two principal modes of in-sewer domestic WWHR (Vestberg, 2017).

Table 4.8. Overview of WWHR Location Properties (Nagpal et al., 2021).

Location	Temperature	Flow Characteristics	Fouling	Proximity to User	Capital
In-Drain	High	Low, intermittent	Lower	Immediate	Low
In-Sewer	Intermediate	Intermediate	Higher	Near	Intermediate
At WWTP	Low	High, consistent	Lower	Far	High

Heat storage technologies

As heat recovery is not met with demand for heat and follows a diurnal pattern that lags behind the pattern of discharge into sewers, systems which allow for recovered heat to be stored improve the value of WWHR systems (Ali et al., 2019). This is done by creating a body of warmer or cooler matter that can be used as heat source or coolant later, as other energy storage technologies such as latent heat storage and chemical energy storage are not economical with the large quantities of low grade heat obtained through WWHR (Welsch et al., 2018).

Ironically, water is a good medium for thermal energy storage for the same reason it is worth trying to recover low grade heat from wastewater: it has a high density, high heat capacity, and can be pumped. Water can be used to store heat either in a well-insulated tank or in underground aquifers (Hoekstra et al., 2020). Figure 4.7 shows the basic operation of aquifer thermal energy storage (ATES) systems, making use of both a hot and a cold well.

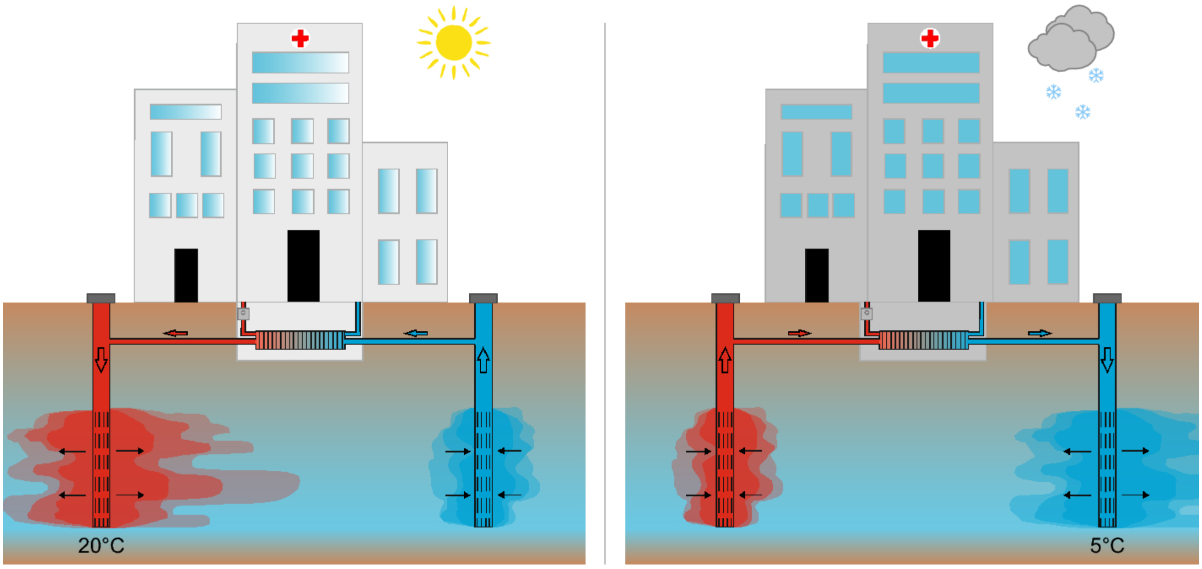

Figure 4.7. ATES working principle. Left: summer (extraction of cold, injection of heat). Right: winter (extraction of heat, injection of cold) (Schüppler et al., 2019).

When there is demand for cooling, cold water is pumped from the cool well and used in heat pumps or direct heat exchange after which it is injected into the warm water well at an elevated temperature (Schüppler et al., 2019). When there is demand for heating, warm water is drawn from the hot well, used in heat pumps, and injected into the cool well at a lower temperature. Depending on demand for either heating or cooling, water that has had its temperature changed by heat pumps during WWHR can be added to either well for long term storage, although in a domestic context in Northern Europe heating demand is likely to always outstrip cooling demand (Hoekstra et al., 2020; Schüppler et al., 2019). ATES is limited by the need for natural aquifers with high hydraulic conductivity, preferably with impermeable layers above and below the aquifer, and favourable water chemistry at high temperatures to minimize fouling at exchanger elements (Novo et al., 2010).

Within the NextGen project, the Westland demo case demonstrated an integrated approach for the regional evaluation of the conditions for implementing high temperature aquifer thermal energy storage systems (HT-ATES) to the overall sustainable thermal energy transition of the Westland area (https://mp.watereurope.eu/d/CaseStudy/12).

From the technical aspects, the regional potential of HT-ATES in the Westland region showed subsurface heat storage with long-term heat efficiencies up to 83% while subsurface cooling capacity with long-term cooling efficiencies up to 93%. More specifically, the currently expected number of geothermal wells combined with HT-ATES can meet about 5% of the heating demand of the horticulture cluster Polanen. These NextGen results have provided the technical data which could make a valuable contribution to its wider application including Filton Airfield. In addition, the gained knowledge can be transferred to increase applicability at other sites and overcome organizational and social acceptance barriers for implementing HT-ATES.

4.1.4. Conclusions

The main objective of closing the energy cycle in Filton Airfield was a feasibility study of low-grade heat recovery from wastewater and local reuse. Specific results drawn from the study are as follows:

- ✓ This study demonstrated that SWMM has great potential for modelling temperature in sewer networks through adaptation of its pollutant function, although minor modifications may be necessary to make this capability more accessible.

- ✓ The results showed that if the wastewater discharge is cooled by 3 °C for heat recovery, it is possible to recover up to 38,788 kWh/y (i.e., 7.85% of the total energy demand for the study area) for the residential area consisting of conventional houses, indicating that the total heat recovery potential is highly dependent on wastewater flow rates.

- ✓ In addition, a decentralized heat recovery system can be the best solution for Filton Airfield. In regard to this, it can be concluded that in-sewer WWHR is the most appropriate and sustainable option for implementing heat recovery in a residential context as it recovers energy where flow rates and temperatures are both highest and closest to the demand point. However, the diurnal pattern of wastewater requires heat storage systems/technologies to balance demand and supply.

While the technology required for recovering heat from sewers is well understood there are still many practical considerations including maintenance and economic viability which remain unclear, and it has not yet been implemented in the UK. This feasibility study conducted during the NextGen project will assist in evaluating the viability of in-sewer wastewater heat recovery in residential areas and demonstrate how to quantify the flow and temperature patterns of wastewater within the sewer network to estimate the energy available for recovery. Therefore, this will support the assessment of the heat recovery reliability from a real large sewer network over different weather conditions within a year.

CHAPTER 5

Deliverable D1.8

Sub-Task 1.4.9: Integrated recovery and use of nutrients at district level

This part was published as:

1. Hodgson, D., Dynamic sewer modelling how using water saving appliances affect nutrient concentrations in wastewater. MEng Research Project, University of Bath, 2021.

5. Closing the Materials Cycle

5.1. Nutrient recovery potential

5.1.1. Introduction

With cities continuing to grow it is important that effective sewer networks are designed, and existing networks are expanded to aid towards a sustainable future. One of the main differences between old and new sewer networks is the change from combined sewer networks to separated sewer networks, where household wastewater and stormwater are not collected together. In combined sewer systems, if the capacity is exceeded, combined sewer overflows (CSOs) can occur, where the excess wastewater is discharged into surface water, which can cause major ecological damage if events such as eutrophication occur due to the high levels of phosphorous and nitrogen in the wastewater. Separated systems therefore reduce the chances of environmental damage caused by CSOs whilst also reducing dilution of nutrients in the wastewater. In the wastewater only sewer system, the overall flow will be reduced as the only inputs into the system will be from connected households, and as water consumption is reduced due to water saving methods, the wastewater concentrations will increase. Increased sewage concentrations could lead to the potential of more effective water treatment as well as nutrient recovery.

Wastewater contains valuable materials, such as nutrients which can be recovered as fertiliser. Through the treatment of wastewater there is a potential to recover many useful nutrients and energy which could release the pressure on the world’s non-renewable resources. At the current rate of mining, phosphorus, which is mostly used for fertilizers in agriculture, could be completely drained by the end of this century (Research, 2022). By removing phosphorus from wastewater and using phosphorus recovery technologies in water treatment, over 20 % of the global requirement could be met (Carrillo et al., 2020).

The issues come since wastewater from the current sewer networks is extremely diluted, so nutrient concentrations are low which reduces the efficiency of nutrient recovery. By separating sewer networks between storm water and residential foul water, and by using water saving appliances in houses, the amount of water and therefore dilution in the sewer networks can be reduced, which would increase the efficiency of water treatment (Verstraete et al., 2011). In parallel, nutrient recovery reduces the likelihood of these problems while also improving water quality and meeting government discharge limits. Another advantage of nutrient recovery is it offers the potential revenue stream by providing nitrogen or phosphorus, a growingly scarce commodity, to agricultural businesses.

This study explored the potential for nutrients recovery within the new Brabazon housing development and the specific objectives are as follows:

- Produce a stochastic model of water discharge patterns and nutrient concentrations using a combination of the SIMDEUM tool (Blokker et al., 2017) calibrated to the UK population and the Storm Water Management Model (SWMM) (Gironás et al., 2010)
- Use the model to test the effect of equipping homes with water saving household appliances, including a water saving toilet, shower head and a waterless washing machine, on nutrient concentration profiles.

5.1.2. Methods

5.1.2.1. Study area description

This study considered the same area that selected for the energy recovery potential study as described in Section 4.1.2.1. As illustrated in Figure 4.1 of a map of the first phase of development housing with its sewer network, the study area includes 80 houses and a tower block containing 33 apartments.

5.1.2.2. Pre-set up for water saving appliance scenario

The same data and procedures were followed to simulate water demand (SIMDEUM) and wastewater discharge patterns (SIMDEUM WW and SWMM) as described in Section 2.4.

Water demand in households depends on the number of water-using appliances in the house, for example a shower, a bath, two toilets, etc. as well as the characteristics of the appliances, such as frequency of use, flow rate, duration of use and desired temperature. Depending on the user of the appliance, the duration and frequency can vary, for example a senior may flush the toilet more often than a teen whilst a teen may take longer and more frequent showers than a senior. Further to this, the duration, frequency, and desired temperature of the appliance can vary from appliance to appliance as well as the application of the appliance. These different applications can be added as subtypes of the appliance in the Watershare Tool, for example a bathroom tap may run hot water for shaving, but cold water for teeth brushing. Due to time constraints and the current unavailability of data in the UK situation, the installation and consumption input sections were taken from demo files provided by the SPG programme. It was therefore assumed that while there may be differences in the household statistics and the time budget data between the Dutch and UK situations, the use of appliances between the two situations is the same. Figure 5.1 shows some of the inputted data into the Watershare Tool for the Installation and Consumption section, taken from the demo_2014 file provided by the SPG.

For the normal household appliance situation there was no subtype for the shower, toilet or washing machine. However, for the water saving appliances situation subtypes were added to each of these appliances. For the toilets, a wcSavePlus subtype was added to each, for the washing machine, a waterless subtype was added and for the shower, a water saving shower head subtype was added. The water saving shower head reduces the flowrate of water, the waterless washing machine fills with less water and the SavePlus toilet fills its reservoir for

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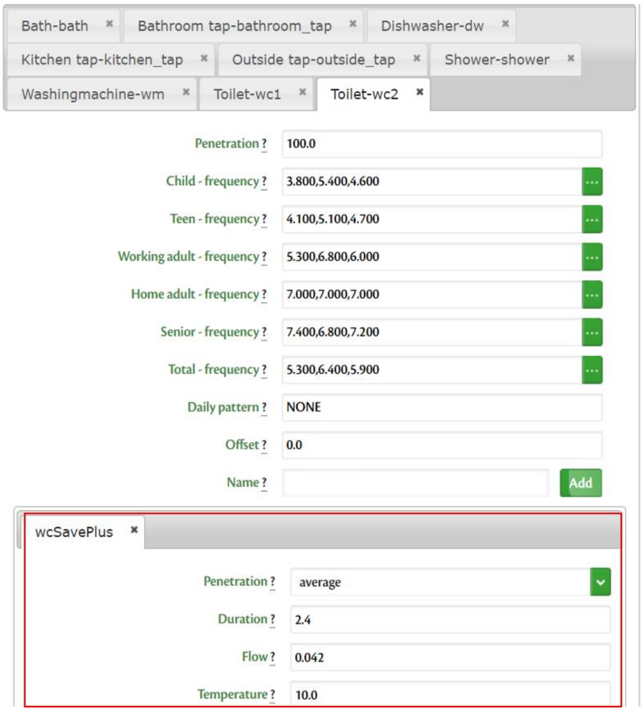
less time at the same flowrate, meaning a decreased reservoir volume and therefore less water into the sewer network per flush.



Penetration ? 100.0
Child - frequency ? 3.800,5.400,4.600
Teen - frequency ? 4.100,5.100,4.700
Working adult - frequency ? 5.300,6.800,6.000
Home adult - frequency ? 7.000,7.000,7.000
Senior - frequency ? 7.400,6.800,7.200
Total - frequency ? 5.300,6.400,5.900
Daily pattern ? NONE
Offset ? 0.0
Name ?

Penetration ? average
Duration ? 2.4
Flow ? 0.042
Temperature ? 10.0

Figure 5.1. Installation and consumption of Watershare Tool.

5.1.2.3. Wastewater discharge quality

The next stage was to input these discharge profiles for each house type into the SIMDEUM WW code to produce appliance-specific wastewater quality profiles. Appropriate input values for the pollutant discharges were found and are summarised in Table 5.1 (Bailey et al., 2020a; Bailey et al., 2020b). Discharge qualities may come from a variety of sources, for example, detergents, food scraps, human waste etc. These discharge qualities were added to MATLAB code as fixed input values. As the discharge qualities shown in Table 5.1 are in g·use^{-1} the code was altered to convert the concentrations into g·L^{-1}. This was done by taking the discharge profile and dividing it by the flowrate, measured in L·s^{-1}. The code in MATLAB was then run to produce .dat files of the water discharge quality patterns for each nutrient type and then each house type with either normal appliances or water saving appliances.

Table 5.1. Appliance specific pollutant concentrations.

Household appliance	Discharge Temperature (°C)	Discharge sewage quality (g·use^{-1})	
		N	P
Shower	35	0.49	0.00
Toilet	23	0.22	0.90
Kitchen Tap	40	0.35	0.03
Bath	36	0.85	0.00
Bathroom Tap	40	0.04	0.00
Washing machine	(35, 35, 35, 40)	0.64	0.00
Dish washer	35	1.35	2.04

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

5.1.2.4. Sewer network simulation

Using the files produced from SIMDEUM WW these stochastic household discharge profiles were integrated into the sewer network developed within SWMM, shown in Figure 2.9 in Section 2.4.4. Each house has a node which can be matched to a specific time series, e.g., a time series of flow rates or a time series of nitrogen and phosphorus concentrations. SWMM runs the wastewater quality model alongside the hydraulic model to produce realistic patterns. The concentration at every node is calculated for every time step, following the conservation of mass. It is assumed that the nodes are well mixed and there is no deposition or accumulation along the system. Dispersion along the conduits is also assumed to be negligible in SWMM and pollutants move through the conduits at a constant velocity. The SWMM simulation can then be run and the time series that results at the outfall for the 5-day period can be exported to Excel.

5.1.3. Results and discussion

5.1.3.1. Wastewater flow rate variations

Once SIMDEUM and SIMDEUM WW had been run using the calibrated model, the output files could be run in SWMM to produce time series data for the wastewater flowrate and the nutrient concentrations at the outfall. The simulation was run for a 5-day period for both the situations of using normal household appliances and water saving household appliances.

Figure 5.2 shows the wastewater flow rate ($L \cdot s^{-1}$) for both household appliance scenarios where NA is normal appliances and WSA is the water saving appliances. A clear diurnal pattern can be seen in Figure 5.2 with both morning peaks and evening peaks. The morning peaks are sharper while the evening peaks are more spread out. This is because people all tend to start work and school at the same time in the UK, around 9:00 AM meaning people tend to shower etc. around the same time before work or school. In the evenings people finish work or school over a larger range of times so the spread of when people are using the water consuming appliances is larger. People also tend to be awake and at home for more hours after work than they are before work, meaning they may use the toilet or taps more times, which explains the wider spreader in the evening peaks.

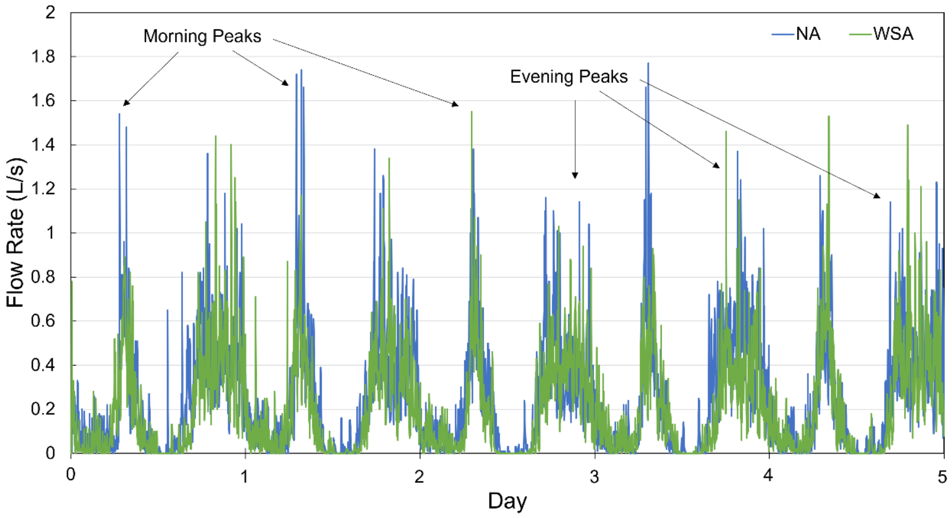


Figure 5.2. Wastewater flowrate at network outfall for a 5-day period. NA: Normal appliances, WSA: Water saving appliances.

In order to compare the effects of using water saving appliances compared to normal appliances, a period of 1 day was chosen to clearly demonstrate the difference, as can be seen in Figure 5.3, with day 1. A morning peak period of 6:30 AM to 9:30 AM and an evening peak period of 4:30 PM to 11:30 PM was chosen based on the data trends. As can be seen in Figure 5.3 the average flowrate over the morning period is 0.11 L·s^{-1} lower on average using the water saving appliances. This confirms the idea that using water saving appliances will lead to a lower flowrate of water into the sewer system and therefore dilution should be reduced.

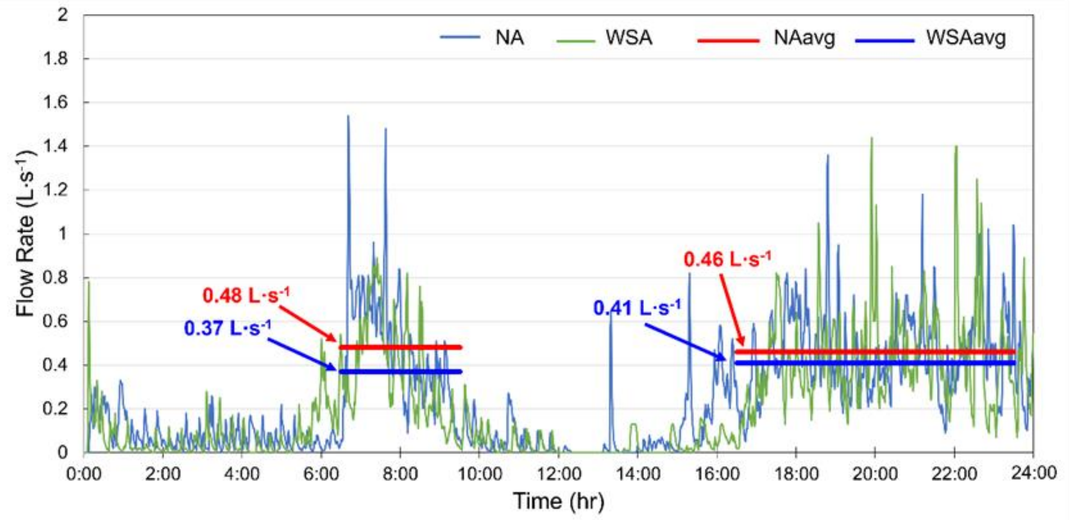


Figure 5.3. Flowrate of wastewater comparing normal household appliances and water saving household appliances. NA: Normal appliances, WSA: Water saving appliances. Morning - 6:30 am-9:30 am, Evening - 4:30 pm-11:30 pm.

These averages were calculated for each of the 5 days that the simulation was run for and compared to check the reliability of a stochastic model. Figure 5.4 shows the average flowrate over the morning period, comparing the normal appliances with water-saving appliances. Error bars are also shown on Figure 5.4.

As can be seen on Figure 5.4 the stochastic model holds true for each day, where the water saving appliances give a lower flowrate of water into the sewer network when compared with the normal appliances. The average flowrate for the whole 5-day period for normal appliances is 0.09 L·s^{-1} higher than for the water saving appliances. Each bar for days 1 to 5 also shows an error bar. This is because the flow rate for each day is different due to the random nature of the stochastic model. The SIMDEUM program gives random usage patterns to each household appliance which can mean, for example, on some days the toilet is flushed more frequently, which would lead to a higher flowrate into the sewer network. The trend does generally hold true, however, that the NA use more water than the WSA for days 1 to 4. On day 5 the average morning flowrate from the NA and the WSA is the same at around 0.48 L·s^{-1}, which can be explained by the random nature of the model.

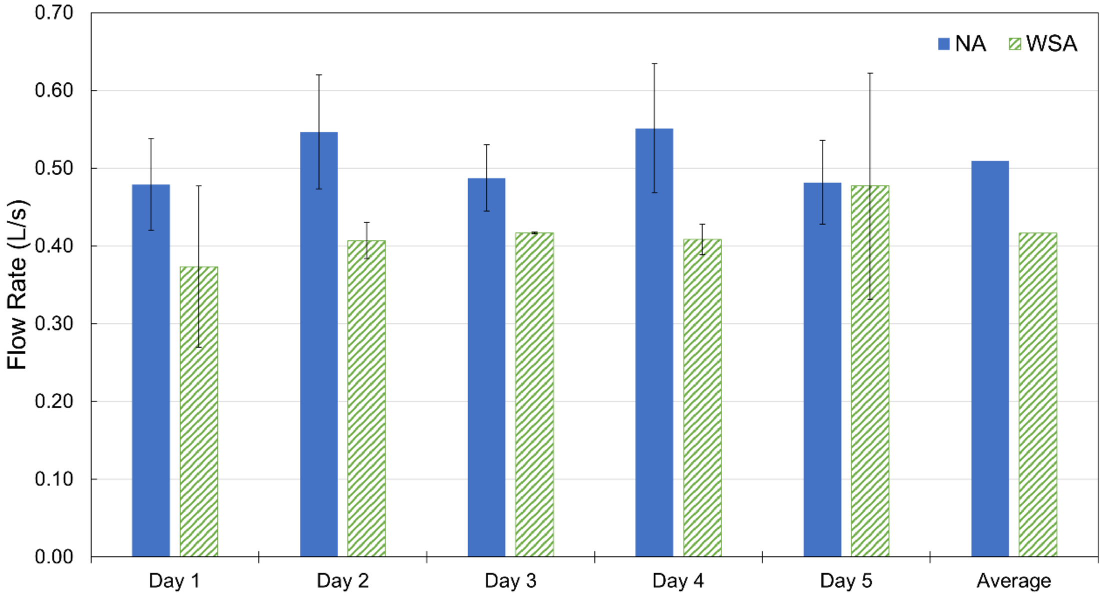


Figure 5.4. Average flowrate over the morning period (6:30 am-9:30 am) for each day. NA: Normal appliances, WSA: Water saving appliances.

5.1.3.2. Nutrient concentrations in wastewater

In order to observe the effects of the decreased flow rate using WSA on the nutrient concentration in the wastewater, the concentration time series produced from SIMDEUM WW were linked to each house type in the SWMM sewer network along with the flow time series and the simulation was run for the same 5-day period. This was done for nitrogen (N), and phosphorus (P) concentrations. The simulation results for the other nutrients can be seen in Figure 5.5 (a) and (b), respectively.

For example, Figure 5.5 (b) below shows the concentration of phosphorous at the outfall of the SWMM sewer network for the 5-day weekday period that the simulation was run for. As for the flowrate in Figure 5.2 the same diurnal pattern can be seen. The phosphorous concentration is higher when people are using the household appliances in the morning and evening periods, and phosphorus is being added to the wastewater system. The concentrations of other components present similar trend with the concentration of phosphorous.

