Sustainability Evaluation of Shared Greywater Recycling in Urban Mixed-use Regeneration Areas

By

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ABSTRACT

Greywater (GW) recycling for non-potable uses (e.g. urinal and toilet flushing) provides an urban water management strategy to help alleviate this risk by reducing mains water demands. The research described in this thesis proposes scenarios for an innovative cross-connected system that collects GW from residential buildings and recycles it for toilet/urinal flushing in both residential and office buildings. The capital cost (CAPEX), operational cost (OPEX), the carbon costs (embodied and operational), and water saving potential are calculated for individual block of residential and office buildings and shared GW recycling system between both building blocks in an urban mixed-use regeneration area in the UK assuming two different treatment processes; a membrane bioreactor (MBR) and a vertical flow constructed wetland (VFCW). The Net Present Value (NPV) method was used to compare the financial performance of each considered scenario from where it was found that over a 15 year period a shared GW recycling system (MBR) was the most economically viable option with an NPV of £213.11k and potable water savings of almost 27% (compared with mains water only system); 12% (compared with individual block GW recycling system). However, over the same time period it was shown that shared CW treatment had the lowest carbon emissions, saving up to 11% (compared to conventional mains supply), whereas a shared MBR increased carbon emissions by up to 27%. The sensitivity of this financial and emission model was assessed considering six parameters (i.e. water supply and sewerage charges, discount rate(s), electricity charges, service life, building description, user behaviour and improved technological efficiency).

DEDICATION

“In the middle of difficulty lies opportunity” Albert Einstein

To my father, for all his love and support. Without his wisdom, knowledge, and encouragement I would never achieve what I have now.

To my mother, for all her love, affection, patience and sacrifices. Her love and comfort makes my life much easier.

To my brother, his love and motivation made everything possible.

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"A master can tell you what he expects of you. A teacher, though, awakens your own expectations" Patricia Neal

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AIC	Average Incremental Cost
ASTM	American Society for Testing and Materials
BAF	Biologically Aerated Filters
BOD_5	Biochemical Oxygen Demand 5-day test
BREEAM	Building Research Establishment Environmental Assessment Method
BSI	British Standards Institution
BSRIA	Building Services Research and Information Association
CAPEX	Capital Expenditure
CBA	Cost benefit analysis
CEA	Cost Effectiveness Analysis
CFU	Colony Forming Units
CIRIA	Construction Industry Research and Information Association
CIWEM	Chartered Institution of Water and Environmental Management
CO2	Carbon Dioxide
COD	Chemical Oxygen Demand
CRD	Capital Regional District
CSH	Code For Sustainable Homes
CSBE	Centre for the Study of the Built Environment
CVM	Contingent Valuation Method
CW	Constructed Wetland
DCLG	Department for Communities and Local Government
DCF	Discount Cash Flow
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
EA	Environment Agency (UK)
EE	Energy Efficiency
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency (USA)
GDP	Gross Domestic Product
GHG	Green House Gas
GRP	Glass Reinforced Plastic
GW	Greywater
HCA	Homes and Communities Agency
HCL	Hydrogen Chloride
LCCA	Life Cycle Cost Analysis
ICWE	International Conference on Water and the Environment
ISO	International Organisation for Standardisation
LHDG	London Housing Design Guide