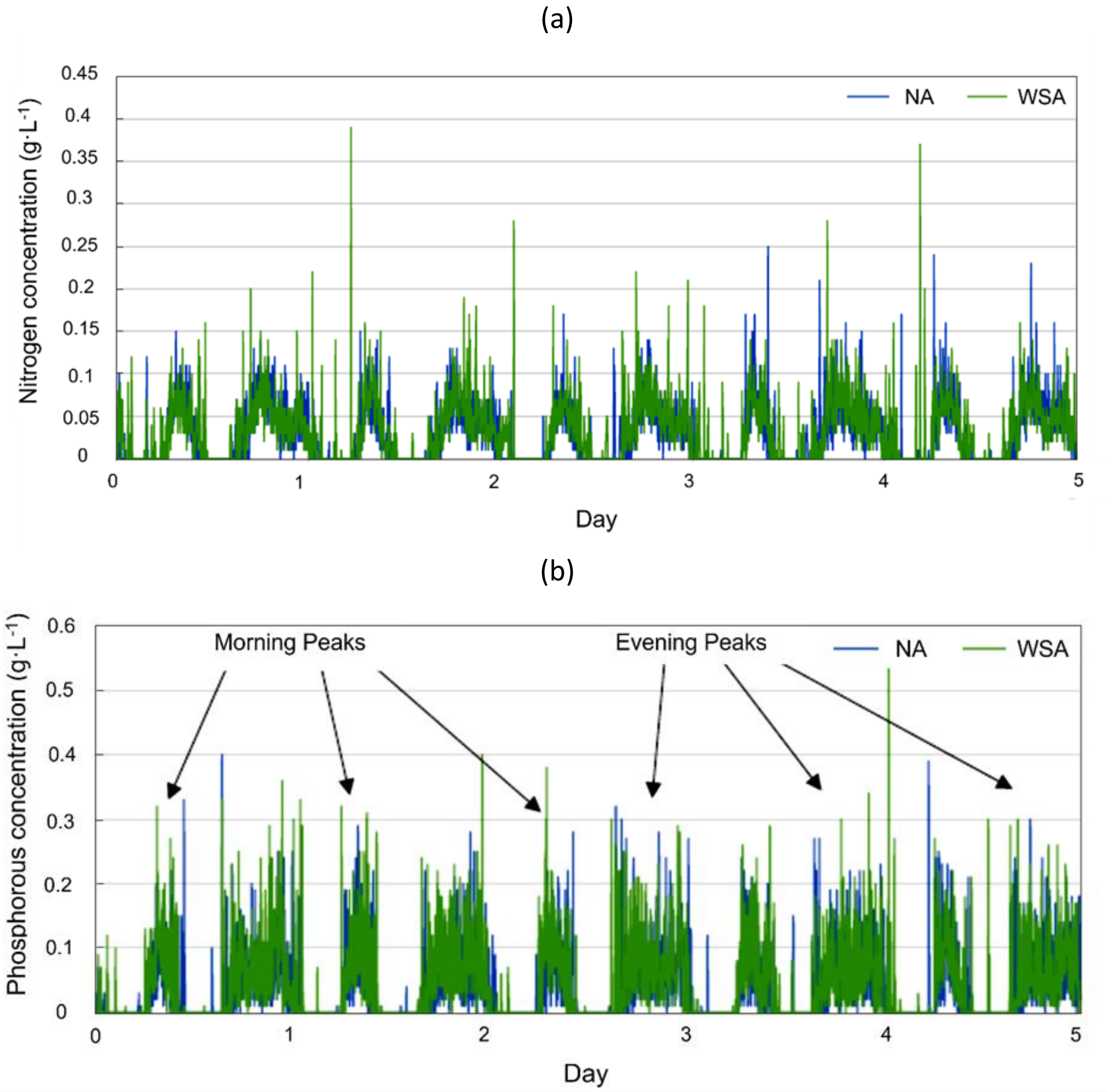


Figure 5.5. 5-weekday simulation results of (a) nitrogen, N, and (b) phosphorous, P. NA: Normal appliances, WSA: Water saving appliances. Morning - 6:30am-9:30am, Evening - 4:30 pm-11:30 pm.

The diurnal pattern can be clearly seen in Figure 5.5 with the morning peaks of phosphorous concentration, followed by very low phosphorus concentrations during the day when people tend to be away from home, and then a more widespread evening peak period where people are at home again and using water appliances such as the shower, and finally a very low concentration period when people are asleep and not using the water appliances before the next morning. Any peaks showing an influx of phosphorus in the wastewater during the night period could be explained by people going to the toilet during the night and then using soap to wash their hands afterwards, which adds phosphorus into the wastewater system and increases the concentration. In order the see the difference in concentration between using the water saving appliances and normal appliances, a single day has been analysed in more depth, as can be seen in Figure 5.6.

Figure 5.6 shows the phosphorous concentration at the outfall for day 1 of the simulation period. The concentration profile for normal appliances and for water saving appliances are both shown with the averages of the morning and evening periods directly compared. As can be seen for the morning period the average phosphorous concentration is 0.019 $g \cdot L^{-1}$ higher for the water saving appliances and is about 0.018 g·L^{-1} higher in the evening period. This confirms the prediction that the lower the flowrate of water into the system, the less dilution there is and the higher the nutrient concentration. With a higher nutrient concentration, the water treatment and nutrient recovery process will be more effective. The phosphorous concentration can be seen to fluctuate late into the night after people tend to go to bed, this may be due to some household appliances such as dishwashers and washing machines being run at night with phosphorus containing detergents.

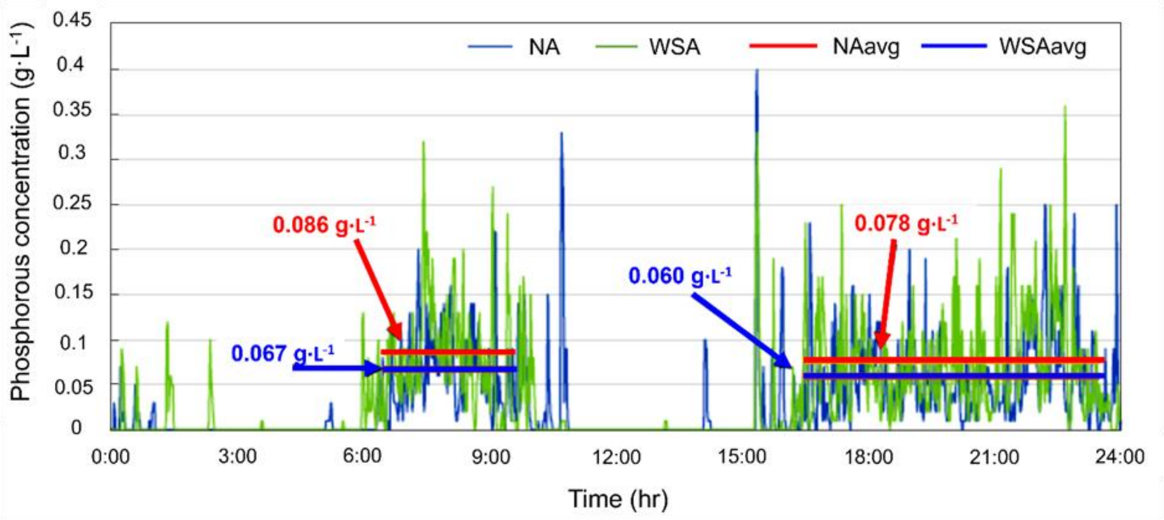


Figure 5.6. Wastewater phosphorus concentration comparing normal household appliances and water saving household appliances. NA: Normal appliances, WSA: Water saving appliances. Morning - 6:30 am-9:30 am, Evening - 4:30 pm-11:30 pm.

To check if this same trend holds true Figure 5.7 shows the average morning concentration for all 5 days of the simulation period, comparing the normal and water saving appliances. As can be seen in Figure 5.7 the phosphorous concentration in the wastewater is consistently higher using the WSA compared to the NA. On average, the phosphorous concentration using the WSA is 0.02 g·L^{-1} higher than with the NA, showing a 28% increase in the nutrient concentration of phosphorus. There is a degree of variance in the improvement from using the WSA. For example, for day 3 the concentration using WSA is 0.027 g·L^{-1} higher, whereas for day 5 the concentration is only 0.014 g·L^{-1} higher using the WSA. This confirms the randomness of the stochastic model used in this research.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

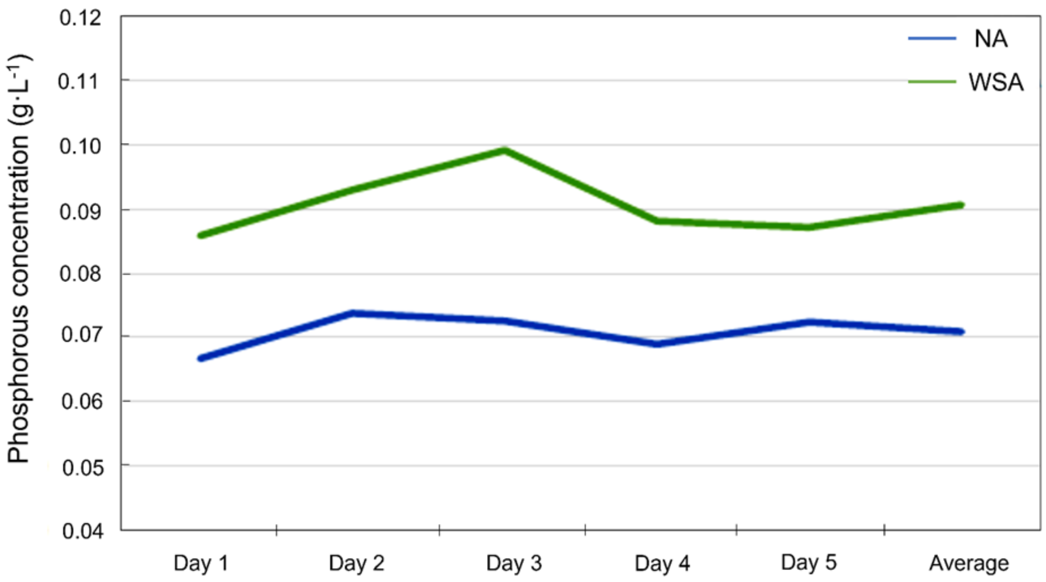


Figure 5.7. Average phosphorous concentration over the morning period (6:30 am- 9:30 am) for each day. NA: Normal appliances, WSA: Water saving appliances.

Overall, the WSA in this project resulted in an average flow reduction of 18.2% for the morning period (6:30 am – 9:30 am). This water use reduction resulted in increased average wastewater concentrations of P and N by 28.4% and 3.4% respectively. These percentages were comparatively low compared to the work of (Bailey et al., 2020b) and could be explained by the fact that in the research conducted by Bailey et al. (2020) five water saving scenarios were simulated, more than the 3 tested in this research. However, the results do follow the same relative trend.

Compared to the work of Pocernich et al. (1997) the concentrations found in these simulations were much larger, for example the phosphorus concentration for the NA scenario was in the order of 7 times the values presented in the work of Pocernich et al. (1997). One of the main reasons for this is due to the fact that there is not a lot of data presented for separated sewer network. Most previous data appear to be for combined sewer networks where the stormwater into the network leads to high levels of dilution. Therefore, it is clear from this work that using a separated sewer network drastically increases the nutrient concentrations and therefore will increase the effectiveness of nutrient recovery at treatment plants. Wastewater treatment plants will have to be extremely effective in removing most of the nutrients in order to reduce environmental impacts such as eutrophication caused by the increased nutrient concentrations. From the data presented here it is also clear that using WSA leads to higher concentrations in the wastewater which will also improve the effectiveness of the treatment plants.

Table 5.3 further compares baseline situation and Nextgen scenario. As explained earlier, baseline refers to the use of normal water-based appliances in houses (NA), while Ecohouse refers to the use of water-saving devices (WSA). As confirmed earlier, the wastewater flow rate decreased when using water-saving appliance. For the nitrogen concentration, for example, the changes varied from 52% to 61%, depending on the house type. In addition, for the phosphorus concentration, the changes varied from 27% to 42%, depending on the house type.

Since this study focused on a feasibility study on nutrient recovery potential at the district level and provided insight on how using water-saving appliances affects wastewater flows and nutrient concentrations, identifying viable resource recovery technologies is still challenging. This section offers benefits and challenges for determining wastewater-based nutrient recovery technologies across small- to large-scale systems.

- Determine an optimal design to utilise the nutrient recovery systems – "system size" (see also Table 5.2)
    - Small-scale systems
    - Medium-scale systems
    - Large-scale systems

- Utilisation of wastewater-based nutrient recovery systems
    - Three different locations: (a) inside the building, (b) inside the sewer network and (c) at a wastewater treatment plant precinct
    - Recovery methods: (a) urine source separation system and (b) water-less/composting/vacuum toilets

- Determine nutrient recovery technologies (Diaz-Elsayed et al., 2019)

Table 5.2. Benefits and challenges of different recovery technologies depending on scale and type of source.

Scale	Source/ location	System type	Benefits	Challenges
Small-scale	Household or building wastewater/on-site	Urine source separation and composting toilets or fertigation (reclaimed water with nutrients)	- High nutrient concentration - Reduces nutrient load on wastewater treatment plants - Local reuse - lower transportation costs	- Toilets would need to be retrofit in existing buildings - Extra pipelines (when separating urine) - High capital costs - Clogging and foul odour can occur - Social acceptance
Medium- and large-scale	Raw wastewater /at WWTPs	Fertiliser production (anaerobic digestion and dewatering)	- Reduces presence of nutrients in treated effluent - Slow release of nutrients compared to commercial fertiliser - Struvite production: concentrated fertiliser is produced with low hazardous metal content (below limits for commercial fertiliser)	- Close proximity to farmlands needed - Public opposition near residential areas - Risk of high concentrations of hazardous substances

The NextGen solutions cover centralised and decentralised material recovery technologies. Filton Airfield focused on nutrient recovery potential at district level to simultaneously explore the impact of wastewater volume on nutrient concentrations in wastewater and provide insight into a circular and sustainable water-nutrient circular solution. In this context, decentralized NextGen recovery technologies can be a more favourable way of ensuring the servicing nutrient recovery in the Filton area.

Among NextGen nutrient recovery technologies, the ion exchanger and the hollow fibre membrane contactors demonstrated in Spernal (UK) can be the most appropriate and sustainable solution to be applied to Filton Airfield. This is because the system is suited to be a decentralized system (i.e., local level) and the source of nutrient recovery considered for the Filton case is wastewater from residential buildings that are located close to each other.

Furthermore, there are NextGen technologies that recover nutrients from sewage sludge. However, only the rapid composting bioreactor demonstrated in Athens (Greece) is suited to be applied in a decentralized system. Therefore, an RCB system would be also considered a sustainable solution to improving circularity in Filton Airfield.

It has to be noted here that NextGen technologies that are centralised and utilise other sources (i.e., industrial wastewater or urine) would not be feasible for the Filton case due to the scope of the current Filton study. However, this would become a feasible solution if the scope of the Filton case study is extended to include a centralised wastewater treatment plant with a nutrient recovery technology being incorporated in the sludge line i.e., thermal treatment and pyrolysis.

Table 5.3. Impact of wastewater flow variations on nitrogen and phosphorus concentrations.

				Units	Total	Average	Comments
Baseline (Conventional house)							
Discharge flow rate	**Apartment**	1 bed	Flowrate	L/d	2706.9	208.2	* Study area - 1st Phase of construction - The Hangar District
		2 bed	Flowrate	L/d	5895.2	294.8	
	Free standing house	2 bed	Flowrate	L/d	4490.6	320.8	
		3 bed	Flowrate	L/d	24956.9	341.9	
		4 bed	Flowrate	L/d	14128.7	353.2	
	Total flow rate			L/d	**52178.2**	**303.8**	
Discharge sewage quality	**Apartment**	1 bed	TKN	mg/L	1381.9	106.3	
			TP	mg/L	52.0	4.0	
		2 bed	TKN	mg/L	2240.0	112.0	
			TP	mg/L	84.0	4.2	
	Free standing house	2 bed	TKN	mg/L	1440.6	102.9	
			TP	mg/L	53.2	3.8	
		3 bed	TKN	mg/L	8979.0	123.0	
			TP	mg/L	306.6	4.2	
		4 bed	TKN	mg/L	4588.0	114.7	
			TP	mg/L	176.0	4.4	
	Total TKN			mg/L	**5,985.7**	**111.8**	
	Total TP			mg/L	**211.1**	**4.1**	
Ecohouse: water saving devices (Impact of flow rate)							
Discharge flow rate	**Apartment**	1 bed	Flowrate	L/d	1271.5	97.8	
		2 bed	Flowrate	L/d	3166.8	158.3	
	Free standing house	2 bed	Flowrate	L/d	1903.6	136.0	
		3 bed	Flowrate	L/d	11293.8	154.7	
		4 bed	Flowrate	L/d	7242.2	181.1	
	Total flow rate			L/d	24877.8	163.7	
Discharge sewage quality	**Apartment**	1 bed	TKN	mg/L	3331.7	256.3	
			TP	mg/L	89.7	6.9	
		2 bed	TKN	mg/L	5693.1	284.7	
			TP	mg/L	144.0	7.2	
	Free standing house	2 bed	TKN	mg/L	3402.9	243.1	
			TP	mg/L	72.8	5.2	
		3 bed	TKN	mg/L	18646.4	255.4	
			TP	mg/L	438.0	6.0	
		4 bed	TKN	mg/L	9600.0	240.0	
			TP	mg/L	248.0	6.2	
	Total TKN			mg/L	**12,627.0**	**255.9**	
	Total TP			mg/L	**303.8**	**6.3**	
Change of WW flowrate and nutrient concentration	**Apartment**	1 bed	Flowrate	%	-53%		(-): Decrease (+): Increase
			TKN_change	%	+59%		
			TP_change	%	+42%		
		2 bed	Flowrate	%	-46%		
			TKN_change	%	+61%		
			TP_change	%	+42%		
	Free standing house	2 bed	Flowrate	%	-58%		
			TKN_change	%	+58%		
			TP_change	%	+27%		
		3 bed	Flowrate	%	-55%		
			TKN_change	%	+52%		
			TP_change	%	+30%		
		4 bed	Flowrate	%	-49%		
			TKN_change	%	+52%		
			TP_change	%	+29%		
	Total flow rate			%	**-52%**		
	Total TKN			%	**+53%**		
	Total TP			%	**+31%**		

5.1.3.3. Considerations for future work

Although the stochastic model developed in this study has shown promising diurnal patterns for wastewater flow and nutrient concentrations from households for a separated sewer network of a residential area, there are a few stages in the development of the model that could be improved upon.

Simulation accuracy - Data collection

A potential change in the future would be to find better calibration data. This could be done by surveying a sample of the UK population in the specific area where the sewer network is being developed in order to account for local habits in terms of water use. A large portion of the data used in this project for the installation and consumption section of the Watershare Tool was obtained from demo files which had been calibrated to the Dutch scenario. In the future, further research could be done on the appliances and the time they are used for in the UK scenario, for example, how often people shower and for how long. This could be done by performing surveys on a sample of the UK population.

Simulation accuracy – SIMDEUM WW

Another change that could be made in the future is to find more recent calibration data on the wastewater quality element of the model. Some of the nutrient discharge concentrations date back a few decades and with advancements in soaps and detergents it is likely that the pollutant qualities from these sources would have changed. With the availability of more time, further studies could be performed to find more recent information on nutrient qualities from household appliances. Another potential issue of the current form of SIMDEUM WW is that it uses average pollutant discharges per appliance. In reality each household appliance has the potential of producing a wide range of wastewater qualities, for example, people may use different detergents in clothes washing. To improve on the current form of the model it would be useful to be able to provide variable discharge qualities in SIMDEUM WW from each household appliance, improving on the stochastic model. A further improvement that could be made to the SIMDEUM WW code is to integrate weekend days into the code. At the moment only weekdays have been simulated and weekday diurnal patterns have been shown. Weekend time budget data is available however, for example, when people wake up and how long they are away from home for. By adapting the SIMDEUM WW code the weekend demand patterns could also be converted into discharge profiles. A final change that could be made in SIMDEUM WW is the usage pattern of the washing machine that sometimes produces errors when the code is run. This is an issue that also occurs when too many days are run in the code. Further investigation could be done to resolve this issue.

Future water use scenarios

The model does allow for more scenarios of water saving appliances and methods to be tested and this is something that could be looked into more in the future. For example, houses may use water saving dishwashers and aerated taps, which if the correct consumption data could be found, could be simulated in this model to observe the effects on wastewater flow and nutrient concentration. As well as this, there are likely to be changing in the future with advancements in household appliances, for example, more eco-friendly soaps become available, more houses have food grinders installed, and government regulations may change peoples' water use habits into the future, although this model allows for adaptations of these kinds.

Nutrient recovery technologies

Small/pilot- and full-scales of nutrient recovery technologies have been demonstrated in NextGen with different applications (i.e., wastewater and sewage sludge). In the frame of Filton Airfield development, decentralized nutrient recovery technologies can be more favourable rather than centralized nutrient recovery technologies. In this context, domestic wastewater and sewage sludge are the main sources for nutrient recovery. There are two potential locations at which decentralised nutrient recovery technologies can be implemented in the residential context: inside individual households (in-drain) and in the sewers those households discharge to (in-sewer). In NextGen, there are two decentralised NextGen technologies that have been applied to recover valuable nutrients from treated wastewater and sludge.

In Spernal (UK), an ion exchange (IEX) for nutrient ammonia and phosphorus removal and recovery and the hollow fibre membrane contactor (HFMC) has been demonstrated. In terms of the system operation and recovery efficiency, maintaining enough ammonium concentration is essential. This is because if its concentration is not high enough to produce ammonium sulphate it can be accumulated via an ion exchanger. However, it has high recovery rates of up to 90% ammonia and 90% phosphorous. In addition, upscaling the system is easy, and the system requires low maintenance costs with a small footprint. During the NextGen demonstration, for N recovery, 1.1 kg ammonium sulphate/d (influent flow 500 m^3/day) was produced as solid fertilisers. This corresponds roughly to 19.4 ton $(NH_4)_2SO_4$/year (i.e., 2.05 ton N/year) that might be expected from a full-scale plant (100,000 PE). For P recovery, 0.5 kg hydroxyapatite/day (influent flow 500 m^3/day) was produced. This corresponds roughly to 9.1 ton $Ca_{10}(PO_4)_6(OH)_2$/year (i.e., 0.28 ton P/year) that might be expected from a full-scale plant (100,000 PE). Technology fact sheet can be found in https://mp.watereurope.eu/d/CaseStudy/10.

Athens (GE) has demonstrated a downscaled, decentralized, controlled environment rapid composting bioreactor (RCB) unit to produce high quality fertiliser from locally available wastewater and sludge. Thus, findings and experiences gained during the NextGen project have provided a technical feasibility to recover nutrients and local reuse.

The RCB system with a sewer mining/wastewater treatment capacity of 250 m^3/day has been operated for 250 days per year for the vegetative period from March to early November. Thus, practically all the nitrogen and phosphorus contents of the sludge and pruning wastes can be fully converted into a high organic content material with slow nutrient release characteristics. From the systems' nutrient recovery perspective, 2.7 ton/year for nitrogen and 0.9 ton/year for phosphorous were produced. Benefits of the RCB unit include recovery of carbon and nutrients from excess sludge and pruning waste and elimination of enteric pathogens during composting. Most importantly, it can be a sustainable solution to replace conventional composting units due to its rapid composting time (i.e., five times faster). Furthermore, there is an opportunity to sell the compost, and this can fulfil the economic perspective for the local community or government. However, the system is cost intensive as a full automation of the process is required. Technology fact sheet can be found in https://mp.watereurope.eu/d/CaseStudy/1.

The decentralized NextGen recovery technologies that have been demonstrated in the Spernal and Athens cases can be more promising technologies of ensuring the servicing of nutrient recovery in the Filton area. It has to be noted here that NextGen technologies that are centralised and utilise other sources (i.e., industrial wastewater or urine) would not be feasible for the Filton case due to the scope of the current Filton study. However, this would become a feasible solution if the scope of the Filton case study is extended to include a centralised wastewater treatment plant with a nutrient recovery technology being incorporated in the sludge line i.e., thermal treatment and pyrolysis. To further disseminate the results, the deliverable *D1.5 New approaches and best practices for closing the material cycle* (Kleyböcker et al. 2022) and non-official deliverables per case study can be found through the Water Europe Marketplace in the case study section: https://mp.watereurope.eu/l/CaseStudy/.

5.1.4. Conclusions

A stochastic household wastewater discharge model has been developed in SIMDEUM and adapted through calibration methods to the UK population, in order to be related to the Filton Airfield case study of a new housing development near Bristol, UK. Separated sewer networks are better for the future of sustainability due to the reduced levels of dilution and lower risk of CSOs causing damaging environmental impacts, and therefore the model developed and demonstrated in this study is for a separated residential sewer network, although the modelling tool, SWMM, does allow for the ability of rainfall being added in a combined sewer network. Using time budget data this model gives accurate results on the effects of water-saving appliances on the flow rate and nutrient concentrations in the sewer network, following clear diurnal patterns.

During this Filton case study, the resulting nutrient discharge patterns could be implemented into the case study's hydraulic model to show the effects of water-saving appliances compared to normal household appliances. Specific results drawn from the study are as follows:

- ✓ By using water-saving toilets, water-saving shower heads and waterless washing machines, the flow rate of wastewater into the sewer network was reduced by as much as 28.7% with an average reduction of 18.2% for the morning period. Both morning and evening periods saw flow reductions although the morning period often saw the largest decrease in flow rate using the water-saving appliances.

- ✓ Using the stochastic nutrient profiles for household discharge produced in SIMDEUM WW, the pollutant concentrations were obtained from simulations in SWMM. The simulations were run for phosphorous and nitrogen. The phosphorous concentration in the wastewater increased by as much as 36.6% using water-saving appliances and increased by an average of 27.9% over the morning period.

- ✓ This allowed for the assessment of the effect of nutrient recovery in water treatment plants from the implementation of water-saving appliances in households. Due to the increased nutrient concentrations from the use of a separated network and water-saving appliances, nutrient recovery would be more efficient, which is necessary for a more sustainable future, especially when natural resources such as phosphorus are becoming extremely depleted in the natural world.