LEED	Leadership in Energy and Environment Design
IRR	Internal Rate of Return
MBR	Membrane Bioreactor
MJA	Marsden Jacob Associates
MPN	Market Transformation Programme
MT	Metric Tons
NaOH	Sodium hydroxide
NAPHCC	National Association of Plumbing-Heating-Cooling Contractors
NPV	Net Present Value
NSW	New South WALES
NTU	Nephelometric Turbidity Unit
OEDC	Organization for Economic Cooperation and Development
Ofgem	Office of Gas & Electricity Markets
Ofwat	Office of Water Services
ONS	Office of National Statics
OPEX	Operating Expenses
PE	Population Equivalent
PVC	Polyvinyl chloride
RPI	Retail Price Index
RWH	Rain Water Harvesting
SBR	Sequencing Batch Reactor
SCBA	Social Cost Benefit Analysis
SODCON	Survey of Domestic Consumption
TJ	Terajoules
TSS	Total Suspended Solids
UK	United Kingdom
UKWIR	United Kingdom Water Industry Research
UN	United Nations
USA	United Stated of America
UV	Ultra violet
VAT	Value Added Tax
VFCW	Vertical Flow Constructed Wetland
WC	Water Closet
WCED	World Commission on Environment and Development
WHO	World Health Organization
WLC	Whole Life Costing
WRAS	Water Resources Situation Assessment
WWAP	World Water Assessment Programme

CHAPTER ONE

INTRODUCTION

1.1 Background

Providing good-quality (i.e. drinking standard) water regularly to a growing world population is an increasing challenge for water supply utilities worldwide (Roznowski, et al., 2009). Many cities are experiencing pressure to satisfy a rapid increase in demands for water by urban areas. Population growth, rapid urbanization, higher standards of living and climate change are making a significant contribution to continues growth of urban water consumption (WWAP, 2009). The global population is expected to exceed nine billion by 2050 and total urban water consumption will increase by 62 % from 1995 (International Water Management Institute, 2002; UN 2010).

There are two approaches that address current and future water demands in urban regions. The first is to increase the water supply, for example, by (i) development of new supply resources (e.g. dams, reservoirs, and deep groundwater abstraction), (ii) water transfer or relocation of demand, (iii) seawater desalination, (iv) upgrading of the water treatment and pipe system and (v) improvements in operational methods such as pressure reduction of flow restrictions (Surrendran, 2001; Hunt and Lombardi, 2006). In many cases, these additional sources are either unavailable or can be developed only at extremely high direct and indirect costs compared with pre-existing water sources. Others are openly criticized by environmentalists, for example, the classic solution of building dams reduces water delivery from local rivers to many coastal areas. This can lead to changes in the natural environment, for example, the distribution of plants and animals and accelerated beach erosion (Walker, 1985; Kondolf, 1997). The more recent solution of desalination is considered to be expensive, energy intensive, and harmful to marine environment (Lattemann and Honer, 2008). As stated by Gleick, (2000) and Vairavamoorthy, (2009) the old pattern of planning and designing water supply systems, through 'techno-focusing', with less consideration to demand management issues and/or public engagement, is far from sustainable.

The second approach to meeting current and future water demands is to reduce potable water demands by: (i) optimizing the existing water supply system (i.e. reducing leakage), (ii) reduction of demand and losses by installing water-saving devices, and/or changing public behaviour; (iii) water re-use and recycling; and (iv) looking for alternative sustainable local sources of water (rainwater harvesting and greywater recycling) (Hunt and Lombardi, 2006). The primary priority should be (and is) given to reduction in water consumption. This is considered to be the cheapest and safest way of preserving water resources (Sharma and Vairavamoorthy, 2008). However, in many countries, a reduction in water consumption alone is not adequate as the water sources are already stressed even with sustainable water consumption rates (Taylor, 2007).

Wastewater reuse/recycling has gained increasing attention in both developing and developed countries. In such cases wastewater has been successfully used for supplying non-potable demands at various scales from centralised (with treatment) at municipal level, to decentralized systems, including reuse in a single building and on-site treatment (Exall et al., 2006). There is a wide ranging consensus that using wastewater to meet non-potable demand (e.g. toilet flushing, gardening, car washing, etc), makes environmental and economic sense, contributing to urban sustainability. Such high quality water is not required for these purposes (York and Burg, 1998). A conventional domestic wastewater management system involves the collection, transport, treatment and disposal (or re-utilisation) of GW and human excreta. The conventional theory of centralised systems dates back to the mid to late 19th Century. A great deal of effort has been put into the collection, treatment, and distribution of reclaimed water at large scale through centralized systems and this water undergoes a complex range of treatment processes. Centralized systems are highly reliant on water to dilute and transport waste. The technical literature includes many examples of adverse economic and environmental impacts associated with this traditional approach of wastewater provision and consequently brings growing concern that this approach may be unsustainable both now and in the future (Mitchell et al., 1997; Maksimovic et al., 1999; Lawrence et al., 1999; Bertrand-Krajewski et al., 2000; Hiessl et al., 2001; Schwartz, 2008).