The reduction of water consumption and discharge from residential houses in urban areas has resulted in an increase in nutrient concentrations. In recent times and into the future, sewer networks are being designed as separated sewer systems, where there are two different pipes for stormwater and wastewater. In the future, households will change to water-saving appliances in order to conserve water in a more sustainable world, the effects of these water-saving techniques on sewer networks and wastewater treatment plants need to be understood in order for the design of the most efficient sewer networks that lead to the best levels of nutrient recovery. Thus, there will be more attention and opportunity to recover valuable nutrients from wastewater and its reuse.

CHAPTER 6

Deliverable D1.8

This chapter was published as:

1. Adeyeye K. et al., *D4.3 Challenges and opportunities across policy and regulatory frameworks*. May 2022. https://watershare.sharepoint.com/:b:/s/nextgen/EZkaJ8J95TlJlL0ArroGvrABlmNzKbohTq4zOwkGZgpqTw
2. Qtaishat, Y. et al. *Circular Water Economy in the EU: Findings from Demonstrator Projects*. Clean Technologies, 2022. 4, 865-892 DOI: 10.3390/cleantechnol4030054.

6. Social Benefits of Circular Technologies Relating to Water Use

6.1. Introduction

Work package 1 (WP1) of the NextGen project aims to demonstrate the feasibility of innovative technological solutions towards a circular economy (CE) in the water sector. With the goal of closing water, energy and materials cycles, several CE technologies have been implemented in demonstration cases in order to collect long-term data on system performances to assess their benefits and drawbacks. Deliverable 2.1 demonstrates the operational status of 10 demo cases deployed in 8 EU Member States and their specific NextGen objectives and CE solutions.

The Filton demo case is located at a former airfield in South Gloucestershire, north of Bristol in the UK. The site was recently bought by YTL, a large Malaysian company with global operations, including Wessex Water in the UK and YTL Developments (UK) Ltd who are developing the site into a district called "Brabazon". It has an area of 142 hectares and has outline planning for over 2,600 residential units and commercial buildings (YTL 2021). A masterplan has been approved, but further evolution of sustainable development ideas to implement the plan is required. The investment project (construction began 2018) includes a strategic Surface Water System (SSW), ensuring reliable drainage and allowing local use of captured rainwater and water reuse.

The CE technologies being considered include:

- Rainwater harvesting (RWH) – can be used for instance for landscape irrigation, toilet flushing, or in washing machines.
- Greywater reuse (GWR)[1]
- Heat recovery systems – from sewer water.
- Nutrient recovery from sewage.

The purpose of this paper is to consider the social benefits of these technologies, as opposed to the cost savings to households and businesses from use of the technologies, which have already been estimated for this deliverable for RWH (D1.8, Section 3.1). For each of the technologies listed above potential social benefits have been identified and, to the extent possible, quantified and valued based on applying existing non-market estimated values from other studies. This informs the wider aim of demonstrating how these values may be transferred to other circular technology contexts.

The broader context of this task is the need to capture social benefits in the assessment of circular technologies to enable a more comprehensive understanding of whether the costs incurred are likely to be justifiable. This is important because circular technologies are

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[1] Note that report D1.8 Section 3.2 considers a hybrid rainwater-greywater system. In this assessment we address RWH and GWR separately.

expensive and have an upward pressure on the price of properties, but when the social benefits of the technologies are not captured there is little scope for the house prices to be above normal market rates. Furthermore, estimation of social benefits of circular technologies can aid discussion with the policy community on the need to provide greater incentives for uptake (see Section 6.8 on Incentive Structures).

6.2. Rainwater Harvesting

6.2.1. Identification of social benefits

Based on a review of sources from organizations promoting rainwater harvesting (RWH)[2] and other relevant literature key proposed social/environmental benefits are summarized below. This excludes direct financial benefits to consumers, primarily cost savings from reduced mains water demand but also the potential for reduced flood insurance and savings resulting from reduced hardness of water (compared with mains supply), such as lower laundry detergent costs and extending the life of the appliances due to reduced scaling.

- *Flood risk reduction:* Water can be captured and held on site to significantly reduce the volume of water discharged to the main drainage system, thus reducing flood risk (Gunawardena et al, 2017). Load reduction can mitigate sewer overflows and decrease water pollution in storm events. Few studies focus on the efficiency of RWH systems in the retention of stormwater in flood-susceptible residential areas. The study by Freni & Liuzzo (2019) found the potential of RWH installation in the mitigation of flood risk is highly related to rainfall amount.
- *CO_2 reduction from mains water:* Replacing centrally supplied water use with RWH systems reduces the amount of water that a water company has to treat and pump to a property and therefore the energy requirements. The reduction in water demand from the mains infrastructure will therefore result in a reduction in the CO_2 embedded in that system. It should be noted that some previous reports (e.g., EA, 2010) have suggested that RWH systems emit more carbon than water supplied by the mains water network. However, recent innovations in design and components have reduced the energy requirements of RWH systems and thus overall carbon emissions. Consequently, more recent studies have shown the emissions associated with RWH to be lower than mains water (Fredenham et al, 2020).
- *Environmental benefits from reduced pressure on water infrastructure and reduced need for additional infrastructure:* RWH systems can help to alleviate the projected increase in water demand and thereby reduce the pressure on water infrastructure and related impacts on the environment. Less water will need to be taken from rivers, lakes and groundwater sources and more will remain within the environment maintaining flows and sustaining ecosystems. RWH systems also reduce the quantity

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[2] Innovative Water Solutions: The Many Benefits and Advantages of Rainwater Harvesting (watercache.com)
Renewable Energy Hub UK: Benefits of Rainwater Collection | The Renewable Energy Hub
Rainwater Harvesting Ltd: The Benefits of Rainwater Harvesting Systems – Rain harvesting Systems

of rainwater that is conveyed to centralised drainage systems providing benefits to the water infrastructure and the environment (Fredenham et al, 2020).

- *Improved water sources for gardens and landscapes:* Some sources promote RWH as a better source of water for plants, due to the minerals that are sometimes found in mains water, especially in hard water areas, raising the pH and affecting nutrient availability[3].
- *Increased awareness of water use:* Rainwater harvesting can help recognition of household water usage and thus encourage water conservation in other ways.

6.2.2. Quantification and valuation of benefits

As might be expected, much of the literature quantifying benefits of RWH systems focuses on direct financial aspects of water saving potential (The D1.8 Report Section 3.1.3.3 for this project includes an economic assessment in terms of the return-on-investment period). The literature review of valuation of benefits of RWH systems found rather limited studies with findings relevant and transferable for this case study (see Table 6.1). This was because in these studies social/environmental benefits were either (i) not included (e.g., Aheeyar & Bandara, 2010), (ii) included but not sufficiently defined or isolated per type of benefit (e.g., Tapsuwan et al, 2014), (iii) of limited relevance to the UK in terms of water scarcity/flooding context (such as studies in Australia (e.g., Tapsuwan et al, 2014) and Japan (e.g., Tsai & Onishi, 2022)) or (iv) they were not recent and may not have focused on the latest RWH technologies (e.g. Hall, 2012).

Based on the literature review this case study has used the findings of the Fredenham et al (2020) review of the costs and benefits of RWH and GWR options in the UK as a basis for tentative estimates of social benefits for RWH systems in the Filton case. The rationale for using this study is that it: (i) is UK focused and based on UK sourced data, where available, (ii) specifically defines the types of social benefits that have been valued, (iii) covers a more comprehensive range of social benefits than other sources and (iv) is recent and therefore better captures latest developments in RWH technologies.

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[3] See for example: Water: collecting, storing and re-using / RHS Gardening

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Table 6.1. Rainwater Harvesting: Selected Studies giving Non-Market Benefits.

Source	Title/theme	Location	Relevant results	Note on transferability
Amos et al (2018)	Economic Analysis and Feasibility of Rainwater Harvesting Systems in Urban and Peri-Urban Environments	Global with focus on Australia and Kenya	Review of studies on financial aspects of RWH systems found often conflicting results. Most economic analyses ignored the full benefits of RWH. Need to standardize methods of economic analysis of RWH systems.	Lack of focus on environmental benefits.
DeBusk & Hunt (2012)	Rainwater Harvesting: A Comprehensive Review of Literature.	Global	Includes environmental considerations but not quantified with a recommendation for further research.	Not recent and limited quantification.
Fredenham et al (2020)	Independent review of the costs and benefits of rainwater harvesting and grey water recycling options.	UK	RWH installations: Social (indirect) benefits (reduced demand on water infrastructure, CO2 savings and flood damage reduction) substantially increase total net benefits over a 20-year system lifetime, for all collection areas and demand requirements.	Key recent source for social benefits of RWH and GWR in UK, with social benefits estimated per type and size of building (see Tables in Summary).
Freni & Liuzzo (2019)	Effectiveness of Rainwater Harvesting Systems for Flood Reduction in Residential Urban Areas	Sicily, Southern Italy	Performance of RWH tanks to supply water for toilet flushing in residential area with high susceptibility to flooding. Results showed the potential of neighbourhood RWH installation in mitigation of flood risk is highly related to rainfall amount.	Recent study showing potential of RWH for flood risk reduction but limited transferability to Filton case.
Gunawardena et al (2017)	Review of non-market values of water sensitive systems and practices	Global but with focus on Australia (23% of reviewed studies)	Survey of literature on non-market benefits delivered through use of water sensitive systems and practices. Outlines type of studies available for different services (green infrastructure; ecological and environmental values of water; benefits of climate change mitigation; non-point source pollution reduction; flood hazard reduction; improved groundwater conditions; securing reliable water supply; and wastewater management). Most	Useful for identifying available studies (for RWH benefits) but limited coverage of the specific social benefits that are the focus of this report. No UK studies found of direct relevance.

Source	Title/theme	Location	Relevant results	Note on transferability
			prevalent are Contingent Valuation, Hedonic Pricing and Choice Experiments.	
Hall (2012)	Analysis of abatement options to remove urban water pollution.	South-East Queensland, Australia	Includes abatement cost per tonne of pollutant for rainwater tanks.	Values specific to Australian context. Limited relevance for Filton?
Ossa-Moreno et al (2017)	Economic analysis of wider benefits to facilitate a Sustainable Urban Drainage Systems (SuDS).	London, UK	Findings for monetised benefits of investment in rainwater tanks includes flood risk reduction for households and at borough level.	Flood risk reduction results useful as a comparison with Fredenham et al (2020) results.
Tapsuwan et al (2014)	Adapting to less water: household willingness to pay for decentralised water systems in urban Australia	South-East Queensland, Australia	Choice experiment results: WTP for greywater systems ($1,700 – $14,100) and for rainwater tanks ($800 - $7,400). Estimated values were lower than installation and maintenance costs of these systems.	Focus is on overall WTP for RWH and GWR in context of water shortages in Queensland. No specific isolation of value of societal benefits.
Tsai, P. Onishi, A. (2022)	Urban households' willingness to pay for improvements in rainwater harvesting and rainwater infiltration systems.	Yokohama, Japan	Mean WTP: rainwater tank = US$274, RII = US$265. When compared with actual market price, results indicate respondents had high interest in these systems. Income, experience of flooding and environmentally conscious behaviour were main affecting factors.	Values specific to Japanese context. Does not isolate specific environmental/societal benefits.
Zhang et al (2015)	The capitalized value of rainwater tanks in the property market	Perth, Australia	Hedonic price analysis found significant positive effect of rainwater tanks on house prices: Rainwater tank added $6,700 to $18,000 to the median price of a typical house. This benefit was large enough to cover total cost of installation and maintenance.	Unclear how added price is apportioned between private and social benefits. Values specific to Perth context.

The Fredenham et al. (2020) study analyses the costs and benefits of domestic RWH installations broken down by size of water collection area/demand requirements. Overall conclusions are that there are total net benefits across all collection areas and demand requirements in residential buildings, and most commercial buildings (except small and very large buildings with high demand), which increases as collection area and demand increases. It also found that the inclusion of social benefits (reduced demand on water infrastructure, CO2 savings and flood damage reduction) substantially increased the potential benefits over a 20-year system lifetime. Table 6.2 and Table 6.3 reproduce the results of costs and benefits of installing RWH based on the size of collection area for residential and commercial building respectively.

Furthermore, it found that RWH installations across all building sizes emit less CO_2 compared with emissions embedded in mains water over this lifetime. Indeed, CO_2 embedded in a RWH system do not increase significantly with size while the amount of CO_2 saved, through reduced water demand, can increase significantly with size and demand of the system.

Social benefits included in the Fredenham et al (2020) study, which has been used as a basis for estimates for the Filton Development, were as follows:

- *CO_2 reduction from mains water:* The reduction in water use from the mains infrastructure through RWH systems assumes a reduction in the CO_2 embedded in that system. Environment Agency (EA, 2008) analysis was used to access the price of carbon embedded in mains water and inflated to reflect the increased carbon price. The amount of carbon in the water was assumed to be constant over the 20-year system lifetime period and the analysis assumed approximately 7 tCO_2/Ml. The annual cost of carbon embedded in mains water supply that is offset by a RWH system with different sizes of collection area was then calculated.
- *Reducing the need for new water infrastructure:* The Average Incremental Social Cost (AISC) of water infrastructure, calculated by the National Infrastructure Commission (NIC, 2018), was used to estimate the benefit of reducing water consumption, through installing RWH. Benefits were assessed based on the amount of water a RWH system offsets with an average value of £0.63 per m^3 used.
- *Reducing flood damage through use of RWH systems:* Limited data are available on the benefits of RWH on flood damage reduction. A case study in London (Ossa-Moreno et al, 2017) provides benefits (£) per m^3 of tank size and this was weighted for different areas of the UK based on potential and severity of flooding. UK flood risk assessments were used to determine the risk to human health and to the economy. Impacts were then weighted by either the population or the number of properties within a river basin catchment area. Flood damage reduction was calculated by: = (benefit per m^3 of tank (£)) x (average tank size) x (geographical weighting). It should be noted that this analysis was conducted on a per installation basis. A small single installation is unlikely to have much impact in reducing flood damage, whereas in the case of a large number of installations in an area, or larger installations, in new housing developments it is more likely that benefits will materialise, particularly when linked to other schemes such as sustainable drainage systems.

Based on the estimates for social benefits per size of RWH collection area for residential and commercial buildings given in Table 6.2 and Table 6.3, combined with information on rooftop catchment areas for buildings in the first phase of the Filton development (given in Kim et al, 2022), tentative estimates of social benefits have been made (Table 6.4). Calculations were made of the ranges of social benefits per m^2 of collected water for each category of collection area/building types based on the Fredenham et al (2020) results. These estimates were than scaled to the size of catchment area for residential and commercial buildings for the first phase of the Filton development to give estimates of the potential range of total social benefits for each type of development (residential houses, residential apartment block and commercial (the YTL Arena)).

The results show potential total social benefits (residential and commercial) in the range £2.3 million to £3.1 million over a 20-year period for the first phase of the Filton development. Estimates for potential social benefits were also made based on the number of housing units and roof surface area assumed for Scenario 4 in Deliverable D1.8 (Table 3.1 in that report). In this scenario a total of 278 housing units were planned (136 flats and 142 houses). The results are given in Table 6.5 and show a range of social benefits from £1.6 to 1.9 million over a 20-year period.

Table 6.4 and Table 6.5 only represent a small part of the potential eventual social benefit for the entire site which has outline planning for 2,675 homes. Table 6.6 makes tentative estates of social benefits for a scenario in which all housing units with outline planning have RWH installed. These are again based on estimates of social benefits for different building types given in Fredenham et al (2020) results which have been scaled to the potential size of the Filton Airfield development. The estimates of total social benefits range from about £15.6 to 18.4 million over 20 years.

It is stressed that the figures given in Table 6.4, Table 6.5 and Table 6.6 are very preliminary estimates based on a number of assumptions but demonstrate the potential order of magnitude of social benefits. Indeed, they are likely to be underestimates as they do not include all the potential social/environmental benefits of RWH identified above, such as improved water sources for gardens and landscapes. In addition, Table 6.5 and Table 6.6 are for residential units only and do not include social benefits of RWH in planned commercial developments and the YTL Arena. Furthermore, the estimates do not include the possibility of further densification of housing in the project area. On the other hand, the average estimates for social benefits in Fredenham et al. (2020) include flood damage reduction (as well as reduced demand on water infrastructure and CO_2 savings) which may not be applicable in the case of the Filton development since current advice is that there are negligible flood risks. Unfortunately, the social benefit estimates in Fredenham et al. (2020) are not disaggregated according to different benefits and, therefore, flood damage reduction could not be eliminated from the estimates made for this paper.

Table 6.2. Range of costs and benefits for installing RWH based on the collection area of a residential building.

Collection area	Example building types	Costs: CAPEX + OPEX ('000 £)	Water cost savings ('000 £)	Private net benefits ('000 £)	Societal benefits ('000 £)	Total net benefit ('000 £)
Small (<500m2)	Standalone dwellings, Houses, Bungalows;	£12 -£19	£1 - £19	-£9 - £26	£21 - £77	£10 - £100
Medium (500 – 2000m2)	Some larger houses or two semi-detached houses;	£25 - £38	£8 - £200	-£17 - £150	£50 - £163	£35 - £340
Large (2000 – 5000m2)	Row of terraced houses or blocks of flats;	£20 - £35	£7 - £150	-£15 - £120	£35 - £335	£20 - £450
Very Large (>5,000m2)	Large scale residential developments (including hybrid developments)	£25 - £60	£70 - £340	-£17 – £280	£30 - £920	£14 – £1,200

Source: Fredenham et al. (2020) (Table 3-11)
NB: These are total costs and benefits over an assumed 20-year lifetime, in 2020 prices.

Table 6.3. Range of costs and benefits for installing RWH based on the collection area of a commercial building.

Collection area	Example building types	Costs: CAPEX + OPEX ('000 £)	Water cost savings ('000 £)	Private net benefits ('000 £)	Societal benefits ('000 £)	Total net benefit ('000 £)
Small (<500m^2)	Small commercial shops (such as a corner shop);	£12 -£19	£1 - £19	-£11 - £28	£8 - £51	-£3 - £80
Medium (500 – 2000m^2)	Retail and commercial stores, leisure centres;	£25 - £38	£8 - £200	-£17 - £160	£23 - £150	£6 - £315
Large (2000 – 5000m^2)	Office blocks, hotels and shopping centres;	£20 - £35	£7 - £140	-£15 - £110	£16 - £190	£1 - £300
Very Large (>5,000m^2)	Large scale commercial developments (including hybrid developments)	£25 - £60	£7 - £315	-£17 – £260	£15- £500	-£3 – £742

Source: Fredenham et al (2020) (Table 3-12)
NB: These are total costs and benefits over an assumed 20-year lifetime, in 2020 prices.

Table 6.4. Tentative estimates of societal benefits from RWH in Buildings in First Phase of Filton Development.

			Societal benefits ('000 £) over 20 years		
Roof catchment	**Number of units**	**Average roof catchment per unit (m^2)**	**Min**	**Max**	**Note**
CA+CB			2,243	2,470	
CA	54 Houses	155	1,170	1,287	Based on social benefit for small collection area per unit (<500m2) from Fredenham et al. (2020).
CB			1,073	1,183	
CB_H	52 Houses	142	1,036	1,140	Based on social benefit for small collection area per unit (<500m2).
CB_A	1 Block	530	37	43	Based on social benefit for medium collection area per unit (500 – 2000m^2) from Fredenham et al. (2020).
YA	1 Arena	13,000	39	650	Based on social benefit for very large collection area (commercial development) per unit (>5,000 m^2). Social benefit more likely to be towards the max estimate since the min social benefit for very large collection area from Fredenham et al. (2020) seems unrealistically low.
YA+CA+CB			**2,282**	**3,120**	
YA+CA			1,209	1,937	
YA+CB			1,112	1,833	

Key:

CA	Residential – free-standing houses (2 to 4 bedrooms)
CB_H	Residential – free-standing houses (2 to 4 bedrooms)
CB_A	Residential – apartment block, ground to fifth floors (1- and 2-bedroom apartments)
YA	YTL Arena - Commercial – entertainment/shopping centre

Table 6.5. Tentative estimates of societal benefits of RWH in Scenario 4 (1).

			Societal benefits ('000 £) over 20 years	
Residential unit type	**Bedrooms**	**Total roof surface area estimate (m²)**	**Min**	**Max**
Apartment	1	850	15	57
	2	1,275	22	85
Houses	2	3,600	504	554
	3	4,680	655	721
	4	2,800	196	228
	5	3,325	233	271
Total		16,530	**1,625**	**1,917**

(1) The assumptions for numbers of residential unit types (totalling 278 units) and roof surface areas are as given in Draft Deliverable 1.8 (Scenario 4).

Table 6.6. Tentative estimates of potential societal benefits of RWH for entire Filton Development.

				Societal benefits ('000 £) over 20 years (3)	
Residential unit type	**Bedrooms**	**Assumed no of units (2)**	**Total roof surface area estimate (m²)**	**Min**	**Max**
Apartment	1	654	8,179	143	548
	2	654	12,268	215	822
Houses	2	346	34,640	4,850	5,335
	3	346	45,032	6,305	6,935
	4	337	26,942	1,830	2,196
	5	337	31,994	2,240	2,608
Total		2,675	159,057	**15,638**	**18,443**

(1) Assumes all housing units with outline planning (2,675 in total) will have RWH installed.

(2) Number of units per type assumes same proportions as those used in the assumptions for Scenario 4 of Deliverable D1.8.

(3) Estimates of societal benefits are based on Fredenham et al, 2020 (Table 3-11). Apartments estimates use societal benefits for "blocks of flats", 2- and 3-bedroom houses use societal benefits for "Houses and bungalows" and 4- and 5-bedroom houses use societal benefits for "larger houses or two semi-detached houses".

6.3. Greywater Recycling

6.3.1. Identification of benefits

Based on a review of sources from organizations promoting GWR[4], and other relevant literature, key proposed social/environmental benefits are summarized below. This excludes direct financial benefits to consumers, primarily cost savings from reduced mains water demand.

- *Reduced freshwater extraction:* Reusing greywater reduces the load of freshwater required for mains water demand with related environmental benefits.
- *Environmental benefits from reduced pressure on wastewater treatment infrastructure*: Reusing greywater reduces the amount of wastewater going to the sewer waste and increases water use efficiency. This can result in reduced energy requirements for wastewater treatment and therefore reduced GHG emissions. It also leads to reduced levels in the amount of chemicals used in water treatment. It also potentially reduces the chance of accidental/non-accidental dumping of chemical waste by sewage processing companies.
- *Environmental benefits from reduced pressure on waste supply infrastructure*: Reduced water demands for households reduces energy required for water supply. This results in reduced GHG emissions.
- *Reuse of nutrients:* The use of greywater for watering plants may include nutrients that would have otherwise been lost to the sewage system. It also reduces the need to use chemical fertilizers due to the nutrients the water contains with resulting improved quality of surface and ground water.

6.3.2. Quantification and valuation of benefits

The literature review found that, while there are a number of assessments of costs and benefits of GWR systems, most have limited relevance and transferability for this case study (see Table 6.7). In the reviewed studies social/environmental benefits were either (i) not included (e.g., Juan et al, 2016), (ii) included in only a partial way (e.g., Memon et al, 2016), (iii) of limited relevance to the UK context (Rodríguez et al, 2020).

Consequently, this case study has used the findings of the Fredenham et al (2020) study in the UK as a basis for tentative estimates of social benefits for GWR systems in the Filton development. The rationale for using this study is this same as for the RWH case, as outlined above.

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[4] Conserve Energy Future: What is Greywater? Ways to Collect and Benefits of Using Greywater - Conserve Energy Future (conserve-energy-future.com)
Cleantech Water: What are the Advantages of Having a Greywater System? (cleantechwater.co.in)
EcoMENA: Reuse of Greywater | EcoMENA

Table 6.7. Greywater Recycling Selected Studies giving Non Market Benefits.

Source	Title/theme	Location	Relevant results	Note on transferability
Boano et al (2020)	A review of nature-based solutions for greywater treatment: Applications, hydraulic design, and environmental benefits	Global	A review of literature provides overview of environmental benefits and shows how LCA studies have demonstrated these benefits.	Limited sources of valuation of non-monetary benefits. Figures given are focused on energy cost.
Fredenham et al (2020)	Independent review of the costs and benefits of rainwater harvesting and grey water recycling options.	UK	GWR installations: For all buildings or developments with more than one dwelling, there is a social net benefit over a 20-year system lifetime (includes reduced demand on water infrastructure, CO_2 savings).	Key recent source for social benefits of RWH and GWR in UK, with social benefits estimated per type and size of building (see Tables in Summary).
Juan et al (2016)	Greywater Reuse System Design and Economic Analysis for Residential Buildings in Taiwan.	Taiwan	A life cycle economic cost analysis for GWR systems. Result show system has minimum payback period of 4 years and provides investment incentives.	Not focused on social benefits.
Memon et al (2016)	Energy and carbon implications of water saving micro-components and greywater reuse systems.	UK	Analysis of energy and carbon footprint of GWR systems. Results show GWR at domestic level can offer considerable per capita water demand reduction potential but can increase energy consumption and carbon load of in-house water use.	Only a partial assessment of energy and carbon footprint as it does not address total energy saving including for water supply and waste-water treatment infrastructure.
Rodríguez et al (2020)	Cost–Benefit Evaluation of Decentralized Greywater Reuse Systems in Rural Public Schools	Chile	CBA results showed implementation of greywater treatment systems would not be economically feasible. Included quantification of environmental benefits in terms of WTP for green areas (recycled greywater in this case is for irrigation of green areas).	Limited transferability of environmental benefit findings due to case specific WTP for green areas.
Tapsuwan et al (2014)	Adapting to less water: household willingness to pay for decentralised water systems in urban Australia	South East Queensland, Australia	Choice experiment results: WTP for greywater systems ($1,700 – $14,100) and for rainwater tanks ($800 - $7,400). Estimated values were lower than installation and maintenance costs of these systems.	Focus is on overall WTP for RWH and GWR in context of water shortages in Queensland. No specific isolation of value of societal benefits.

The Fredenham et al (2020) study analyses the costs and benefits of installing a GWR system broken down by the expected yield (greywater produced) of the system in different types/sizes of new residential and commercial buildings (rather than retrofits in existing buildings). Light GWR is assumed, i.e., wastewater from the baths, showers, and hand basins but excluding from kitchen sinks, washing machines and toilets. It finds that for the smallest system types (installed in individual houses or small blocks of flats) there is a net private cost for all systems over a 20-year lifetime. For larger buildings (including larger blocks of flats, large multi house residential developments or community developments) there is a net private benefit of installing the system. When the social benefits (this includes the CO_2 impacts and reduced stress of water infrastructure) are included there is still a total net cost for low and small yield buildings, but a total net benefit for medium and larger buildings; essentially, all buildings or developments with more than one dwelling. Table 6.8 reproduces the results of costs and benefits of installing GWR systems in various types of new buildings based on the system yields of greywater.

Social benefits included in the Fredenham et al (2020) study and methodologies used for estimates were as follows:

- *CO_2 reduction from mains water:* The reduction in water from the mains infrastructure assumes a reduction in the CO_2 embedded in that system. Analysis undertaken by the Environment Agency (EA, 2008) was used to access the price of carbon embedded in mains water and this was inflated to reflect the increased carbon price. The amount of carbon in the water is expected to be constant over the 20-year lifetime period while the carbon price increases. The analysis assumed approximately 7 tCO_2/Ml.
- *Reducing the need for new water infrastructure:* As in the case of RWH, the Average Incremental Social Cost (AISC) of water infrastructure was used to calculate the benefit in reducing water consumption, through installing GWR, on national infrastructure. The AISC can be used to understand the benefit that an installation would have based on the amount of water it offsets.
- *Reducing flood damage:* While GWH reduces the amount of wastewater sent to the sewage system and therefore allows more capacity for surface water, the impact of this is likely to be minimal and therefore was not modelled in the analysis.

Based on the estimates for social benefits per yield of GWR systems in different types/sizes of new residential and commercial buildings given in Table 6.8, tentative estimates of social benefits have been made for the first phase of the Filton Airfield development (using housing unit information in Table 1 of Kim et al, 2022) in Table 6.99. This assumes light GWR as defined in Kim et al, 2022. The results show potential total social benefits (residential and commercial) of around £2.1 million over a 20-year period for the first phase of the Filton development. Unlike the results for RWH, given above, there is no high to low range because the source (reproduced in Table 6.8) only gives a single estimate of social benefits per type of yield/property category.

Estimates for potential social benefits were also made for the number of housing units and roof surface area assumed for Scenario 4 in Deliverable D1.8 (Table 3.1), based the Fredenham et al (2020) results (Table 6.8). In this scenario a total of 278 housing units were planned and commercial units are not included. The results given in Table 6.10 show estimated total social benefits of about £2.2 million over a 20-year period.

As in the case of the RWH social benefit estimates discussed above, the estimates for GWR in Table 6.9 and Table 6.10 only represent a small part of the potential eventual social benefit for the entire site. Table 6.11 gives tentative estates of social benefits for a scenario in which all 2,675 housing units with outline planning have light GWR installed. These estimates are based on figures for social benefits for different types and sizes of residential building given in Table 6.8, scaled to the potential size of the Filton Airfield development. The estimates of total social benefits are about £22 million over 20 years.

It is stressed that the figures given in Table 6.9, Table 6.10 and Table 6.11 are tentative and based on generic estimates of social benefits for GWR for different types and sizes of building. They are intended to demonstrate the potential order of magnitude of social benefits in the Filton Development. However, they may be underestimates since they do not include all potential social/environmental benefits of GWR identified above, such as reuse of nutrients, and Table 6.10 and Table 6.11 only include residential units, without planned commercial developments. Furthermore, the estimates do not include the possibility of further densification of housing in the project area.

Table 6.8. Costs and benefits of installing a GWR system in a building based on the systems yield (greywater produced).

Yield	Example building types	Costs: CAPEX + OPEX ('000 £)	Total water cost savings ('000 £)	Private net benefits ('000 £)	Societal benefits ('000 £)	Total net benefit ('000 £)
Low ($<500m^3$)	Smaller households (such as retired people or young adults), small commercial shops	45	5	-40	2	-37
Small (500 – 1,500m^3)	Larger households (potentially families).	100	52	-48	18	-30
Medium (1,500 – 4,000m^3)	Retail and commercial stores, leisure centres, some offices.	120	108	-13	34	25
Large (4,000 – 10,000m^3)	Large commercial settings such as shopping centres, multi-unit offices or flats.	170	190	21	67	88
Significant ($>10,000m^3$)	High rise offices or blocks of flat, hotels, multi-purpose developments.	270	780	510	275	787

Source: Fredenham et al (2020) (Table 4-8)
NB: These are total costs and benefits over an assumed 20-year lifetime, in 2020 prices.

Table 6.9. Tentative estimates of Social Benefits of GWR in Buildings in First Phase of Filton Development.

Catchment	Building type	Bedrooms	No of Units (2)	Total Units	Total social benefit ('000 £) over 20 years
YTL Arena	Commercial – entertainment/shopping centre		1		275
CA	Residential – free-standing houses	2	2		4
		3	15		270
		4	37	54	666
CB	Residential – apartment (1)	1	13		26
		2	20	33	40
	Residential – free-standing houses	2	6		12
		3	43		774
		4	3	52	54
Total units (2)			139	139	**2,121**

(1) This is one mid-rise (Ground to 5th Floor) apartment block

(2) Number of units from Kim, et al (2022).

Table 6.10. Tentative estimates of societal benefits of GWR for Filton (Scenario 4) (1).

Residential unit type	Bedrooms	Assumed quantity	Societal benefits ('000 £) over 20 years (1)
Apartment	1	68	136
	2	68	136
Houses	2	36	72
	3	36	648
	4	35	630
	5	35	630
Total		278	**2,252**

(1) Based on results for typical social benefits per type of property from Fredenham et al (2020) and housing units in Scenario 4 in draft Deliverable D1.8 (Table 4.2).

Table 6.11. Tentative estimates of potential societal benefits of GWR for entire Filton Development.

Building types	Bedrooms	Assumed no of units (1)	Societal benefits ('000 £) over 20 years (2) (3)
Apartment	1	654	1,309
	2	654	1,309
Houses	2	346	693
	3	346	6,235
	4	337	6,062
	5	337	6,062
Total		2,675	**21,669**

(1) Number of units per type assumes same proportions as those used in the assumptions for Scenario 4 of Deliverable D1.8.

(2) Assumes all housing units with outline planning (2,675 in total) will have GWR installed.

(3) Estimates of societal benefits are based estimates for different property sizes in Fredenham et al, 2020 (Table 4-8).

6.4. Heat recovery systems

6.4.1. Identification of benefits

"Wastewater from domestic, industrial and commercial developments maintains considerable amounts of thermal energy after discharging into the sewer system. It is possible to recover this heat by using technologies like heat exchangers and heat pumps; and to reuse it to satisfy heating demands" (Nagpal et al, 2021).

Wastewater heat recovery (WWHR) can be made at different points in the sewer system from end-user to water treatment (i.e., at component level, in buildings, in public sewers and at Wastewater treatment plants (WWTPs). These points each have specific advantages and disadvantages concerning energy, economic and environmental dimensions (Nagpal et al, 2021).

Based on a review of sources from organizations promoting WWHR[5], and other relevant literature, key proposed benefits are related to it being a renewable and readily available form of energy, with direct **economic benefits/cost savings.** The only social/environmental benefits highlighted in the reviewed sources are the reductions in reliance on fossil fuels and in associated GHG emissions. Unlike RWH and GWR, covered above, social benefits of WWHR were not identified in the sources in terms of reduced pressure on the waste supply infrastructure and wastewater treatment infrastructure. However, WWHR could have an impact on water flow and thus energy and maintenance needs of the water infrastructure/WWTP depending on the distance between the system and the WWTP, which will determine the temperature of the wastewater arriving at the sewage works.

It should also be noted that some studies identify environmental costs of WWHR. For example, lower discharge temperatures from WWTPs could disrupt the aquatic ecosystems (Hawley & Fenner, 2012). A case study in Sweden by Bergstrand (2020) found that colder wastewater arriving in the wastewater treatment plant due to large scale wastewater heat recovery upstream can reduce the removal of nitrogen, in particular, and of phosphorus to some extent. However, it is noted in the research review by Nagpal (2021) that there is limited life-cycle assessment (LCA) to analyse the overall sustainability of WWHR (including environmental impacts).

6.4.2. Quantification and valuation of benefits

The literature review found that there are a range of recent studies and projects in many countries, including the UK, on various aspects of implementation of WWHR. A key focus is on energy saving potential and economic viability. In this regard, for implementation at building level a reference guideline for use of WWHR with a heat pump at building level is

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[5] Such as: Scottish Water: Heat from Waste Water - Scottish Water
WRI: Wastewater: The Best Hidden Energy Source You've Never Heard Of | World Resources Institute (wri.org)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

wastewater flow of at least 8000 to 10,000 L/day (equivalent to 60 people or 30 residential units) is given in Müller et al (2009). This means that WWHR can have most significant potential in buildings with a large number of residents, such as apartment buildings, multi occupancy units and hotels.

The recent extensive literature review of WWHR studies by Nagpal et al (2021) concluded that case studies of existing WWHR systems in a number of countries show strong evidence of significant energy saving potential with up to 50% reduction in primary energy consumption. In terms of social/environmental benefits the focus is mostly on reduction in GHG emissions due to WWHR being a renewable energy source replacing fossil fuel sources. Thus, the only social benefit focused on in the reviewed studies was reduction in CO_2 emissions, as summarized in Table 6.12. The Nagpal et al (2021) review found four studies giving "emissions analysis" at building level (e.g., Spriet & Hendrick (2017) and Spriet & McNabola (2019) outlined in Table 6.12). The study by Farman Ali & Gillich (2020) also gives examples of reduction in CO_2 of various WWHR projects. The most relevant international projects with findings potentially transferable to the Filton case are for Canada (Oloman, 2012), Switzerland (Intelligent Energy Europe Report, 2007) and Norway (Mikkonen, 2013).

In the UK, key examples are the WWHR projects at Borders College, Galashiels, Scotland (Dunsmore, 2016) and Kingston upon Thames (Thames Water, 2021)[6]. Broader assessments of the potential for WWHR in the UK are given in Hawley & Fenner (2012) and Farman Ali & Gillich (2020 and 2021).

In conclusion:

- The literature research did not find a consolidated review (equivalent to Fredenham et al (2020) for RWH and GWR) of costs and benefits (including social benefits) of WWHR systems at different levels (i.e., at component level, in buildings, in public sewers and WWTPs) either for the UK or further afield.
- The available studies are focused on pilot projects of variable relevance to the Filton case (see Table 6.8). These studies generally give estimates of CO_2 emissions reductions of using WWHR, although these are not translated into monetary valuations.
- More details on proposed systems and scale for the Filton development (the focus in Report D1.8 Section 5 has been on recovery from larger collection sewers) are needed to fully assess the transferability of findings of the studies given in Table 6.12 and to make quantitative estimates and valuations of social benefits.

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[6] See also: London's hidden energy source: recovering heat from sewage: A new wastewater heat-recovery project announced by Thames Water and Kingston Council could provide a model for future schemes in London: London's hidden energy source: recovering heat from sewage – CIBSE Journal

Table 6.12. Heat Recovery Systems from Wastewater: Selected studies covering social benefits.

Source	Title/theme	Location	Relevant results	Note on transferability
Dunsmore (2016)	Heat from Wastewater - UK Water Projects – Renewable Energy UK Water Projects.	UK, Scotland.	WWHR project at Borders College, Galashiels, Scotland. 2 heat pumps of 400kW producing 1.9 GWh annually providing around 95% of the heat demand of the college. Annual carbon savings of 150 tonnes of CO_2 with monetary savings of around £10,000 annually for college.	For a college, not residential buildings.
Farman Ali & Gillich (2020)	The potential of the heat recovery from urban sewage wastewater for use in residential and commercial buildings.	UK and global	Gives examples of Heat Recovery from Wastewater projects, in Korea, Canada, Netherlands, Switzerland, Norway and Scotland.	Example project results for energy saving and CO2 reduction could be used in estimates of benefits for Filton?
Intelligent Energy Europe Report (2007)	Heating with wastewater heat Best Practice Catalogue: Examples from Germany, Switzerland, Austria, Norway and Sweden.	Switzerland	Examples given (1) project at Binningen reduced CO_2 emission to 675 tonnes per year by substituting oil consumption with WWHR. (2) Project at Seeblick for 3 residential blocks totalling 52 flats. WWHR avoided 157 tonnes oil and reduced emission from 340 to 412 tons CO_2.	Residential projects but not recent results. Therefore, may have limited transferability for latest WWHR technology.
Mikkonen et al (2013)	Heat recovery from wastewater: Assessing the potential in northern areas.	Norway	Norway: Half of energy used in Sandvika offices and residential buildings supplied from WWTP where heat is recovered by four heat pumps. As CO_2 emissions reduced by 6,000 tons per annum.	Recovery from WWTP so may not be relevant for Filton if it is proposing residential WWHR.
Oloman (2012)	Turning Waste into Energy. Report on WWHR system extracting heat from sewage in condominium estate in Vancouver.	Canada	Residential estate reduced GHG emissions by 150 tonnes (30% to 85% reduction).	Not recent results. Therefore, may have limited transferability for latest WWHR technology.
Spriet & Hendrick (2017)	Wastewater as a heat source for individual residence heating: A techno-economic feasibility study in the Brussels capital region.	Belgium	WWHR system showed reduction in equivalent CO_2 emissions of around 49% over its 20 year lifetime of 20 years, compared to gas boilers. This could represent a significant reduction in GHG emissions in the Brussels Capital Region.	Transferability of GHG emission estimates depends on establishing details of proposed WWHR systems at Filton.

Source	Title/theme	Location	Relevant results	Note on transferability
Spriet & McNabola (2019)	Decentralized drain water heat recovery: A probabilistic method for prediction of wastewater and heating system interaction.	Ireland	Potential for reduction in heating related GHG emissions by 7.6% to 22%. However, cost of WWHR system for a single residence not financially competitive with traditional systems, due to significant capital investment.	Transferability of GHG emission estimates depends on establishing details of proposed WWHR systems at Filton.
Thames Water (2021)	England's first sewage-powered domestic heating scheme planned for Kingston. WWHR project for a WWTP ito provide heating for over 2,000 homes.	UK, England.	Renewable heat project at Hogsmill is estimated to save 105 kilo tonnes of carbon dioxide equivalent ($ktCO_2e$) emissions over 30 years.	This could be a promising source to inform Filton case in that it is recent and UK based. But heat recovery is from WWTP not residential buildings.

6.5. Nutrient recovery from sewage

The focus for the Filton case is on domestic wastewater (sewage - greywater and blackwater), although urban wastewater (as treated in WWTPs) can include industrial wastewater and/or runoff rainwater. Recoverable nutrients in wastewater include mainly nitrogen, phosphorus and potassium (although K has limited potential due to low market value and abundant reserves and therefore the focus of studies in mainly on N and P). These can be recovered as separate resources or as a complex substance such as struvite that forms in WWTPs pipes and pumps (causing reductions in plant efficiency and high maintenance costs) (Dionisi et al, 2018). Recovery of nutrients is largely unexploited currently in UK and EU but could potentially be recovered through application of a large range of developing technologies. These are summarized in Kisser et al (2020), Batstone et al (2014), Johannesdottir et al (2020), Dionisi et al (2018), Shaddel et al (2019) and other studies. According to Renfrew et al (2022), despite the many resource recovery technologies there are few industrial examples of implementation which hinders strategic decision making.

Kisser et al (2020) divides application of resource recovery into household, district and city scales. Most of the technologies discussed in the reviewed sources are applied in the wastewater infrastructure (i.e., district, city level) not at household level. However, there are examples of source separation of wastewater (e.g., greywater and blackwater) at the household level which, coupled to decentralised treatment/recovery of domestic wastewater could allow the recovery of nutrients (as well as energy and water) more efficiently. There are also examples of innovative household level nutrient recovery systems that remove and recycle nitrates and phosphates[7].

6.5.1. Identification of benefits

Benefits of nutrient recovery from wastewater is presented in the reviewed sources mainly in terms of direct economic and operating benefits in wastewater treatment, as well as allowing for reuse of resources within the agricultural sector[8]. These include reducing operating costs, revenue from recovered product, reducing fouling of equipment (struvite scaling) and thus maintenance costs, and helping to meet discharge limits. Key social/environmental benefits can be summarized as:

- *Environmental benefits from optimising operation of wastewater treatment infrastructure resulting from resource recovery:* WWTPs use energy intensive processes, hence any reduction in energy use will have GHG emission benefits (Mayer et al, 2016). Also, reductions in fouling of equipment with struvite scaling improves plant efficiency with resulting energy and resource/maintenance cost savings (Dionisi et al, 2018).
- *Environmental benefits from nutrient recovery:* Recovering nutrients (N and P) from wastewater and re-using as fertiliser reduces GHG emissions as fertilizer production is an energy-intensive process that accounts for approximately 1% of global energy

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[7] For example: ECO Houses with nutrient recovery and composting system to recycle Nitrates and Phosphates - Herr Ltd

[8] See for example: Realizing the Benefits of Nutrient Recovery at WRRFs | Hazen and Sawyer

consumption (Mayer et al, 2016). The study by Theregowda et al (2019) found that fertilizer production from recovered struvite enabled significant energy saving compared with traditional commercial fertilizers production.

- *Environmental benefit from prevention of impacts of nutrients on receiving waters:* The potential for eutrophication in receiving waters is addressed by treatment for wastewaters to remove N and P in WWTPs. However, where this is not fully effective there is still a possible environment impact, for example, the study by Bunce et al (2018) found a shortage of treatment technologies for P-removal at smaller scales.
- *Social benefit of nutrient recovery through contributing to food security/poverty relief:* This may be through (1) reduced fertilizer costs (2) reduced malnutrition due to improved nutritional variety and household food security, and (3) increased income from surplus crop marketing (Mayer et al, 2016 proposes these benefits in the context of P recovery). This is likely to be more relevant in the developing country and agricultural community context.

6.5.2. Quantification and valuation of benefits

Although there is much ongoing research to establish the potential of a range of technologies for nutrient recovery in wastewater, both globally (as reviewed in e.g., Johannesdottir et al, 2020) and in the UK (as reviewed in e.g., Renfrew et al, 2022) the availability of quantification and valuation of social/environmental benefits is very limited, based on our literature review. This may be partly explained by much of the range of technologies for nutrient recovery being at the development stage (or at a range of different technology readiness levels (TRLs)). This means we did not find consolidated reviews/analysis of social benefits for the range of different types of technologies that could be used as a basis to estimate potential social benefits at the Filton site, based on the assessment made of the potential of nutrient recovery given in the D1.8 report (Section 5.1).

Some example studies of interest are given in Table 6.13. These mostly focus on energy saving and CO_2 reductions, but with limited quantitative estimation of these benefits. Other social benefits are generally only covered in a qualitative way. The study with perhaps the most relevant quantitative results is the report for CREW (Dionisi et al, 2018) which includes estimates of potential energy and CO_2 savings for N, P, K. recovery from wastewaters. However, it does not consider costs, energy and carbon dioxide emissions due to the recovery technologies so states that results are “maximum potential benefits” and “should be interpreted with caution”.

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Table 6.13. Nutrient Recovery from Wastewater: Selected studies covering social benefits.

Source	Title/theme	Location	Relevant results	Note on transferability
Batstone et al (2014)	Platforms for energy and nutrient recovery from domestic wastewater: A review.	Australia	Reviews practical application of two processes (low energy mainline (LEM) and partition–release–recover (PRR) with a focus on energy costs.	Need to establish whether technology used are relevant for Filton. If so, energy results may be relevant for CO2 saving estimates?
Dionisi et al (2018)	Water and the circular economy – Where is the greatest sustainable economic benefit for resource recovery in the water cycle?	UK, Scotland	Energy and CO_2 saving for N, P, K. recovery of from waters and wastewaters: For N recovery from wastewaters: Energy savings and of up to 127 GWh/y and CO_2 savings 45 kt/y. (See Table 4-2. Calculated potential resources and benefits).	Need to establish whether technology used, and other assumptions are relevant for Filton.
Kuwayama & Olmstead (2020)	Hydro economic modelling of resource recovery from wastewater: Implications for water quality and quantity management.	Theoretical paper	Presents hydro-economic framework that can be used to explore socioeconomic implications of strategies for wastewater treatment with resource recovery, especially nutrients, at multiple scales. Includes societal costs and benefits of adopting a technology.	Interesting theoretical paper but not clear how useful in this context?
Theregowda et al 2019	Nutrient Recovery from Municipal Wastewater for Sustainable Food Production Systems: An Alternative to Traditional Fertilizers.	US	Found that fertilizer production from recovered struvite used one order of magnitude less energy[9] than traditional commercial fertilizers production to produce one unit of fertilizer.	Need to establish whether technology used, and other assumptions are relevant for Filton.

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[9] Emergy is defined as the available energy required directly and indirectly through all transformations to make a product, process, or service.

6.6. Conclusions

Key conclusions on the assessment of social benefits of circular technologies being considered for the Filton Airfield site are as follows:

- ✓ Key proposed social/environmental benefits of **RWH** include: (i) Flood risk reduction: (ii) CO_2 reduction from mains water: (iii) Environmental benefits from reduced pressure on water infrastructure and reduced need for additional infrastructure: (iv) Improved water sources for gardens and landscapes and (v) Increased awareness of water use.
- ✓ Reviewed literature on costs and benefits of domestic RWH installations found that the inclusion of social benefits substantially increased the potential benefits over a system lifetime.
- ✓ Tentative estimates of social benefits of RWH installation at the Filton Airfield Development have been made based on results per collection area and types of building from Fredenham et al (2020) (which includes social benefits from reduced demand on water infrastructure, CO_2 savings and flood damage reduction).
- ✓ The results show potential total social benefits (residential and commercial) in the range £2.3 million to £3.1 million over a 20-year period for the first phase of the Filton development. Estimates based on the number of housing units and roof surface area assumed for Scenario 4 in Deliverable D1.8 (Table 3.2) show a range of social benefits from £1.6 to 1.9 million over a 20-year period.
- ✓ Estimates of the potential social benefit for the entire site, assuming all housing units with outline planning have RWH installed, range from about £15.6 to 18.4 million over 20 years.
- ✓ Key proposed social/environmental benefits of GWR include: (i) Reduced freshwater extraction: (ii) Environmental benefits from reduced pressure on wastewater treatment infrastructure: (iii) Environmental benefits from reduced pressure on waste supply infrastructure: and (iv) Reuse of nutrients.
- ✓ Tentative estimates of social benefits of GWR installation at the Filton Airfield Development have been made based on results per types of building from Fredenham et al (2020) (which includes social benefits from CO_2 reduction from mains water and reducing the need for new water infrastructure).
- ✓ The results show potential total social benefits (residential and commercial) of about £2.1 million over a 20-year period for the first phase of the Filton development. Estimates based on the number of housing units in Scenario 4 in Deliverable D1.8 (Table 3.2) show social benefits of about over a 20-year period.
- ✓ The estimate of the potential social benefit for the entire site, assuming all housing units with outline planning have GWR installed, is calculated at about £22 million over 20 years.
- ✓ It is stressed that the social benefit estimates for RWH and GWR in this report are illustrative only and depend on a number of key assumptions as outlined in this report. This intention is to demonstrate the potential order of magnitude of social benefits given the current availability of data and caveats are needed in interpreting the results. In the future, further details on full development of the Filton site and choice of technology/level of RWH and GWR installation would allow more accurate assessment of social benefits.

- ✓ Key proposed benefits of WWHR are related to it being a renewable and readily available form of energy, with direct economic benefits/cost savings. The only social/environmental benefits highlighted in the reviewed sources are the reductions in reliance on fossil fuels and in associated GHG emissions.
- ✓ Case studies of existing WWHR systems in a number of countries show strong evidence of significant energy saving potential. However, the literature research did not find a consolidated review of costs and benefits (including social benefits) of WWHR systems at different levels (i.e., at component level, in buildings, in public sewers and WWTPs) either for the UK or further afield. More details on proposed systems and scale for the Filton development are needed to fully assess the transferability of findings of existing studies and to make quantitative estimates and valuations of social benefits.
- ✓ Key proposed social/environmental benefits of nutrient recovery from sewage include energy savings and reduced GHG emissions from: (i) optimising operation of wastewater treatment infrastructure resulting from resource recovery and (ii) fertilizer production; (iii) *prevention of impacts of nutrients on receiving wa*ters: and (iv) Social benefit of nutrient recovery through contributing to food security/poverty relief.
- ✓ There is limited availability of studies giving quantification and valuation of the social/environmental benefits of nutrient recovery from sewage. This meant that quantitative estimates and valuations of potential social benefits at the Filton site are not practical at present.
- ✓ Policy context: A key aim of identifying and valuing social benefits in the assessment of circular technologies is to inform a more comprehensive understanding of their full costs and benefits. This is important in the context of the Filton Airfield development both for capturing the benefits to society of circular technologies when currently such benefits are not reflected in property prices and to contribute to discussion at the policy level on how to provide greater incentives for uptake of circular technologies (see Section 8 on Incentive Structures).