An alternative to the centralized reuse of water is decentralized system. Decentralized wastewater systems are defined as those which can collect, store, treat then reuse (or dispose when necessary) small volumes of wastewater at or near its point of generation (Tanaka et al., 1998). Decentralized systems include single home, on-site systems and cluster systems that may serve hundreds of homes (Rocky Mountain Institute, 2004). This system has been reported to offer a more sustainable alternative to conventional water supplies as they can reduce energy required to transport water from the point of production to the point of use (OECD, 2009), resulting in beneficial reuse of GW (or use of rainwater), as well as providing greater consistency and more flexibility in a cost-effective manner (Zhang, et al, 2009).

Greywater recycling is receiving increasing attention as part of an overarching urban water management plan. Greywater (GW) is defined as the wastewater from baths, showers, handbasins, washing machines, dishwashers and kitchen sinks, and explicitly excludes streams from toilets (Jefferson et al., 2004; Briks and hills 2007). Toilet wastes are the most polluted portion of the wastewater streams from households. If such portions are removed from wastewater streams, the remaining wastewater has potential for reuse with less requirement for advanced treatment process. Further sub-division is common in the literature by restricting the GW sources to human washing operation such as water available from baths, showers and hand basins (Friedler et al., 2005; Memon et al., 2005). This GW is commonly called light GW due to containing less heavily polluted sources (Jefferon et al., 2004; Alkhatib, 2008). Light GW has generally uses at small scales (i.e. household) as it requires less advance treatments and there is a balance between available water supplies and demands. A wide variety of treatment options exist, from very simple to high-tech. An overview of the technologies available for GW treatment are further described in Chapter 2.

GW systems have been on the market for several years and there are numerous case studies of installed GW systems within individual family dwellings, multiple housing dwellings, multi-storey office buildings, and individual (multi-room) hotel buildings (Santala et al., 1998; Surrendran and Wheatley, 1998; Brewer *et al*, 2000; Smith *et al*, 2000; Leggett *et al*, 2001a; Day, 2002; Hills *et al*, 2002; Bray, 2003; Coombes et al., 2003a; Lodge, 2004; Paul & Bray, 2004; CIWEM, 2007). Existing GW systems generally reflect the view that “greywater could play a role in future management of water resources and in the solutions required to address water stress” (DEFRA, 2008). Governments and regulating bodies are trying to develop new ways to preserve fading water resources, and GW reuse (with or without treatment) is one of the key methods being considered (CRD, 2004). These systems can form part of a new urban water management paradigm that has the potential to be more sustainable than the traditional methods.

The challenges that have faced the implementation of GW recycling systems in the past have generally not been due to the practicalities; the engineering aspect of these systems has long been well established. Many GW recycling systems were found to suffer from some form of operational fault. The most common fault was insufficient water flow to flush the toilet, potentially related to failure of the backup potable water supply, especially in individual systems (EA, 2010). GW recycling systems do have social and to a lesser extent financial constraints. For example, there is the perception that GW recycling systems pose an unsustainable economic cost (Memon et al., 2005). In other words GW can be treated to suit all end-purposes but the limiting factors to date are cited as insufficient supply, prohibitive costs, and a lack of social acceptability.