6.7. Policy and Regulations

6.7.1. Barriers and challenges

Water and wastewater generated by human activities are carriers of energy and materials (Nika et al., 2020). In particular, it has been recognised that wastewater is a valuable resource for nutrition used in agricultural sector as it contains nitrogen, phosphorous, and organic matter (Abu-Ghunmi et al., 2016). Additionally, low-grade thermal energy can be retrieved from grey and wastewater to be applied onsite for space and water heating and other domestic purposes (Hervás-Blasco et al., 2020). Thus, as discussed in previous chapters 3, 4 and 5, closing the water, energy and materials cycles demonstrated for the greenfield implementation in Filton Airfield can provide benefit society by contributing to self-sufficiency and circularity. However, there is a need to explore opportunities and constrains in the policy, process, and procedural frameworks as a starting point to improve an applicability of such solutions.

This chapter therefore focuses on the opportunities and barriers within national legislations, building regulations, and planning requirements for decentralised circular water solutions within the Filton Airfield development scheme.

6.7.2. Policy and regulations

As shown in Table 6.14, Qtaishat et al. (2022) pointed out that the Filton case do not include domestic or decentralised circular solutions in their water and building-related legislations. Therefore, the process of obtaining permits and authorisation for this project was usually lengthy and complicated. In this case, multiple permits such as health, water, municipality, and safety were required in addition to standard building requirements. Furthermore, it does not have financial supports and strategies, which is direct governmental financial subsidies which reflect a larger picture regarding incentives directed toward decentralised circular water solutions. Table 6.15 further presents the state-of-the-art review of regulatory and legal frameworks for circular water solutions for the Filton case. It focuses on the current regulations for water reuse, domestic circular water solutions, building and planning, permit and authorization, and financing incentives. The UK do not have specific regulations for decentralised circular water solutions. In addition, local authorities do not enforce any circular water solutions except for water-saving measures and equipment. Consequently, circular water solutions are encouraged but not required.

The main barriers were issues related to initial costs, permits, authorisation, and the absence of supportive financial and legislation tools. Whereas the least important barriers to implementing circular water solutions were design and technology limitations. Specifically, when considering rainwater harvesting within the YTL Arena and forming lakes/ponds within the Filton Airfield development, the preferred type of circular water solution was to install rainwater butts on a plot-by-plot basis if required by the local design and planning authority. This indicates that the application of circular water solutions in this case study is linked to users' and owners' wishes. In addition, this highlights that increasing circular economy for water uptake is not related to the availability of innovative or conventional technologies or their effectiveness.

Table 6.14. Summary of survey results from the Filton Airfield case.

Location	Bristol, UK
Year	On-going
Purpose	Mixed-use urban development
Types of water reuse systems	Rainwater, Blackwater, Greywater, Heat recovery, Nutrient recovery
Beneficiaries	Occupants/users of the project;
Water applications	Non-potable domestic use; Outdoor communal purposes
ROI	Unknown
Payback period	Unknown
Incentives	None were available/offered.
Required permits	Building regulations or compliance permits; Planning permit.

Table 6.15. State-of-the-art regulatory and legal framework for circular water solutions in case study – Filton Airfield.

Country	UK
Policy Framework	The water Act (2014) and its implementation. The Environment Act (1995), Environmental Permitting (England and Wales) Regulations (EPR)
Building and planning framework	BS 8525-1:2010 Greywater a code of practice (BS 8525). BS 8515:2009 Rainwater Harvesting Systems-Code of Practice (BS 8515). The Environment Agency information guide on rainwater and greywater harvesting for more guidance.
Circular water legislation	BS EN 16941-1:2018 and the EU directive on Water Reuse (2019)
Wastewater	No use
Rainwater	Non-potable purposes
Greywater	Non-potable purposes
Governmental subsidies	Non-available
Approval process	The local water authority notified
Water discharge Fee	None

Since there are no comprehensive building regulations for circular water solutions in UK national or regional building and planning codes, the current regulatory framework and building codes do not currently encourage developers to use circular water solutions. Only general provisions for water management and water-saving solutions are included in the building code of the UK. In addition, there were no special requirement for the use of circular water solutions.

In this context, although current building regulations might not be limiting for circular solutions, they are also not encouraging. As a domestic project, in Filton Airfield, water, energy and nutrient recovery and reuse solutions discussed in chapters 3, 4 and 5 can be implemented or encouraged but they are not enforced by local governments. For example, the rainwater in the YTL Arena was shown on the planning application. This was not a prerequisite within planning but was an added benefit. There is a water calculation that forms part of building regulations – this does not appear to be strictly enforced by local authorities or regulations. However, more depending on the design they can be applicable, profitable and innovative, e.g., integrating harvesting rainwater and subsurface storage and recovery or greywater recycling (Westland, https://mp.watereurope.eu/d/CaseStudy/12 and Gotland, https://mp.watereurope.eu/d/CaseStudy/29).

6.7.3. Opportunities

Issues and barriers could be addressed by opportunities that exist in the field of decentralized water solutions that can increase both the public and developers' interest in the topic and raise the uptake of such decentralised water projects required to combat water shortage and climate change. These include

- Opportunities to optimize rather than create new legislations: There already exist some water-saving requirements in most building codes and legislations that can be altered and tweaked to include compulsory circular water solutions. This is appropriate if suitable financing options and incentives were provided to increase the uptake of these solutions.

- CE for water can support flooding and other climate-resilience strategies: Local government and water authorities/companies are open to the idea of reusing water, as there is likely a need for major investments in the centralized water infrastructure if the system has not been modernised. A circular solution for water on housing and local street levels can help fix existing issues with sewage and storm drainage, which can directly benefit local municipal and water authorities. In addition, green spaces, soft landscapes, and water features require a significant amount of water to maintain, which drives the need for communal circular solutions.

- Early-stage integration in large-scale housing and urban schemes: High-density and mixed-use developments provide both economic advantages and better chances to deliver circular solutions in design and urban planning. New housing developments like Filton Airfield provide good opportunities to implement and drive circular innovation solutions. Developers consider installing rainwater butts and rainwater control measures on plots as most planning frameworks require them. These can be made to be retrofitted or upgraded in the future for rainwater harvesting. Similarly, new mixed-use housing developments could be built with a separated sewer network system (one for greywater and one for blackwater) to allow future house owners to install greywater treatment and heat-recovery systems. If the timing is right, there is also a possibility of implementing circular regulations on ongoing projects.

- Demonstrator projects help to raise awareness, explore, and enhance financial and non-financial value of CE for water solutions: The cost-benefit analysis of schemes should include other value metrics such as water-saving requirements and environmental beliefs. Innovative circular water solutions combined with good marketing strategy make schemes more attractive and competitive for investment. It was demonstrated that successful demo case projects can drive and encourage local and national legislation. First, it is important to have pilot projects as demonstration/reference points of innovative circular technologies. Then, it is important to train, educate, and sensitise the local authorities to be able to support the operation of such configurations and technologies. This should be done in a wellstructured manner through a dedicated piece of legislation. This kind of activity can be implemented through a top-down approach as first the decision of the planning is down to a high level and then the implementation part is performed by a user/technician.

- Maximise existing opportunities for decentralised treatment and reuse: Current circular-water technologies allow water to be extracted from sewers and treated locally in space-limited units for reuse at the point of demand. What is left is the optimisation of the configuration in terms of efficiency and cost-benefit balance for developers and users.

- Lastly, an opportunity for European countries lies in the implementation of the new EU regulation on minimum requirements for water reuse, which will provide the legal baseline for water reuse for agriculture and encourages local authorities to adopt suitable regulations in the future for urban reuse as well.

6.7.4. Conclusions

This chapter addressed the current regulatory challenges and opportunities to improve uptake and promote a new circular economy for water-delivery models.

It was found that the UK has its set of permits, risk assessments, and authorisation requirements and protocols for circular-water solutions. It was also found that implementing circular economy for water continues to be hampered by the cost-benefit gap for those investing in systems. Other challenges include the disparate approaches to incentives, the complexity and bureaucracy of permits, disparate technical standards, technical competencies, lack of knowledge about circular economy, and how to best implement it within the business and financial models. The findings ultimately indicated that the policy and regulatory requirements covering circular economy technologies and their products are split between many different directives, and alignment between them is still poor. It was confirmed that circular economy for greenfield implementation like Filton Airfield has hampered by a lack of knowledge on how to implement it in business models.

The findings ultimately indicated that the policy and regulatory requirements covering circular economy technologies and their products are split between many different directives, and alignment between them is still poor. It was confirmed that circular economy for greenfield implementation like Filton Airfield has hampered by a lack of knowledge on how to implement it in business models. Barriers, challenges and opportunities explored in this chapter can support establishing new and revised policies and regulations that enhance the uptake of circular solutions demonstrated in Filton Airfield. Therefore, it is concluded with recommendations, which are intended for implementing circular economy for water in key sectors.

1. The adoption of the fit-for-purpose water production will lead to reduce the unnecessary water use and treatment technologies and additional cost to maintain high water quality requirements.

2. The context, application (product quality and risk management), and scale (system) should be considered to improve policy, guidelines, processes, and protocols for circular water reuse.

3. Finally, it is required to improve knowledge and awareness across all sectors and user groups. Social participation and collaboration platforms (e.g., living labs, training workshops, focus groups, interviews and appreciative inquiry) will provide a coherent justification and knowledge of the environmental, economic, and social benefits and impact. This will thus propose new business models and services that transform the current water systems and services into factories integrated into the production chain (e.g., potable and non-potable water reuse, low-grade heat reuse for space heating, nitrogen and phosphorus fertiliser production and local reuse).

6.8. Incentive Structures to Create Circular Solutions: The Built Environment

6.8.1. Introduction

This section discusses incentive structures to support the development and uptake of circular economy principles and related technologies. The focus is on the circular economy policy landscape for built environment in the UK, with some additional international examples. It gives a brief overview of the typology of policy options for enabling and promoting circular economy generally and for built environment. It also discusses the issues effecting uptake of circular technologies, particularly at the design and construction phase of developments. This sets the scene for an examination of the range of possible incentive structures for circular technologies uptake in the built environment and their relevance to the types of technologies for closing water cycles envisaged in the Filton Airfield development, including a matrix presenting details and examples of the key such structures (financial support, fiscal measures, engagement, regulation). This enables some general conclusions on which are most applicable and promising for supporting uptake of circular technologies at Filton Airfield.

6.8.2. Circular economy and the built environment

The literature on policy options for enabling a transition to a circular economy emphasizes the need for a range of complementary instruments and approaches, including regulatory measures, economic incentives, education and awareness raising, and targeted funding for innovation and research. Table 6.16 gives an overview of possible types of policy options.

Table 6.16. Overview of Types Policy to Enable Circular Economy.

Policy Types	Examples
Regulatory frameworks	- EU and national strategies for WHO European Member States including targets, e.g., EU Action Plan on circular economy. - Product standards and regulations, e.g., REACH - Waste regulations, e.g., Waste Framework Directive, Waste Electrical and Electronic Equipment Directive, RoHS Directive, and related national legislation.
Economic instruments	- Consumer incentives e.g., VAT reductions for circular products. - Tax shift from labour to resources, e.g., Landfill tax - Financial support to business, for example subsidies, financial guarantees.
Education, information & awareness	- Public communication and information campaigns. - Business collaboration platforms for information and best practice sharing, e.g., ACES. - Technical business support for advice, training and demonstration projects. - NGO information and awareness initiatives.
Research and innovation policy	- R&D programmes e.g., EC DG Research Horizon 2020 projects on Circular Economy, COST; Circular Impacts project, international development bank projects.
Public procurement	- Circular economy standards in procurement law or guidelines, e.g., Danish Government Strategy on Intelligent Public Procurement.

Source: Adapted from Hunt, A, Dale, N & George, F (2018) & EMF (2015b).

The research and promotional literature on the circular economy includes broad visions of how circular principles can be further introduced and implemented in the built environment, including closing water, nutrition, material, and energy loops through circular design, construction and urban planning (e.g., see ARUP, 2016; Cheshire, 2016; EMF, 2015a). “Growth within: a circular economy vision for a competitive Europe” (EMF, 2015a) outlines six areas in which the built environment could advance towards a less wasteful model based on circular principles: (1) Industrial production and 3D printing; (2) Energy generation and use (in which reduced water consumption, water reuse and recirculation such as RWH is included); (3) Shared residential space, (4) Shared and virtual office space; (5) Modularity and durability; and (6) Urban planning. The ARUP (2016) report underlines the broad environmental and social benefits of implementing circular principles in the built environment, including impacts on climate change, water, soil, noise and air pollution, and implications for human health and well-being.

EMF/ARUP (2019) presents an overview of policy levers enabling a circular economy transition focusing specifically at the city level. It identifies ten policy levers (under 5 headings) as key to urban circular economy transitions.

- Vision (Road maps and strategies)
- Engagement (convening and partnering, raising awareness, capacity building)
- Urban management (urban planning, asset management, public procurement)
- Economic incentives (financial support, fiscal measures)
- Regulation (legislation and regulation).

There is, however, a recognition that further development is needed in how to practically enable the application of circular economy principles for the built environment. ARUP/EMF (2020) presents ways in which "circular economy thinking offers real estate investors a framework for achieving environmental and social goals while at the same time delivering better economic performance". As well as design strategies, the ARUP/EMF report argues that real estate business models need to change if circular economy principles are to be widely adapted and presents new circular real estate business models which can deliver better returns on a reduced resource footprint. Five models (Flexible spaces, Adaptable Assets, Relocatable Buildings, Residual Value, Performance Procurement) are used to demonstrate how implementation of circular economy principles can deliver improved financial performance to real estate investors and construction clients. The report by Schröder & Raes (2021) also highlights the need to de-risk and incentivize financial investments in circular models and put the case for integrating the circular economy more directly into public investment and stimulus packages.

6.8.3. Cost of circular economy innovations at the design and construction phase

The literature on circular economy and built environment promotes enhanced productivity and savings for the global construction industry (ARUP, 2016). The UKGBC (2019) gives guidelines for applying CE principles at the project brief and construction stages and identifies examples of cost savings to be made at this stage[10]. However, it is noted that such examples of cost saving are not given in the circular economy literature for technologies such as RWH, GWR and WWHR. as proposed in the Filton Airfield project (cost savings are assessed for RWH in Report D1.8). Indeed, while the built environment CE reports reviewed (such as UKGBC (2019), CE & WBCSD (2018) and EMF/ARUP (2019)), refer to reuse of materials and water, there is limited specific mention of these technologies (ARUP (2015) includes "Rainwater harvesting, grey water recycling" in a summary of CE design).

Notwithstanding these examples of costs savings, many still consider circular construction to be a more expensive option resulting in reluctance to invest in circular solutions (Braakman et al, 2021). It is argued that cost increases associated with more sustainable approaches have often been difficult for construction to absorb during a period of tight margins. Moreover, most of the costs may be incurred at the design and construction phases while savings will be accrued after sale/rental of properties to end-users of a building throughout its lifetime. For example, it is proposed in EMF (2015) that the direct housing (cash-out) cost per household could be reduced by as much as 30–35 percent, largely due to reduced utility costs driven by increased energy efficiency, distributed production and water recirculation. Thus, while whole life cost modelling may demonstrate overall savings these do not necessarily arise at the construction stage, meaning that "the upfront costs of introducing a more circular

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[10] (1) An initial assessment of the 2,800-home Merton Regeneration Project in South-West London estimates £5 million cost savings in waste disposal and materials purchase at the demolition and construction phase.
(2) The Brighouse and Sowerby Bridge leisure centres estimate a 0.5% reduction in total project costs and a saving of £56,175 through designing out waste and associated landfill costs.

approach represent a barrier that may need economic stimulus to overcome"11. In essence, developers can currently face higher investment costs for circular solutions, but these properties do not necessarily attract higher values in the market. Thus, incentive structures are needed for circular solutions to become more viable for developers, as outlined in the next section.

It should be noted, however, that the issue of initial costs is nuanced in that the level and type of circular technology defines life cycle costs and costs of construction. The study by Braakman et al., (2021) found that it was possible to double the Level of Circularity (LoC) in the design of a family house without increasing the Life Cycle Costs (LCC) but increasing the circularity level further resulted in a sharp increase in product costs, and therefore an increase in LCC, making it less economically attractive for construction companies.

6.8.4. Types of incentive structure

The various ways to incentivise the uptake of circular economy and sustainable approaches in the design and construction phases are the subject of the following discussion and matrix of options (Table 6.17 gives details of types of incentive, stakeholders, and examples). This focuses on the most relevant types of incentives for the Filton Airfield development from the range of policy levers outlined above (and based on the structure of policy levers given in EMF/ARUP, 2019):

- Financial support: This covers grants, subsidies, direct and indirect investments, and loans. Much of the current support for circular economy is direct funding for research and development focused on supporting innovation and pilot projects. There are also examples of co-financing of circular economy related projects and public-private partnerships to support development of circular technologies in construction. Use of public-private partnership performance frameworks, including circular procurement criteria, are promoted for large-scale construction projects involving city governments to help mitigate and share risk (ARUP/EMF, 2020). It should be noted that the funding landscape is constantly evolving so continued review of latest opportunities is recommended, such as through the Circular Economy Club (See Table 5 Useful Links in Appendix). It is also the case that recent changes to funding opportunities appear - to some extent - to be related to loss of access to EU funding initiatives. The Circular City Funding Guide (See Table 5 Useful Links in Appendix), while EU focused, provides a useful overview of funding options (Grants, Equity, Guarantees, Loans) for different types of projects.

- Fiscal measures: Includes a range of measures aimed to provide incentives and raise revenue to support transition to a Circular Economy. These can be tax breaks for circular economy activities by businesses or for circular economy products, or charges, fees and fines designed to disincentivise wasteful linear practices.

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[11] "Can the circular economy make construction more sustainable?", Article in Planning and Construction News, April 2020.
Can the circular economy make construction more sustainable? (pbctoday.co.uk).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

The current framework of environmental taxes in the UK[12] (Climate Change Levy, Emissions trading, Capital allowances on energy-efficient items, Landfill Tax, Aggregates Levy, Plastic Packaging Tax) makes limited specific references to Circular Economy (although the Landfill Tax and Aggregates Levy provide incentives for materials efficiency and reuse) and taxes do not give specific relief for innovative technological solutions to close the water cycles in construction projects, such as those proposed for Filton Airfield development.

The broader tax framework in the UK applicable to building design and construction does not currently provide specific incentives for circular economy innovations, although there are some examples (in Table 6.2) of this internationally. In fact, there are arguments that some UK current tax schemes work against circular economy activities[13]. How to adjust the current tax framework to incentivise Circular Economy innovations is an area for further policy debate and development (such as introducing incentives through differential rates of VAT, business rates or corporation tax). There are, however, examples of water companies providing discounts in fees for customers with water recycling technologies (inc. RWH and GWR). The Thames Water discount scheme is motivated by the need to address water stress in the region (see Table 6.3). There is also a broader discussion in the literature of how to design a circular economy taxation framework including raw material resource tax, reuse/repair tax relief, and a waste hierarchy tax (Milios, 2021). However, the focus here is on the current tax framework.

- Engagement: In particular, this refers to actions that raise awareness among business and house buyers/renters on circular economy opportunities. Circular economy related strategies, action plans, roadmaps at national and local level generally have a large element of awareness raising, through reaching out to a range of stakeholders and identification of the potential size of the benefits. This can be through online information, communication campaigns, hosting events and setting up exemplar projects (EMF/ARUP, 2019). National and city initiatives offer advice and support (including Peterborough and Glasgow – see Table 6.2), including identifying funding opportunities: e.g., Circular Economy Business Support Service (Scotland)[14]. However, the engagement plans and related services reviewed for this report do not in general focus on communicating in detail regarding impacts on typical household savings. In this context, such future awareness raising could focus more on communicating the potential magnitude of future savings in energy and water costs to end-users throughout the lifespan of a building (Deliverable D1.8, Section 4 includes some costs savings estimates for RWH). This is especially pertinent in an era of sharply rising energy prices and communicating the order of magnitude of future savings to end users may become an increasingly important issue in property buying decisions, thus

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[12] Environmental taxes, reliefs and schemes for businesses: Overview - GOV.UK (www.gov.uk)

[13] This article argues that the Enterprise Investment Scheme (SEIS) and the Enterprise Investment Scheme (EIS) explicitly exclude some circular economy activities from tax relief available in the schemes. UK legislation Is Working Against The Circular Economy (forbes.com)

[14] Circular Economy Business Support Service | Zero Waste Scotland

providing incentives for an uplift in demand and value of properties with circular technologies.

- Regulation: Includes legislation at national or city level, such as standards, rules, by-laws and bans that can promote development of circular economy innovations and opportunities. It should be viewed as working in combination with other policies for engagement, fiscal measures and urban planning. In this context regulation can refer to, for example, reuse and recovery of resources (including safe use of recycled water), and waste generation and disposal. As well as new legislation, promoting circular economy opportunities may also entail revising or remove existing regulations that restrict innovations. In the context of sustainability/circularity, the current focus of building regulation in the UK is on meeting carbon emission targets, such as new energy efficiency standards. While this will incentivise circular solutions in general, current regulation is not specifically focused on promoting circular innovations currently envisaged for Filton Airfield.

Table 6.18 gives more details and links to specific examples of Circular Economy incentives in UK focused on national and city level initiatives for financial support and engagement. Key UK examples of local circular economy engagement are the Circular Peterborough and Circular Glasgow initiatives. The South Gloucestershire Council “Resource and Waste Strategy: 2020 and Beyond” also includes commitment to implementing circular principles although the strategy does not focus specifically on the types of circular technologies being considered for the Filton site.

Table 6.17. Matrix of Circular Economy Incentive Options for Built Environment.

Type of Incentive	Details of operation	Operator/stakeholders	Relevance to Filton Development	Examples/Links
Financial support				
Direct Funding for Research and Development	Research development funding to further understanding of urban circular economy opportunities.	Research organizations, central government, city governments, business.	UK funding opportunities are focused on supporting innovation and pilot projects. This is open to businesses but grants relatively small and mainly focused on SMEs.	Examples in UK (See Table 6.3): - UK Research and Innovation National Interdisciplinary Circular Economy Research (NICER), - The Circular Future Fund, - Cymru: Circular Economy Fund. Examples in Europe: - Amsterdam[15] and Brussels[16].
Co-Financing Development of Circular Economy Related Projects	Co-financing to stimulate innovations and uptake to meet public policy targets such as zero waste and climate commitments.	Central government, city governments, business.	Examples in UK focus on support of SMEs and incubator programmes.	Examples in UK: - Advance London investment programme. London Waste and Recycling Board (LWARB) and Greater London Authority are co-investors. Examples in Europe: - Amsterdam[17] and Hamburg[18].
Public-Private Investment Funds	Collaborative investment schemes with funding from the public and private sector to share, reduce and mitigate high risks of costly projects.	Funding organizations/banks, city governments, business/private sector.	This form of financial support is most relevant for large projects such as Filton, but in the literature review examples for circular economy investment are focused on EU.	Examples in Europe: - JESSICA Urban Development Funds (Council of European Development Bank and European Investment Fund). Equity, loans, and guarantees for projects that support sustainable urban development and regeneration[19]. - Urban Innovation Action Fund:[20]
Fiscal Measures				
Tax breaks to incentivize circular economy practices.	Tax rebates, preferential rates and discounts, provided by national or local governments	Tax authority, city government, business, house buyers.	The review of UK tax framework applicable to building design and construction does not currently	International examples: - Cleveland and Cincinnati[21] offered tax abatements for new construction and

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[15] Amsterdam Institute for Advanced Metropolitan Solutions (AMS) collaboration between knowledge institutions, business and public stakeholders to deliver metropolitan solutions to urban challenges. AMS Institute - Circularity in Urban Regions (ams-institute.org)

[16] Brussels Regional Programme for a Circular Economy: be circular be.brussels (circulareconomy.brussels)

[17] C40 Good Practice Guides: Amsterdam - Sustainability Fund and Amsterdam Climate & Energy Fund - C40 Cities

[18] Hamburg Investment and Development Bank provides co financing for businesses investing in resource efficient measures.

[19] Jessica: A new way of using EU funding to promote sustainable investments and growth in urban areas (eib.org)

[20] UIA - Urban Innovative Actions (uia-initiative.eu)

[21] USGBC case study profiles successful Cincinnati residential tax abatement | U.S. Green Building Council

Type of Incentive	Details of operation	Operator/stakeholders	Relevance to Filton Development	Examples/Links
	for circular economy products, businesses and projects.		provide specific incentives for circular economy innovations. Future potential for tax incentives given political will.	existing building retrofits that are LEED certified[22]. - Shandong city offers VAT refunds to manufacturers of prefabricated modularised components and cost refunds for use of prefabricated walls.
Charges/fees to incentivise behaviour change.	Charges or differential fees mainly refer to consumption of goods and services.	Tax authority, city government, business, consumers.	Examples of water companies providing discounts for properties with water recycling technologies. Water metering of properties also provides incentives for water recycling. Potential for future charges/fees incentivizing circular economy given political will.	- Thames Water discounts for RWH and GWR new connections (see Table 6.3) - UK Landfill Tax and Aggregates Levy provide incentives for materials efficiency and reuse. - Most examples in the literature are for consumer goods (e.g., carrier bag charges in UK), transport (e.g., congestion charges in London, Milan, Oslo and Stockholm. etc.) and waste collection/disposal by volume (such as Landfill Tax).
Engagement				
Awareness raising	Raising awareness of circular economy opportunities is key stakeholders via to Knowledge sharing and communication campaigns, hosting events and exemplar projects.	City and Local Authorities, National Government, Construction companies, Property buyers/renters.	- Calculating and communicating potential magnitude of future savings in energy and water costs to end-users throughout the lifespan of a building. - Raising awareness of environmental and social benefits of circular economy technologies to buyers, potential funders and Government.	National and city level circular economy strategies and roadmaps have high focus on awareness raising including identifying funding opportunities. - City initiatives such as Peterborough and Glasgow include opportunities for construction sector (Table 6.3). - National level initiatives include Circular Economy Business Support Service (Scotland).
Capacity building	Training and advisory support for circular economy opportunities in the built environment. Such capacity building programmes can be	Construction companies, Property buyers/renters, City and Local Authorities, National Government.	Linked to awareness raising. Existing or new training and advisory services could include how to estimate potential cost saving per property.	London's Advance London Accelerator programme offered bespoke circular economy advice to qualifying small and medium-sized enterprises. appropriate circular economy finance opportunities.

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[22] LEED rating system | U.S. Green Building Council (usgbc.org)

Type of Incentive	Details of operation	Operator/stakeholders	Relevance to Filton Development	Examples/Links
	underpinned by financial support.			
Regulation				
Bylaws promoting circular economy practices.	Circular economy principles can be promoted in the construction sector through zoning plans, building standards, building codes and land tenders. This can be part of overall plans for circular redevelopment of specific areas of a city.	Central government, city authorities, building developers, householders.	The focus of building regulation in the UK relevant for sustainability/circularity is meeting carbon emission targets, such as new energy efficiency standards [23]. This will incentivise circular solutions but current regulation is not specifically focused on promoting circular water system innovations envisaged for Filton.	By laws enabling circular economy practices at city level: - City of Palm Desert, California, has regulated for building permit requiring circular economy principle in Waste Management Plans[24]. - Circular zones are being considered for Amsterdam where developments would have supportive regulation.
Revising and updating existing laws	Revision and updating may refer to: (i) providing better foundation to promote circularity or (ii) managing unintended consequences of existing legislation.	Central government, city authorities, building developers, householders.	For discussion with YTL: Are there any current specific regulatory/legislative barriers to circular technologies at Filton. What are the solutions?	In Baltimore[25] and New York City amendments to zoning regulations have eliminated barriers to construction and retrofitting of buildings using green/circular principles.

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[23] Rigorous new targets for green building revolution - GOV.UK (www.gov.uk)

[24] Construction and Demolition | Foster City California

[25] The Most Green Building Friendly Zoning Code in the Nation - Baltimore? | Green Building Law Update

Table 6.18. Examples of Circular Economy Incentives in UK.

Programme/Source	Details	Link
Financial Support		
UK Research and Innovation National Interdisciplinary Circular Economy Research (NICER) programme	Circular economy for SMEs: Small grant funding to research, test and develop step-change circular economy (includes construction materials). Eligibility: UK registered SMEs	Circular Economy for SMEs - innovating with NICER, round 2 - Innovate UK KTN (ktn-uk.org)
Welsh Government and WRAP Cymru: Circular Economy Fund	£6.5 million in Grants for circular economy projects. But not currently open for applications and not construction focused.	Grants and investments | WRAP
The Circular Future Fund: The Million Pound Challenge	John Lewis Partnership £1 million fund to support ideas and innovations that accelerate the transition towards a more circular economy.	The Circular Future Fund — Home
Circular Economy Investment Fund, Scotland.	Administered by Zero Waste Scotland, offering investment grants for SMEs based in Scotland. Supported by Scottish Government and European Regional Development Fund through £73 million Resource Efficiency Circular Economy Accelerator Programme. ERDF support will end in December 2022. A successor programme is being prepared, with similar objectives for projects commencing in 2023.	Circular Economy Investment Fund | Zero Waste Scotland
Fiscal Measures		
Thames Water (Charging for new connection services)	Financial incentives for water recycling technologies for your new development (inc. RWH and GWR). Discounts of up to £1,000 per property.	Charging arrangements for new connection services (thameswater.co.uk)
Engagement		
Circular Economy Business Support Service (Scotland)	Includes identifying funding opportunities.	Circular Economy Business Support Service | Zero Waste Scotland
Circular Peterborough	Circular City Roadmap. Includes opportunities for construction sector.	Future Peterborough - Opportunity Peterborough See also Opportunity Peterborough (2018).
Circular Glasgow: Construction Sector Information Hub.	Benefits of circular economy solutions for construction sector and provides links to case studies.	Construction sector information hub – Circular Glasgow
Climate Smart Cities Challenge: ristol	The challenge is looking for innovative business models, services and/or products that can help shape a new housing development appraisal and financing model that enables the development of affordable, zero carbon new homes in the city starting in 2023. Among other items, Finalist will be offered access and signposting to datasets and studies, including housing and financing data.	Bristol - Climate Smart Cities (citieschallenge.org)
South Gloucestershire Council: Resource and Waste Strategy: 2020 and Beyond	Waste strategy with focus on materials and waste, but with commitment to implementing circular principles.	South Gloucestershire Council (southglos.gov.uk)

6.8.5. Conclusions

Which policy levers and other incentive options are most appropriate and realizable to promote uptake of circular economy technologies, particularly in the context of innovations proposed at the Filton Airfield Development?

- Financial support: The review for this study found limited opportunities for direct funding of investment in circular economy technologies for large construction projects in the UK. Most of the currently available schemes are for supporting research and development, with small grants for innovation in incubator and pilot projects. Examples of Co-Financing Development and Public-Private Investment Funds available for Circular Economy Related Projects were generally for EU Member States.

- Fiscal Measures: The review found limited examples of fiscal measures in the UK designed directly to support circular economy technologies in construction projects, although some international examples are available. The UK Landfill Tax and Aggregates Levy provide incentives for materials efficiency and reuse, but the tax framework does not give specific relief for innovative technological solutions to close water and energy cycles in construction projects (such as via RWH and GWR). How the current tax framework can be used to incentivise Circular Economy innovations in the future is an area for further policy debate and developments will depend on political will.

- Discounts in fees: As well as tax breaks, uptake of water recycling technologies can also be supported by water companies (see Thames Water example in Table 6.2) by providing discounts in fees. This could be a promising development of relevance to the Filton development if adopted in the region. Although the design of schemes such as that offered by Thames Water is focused on uptake by homeowners, cost savings are in addition to those from water consumption savings in order to provide an extra and direct incentive for investment in RWH, GWR etc. This would be an additional reason for increasing awareness raising on cost savings for potential buyers (see below) in order to boost property values to reflect private and external benefits.

- Engagement: Circular economy related strategies, roadmaps and other initiatives at national and local level generally have a large element of awareness raising, including through identification of the potential size of the benefits to stakeholders. However, the initiatives reviewed for this report do not focus in much financial detail on communicating the cost savings for circular technologies in the built environment, including water reuse technologies. While some sources provide estimates of typical household savings[26], we suggest there is much scope for estimating in more detail the potential magnitude of future savings in energy and water costs to end-users throughout the lifetime of a property (per type and size) and communicating this to potential buyers via marketing campaigns. Such estimates could become a more important element in the decision making of property buyers in an era of sharply rising

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[26] For example, see general savings estimates given here for RWH technologies: How A Rainwater Harvesting System Can Help Save You Money (rainharvesting.co.uk)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

  utility prices and effectively communicating the order of magnitude of future savings may contribute to an uplift in the demand for and value of properties incorporating these circular technologies.

  Also of relevance to engagement is communication with potential funders and policy makers in efforts to incentivize uptake. For example, the estimation of social benefits for RWH, GWR, WWHR and other circular technologies can aid discussion with policy makers, funders etc. on the need to provide greater incentives for uptake since, in the experience of YTL, there is currently limited scope for external benefits of circular technology to be included in the price of properties.

  It is also suggested that efforts to promote uptake of circular technologies at the Filton development may benefit from further engagement with other initiatives, both through sharing ideas and information with the active circular economy community (see Table 6 Useful Links in Annex) and connecting with relevant local initiatives. For example, circular economy principles are central to the South Gloucestershire Council (2020) *Resource and Waste Strategy: 2020 and Beyond*[27].

  - Regulation: In terms of promoting sustainability/circular economy technologies the current focus of building regulation in the UK is meeting carbon emission targets. However, current regulation is not specifically focused on promoting circular innovations envisaged for Filton Airfield. Changes in building regulation could be used as a policy lever for uptake of such technologies in the future but this would be a more long-term development.

- Expansion of use of circular principles: While the focus of this report is circular economy technologies envisaged for the Filton Airfield development, the vision of a circular economy for built the environment presented in, for example, ARUP (2016) and EMF (2020) is much broader including new models of building materials reuse and recycling, modularity and durability, and shared residential space. These are presented as having potential to create substantial cost savings including at design and construction phases. Therefore, we suggest there could be further consideration of which additional aspects of circular economy for the built environment could be considered appropriate and practical for the Filton Development. In particular, if savings promoted for these additional aspects could be realised by developers, then one option would be to cross subsidize the additional investment in technologies that have higher initial costs to developers (such as RWH and GWR).

Overall, the aim of the options discussed above is to address the commercial risk associated with potentially higher up-front costs of implementing circular solutions. “Overcoming these barriers will require collaboration, not only within the construction industry between clients, contractors and suppliers to consider commercial risk but also with the insurance and legal sectors in order to fully understand the risks and opportunities associated with circular economy in construction and develop appropriate instruments which not only safeguard

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[27] While the focus of the South Gloucestershire strategy is on materials and waste, there is an explicit commitment to implementing circular principles.

companies from excessive exposure but encourage innovation that will move the circular economy forward”[28].

Finally, it is noted that many of these specific conclusions on incentive options in the context of innovations proposed at the Filton Airfield Development are consistent with more general conclusions given in Adeyeye et al (2022) (D4.3 of the NextGen project) on the challenges and opportunities across regulatory and policy frameworks related to circular water systems and services. Although the report focuses on European legislation national/regional legislative frameworks in Member States, some general conclusions are relevant for consideration in the UK context. These refer to: (i) an overall regulatory gap around how smaller-scale (building-scale) circular solutions are addressed; (ii) how interest in energy and materials recovery technologies amongst utilities “has not yet been matched with the emergence of a coherent policy and regulatory framework around technology adoption and bringing products to market” and (iii) clear opportunities “for circular solutions to become part of the ESG (Environmental, Social and Governance) investment landscape, and a focal point for more public-private partnerships”.

The recommendations of Adeyeye et al (2022) for national governments, also worthy of further consideration in the UK context, includes such incentive measures as (i) adjusting tariff systems to better support circular solutions, (ii) explicitly incorporating small-scale circular solutions in planning and building frameworks and (iii) supporting efficient risk sharing in contracting for Public-Private-Partnership arrangements.

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[28] What do we need in order to achieve Circular Economy in construction? (ciria.org)

CHAPTER 7

Deliverable D1.8

7. Upscaling and Future Implementations

Given that urban water recovery and reuse has the potential to be a secure and sustainable solution, the implementation of rainwater harvesting has shown two main benefits: first, it saves mains water, and second, it decreases the amount of rainwater runoff. Although the former benefit has been examined in previous studies, the latter has rarely been addressed because most of the studies have considered a combined sewage system. In other words, those studies did not consider the water disposal cost in the economic analysis since spillage from a rain tank is discharged to a combined sewer network, rendering the contribution of the water disposal cost to the total cost of the system insignificantly compared with other economic factors such as mains water price (Abas et al., 2019; Domènech et al., 2011; Lade et al., 2017; Nnaji et al., 2020). In addition, as mentioned above, this rainwater harvesting feasibility study considered the water disposal cost, as it is a site-specific study, and all the assumptions were made in the light of Filton Airfield's development master plan. In the plan, this area is expected to have a separate sewage network system. Thus, this study considered the costs related to mains water supply and sewer discharge separately. The results drawn from the RWH system study imply that the use of the RWH system allows reducing mains water consumption. However, if the harvested rainwater is not continuously utilised for non-potable end uses, the RWH system would become economically unfeasible. In this context, a decentralised hybrid RWH and GWR recycling system could be more promising to balance between discontinuous rainwater yield and continuous greywater production with a significant reduction of potable water consumption. The quantitative approach to these benefits would provide an additional boost to the public perception of the urban water management system and improves the widespread adoption of urban resource recovery technologies with different scales in the future.

In addition, while the technology required for recovering low-grade heat from sewers is well understood there are still many practical considerations including maintenance and economic viability which remain unclear, and it has not yet been implemented in the UK. However, the study conducted within the Filton Airfield development will assist in evaluating the viability of in-sewer wastewater heat recovery in residential areas and demonstrate how to quantify the flow and temperature patterns of wastewater within the sewer network to estimate the energy available for recovery. Therefore, this study will support the further assessment and implementation of the heat recovery reliability and applicability from a real large sewer network over different weather conditions within a year.

Finally, the feasibility of local recovery of nutrients and local application as a fertiliser in the green spaces in the Filton area is necessary as the urban water-nutrient nexus heads to a more sustainable urban development plan and its future implementation. The implemented approach during the NextGen project can be applied to a new sewer design that transports wastewater at a higher density (lower water content), enhancing recovery efficiency. Results obtained from the project can be used to understand the nutrient recovery potential in the pre-design stage of a new housing district development.

Most importantly, according to the proposed YTL Development Plan submitted in April 2022 (YTL, 2022), the number of residential units will be increased from 2,675 to 6,500. Table 7.1 presents key changes proposed for the new planning application. This will lead to differences in the availability of urban resources. Upscaling and future implementation of the NextGen technologies and approaches will be a key challenge within the Filton Airfield development scheme. Adopting NextGen technologies demonstrated for recovering water, energy and material/nutrients requires upscaling of components and products, establishing new relationships and developing new skills. This is also highly associated to the high starting capital and operational costs and is connected to multiple stakeholders.

Thus, the socio-economic impact of the NextGen solutions demonstrated in this study needs to be further investigated to provide clear benefits and drawbacks for public and society. The findings obtained from the future investigation will become a substantial part of current circular value chains in the water sector and contribute to upscaling solutions and transferring technologies to other regions.

Table 7.1. Key changes to development proposals between the extant planning consent and new proposed planning application.

Development Type	Extant Planning Consent	New Planning Application
Dwellings	2,675	6,500
Hotel	120-bed hotel	3 hotels
Rail Station	Rail Station	No change
Secondary School	Secondary School	No change
Primary School	2 x primary school	No change
Nursery	2 x nurseries	No change
Further Education	None	55,000 m^2
Library	Library	No change
Sports Facilities	Sports facilities (including a cricket pitch, football pitches, a hockey pitch and a rugby pitch)	No change
Doctors Surgery	6 no. Doctors surgeries	To be agreed
Dental Surgery	800 m^2 Dental surgery	To be agreed
Extra Care Facility	70 Bed Extra Care Facility	600 units of extra care
Food/drink	Food/drink facilities	No change
Supermarket	2,787 m^2 Supermarket	Flexible provision
Drinking Establishments	Drinking Establishments	No change
Business Offices	500 m^2	270,000 m^2 of Business Offices and Research Development
Student Accommodation	None	55,000m^2

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CHAPTER 8

Deliverable D1.8

8. Conclusions and Recommendations

Three main areas covered during the NextGen project are alternative water resources, recovery of energy and recovery of nutrients (Chapter 3, 4 and 5, respectively). Tasks are focused on demonstrating the feasibility of the proposed approaches in implementing integrated circular economy schemes in Filton Airfield. In addition, the study explored the future opportunities and constraints in the policy and regulations and finally proposed recommendations.

Rainwater harvesting systems were demonstrated by assessing the water saving efficiency, storm water capture efficiency and loss factor. Results show that the tank storage capacity is the most significant determinant of system performance. In addition, the choice of water mass balance operating algorithm was found to have no considerable effect on performance. The decentralised system exhibits better performance due to a higher catchment-demand ratio which equates to greater cost savings from reduced mains usage. Although the decentralised system offers a better return on investment, it only serves 8.3% of the demand served by the centralised system; therefore, the effect from economies of scale may render the centralised system as the best choice for the case study, in particular for a large-scale RWH system (i.e., YTL Arena application as demonstrated in this study). These results provided reference for an optimisation approach of RWH systems used to improve water savings and stormwater reduction performance for the urban development at Filton Airfield. In order to improve an urban resource management strategy, the urban water cycle with different water management options - RWH; GWR; and combined RWH and GWR – were demonstrated using UWOT. Four indicators of urban harvesting potential assessment were used - demand minimisation index (DMI), wastewater output index (WOI), self-sufficiency index (SSI), and resource exported index (REI). The results confirmed the improvement of the DMI going from 0% to 78% and the WOI going from 100% to 56% due to additional water being supplied from the recycling of greywater. In addition, the integrating greywater with rainwater had the large potential of wastewater discharge (i.e., overflow from the storage system, WOI >>100%) if rainwater or greywater is not exported or if the storage size is limited. However, the WOI can be further improved by exporting the excess treated greywater to be applied for other non-potable uses such as car washing and irrigation.

Heat recovery potential in urban water cycle and local use for domestic uses including space heating and water heating was investigated. Modelling and prediction of heat recovery and supply potential from wastewater in the Filton Airfield development was demonstrated as a decision support for sustainable urban energy management option selection in Filton development area. the results showed that if the wastewater discharge is cooled by 3 °C for heat recovery, it is possible to recover up to 38,788 kWh/y (i.e., 7.85% of the total energy demand for the Filton area) for the residential area consisting of conventional houses, indicating that the total heat recovery potential is highly dependent on wastewater flow rates. Results suggest that in-sewer WWHR is the most appropriate and sustainable option for implementing heat recovery in a residential context as it recovers energy where flow rates and temperatures are both highest and closest to the demand point. However, the diurnal pattern of wastewater requires heat storage systems/technologies to balance demand and supply.

The application on a case study in Filton Airfield demonstrated the suitability of the suggested method as well as the promising potential of nutrient recovery, and the role it can play to reach sustainable circular economy targets. Nutrient recovery potential of urban wastewater sewer network is demonstrated using two scenarios were considered: baseline and ecohouse. By using water-saving toilets, water-saving shower heads and waterless washing machines, the flow rate of wastewater into the sewer network was reduced by as much as 28.7% with an average reduction of 18.2% for the morning period. Thus, the phosphorous concentration in the wastewater increased by as much as 36.6% using water-saving appliances and increased by an average of 27.9% over the morning period.

Since the long-term ambition is to develop the Filton area into a showcase in urban development for the UK, further activities beyond NextGen will include exploration resource recovery from wastewater – either locally or nationally by considering the impact of urban resource recovery on centralised water systems and services. Although this study demonstrated the feasibility of urban resource recovery and reuse, the upscaling and future implementation will be challenged regarding acceptability by regulators, impact of benefits and drawbacks and capital and operational cost. Thus, significant research efforts are still needed to have operational and performance data directly relevant and applicable to the real world and fulfil the empirical and experimental perspective for urban designers and developers. This chapter therefore proposes three recommendations as follows:

1. <u>Water quality requirements</u>

Wastewater reuse requires proper treatment facilities to control water quality and prevent risks to human health. Conducting a risk analysis is crucial to address potential risks affecting the commercialisation of secondary products. For instance, greywater reuse is one of the most promising strategies available to address water scarcity. Indeed, there have been tremendous efforts made to apply reclaimed wastewater for non-potable and potable purposes. However, the portion of directly reused greywater/wastewater for potable use is less than around 5%, whereas for agricultural use (non-potable) it stands at around 32% due to fewer restrictions and lower treatment costs than there are for drinking water application (Capodaglio, 2020). Although conventional and advanced treatment technologies are capable of removing a wide range of contaminants, indicating that the treated water is suitable for the irrigation of a wide range of crops, it requires careful salinity risk management. In this context, it is recommended to create a list of water quality parameters of alternative water sources (greywater, rainwater and surface runoff) as well as risk assessment of secondary products (treated wastewater and fertilisers recovered from urine/wastewater). Social attitudes to the use of treated wastewater can be enhanced by managing the quality better.

2. <u>Circular solution data at a large-scale</u>

This study has shown a great deal of effort into the circular economy. However, the current challenge is that a large-scale operation of a circular economy is still required as potential benefits and drawbacks for water companies and end-users are currently theoretical. Thus, it requires ways or mechanisms that would foster strengthening trust. In this context, urban water, energy and nutrients data at a large scale and develop new sustainability indicators that can provide end-users make fast and direct decisions. This will therefore advance scientific and practical value beyond the current efforts and support to evaluate the progress of efforts toward circularity.

3. Overcome challenges of transforming water services

Although the public and industry have become familiar with using treated wastewater, seasonal water demand and the unwillingness of end-users lead to some treated wastewater still being discharged into the environment. Development of a new roadmap to make an interactive learning platform, which can achieve enhanced public acceptance and engagement of relevant stakeholders and successful implementation of small-, medium- and full-scale resource recovery projects. In addition, since there are no building regulations for circular water solutions in the UK, it is recommended to have appropriate design codes/Building regulations including incentives that is provided by national or local governments.

References

Abas, P.E., Mahlia, T. 2019. Techno-Economic and Sensitivity Analysis of Rainwater Harvesting System as Alternative Water Source. *Sustainability*, **11**(8), 2365.

Abdollahi, Z., Kavian, A., Sadeghi, S. 2017. Spatio-temporal changes of water quality variables in a highly disturbed river. **3**(3), 243-256.

Abu-Ghunmi, D., Abu-Ghunmi, L., Kayal, B., et al. 2016. Circular economy and the opportunity cost of not 'closing the loop'of water industry: The case of Jordan. *Journal of cleaner production*, **131**, 228-236.

Acharya, D., Boyd, R., Finch, O. 2020. From Principles to Practices: Realising the value of circular economy in real estate. *Ellen MacArthur Foundation & Arup*, Realising the value from circular economy in real estate - Arup.

Adeyeye, K., Qtaishat, Y., Zhiteneva, V., Kleyböcker, A., Larkin, C. Smith, H. (2022) *Challenges and opportunities across policy and regulatory frameworks,* Final Report D4.3 for NextGen Project.

Adhikary, P.P., Chandrasekharan, H., Chakraborty, D., et al. 2010. Assessment of groundwater pollution in West Delhi, India using geostatistical approach. *Environmental Monitoring and Assessment*, **167**(1-4), 599-615.

Agudelo-Vera, C.M., Keesman, K.J., Mels, A.R., et al. 2013. Evaluating the potential of improving residential water balance at building scale. *Water research*, **47**(20), 7287-7299.

Agudelo-Vera, C.M., Leduc, W.R., Mels, A.R., et al. 2012. Harvesting urban resources towards more resilient cities. *Resources, conservation and recycling*, **64**, 3-12.

Agudelo-Vera, C.M., Mels, A., Keesman, K., et al. 2012. The urban harvest approach as an aid for sustainable urban resource planning. *Journal of Industrial Ecology*, **16**(6), 839-850.

Aheeyar, M.M.M., and Bandara, M.A.C.S. (2010). Economic evaluation of institutional level rainwater harvesting. HARTI Research Report No: 134, Hector Kobbekaduwa Agrarian Research and Training Institute, Colombo, Sri Lanka

Ali, S., Gillich, A. 2019. Determining the UK's potential for heat recovery from wastewater using steady state and dynamic modelling-preliminary results. *2nd Global Conference on Energy and Sustainable Development, GCESD2018*. WEENTECH.

Ali, S., Zhang, S., Yue, T. 2020. Environmental and economic assessment of rainwater harvesting systems under five climatic conditions of Pakistan. *Journal of Cleaner Production*, 120829.

Alim, M.A., Rahman, A., Tao, Z., et al. 2019. Suitability of Roof Harvested Rainwater for Potential Potable Water Production: A Scoping Review. *Journal of Cleaner Production*, 119226.

Al-Khashman, O.A., Alnawafleh, H.M., Jrai, A.M.A., et al. 2017. Monitoring and Assessing of Spring Water Quality in Southwestern Basin of Jordan. *Open Journal of Modern Hydrology*, **7**(4), 331-349.

Amos, C. C., Rahman, A., & Gathenya, J. M. (2016) Economic Analysis and Feasibility of Rainwater Harvesting Systems in Urban and Peri-Urban Environments: A Review of the Global Situation with a Special Focus on Australia and Kenya, Water 2016, 8.

Amos, C.C., Rahman, A., Gathenya, J.M. 2018. Economic analysis of rainwater harvesting systems comparing developing and developed countries: A case study of Australia and Kenya. *Journal of Cleaner Production*, **172**, 196-207.

An, K.J., Lam, Y.F., Hao, S., et al. 2015. Multi-purpose rainwater harvesting for water resource recovery and the cooling effect. *Water Research*, **86**, 116-121.

Aquaterra. 2008. International comparisons of domestic per capita consumption Environment Agency.

Archer, J., Worter, M. 1997. Wastewater heat recovering unit and dishwashing machine, Google Patents.

ARUP (2016) *The Circular Economy in the Built Environment*, ARUP, London, September 2016.

ARUP. 2016. The Circular Economy in the Built Environment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

ARUP/EMF (2020) From Principles to Practices: Realising the value of circular economy in real estate. ARUP and Ellen MacArthur Foundation. Realising the value from circular economy in real estate - Arup

Arup_CircularEconomy_BuiltEnvironment.pdf

ASCE, T.C.o.H.H.o.M.G.D.o. 1996. Hydrology handbook. American Society of Civil Engineers.

Assefa, Y.T., Babel, M.S., Sušnik, J., et al. 2018. Development of a generic domestic water security index, and its application in Addis Ababa, Ethiopia. *Water*, **11**(1), 37.

Bailer, P., Pietrucha, U. 2006. District heating and district cooling with large centrifugal chiller–heat pumps. *Proc. 10th Int. Symp. on District Heating and Cooling*. pp. 3-5.

Bailey, O., Arnot, T., Blokker, E., et al. 2019. Developing a stochastic sewer model to support sewer design under water conservation measures. *Journal of Hydrology*, **573**, 908-917.

Bailey, O., Arnot, T., Blokker, E., et al. 2020a. Predicting impacts of water conservation with a stochastic sewer model. *Water Science and Technology*, **80**.

Bailey, O., Zlatanovic, L., van der Hoek, J.P., et al. 2020b. A Stochastic Model to Predict Flow, Nutrient and Temperature Changes in a Sewer under Water Conservation Scenarios. *Water*, **12**(4), 1187.