1.2 Aims and objectives

The aim of this research is: *to evaluate the sustainability advantages of a shared GW recycling system,i.e. between residential and office building blocks, as compared to individual GW recycling systems therein.*

Particular attention is given to WC flushing in new UK building developments in urban mixed-use regeneration areas. The focus is on MBR (Membrane bioreactors), CW (Constructed Wetlands) and comparisons include financial assessment (NPV) and carbon emissions (including embodied).

The objectives of this thesis are therefore to:

1. Review the literature on existing GW recycling systems in the UK, principally in relation to the prediction of financial performance, and to identify gaps in existing knowledge.
2. Develop a computer-based modelling tool for the mass-balance analysis, financial assessment, and CO_2 emission assessment of shared GW recycling systems for WC

flushing at the new build multi-story residential and office buildings in urban mixed use regeneration areas in UK

3. Gather relevant data with which to populate the new model

4. Apply a model to conduct a detailed financial analysis and CO_2 emission analysis to compare the performance of proposed shared GW system with individual GW recycling system, with an emphasis on multi-story residential and office buildings.

5. Evaluate the model outputs by changing a number of key parameters: User behaviour, technology adopted, occupancy rate, water and wastewater charges, electricity charges, discount rate, building description and service life.

As a result, it shall be shown if a certain project satisfies the economic and environmental criteria of sustainability. The result from this project shows every interested person the advantages and disadvantages of shared GW recycling system in urban mixed-use areas and the information can support planners, designers and decision makers to have a better perspective of GW recycling system for new projects.

1.3 Thesis structure

The structure of the thesis reflects the stated aims and objectives and is rationally developed through the steps required to meet them.

Table 1.1 shows the indicators and tools and data sources that have been used in order to assess sustainability of the proposed shared GW recycling system in this research project. The sustainability indicators for assessing the sustainability of proposed shared GW recycling system and individual GW recycling system were selected to be as broad as possible, attempting to capture the potential concerns of the various stakeholders (e.g. planners, investors, end-users) likely to invest in or adopt a newly developed GW system.

Table 1.1 Summary of indicators, and data sources used in the sustainability evaluation

Indicators	**Data sources and tools**	**Location within thesis**
Technical Criteria		
Ability to meet treatment standards	Literature	Chapter 2
Ability to meet capacity requirements	Detailed supply/demand analysis (mass-balance analysis)	Chapter 4 & Chapter 6 Chapter 7
Environmental Criteria (Resource Consumption)		
CO_2 Equivalent Emission	Detailed carbon analysis Consumption records Bath ICE database DEFRA database Literature	Chapter 5
Water Consumption	UK consumption records	Chapter 4
Economic Criteria		
Capital cost	Detailed financial analysis Cost records Literature	Chapter 4
Annual O&M cost	Detailed financial analysis Cost records Literature	Chapter 4
Social Criteria		
User Acceptability and Desirability	Literature	Chapter 6
Stakeholder participation	Literature	Chapter 6

The thesis contains 8 chapters:

Chapter 2 provides a literature review of GW, including: its definition, characteristics and treatment methods, quantities of GW generated from different types of users, different types and configuration of GW systems commonly employed in developed countries, the key components that modern GW systems consist of; it also reviews the benefits and barriers of GW implementation. Chapter 3 discuss the methodology undertaken in this research, and describes the case study selected for exploring the research aim. Chapter 4 presents the financial analysis adopted within this study for the chosen case study, this includes sensitivity analysis of relevant parameters influential on financial performance of the GW recycling system this includes: water and wastewater prices, electricity prices, discount rates, service life, and building dimensions. In Chapter 5 the carbon emissions (embodied and operational) of the shared GW recycling system, including the method and data collection, and results are discussed through consideration of a sensitivity analysis on key parameters like: building description, and service life. Chapter 6 considers the effect of changes to user behaviour (in both residential and office buildings) on the financial performance and CO_2 emissions of system. Change in the occupancy rate for both residential and office blocks are also examined. A brief discussion about social acceptability is included. In Chapter 7 the effect of changes to technological efficiency within both buildings types are analysed and their impact on financial and energy performance as part of individual and shared GW recycling systems are assessed. Finally, the conclusions, recommendations and potential for further work are summarized in Chapter 8 of this thesis.

CHAPTER TWO

LITERATURE REVIEW ON GREYWATER RECYCLING

2.1 Introduction

GW is defined as the effluent coming from showers, laundry, bathing, etc. and excludes the effluents from toilet flushing (Lombardo, 1982; Erikson et al., 2002) (see Figure 2.1). These uses are estimated to comprise 50-80% of residential total freshwater consumption (Novonty et al., 2010, Eriksson et al., 2002). Compared to Blackwater, GW generally has less pathogen, decomposes much faster and contains 90% less nitrogen (Chan, 2007; Zhang et al., 2010).

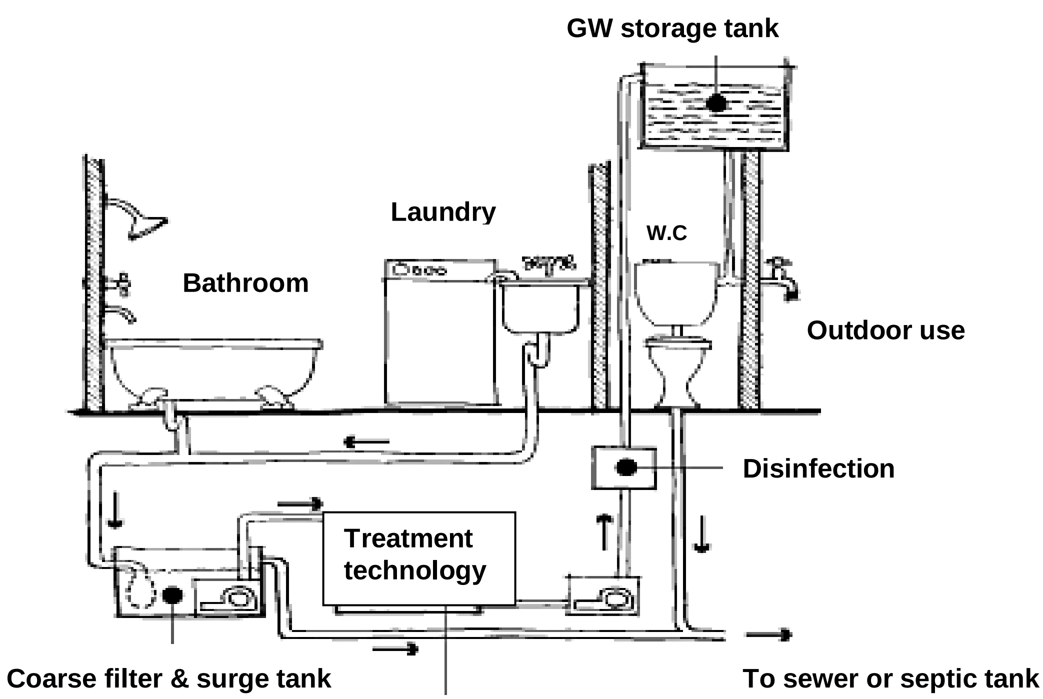


Figure 2.1 Flow path diagram demonstrating fundamental GW recycling processes (Nolde, 1995)

GW recycling systems vary greatly in their complexity and size, ranging from small systems with very simple treatment processes (e.g. sand filtration) to large systems with complex treatment processes.

For many decades, simply designed lower cost systems have been utilized in rural areas to irrigate landscapes where there were no centralized sewer systems in place (Jeppesen, 1996). More advanced GW recycling systems, which have quite high capital costs and significant installation, operation and maintenance requirements, are more economically favourable in large industrial premises where high volumes of process water are requires (BSRIA, 1997).