Batstone, D.J., et al. (2014) Platforms for energy and nutrient recovery from domestic wastewater: A review. *Chemosphere,* 2014.10.021.

BEIS. 2021. National Energy Efficiency Data-Framework (NEED), Department for Business, Energy and Industrial Strategy (BEIS) London.

Bergstrand, S. (2020) A study on the effects on a wastewater treatment plant when recovering the heat from the wastewater, Thesis for KTH School of Industrial Engineering and Management.

Birks, R., Colbourne, J., Hills, S., et al. 2004. Microbiological water quality in a large in-building, water recycling facility. *Water Science and Technology*, **50**(2), 165-172.

Birks, R., Hills, S. 2007. Characterisation of indicator organisms and pathogens in domestic greywater for recycling. *Environmental monitoring and assessment*, **129**(1), 61-69.

Blokker, E.J.M. 2010. Stochastic water demand modelling for a better understanding of hydraulics in water distribution networks.

Blokker, M., Agudelo-Vera, C., Moerman, A., et al. 2017. Review of applications for SIMDEUM, a stochastic drinking water demand model with a small temporal and spatial scale. *Drinking Water Engineering and Science*, **10**(1), 1-12.

Boano, F. et al (2020) A review of nature-based solutions for greywater treatment: Applications, hydraulic design, and environmental benefits, *Science of The Total Environment*, 711, 2020.

Bocanegra-Martínez, A., Ponce-Ortega, J.M., Nápoles-Rivera, F., et al. 2014. Optimal design of rainwater collecting systems for domestic use into a residential development. *Resources, Conservation and Recycling*, **84**, 44-56.

BPIE (2020) An Action Plan for the Renovation Wave: Collectively achieving sustainable buildings in Europe, Buildings Performance Institute Europe (April 2020). An-action-plan-for-the-renovation-wave_DIGITAL_final.pdf (bpie.eu)

Braakman, L. et al. (2021) “Exploring the relationship between the level of circularity and the life cycle costs of a one-family house”, *Resources, Conservation & Recycling* 164 (2021) 105149

Braakman, L., Bhochhibhoya, S., de Graaf, R. 2021. Exploring the relationship between the level of circularity and the life cycle costs of a one-family house. *Resources, conservation and recycling*, **164**, 105149.

BristolWater. 2021. Bristol Water Wholesale Charges Schedule 2020-21.

Campisano, A., Butler, D., Ward, S., et al. 2017. Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Research*, **115**, 195-209.

Campisano, A., Modica, C. 2012a. Optimal sizing of storage tanks for domestic rainwater harvesting in Sicily. *Resources, Conservation and Recycling*, **63**, 9-16.

Campisano, A., Modica, C. 2012b. Regional scale analysis for the design of storage tanks for domestic rainwater harvesting systems. *Water Science and Technology*, **66**(1), 1-8.

Campisano, A., Modica, C. 2014. Selecting time scale resolution to evaluate water saving and retention potential of rainwater harvesting tanks. *Procedia Engineering*, **70**, 218-227.

Capodaglio, A.G. 2020. Fit-for-purpose urban wastewater reuse: Analysis of issues and available technologies for sustainable multiple barrier approaches. *Critical Reviews in Environmental Science and Technology*, 1-48.

Carrillo, V., Fuentes, B., Gómez, G., et al. 2020. Characterization and recovery of phosphorus from wastewater by combined technologies. *Reviews in Environmental Science and Bio/Technology*, **19**(2), 389-418.

CE & WBCSD (2018) Circle Economy and World Business Council for Sustainable Development, Scaling the circular built environment: pathways for business and government (November 2018). Scaling the Circular Built Environment: pathways for business and government (wbcsd.org)

Cheshire D (2016). *Building revolutions: applying the circular economy to the built environment*. Riba Publishing, London.

Cheshire, D. 2019. *Building revolutions: Applying the circular economy to the built environment*. Routledge.

Christian Amos, C., Rahman, A., Mwangi Gathenya, J. 2016. Economic analysis and feasibility of rainwater harvesting systems in urban and peri-urban environments: a review of the global situation with a special focus on Australia and Kenya. *Water*, **8**(4), 149.

Dale, N., Hunt, A., Fischer, T., Hurley, F., Nowacki, J., George, F. (2019) Assessing the Health Impacts of a Circular Economy, World Health Organization. Assessing the health impacts of a circular economy (who.int)

Dale, N., Hunt, A., Fischer, T.B., et al. 2019. Assessing the health impacts of a circular economy, Assessing the health impacts of a circular economy (who.int), OMS. Copenhagen.

Dallman, S. & Anita M. Chaudhry & Misgana K. Muleta & Juneseok Lee, 2016. "The Value of Rain: Benefit-Cost Analysis of Rainwater Harvesting Systems," Water Resources Management: An International Journal, Published for the European Water Resources Association (EWRA), Springer;European Water Resources Association (EWRA), vol. 30(12), pages 4415-4428, September.

Dallman, S., Chaudhry, A.M., Muleta, M.K., et al. 2021. Is rainwater harvesting worthwhile? A benefit–cost analysis. *Journal of Water Resources Planning and Management*, **147**(4), 04021011.

DBEIS. 2018. What is a heat network?, (Ed.) E.I.S. Department for Business, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/696273/HNIP_What_is_a_heat_network.pdf.

de Gois, E.H., Rios, C.A., Costanzi, R.N. 2015. Evaluation of water conservation and reuse: a case study of a shopping mall in southern Brazil. *Journal of Cleaner Production*, **96**, 263-271.

DeBusk, K. and Hunt, W., (2012) Rainwater Harvesting: A Comprehensive Review of Literature. *Biological & Agricultural Engineering*, North Carolina State University. North Carolina Water Resources Research Institute. Project No. 11-12-W, 2012.

Diaz-Elsayed, N., Rezaei, N., Guo, T., et al. 2019. Wastewater-based resource recovery technologies across scale: a review. *Resources, Conservation and Recycling*, **145**, 94-112.

Dionisi,D. Geris, J. & Bolaji, I. (2018) Water and the circular economy – Where is the greatest sustainable economic benefit for resource recovery in the water cycle? Published by CREW – Scotland's Centre of Expertise for Waters.

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.

Domènech, L., Saurí, D. 2011. A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the Metropolitan Area of Barcelona (Spain): social experience, drinking water savings and economic costs. *Journal of Cleaner production*, **19**(6-7), 598-608.

Doncaster, S., Blanksby, J., Shepherd, W. 2012. Rainwater harvesting-An investigation into the potential for rainwater harvesting in Bradford.

Dunsmore, I. (2016) Heat from Wastewater - UK Water Projects – Renewable Energy UK Water Projects. Scottish_SHARC_2016.indd (waterprojectsonline.com)

Dürrenmatt, D.J., Wanner, O. 2014. A mathematical model to predict the effect of heat recovery on the wastewater temperature in sewers. *Water research*, **48**, 548-558.

EA (2008) Greenhouse gas emissions of water supply and demand management options, Environment Agency.

EA (2010) Energy and carbon implications of rainwater harvesting and greywater recycling, Environment Agency, Bristol, UK.

EC (2020) A New Circular Economy Action Plan: For a cleaner and more competitive Europe, European Commission, Brussels, 11.3.2020 COM(2020) 98 final.

Elías-Maxil, J., Van Der Hoek, J.P., Hofman, J., et al. 2014. Energy in the urban water cycle: Actions to reduce the total expenditure of fossil fuels with emphasis on heat reclamation from urban water. *Renewable and Sustainable Energy Reviews*, **30**, 808-820.

EMF (2015a) Growth within: a circular economy vision for a competitive Europe, , Ellen MacArthur Foundation. Benefits of adopting a circular economy for Europe | Report (ellenmacarthurfoundation.org)

EMF (2015b). Towards a circular economy: business rationale for an accelerated transition. Cowes: Ellen MacArthur Foundation.

EMF (2020) Circular investment opportunities for a low-carbon and prosperous recovery, Ellen MacArthur Foundation, Covid 19 Recovery Series: The Built Environment Circular economy and the Covid-19 recovery - The Built Environment | Shared by Comms (thirdlight.com)

EMF. 2020. Circular investment opportunities for a low-carbon and prosperous recovery, Ellen MacArthur Foundation Covid 19 Recovery Series: The Built Environment Ellen MacArthur Foundation

EMF/ARUP (2019) *City governments and their role in enabling a circular economy transition: an overview of urban policy levers*, Ellen MacArthur Foundation and ARUP, March 2019.

EMF/ARUP. 2019. City governments and their role in enabling a circular economy transition: an overview of urban policy levers.

Evans-Gavhure, T.J., (2021) Modelling the potential of heat recovery from UK housing developments. MEng Research Project, University of Bath, 2021.

Farman Ali, S. & Gillich, A. (2020) The potential of the heat recovery from urban sewage wastewater for use in residential and commercial buildings, *CIBSE ASHRAE Technical Symposium*, Glasgow, UK 16-17 April 2020.

Farman Ali, S. & Gillich, A. (2021) Opportunities to decarbonize heat in the UK using Urban Wastewater Heat Recovery. *Building Services Engineering Research and Technology*. 2021;42(6):715-732.

Farman Ali, S., Gillich, A. 2021. Opportunities to decarbonize heat in the UK using Urban Wastewater Heat Recovery. *Building Services Engineering Research and Technology*, **42**(6), 715-732.

Farreny, R., Gabarrell, X., Rieradevall, J. 2011. Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods. *Resources, Conservation and Recycling*, **55**(7), 686-694.

Fewkes, A. 2012. A review of rainwater harvesting in the UK. *Structural Survey*, **30**(2), 174-194.

Fewkes, A., Butler, D. 2000. Simulating the performance of rainwater collection and reuse systems using behavioural models. *Building Services Engineering Research and Technology*, **21**(2), 99-106.

Fox, C., McIntosh, B.S., Jeffrey, P. 2009. Classifying households for water demand forecasting using physical property characteristics. *Land use policy*, **26**(3), 558-568.

Frank Oesterholt, J.H. 2014. Feasibility of Small Scale Heat Recovery from Sewers. KWR.

Fredenham, E., Longshaw, M., Ballinger, S. & Sam Stephenson, S. (2020) *Independent review of the costs and benefits of rainwater harvesting and grey water recycling options in the UK*, Report for Waterwise, prepared by Ricardo Energy & Environment, September 2020.

Freni, G. & Liuzzo, L. (2019) Effectiveness of Rainwater Harvesting Systems for Flood Reduction in Residential Urban Areas, *Water* 2019, 11, 1389; doi:10.3390/w11071389

Friedler, E., Kovalio, R., Galil, N. 2005. On-site greywater treatment and reuse in multi-storey buildings. *Water science and technology*, **51**(10), 187-194.

Fulton, L. 2018. A Simulation of Rainwater Harvesting Design and Demand-Side Controls for Large Hospitals. *Sustainability*, **10**(5), 1659.

Funamizu, N., Iida, M., Sakakura, Y., et al. 2001. Reuse of heat energy in wastewater: implementation examples in Japan. *Water Science and Technology*, **43**(10), 277-285.

Gerolin, A., Kellagher, R., Faram, M. 2010. Rainwater harvesting systems for stormwater management: Feasibility and sizing considerations for the UK. *NOVATECH 2010*.

Gershuny, J., Sullivan, O. 2017. United Kingdom Time Use Survey, 2014-2015, http://doi.org/10.5255/UKDA-SN-8128-1, [data collection]. UK Data Service. SN: 8128.

Ghimire, S.R., Johnston, J.M., Garland, J., et al. 2019. Life cycle assessment of a rainwater harvesting system compared with an AC condensate harvesting system. *Resources, Conservation and Recycling*, **146**, 536-548.

Ghimire, S.R., Johnston, J.M., Ingwersen, W.W., et al. 2017. Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system. *Journal of Cleaner Production*, **151**, 74-86.

Gunawardena, A., Zhang, F., Fogarty, J., Iftekhar, M. S., (2017). Review of non-market values of water sensitive systems and practices: An update. Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Hajani, E., Rahman, A. 2014. Reliability and cost analysis of a rainwater harvesting system in peri-urban regions of Greater Sydney, Australia. *Water*, **6**(4), 945-960.

Haque, M.M., Rahman, A., Samali, B. 2016. Evaluation of climate change impacts on rainwater harvesting. *Journal of Cleaner Production*, **137**, 60-69.

Hawley, C. & Fenner, R. (2012) The potential for thermal energy recovery from wastewater treatment works in southern England. *J Water Clim Change* 2012; 3(4): 287–299.

Herut, B., Starinsky, A., Katz, A., et al. 2000. Relationship between the acidity and chemical composition of rainwater and climatological conditions along a transition zone between large deserts and Mediterranean climate, Israel. *Atmospheric Environment*, **34**(8), 1281-1292.

Hervás-Blasco, E., Navarro-Peris, E., Corberán, J.M. 2020. Closing the residential energy loop: Grey-water heat recovery system for domestic hot water production based on heat pumps. *Energy and Buildings*, **216**, 109962.

Hills, S., Birks, R., McKenzie, B. 2002. The Millennium Dome "Watercycle" experiment: to evaluate water efficiency and customer perception at a recycling scheme for 6 million visitors. *Water Science and Technology*, **46**(6-7), 233-240.

Hills, S., Smith, A., Hardy, P., et al. 2001. Water recycling at the Millennium Dome. *Water science and technology*, **43**(10), 287-294.

Hingray, B., Haha, M.B. 2005. Statistical performances of various deterministic and stochastic models for rainfall series disaggregation. *Atmospheric Research*, **77**(1-4), 152-175.

Hoekstra, N., Pellegrini, M., Bloemendal, M., et al. 2020. Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage. *Science of the Total Environment*, **709**, 136142.

Hrabová, K., Hrdlička, T., Tlašek, M. 2019. Use of Heat from Wastewater. *IOP Conference Series: Earth and Environmental Science*. IOP Publishing. pp. 012095.

Hunt, A, Dale, N & George, F (2018) Circular Economy and Health: Opportunities and Risks, WHO European Region. Circular-Economy_EN_WHO_web_august-2018.pdf

Imteaz, M.A., Ahsan, A., Shanableh, A. 2013. Reliability analysis of rainwater tanks using daily water balance model: Variations within a large city. *Resources, Conservation and Recycling*, **77**, 37-43.

Imteaz, M.A., Karki, R., Hossain, I., et al. 2017. Climatic and spatial variabilities of potential rainwater savings and economic benefits for Kathmandu Valley. *International Journal of Hydrology Science and Technology*, **7**(3), 213-227.

Intelligent Energy Europe Report (2007) Heating with wastewater heat Best Practice Catalogue: Examples from Germany, Switzerland, Austria, Norway and Sweden. Intelligent Energy Europe Programme of the European Community.

IWA. 2018. Wastewater Report 2018: The reuse opportunity. International water association.

Jenkins, D., Pearson, F. 1978. Feasibility of rainwater collection systems in California. *Contribution-California. University*.

Johannesdottir S. et al (2020) What evidence exists on ecotechnologies for recycling carbon and nutrients from domestic wastewater? *Environ Evid* (2020) 9:24

Juan, Y.K., Chen, Y. and Lin, J., M., (2016) Greywater Reuse System Design and Economic Analysis for Residential Buildings in Taiwan, *Water*, 2016.

Khastagir, A., Jayasuriya, N. 2011. Investment evaluation of rainwater tanks. *Water resources management*, **25**(14), 3769.

Kim B, Anderson K, Lee S, Kim H (2014) A real option perspective to value the multi-stage construction of rainwater harvesting systems reusing septic tank. Water Resour Manag 28:2279–2291. https://doi.org/10.1007/s11269-014-0613-3

Kim, J.E., Phuntsho, S., Chekli, L., et al. 2017. Environmental and economic impacts of fertilizer drawn forward osmosis and nanofiltration hybrid system. *Desalination*, **416**, 76-85.

Kim, J.E., Phuntsho, S., Chekli, L., et al. 2018. Environmental and economic assessment of hybrid FO-RO/NF system with selected inorganic draw solutes for the treatment of mine impaired water. *Desalination*, **429**, 96-104.

Kim, J.E., Teh, E.X., Humphrey, D., et al. 2021. Optimal storage sizing for indoor arena rainwater harvesting: Hydraulic simulation and economic assessment. *Journal of Environmental Management*, **280**, 111847.

Kim, Jung Eun; Daniel Humphrey & Jan Hofman (2022) Evaluation of harvesting urban water resources for sustainable water management: Case study in Filton Airfield, UK. *Journal of Environmental Management* 322 (2022) 116049 Reporting results for NextGen: Towards the next generation of water systems and services for the circular economy.

Kim, R.-H., Lee, S., Jeong, J., et al. 2007. Reuse of greywater and rainwater using fiber filter media and metal membrane. *Desalination*, **202**(1-3), 326-332.

Kisser J. et al (2020) A review of nature-based solutions for resource recovery in cities, *Blue-Green Systems*, Vol 2 No 1.

Koutsoyiannis, D., Pachakis, D. 1996. Deterministic chaos versus stochasticity in analysis and modeling of point rainfall series. *Journal of Geophysical Research: Atmospheres*, **101**(D21), 26441-26451.

Kulshrestha, U., Kulshrestha, M.J., Sekar, R., et al. 2003. Chemical characteristics of rainwater at an urban site of south-central India. *Atmospheric Environment*, **37**(21), 3019-3026.

Kurothe, R., Goel, N.K., Mathur, B. 1997. Derived flood frequency distribution for negatively correlated rainfall intensity and duration. *Water Resources Research*, **33**(9), 2103-2107.

Kuwayama Y, & Olmstead S.M. (2020) Hydroeconomic modeling of resource recovery from wastewater: Implications for water quality and quantity management. *J Environ Qual*. 2020;49(3):593-602. doi:10.1002/jeq2.20050

Lade, O., Oloke, D. 2017. Performance Evaluation of a Rainwater harvesting system: A Case Study of University College Hospital, Ibadan City, Nigeria. https://doi.org/10.9734/CJAST/2017/36623.

Lani, N.H.M., Syafiuddin, A., Yusop, Z., et al. 2018. Performance of small and large scales rainwater harvesting systems in commercial buildings under different reliability and future water tariff scenarios. *Science of The Total Environment*, **636**, 1171-1179.

Leusbrock, I., Nanninga, T., Lieberg, K., et al. 2015. The urban harvest approach as framework and planning tool for improved water and resource cycles. *Water Science and Technology*, **72**(6), 998-1006.

Li, Z., Boyle, F., Reynolds, A. 2010. Rainwater harvesting and greywater treatment systems for domestic application in Ireland. *Desalination*, **260**(1), 1-8.

Liang, X., van Dijk, M.P. 2011. Economic and financial analysis on rainwater harvesting for agricultural irrigation in the rural areas of Beijing. *Resources, conservation and recycling*, **55**(11), 1100-1108.

Linares, R.V., Li, Z., Yangali-Quintanilla, V., et al. 2016. Life cycle cost of a hybrid forward osmosis–low pressure reverse osmosis system for seawater desalination and wastewater recovery. *Water research*, **88**, 225-234.

MacArthur, E. 2015. Towards a circular economy: business rationale for an accelerated transition. *Greener Manag International*, **20**.

Makropoulos, C.K., Natsis, K., Liu, S., et al. 2008. Decision support for sustainable option selection in integrated urban water management. *Environmental modelling & software*, **23**(12), 1448-1460.

Marleni, N., Gray, S., Sharma, A., et al. 2012. Impact of water source management practices in residential areas on sewer networks–a review. *Water Science and Technology*, **65**(4), 624-642.

Matos, C., Bentes, I., Santos, C., et al. 2015. Economic analysis of a rainwater harvesting system in a commercial building. *Water Resources Management*, **29**(11), 3971-3986.

Matos, C., Santos, C., Pereira, S., et al. 2013. Rainwater storage tank sizing: Case study of a commercial building. *International Journal of Sustainable Built Environment*, **2**(2), 109-118.

Mayor, B. et al (2016) Total Value of Phosphorus Recovery, *Environ. Sci. Technol*. 2016, 50, 6606−6620.

McKee, T.B., Doesken, N.J., Kleist, J. 1993. The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology*. Boston. pp. 179-183.

Memon, F.A., Fidar, A.M., Ward. S., Butler. D., and Alsharif. K., (2016) Energy and carbon implications of water saving micro-components and greywater reuse systems. In: *Alternative Water Supply Systems.* Eds: Memon, F.A., Fidar, A.M. and Ward. S., 2016.

Meneses, M., Pasqualino, J.C., Castells, F. 2010. Environmental assessment of urban wastewater reuse: Treatment alternatives and applications. *Chemosphere*, **81**(2), 266-272.

Mikkonen, L., Rämö, J., Keiski, L. and Pongrácz, E. (2013) Heat recovery from wastewater: Assessing the potential in northern areas. In Water Research Conference, Thule Institute, University of Oulu Finland, 15th August, 2013.

Milios, L. 2021. Towards a circular economy taxation framework: Expectations and challenges of implementation. *Circular Economy and Sustainability*, **1**(2), 477-498.

Milios, L. Towards a Circular Economy Taxation Framework: Expectations and Challenges of Implementation. Circ.Econ.Sust. 1, 477–498 (2021). https://doi.org/10.1007/s43615-020-00002-z

Müller, E.; Schmid, F.; Kobel, B.; Stadtmeister, W. Heizen und Kühlen Mit Abwasser-Ratgeber für Bauträger und Kommunen Energierückgewinnung aus Häuslichem und Kommunalem Abwasser; Deutsche Bundesstiftung Umwelt: Osnabrück, Germany, 2009.

Nagpal, H., Spriet, J., Murali, M.K., et al. 2021. Heat recovery from wastewater—A review of available resource. *Water*, **13**(9), 1274.

Nagpal, H.; Spriet, J.; Krishna Murali, M.; McNabola, A. (2021) Heat Recovery from Wastewater—A Review of Available Resource. *Water*, 2021, 13, 1274.

NIC (2018) Preparing for a drier future England's water infrastructure needs, National Infrastructure Commission.

Niemela, M., Saarela, R. 2009. The wastewater utilization in Kakola heat pump plant, The International District Energy Climate Awards.

Nika, C., Vasilaki, V., Expósito, A., et al. 2020. Water cycle and circular economy: developing a circularity assessment framework for complex water systems. *Water Research*, **187**, 116423.

Nnaji, C.C., Aigbavboa, C. 2020. A Scenario-Driven Assessment of the Economic Feasibility of Rainwater Harvesting Using Optimized Storage. Water Resources Management, https://doi.org/10.1007/s11269-019-02462-x, 1-16.

Novo, A.V., Bayon, J.R., Castro-Fresno, D., et al. 2010. Review of seasonal heat storage in large basins: Water tanks and gravel–water pits. *Applied Energy*, **87**(2), 390-397.

Okoye, C.O., Solyalı, O., Akıntuğ, B. 2015. Optimal sizing of storage tanks in domestic rainwater harvesting systems: A linear programming approach. *Resources, Conservation and Recycling*, **104**, 131-140.

Oliver, J.E. 1980. Monthly precipitation distribution: a comparative index. *The Professional Geographer*, **32**(3), 300-309.

Oloman, R. (2012) Turning Waste into Energy: Clean Tech's Best Kept Secret. *Construction Business*, September/October 2012

ONS, O.f.N.S. 2021. Energy consumption in the UK 2021.

Opportunity Peterborough (2018) Circular Peterborough: Circular City Roadmap - an ambitious plan & performance monitoring framework towards 2021. PREVIEW_Peterboroughs-Circular-City-Roadmap.pdf (opportunitypeterborough.co.uk)

Ossa-Moreno, J., Smith, K.M. and Mijic, A. (2017) Economic analysis of wider benefits to facilitate SuDS uptake in London, UK*, Sustainable Cities and Society* 28, 2017.

Pacheco GCR, Campos MAS (2016) Economic feasibility of rainwater harvesting systems: a systematic literature review. J Water Supply Res T 66:1–14. https://doi.org/10.2166/aqua.2016.048

Pacheco, G.C.R., Campos, M.A.S. (2019) Real Options Analysis as an Economic Evaluation Method for Rainwater Harvesting Systems. Water Resour Manage 33, 4401–4415 (2019). https://doi.org/10.1007/s11269-019-02371-z

Parker, S. 2021. Final Energy Consumption by sector and fuel 1970-2020, (Ed.) N. Statistics, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1021836/Energy_Consumption_in_the_UK_2021.pdf.

Pavolová, H., Bakalár, T., Kudelas, D., et al. 2019. Environmental and economic assessment of rainwater application in households. *Journal of cleaner production*, **209**, 1119-1125.

Penn, R., Schütze, M., Friedler, E. 2013. Modelling the effects of on-site greywater reuse and low flush toilets on municipal sewer systems. *Journal of Environmental Management*, **114**, 72-83.

Perez, A., Stadler, I., Janocha, S., et al. 2016. Heat recovery from sewage water using heat pumps in cologne: A case study. *2016 International Energy and Sustainability Conference (IESC)*. IEEE. pp. 1-7.

Peterborough, O. 2018. Circular Peterborough: Circular City Roadmap - an ambitious plan & performance monitoring framework towards 2021.

Petersen, A.B., Energi, G. 2017. ReUseHeat Handbook-Experiences from other urban waste heat recovery investments, Kolding Denmark).

Pocernich, M., Litke, D.W. 1997. Nutrient concentrations in wastewater treatment plant effluents, south platte rwer basin 1. *JAWRA Journal of the American Water Resources Association*, **33**(1), 205-214.

Qtaishat, Y., Hofman, J., Adeyeye, K. 2022. Circular Water Economy in the EU: Findings from Demonstrator Projects. in: *Clean Technologies*, Vol. 4, pp. 865-892.