GW recycling systems typically consist of the following component parts:

1. GW source (i.e. Bathroom and laundry in Figure 2.1) _ selecting the source has a significant influence on the quality of GW. According to the literature GW is categorized as: light or heavy (Ramon et al., 2004). However, UK guidance has suggested that use of water from some of these sources should be restricted in recycling particularly in homes (WRAS, 1999). The majority of GW recycling literature prefers to exclude water from kitchen sinks and dishwashers since the inclusion of such wastewater has a negative impact on the quality of GW (See 2.4.1);

*2. Transporting system*_ for collecting GW from its sources and distribute it to end users;

3. A pre-treatment tank (i.e. Coarse filter and surge tank in Figure 2.1) _ where GW is stored before and after treatment;

*4. The diverted valve*_ for excess GW yield to go in wastewater sewers;

*5. The float valve_* for mains water back up in case of shortage of supply;

*6. Treatment process_* which may vary from simple systems to highly complex and costly systems;

*7. Pumping process_* for extracting the water from storage tank and send it to end users;

8. Non-potable end use (i.e. WC in figure 2.1) _ examples of non-potable end uses for GW includes: WC flushing (Karpiscak et al., 1990), urinal flushing (Cooper, 2001; Environment Agency, 2005), laundry cleaning (washing machines) (Ratcliffe, 2002), garden/landscape irrigation (Criswell et al., 2005), car washing (Leggett *et al*, 2001a), and fire-fighting (Gould & Nissen-Peterson, 1999).

2.2 GW recycling in a modern context

GW recycling is an increasing practice during the last decade, and it has been investigated intensively especially in countries where regulations encourage this practice, such as Australia, European Union, Israel, Japan, Jordan and USA (Sayers, 2000; Nolde, 1999; Ogoshi et al., 2001; Friedler et al., 2006; Al-Jayyousi, 2003; Prathapar et al., 2005; Gross et al., 2008; Tjandraatmadja et al., 2013). In 1996 according to Jeppesen and Solley the western states of the US and Japan were the world leaders in GW reuse. However, more recently Australia appears to be at the forefront of implementing GW reuse options as one of the key methods of residential water conservation (CRD, 2004). This is not surprising given the limited available water resources for national supply.

Previous international studies on GW recycling mostly focus on urban areas (Nolde, 1999; Ogoshi and Asano, 2001; Friedler and Hadari 2006; Al-jayyousi 2003; Dixon et al., 1999; Diaper et al., 2001; Ghisis, and Ferreira, 2007; Memon et al., 2005; Zhang et al., 2009; Mandal et al., 2011; Shanableh et al., 2012).

GW systems have been installed in a wide range of building types including domestic properties (Leggett *et al*, 2001a; Coombes et al., 2003a; Day, 2002), multi-story buildings (Santala et al., 1998), schools (Bray, 2003; Paul & Bray, 2004), offices (Brewer *et al*, 2000), sports stadiums (Lodge, 2004), student accommodations (Brewer et al., 2000; Surrendran and Wheatley, 1998), and exhibition centres such as the Millennium Dome in London (Lodge, 2000; Smith *et al*, 2000; Hills *et al*, 2001; Hills *et al*, 2002) and the Eden Project in Cornwall (CIWEM, 2007).

According to CSBE (2003), GW reuse is not widespread in the UK. Presently, GW recycling systems have an inconsequential impact on urban UK water demand and supply. This provides significant investment opportunities for numerous benefits of using GW to be gained through widespread uptake of these systems (Leggett, 2001).

2.3 Common drivers for GW recycling systems in the developed world

Until the 1990's water was considered only a single use product not a reusable or recyclable product (Dillon, 2002). The onset of climate change, increasing water prices, population growth, improved living standards, and energy saving are now recognised as key drivers for implementing sustainable alternative water sources. As the pressures on potable water supplies increase worldwide, there is growing interest from water providers/users in the use of alternative water sources such as GW reuse/recycling (OECD, 2009). Five drivers for water reuse were identified in literature as listed below:

- *Increasing demand for fresh water*; this is the most common driver in generally developing countries and needs to be managed in order to sustain population and industrial growth.
- *Reduced availability of water supply;* especially in arid and semi-arid regions. Water reuse is vital in these regions to continue agricultural and economic activities.
- *Environmental protection*; particularly in countries with more stringent wastewater discharge standards, e.g. Australia and Europe.
- *Public health and policies concerns*; are becoming increasingly important to the implementation of water reuse projects.
- *Affordability and practicality;* of water reuse as a local solution.