Renfrew et al (2022). Where is the greatest potential for resource recovery in wastewater treatment plants? *Water Research* 220 (2022) 118673.

Research, W.U.a. 2022. Recovering nutrients from waste water, Vol. 2022.

Rey, S.J. 2015. Mathematical models in geography. in: *International Encyclopedia of the Social & Behavioral Sciences: Second Edition*, Elsevier Inc., pp. 785-790.

Rodríguez, C. et al (2020) Cost–Benefit Evaluation of Decentralized Greywater Reuse Systems in Rural Public Schools in Chile, *Water,* 2020, 12.

Roebuck, R., Ashley, R. 2007. Predicting the hydraulic and life-cycle cost performance of rainwater harvesting systems using a computer based modelling tool. *Water Practice and Technology*, **2**(2).

Roebuck, R., Oltean-Dumbrava, C., Tait, S. 2011. Whole life cost performance of domestic rainwater harvesting systems in the United Kingdom. *Water and Environment Journal*, **25**(3), 355-365.

Rozos, E., Makropoulos, C. 2012. Assessing the combined benefits of water recycling technologies by modelling the total urban water cycle. *Urban Water Journal*, **9**(1), 1-10.

Rozos, E., Makropoulos, C. 2013. Source to tap urban water cycle modelling. *Environmental Modelling & Software*, **41**, 139-150.

Rozos, E., Makropoulos, C., Butler, D. 2010. Design robustness of local water-recycling schemes. *Journal of Water Resources Planning and Management*, **136**(5), 531-538.

Ruso, M., Akıntuğ, B., Kentel, E. 2019. Optimum tank size for a rainwater harvesting system: Case study for Northern Cyprus. *IOP Conference Series: Earth and Environmental Science*. IOP Publishing. pp. 012026.

Salman, J., Abd-Al-Hussein, N., Al-Hashimi, O. 2015. Assessment of water quality of Hilla River for Drinking water purpose by Canadian Index (CCME WQI). *International Journal of Recent Scientific Research*, **6**(2), 2746-2749.

Sample, D.J., Liu, J. 2014. Optimizing rainwater harvesting systems for the dual purposes of water supply and runoff capture. *Journal of cleaner production*, **75**, 174-194.

Schröder, P. & Raes, J. (2021) Financing an inclusive circular economy: De-risking investments for circular business models and the SDGs, Research Paper for Chatham House, The Royal Institute of International Affairs. Financing an inclusive circular economy | Chatham House – International Affairs Think Tank

Schulze, G. 2016. Growth within: A circular economy vision for a competitive Europe. *Ellen MacArthur Foundation and the McKinsey Center for Business and Environment*, 1-22.

Schüppler, S., Fleuchaus, P., Blum, P. 2019. Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage (ATES) in Germany. *Geothermal Energy*, **7**(1), 11.

Semaan, M., Day, S.D., Garvin, M., et al. 2020. Optimal sizing of rainwater harvesting systems for domestic water usages: A systematic literature review. *Resources, Conservation & Recycling: X*, 100033.

Sendanayke, S. 2016. *Rainwater Harvesting for Urban Living*. South Asian Institue of Technology and Medicine.

Shaddel, S. et al (2019) Sustainable Sewage Sludge Management: From Current Practices to Emerging Nutrient Recovery Technologies, *Sustainability*, 2019, 11, 3435.

Shi, L., Zan, C. 2008. Large-scale application of municipal reclaimed water source heat pump to a DHC system in the Beijing Olympic Village. *9th IEA Heat Pump Conference*.

Silva CM, Sousa V, Carvalho NV (2015) Evaluation of rainwater harvesting in Portugal: application to single-family residences. Resour Conserv Recycl 94:21–34. https://doi.org/10.1016/j.resconrec.2014.11.004

Silva, C.M., Sousa, V., Carvalho, N.V. 2015. Evaluation of rainwater harvesting in Portugal: Application to single-family residences. *Resources, Conservation and Recycling*, **94**, 21-34.

Słyś, D., Stec, A. 2020. Centralized or Decentralized Rainwater Harvesting Systems: A Case Study. *Resources*, **9**(1), 5.

South Gloucestershire Council (2020) Resource and Waste Strategy: 2020 and Beyond, Our waste strategy | South Gloucestershire Council (southglos.gov.uk)

Spriet, J.; Hendrick, P. (2017) Wastewater as a heat source for individual residence heating: A techno-economic feasibility study in the Brussels capital region. *J. Sustain. Dev. Energy Water Environ. Syst.* 2017, 5, 289–308. [

Spriet, J.; McNabola, A. (2019) Decentralized drain water heat recovery: A probabilistic method for prediction of wastewater and heating system interaction. *Energy Build*. 2019, 183, 684–696.

Statistics, O.f.N. 2020. 2011 Census: Aggregate Data, http://doi.org/10.5257/census/aggregate-2011-2, UK Data Service.

Steenvoorden, J. 2007. Wastewater re-use and groundwater quality: Introduction. *Water and Energy Abstracts*, **17**(2).

Tanguy, M., Dixon, H., Prosdocimi, I., et al. 2019. Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2017) [CEH-GEAR], https://eip.ceh.ac.uk/apps/rainfall/gb.html, NERC Environmental Information Data Centre.

Tapsuwan, S., Burton, M., Mankad, A., Tucker, D. & Greenhill, M. (2014) Adapting to less water: household willingness to pay for decentralised water systems in urban Australia. *Water resources management*, 28, 1111-1125.

Thames Water (2021) England's first sewage-powered domestic heating scheme planned for Kingston. England's first sewage-powered domestic heating | Newsroom | Thames Water

Theregowda, R. et al (2019) Nutrient Recovery from Municipal Wastewater for Sustainable Food Production Systems: An Alternative to Traditional Fertilizers, *Environmental Engineering Science*, Volume 36, Number 7, 2019.

Trust, E.S. 2013. At Home with Water - Energy Saving Trust.

Tsai, P. & Onishi, A. (2022) Urban households' willingness to pay for improvements in rainwater harvesting and rainwater infiltration system: Case study in Japan, *Water and Environment Journal*, 2022-03-18.

UKAS. 2020. United Kingdom Accreditation Service.

UKGBC (2019) Circular economy guidance for construction clients: How to practically apply circular economy principles at the project brief stage, UK Green Building Council. Circular-Economy-Report.pdf (ukgbc.org)

UKGBC. 2019. Circular economy guidance for construction clients: How to practically apply circular economy principles at the project brief stage. *UK GBC*, Circular-Economy-Report.pdf (ukgbc.org).

Umapathi, S., Pezzaniti, D., Beecham, S., et al. 2019. Sizing of Domestic Rainwater Harvesting Systems Using Economic Performance Indicators to Support Water Supply Systems. *Water*, **11**(4), 783.

Underground, W. 2020. Weather underground. in: Retrieved from Weather, https://www.wunderground.com/weather/gb/filton/IBRISTOL3.

Valdez, M.C., Adler, I., Barrett, M., et al. 2016. The water-energy-carbon nexus: optimising rainwater harvesting in Mexico City. *Environmental Processes*, **3**(2), 307-323.

Verstraete, W., Vlaeminck, S.E. 2011. ZeroWasteWater: short-cycling of wastewater resources for sustainable cities of the future. *International Journal of Sustainable Development & World Ecology*, **18**(3), 253-264.

Vestberg, O. 2017. Heat recovery from untreated wastewater : A case study of heat recovery from sewerline to district heating network. in: *TRITA-ITM-EX*, Vol. EGI_2017:0014, pp. 49.

Voinov, A., Farley, J. 2007. Reconciling sustainability, systems theory and discounting. *Ecological Economics*, **63**(1), 104-113.

Voulvoulis, N. 2018. Water reuse from a circular economy perspective and potential risks from an unregulated approach. *Current Opinion in Environmental Science & Health*, **2**, 32-45.

Wallace, C.D., Bailey, R.T., Arabi, M. 2015. Rainwater catchment system design using simulated future climate data. *Journal of Hydrology*, **529**, 1798-1809.

Wang, R., Zimmerman, J.B. 2015. Economic and environmental assessment of office building rainwater harvesting systems in various US cities. *Environmental science & technology*, **49**(3), 1768-1778.

Ward, S. 2007. Rainwater Harvesting in the UK–Current Practice and Future Trends. *Exeter, UK: Centre for Water Systems, University of Exeter, pg*, **1**.

Ward, S., Memon, F., Butler, D. 2010a. Harvested rainwater quality: the importance of appropriate design. *Water Science and Technology*, **61**(7), 1707-1714.

Ward, S., Memon, F.A., Butler, D. 2010b. Rainwater harvesting: model-based design evaluation. *Water Science and Technology*, **61**(1), 85-96.

Ward, S., Memon, F.A., Butler, D. 2012. Performance of a large building rainwater harvesting system. *Water Research*, **46**(16), 5127-5134.

WBCSD, C. 2018. Circle Economy and World Business Council for Sustainable Development, Scaling the circular built environment: pathways for business and government

Weber, B., Cornel, P., Wagner, M. 2007. Semi-centralised supply and treatment systems for (fast growing) urban areas. *Water Science and Technology*, **55**(1-2), 349-356.

Weissenbacher, N., Müllegger, E. 2009. Combined greywater reuse and rainwater harvesting in an office building in Austria: analyses of practical operation. *Sustainable Sanitation Practice*, **10**(1), 4-9.

Welsch, B., Göllner-Völker, L., Schulte, D.O., et al. 2018. Environmental and economic assessment of borehole thermal energy storage in district heating systems. *Applied Energy*, **216**, 73-90.

WHO. 2017. Guidelines for drinking-water quality, 4th Edition. 4th ed, https://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/, pp. 472-475.

YTL. 2021. YTL Masterplan, https://www.brabazon.co.uk/the-hangar-district.

YTL. 2021. 'YTL Masterplan'. https://www.ytldevelopments.co.uk/developments/ytl-arena-bristol.

YTL. 2022. Environmental Statement – Non-Technical Summary.

YTLGroup. 2020. Wholesale charges 2020-2021.

YTLGroup. 2021. Wholesale charges 2020-2021.

Zadeh, S., Hunt, D., Lombardi, D., et al. 2013. Shared urban greywater recycling systems: water resource savings and economic investment. *Sustainability*, **5**(7), 2887-2912.

Zarei ,M. (2020) Wastewater resources management for energy recovery from circular economy perspective, *Water-Energy Nexus* 3 (2020) 170–185.

Zhang, D., Gersberg, R.M., Wilhelm, C., et al. 2009. Decentralized water management: rainwater harvesting and greywater reuse in an urban area of Beijing, China. *Urban Water Journal*, **6**(5), 375-385.

Zhang, F., Polyakov, M., Fogarty, J. & Pannell, D. J. (2015) The capitalized value of rainwater tanks in the property market of Perth, Australia. Journal of Hydrology, 522, 317-325

Zhang, M., Chen, H., Wang, J., et al. 2010. Rainwater utilization and storm pollution control based on urban runoff characterization. *Journal of Environmental Sciences*, **22**(1), 40-46.

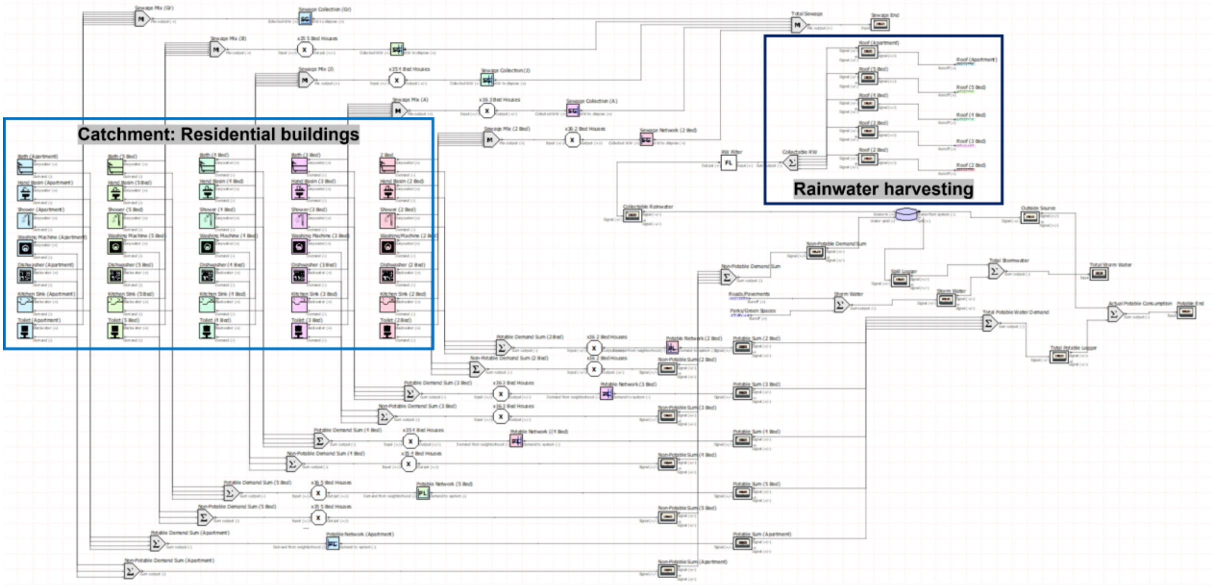
Zhang, S., Guo, Y. 2013. Explicit equation for estimating storm-water capture efficiency of rain gardens. *Journal of Hydrologic Engineering*, **18**(12), 1739-1748.

Zhang, S., Zhang, J., Jing, X., et al. 2018. Water saving efficiency and reliability of rainwater harvesting systems in the context of climate change. *Journal of cleaner production*, **196**, 1341-1355.

Zogg, M. 2008. History of heat pumps-Swiss contributions and international milestones.

Appendix

UWOT simulation



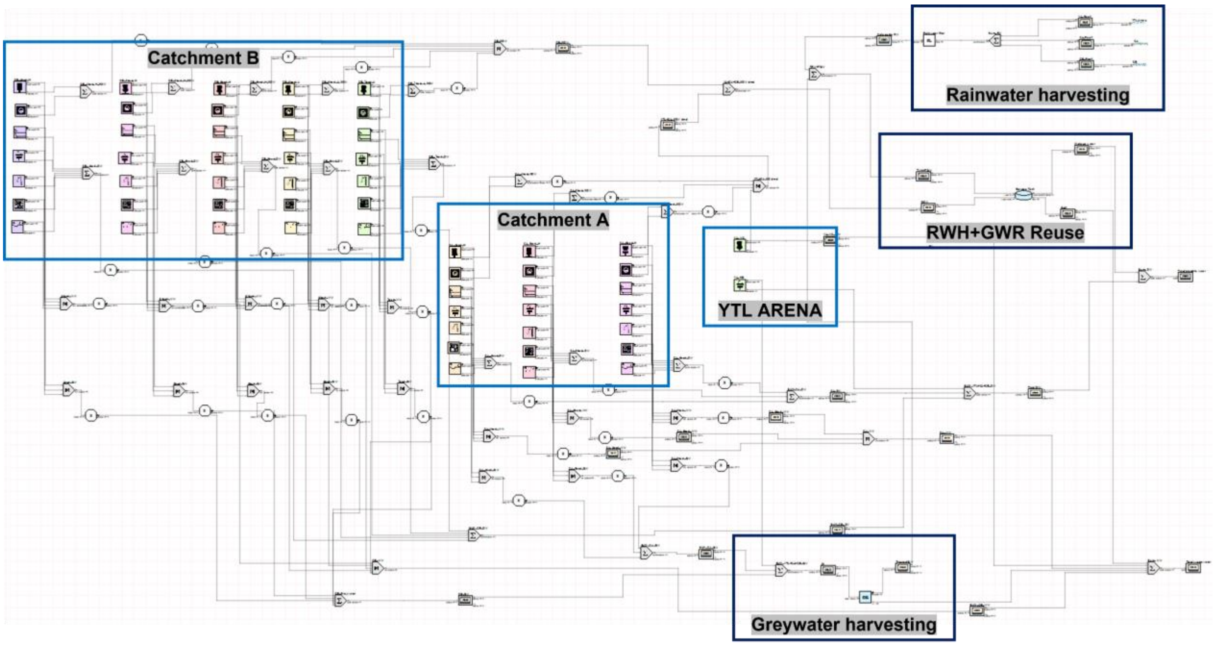


Table 1. Physio-chemical and microbial characteristics of raw rainwater.

Parameters	Units	Range (Min-Max)	Mean	SD	Irrigation water quality standards	Drinking water quality standards
Physiochemical parameters						
pH	-	7.0-8.4	7.57	0.36	6.5-8.4[a]	6.5-8.5[b]
Conductivity at 25 °C	µm/cm	8-62	25.20	16.02	700[a,c]	400[b]
Turbidity	NTU	0.11-0.6	0.25	0.11	5[b]	5[b]
Alkalinity ($CaCO_3$)	mg/L	<20	-	-	100[b]	100[b]
Total dissolved solids, TDS	mg/L	2.9-60	20.69	17.35	500[a,c]	500[d]
BOD	mg/L	<4	-	-	NS	NS
COD	mg/L	<50	-	-	NS	NS
Total hardness ($CaCO_3$)	mg/L	1.0-8.32	3.86	2.15	0-460[a]	500[e]
Ca. Hardness	mg/L	1.0-7.5	3.06	2.06	NS	NS
Mg. Hardness	mg/L	0.4-1.6	0.88	0.28	NS	NS
Microbiological parameters						
Chloride, Cl	mg/L	<3			250[c]	250[b]
Nitrite, NO_2	mg/L	<0.04	-	-	NS	3[b,d]
Nitrate, NO_3	mg/L	<0.2	-	-	5	50[b,d]
Ammonium, NH_4	mg/L	<0.4	-	-	0.5[c]	0.2[b]
Sulphate, SO_4	mg/L	<10	-	-	2-170	250[b]
Fluoride, F	mg/L	<0.04	-	-	1.5[c]	1.5[d]
Calcium, Ca	mg/L	0.3-3.0	1.19	0.84	NS	100[b]
Potassium, K	mg/L	0.1-1.0	0.22	0.25	12[c]	20[e]
Magnesium, Mg	mg/L	0.1-0.4	0.22	0.07	140	50[e]
Sodium, Na	mg/L	0.6-2.9	1.56	0.60	70[b,c]	50[d]
Iron, Fe	mg/L	<0.01	-	-	5.0[c]	0.3[b]
Manganese, Mn	mg/L	<0.001	-	-	0.2[c]	0.5[e]
Copper, Cu	mg/L	<0.01	-	-	NS	2.00[d]
Chromium, Cr	mg/L	<0.001	-	-	0.10[c]	0.05[b,d]
Cadmium, Cd	mg/L	<0.0001	-	-	0.01[c]	0.003[d]
Nickel, Ni	mg/L	<0.002	-	-	0.20[c]	0.07[d]
Zinc, Zn	mg/L	<0.01	-	-	2.0[c]	3.0[e]
Lead, Pb	mg/L	<0.0001	-	-	5.0[c]	0.01[b,d]
Microbiological parameters						
E.Coli	no/100 ml	30-500	109.6	130.02	1000[c]	0[d]

NS: Not Specified
SD: Standard deviation
[a] Abdollahi et al. (2017), Food and Agriculture Organization (FAO)
[b] Adhikary et al. (2010) and Salman et al. (2015)
[c] 98/93/EU directive, Steenvoorden (2007)
[d] WHO (2017)
[e] Al-Khashman et al. (2017)

Table 2. The quality of air in Central Bristol from 2007 to 2020.

Annual Mean, $\mu g/m^3$	NO_2	SO_2	PM_{10}
2007	31	2	20
2008	32	2	20
2009	30	2	19
2010	32	2	20
2011	27	2	N/A
2012	32	2	18
2013	28	N/A	18
2014	28	N/A	17
2015	26	N/A	15
2016	27	N/A	15
2017	24	N/A	15
2018	24	N/A	15
2019	23	N/A	16

Data is only available from 2007. N/A: not available
NO_2: Annual mean < 40 $\mu g/m^3$
SO_2: Annual mean < 20 $\mu g/m^3$
PM_{10} particulate matter (hourly measured): Annual mean < 40 $\mu g/m^3$
https://www.airqualityengland.co.uk/site/statistics?site_id=BRS8

Table 3. Daily water demand (L/p/day) for different household types for each catchment.

	Catchment A			Catchment B				
	Houses			Apartment		Houses		
	2-bed	3-bed	4-bed	1-bed	2-bed	2-bed	3-bed	4-bed
BH	3.1	3.4	3.3	3.9	3.3	3.7	3.4	3.0
BT	3.5	3.9	3.8	4.4	3.8	4.2	3.9	3.5
DW	1.7	1.8	1.8	2.1	1.8	2.0	1.8	1.6
KT	12.9	14.3	14.1	16.4	14.1	15.6	14.3	12.8
OT	11.7	13.0	12.7	0.0	0.0	14.1	13.0	11.6
SH	40.1	44.4	43.6	51.0	43.8	48.4	44.4	39.7
WC	31.4	34.7	34.1	39.9	34.2	37.9	34.7	31.0
WM	15.0	16.5	16.2	19.0	16.3	18.0	16.5	14.8
Total	119.4	132.1	129.6	136.7	117.4	144.0	132.0	118.1
Average	127.0			129.6				

Table 4. YAS water balance analysis for standard plan and an optimal storage tank for each scenario.

Hydraulic and Economic parameters	Unit	Residential (R)			Commercial (C)	Residential and Commercial (RC)		
		R1	R2	R3	C1	RC1	RC2	RC3
Mains water added in the tank	m^3/y	1,535	461	723	26,402	24,362	24,587	25,803
Rainwater harvested	m^3/y	9,503	4,876	4,628	7,585	17,088	12,460	12,212
Overflow	m^3/y	5,529	3,145	2,032	455	2,410	1,325	1,168
Total demand (WC+WM)	m^3/y	5,508	2,192	3,317	33,531	39,039	35,723	36,848
Water Saving Efficiency (WSE)	%	72%	79%	75%	21%	38%	31%	30%
Stormwater Capture Efficiency (SCE)	%	42%	36%	59%	94%	86%	89%	90%
Total LCC of RWH system	£/y	5,719	3,245	3,053	14,791	16,635	15,248	15,751
Total LCC of equivalent mains-only system	£/y	2,736	1,089	1,648	16,658	19,395	17,747	18,306
RWH savings	£/y	-2,983	-2,156	-1,406	1,868	2,760	2,499	2,555
Cost of harvested water	£/m^3	1.04	1.48	0.92	0.44	0.43	0.43	0.43
Cost of mains water, £/m³	£/m^3	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Demand met	%	173%	222%	140%	23%	44%	35%	33%
Optimal Tank Size	m^3	***100***	***50***	***100***	***100***	***300***	***200***	***200***

Table 5. Useful Links.

Source	Detail	Link
Climate Smart Cities Challenge: Bristol	The challenge is looking for innovative business models, services and/or products that can help shape a new housing development appraisal and financing model that enables the development of affordable, zero carbon new homes in the city starting in 2023.	Bristol - Climate Smart Cities (citieschallenge.org)
Bristol One City Plan (Launched in 2019)	Homes and Communities Board: Aim by 2050 is to build 60,000 new homes, of which 24,000 are affordable, and by 2037 all new homes built in the city will be fully accessible.	About the One City Plan - Bristol One City Homes and Communities Board - Bristol One City
Circular Economy Club (CEC)	Non-profit arm of the Circular Economy Institute (CEI). An international network for circular economy, including professionals. Including information on funding opportunities.	Awards & Funding | Circular Economy Club (CEC)
Circular City Funding Guide, produced for Urban Agenda Partnership for Circular Economy	Overview of circular economy funding options for different types of organisation and project. EU focused.	Funding types and their applicability » Circular City Funding Guide
Circular Glasgow: Construction Sector Information Hub	Benefits of circular economy solutions for construction sector and provides links to case studies.	Construction sector information hub – Circular Glasgow

London Accelerator Programme	Run by London Waste and Recycling Board (LWARB) Advance London programme. Dedicated to commercialising best new circular economy start-up business innovations. The focus for the first accelerator was the built environment sector.	New accelerator programme launched for London’s circular economy start-ups - ReLondon
UKGBC: Circular economy actor and resource map	Shares information on circular economy initiatives within the built environment. The purpose is to allow organisations to use existing knowledge and methodologies to successfully implement circular economy principles without repeating the work of others.	Circular economy actor and resource map - UKGBC - UK Green Building Council
Interdisciplinary Circular Economy Centre for Mineral-based Construction Materials (ICEC-MCM)	Part of The National Interdisciplinary Circular Economy Research (NICER) Programme. A four-year £30 million investment from UKRI to move the UK towards a circular economy.	CENTRE FOR MINERAL-BASED CONSTRUCTION MATERIALS - CE Hub (ce-hub.org)

Table 6. Useful Links.

Source	Detail	Link
South Gloucestershire Council: Resource and Waste Strategy: 2020 and beyond	Waste strategy with focus on materials and waste, but with commitment to implementing circular principles.	South Gloucestershire Council (southglos.gov.uk)
South Gloucestershire Housing Strategy 2022 to 2052	Set out the long-term ambition and vision for housing over the next 30 years. Projects 28,000 new homes needed by 2040. A key aim is sustainable homes with new housing stock delivered at net zero carbon.	South Gloucestershire Housing Strategy 2022 to 2052 | BETA - South Gloucestershire Council (southglos.gov.uk)
BAMB Initiative Enabling a circular building industry	European project promoting circular economy in building industry.	BAMB - Buildings As Material Banks (BAMB2020) - BAMB
Circular Economy Club (CEC)	Non-profit arm of the Circular Economy Institute (CEI). An international network for circular economy, including professionals. Including information on funding opportunities.	Awards & Funding | Circular Economy Club (CEC)
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