In particular, domestic GW recycling is receiving increasing attention (e.g. Maimon et al., 2010; Liu et al., 2010). This is because of the obvious benefits in terms of fresh water savings and also a lower organic pollutant and pathogen content in GW than combined municipal wastewater that contains toilet waste (Erikson et al., 2002). Consequently, domestic GW is considered mostly suitable for on-site (i.e. decentralised) reuse and recycling. GW recycling schemes have already been piloted in many countries worldwide and are becoming an increasingly favourable strategy. However, in some cases the proposals for adopting GW recycling systems are not always focused directly in the lead to attaining a more sustainable future; rather they are short-term reactions to water scarcity. This is not to say that the two concepts are not inextricably linked.

2.4 GW characteristic and treatment

For its successful adoption in the UK, it is required to know more information on the quality of raw GW and expected (i.e. Legally, economically and socially accepted) quality of treated GW water in order to design a consistent, acceptable and cost effective urban GW treatment (Friedler et al., 2005; Surrendran,2001). In other words by characterizing the level of contamination in raw GW, estimation can be made of the potential health risks and exhibit negative environmental and suggestions of its use for recycling (e.g. Toilet flushing or gardening), the type of treatment that is necessary and the related economic feasibility (Briks and Hills, 2007).

2.4.1 GW quality

Untreated GW generally contains significant microbiological contamination, high levels of bacteria, high variability in organic concentration, it is nutrient rich and warm which make it an ideal medium for bacteriological growth and microbial activity (Birks et al., 2004;

Lazarova et al., 2003; Leggett, 2001; Surrendran and Wheatley 1998; Rose et al., 1991). Various studies on raw GW characteristics have been shown in Table 2.1. It can be seen that the organics concentration in GW is similar to settled domestic wastewater but the suspended solids concentration is much lower as toilet water is excluded (Jefferson et al, 2004). The quantity and quality of GW is mainly influenced by: the user's behaviour, consumption patterns and local circumstances (Nolde, 1999), and which GW sources have been used (Dixon, 1999). For example, whether it includes or excludes the wastewater from kitchen, dishwasher or washing machine.

Table 2.1 Untreated GW characterisation

Reference	**Erkison et al., 2002**	**Friedler et al., 2005**	**Casanova et al., 2001**	**Nolde, 1999**	**Christova-Boal et al., 1996**		**Surrendran and Wheatley, 1998**	**Jamrah et al.,2008**
source	Composite, range	Composite ,mean	Composite, mean	Bath/ shower	Bathroom	Laundry	Personal washing	Shower
P ,total				0.2-0.6			1.64	-
pH	7.6-8.6	7	7.47	7	6.4-8.1	9.3-10	7.9	7.3
BOD_5 *(mg/l)*	26-130	237	64.85	228	76-200	48-290	68	380
TSS *(mg/l)*	4-207	303	35.09	134				242
Turbidity *(NTU)*	0.28-0.779	-		207	60-240	50-120	105	346
Sulphate *(mg/l)*	-	-	59.59		-	-		-
Chloride *(mg/l)*	-	-	20.54		9.0-18	9.0-88		-
Total Coliform *(CFU/100ml)*	6.0E3-3.2E5	2.8E7	8.03E7	10E2-10E3	MPN 500-2.4E7	MPN 2.23E3-3.3E5	4E6	-
Faecal coliforms, *(CFU/100 ml)*	-	1.82E4-7.94E6	5.63E5	10E-1-10E1	MPN 170-3.3E3	MPN 110-1.09E3	266	-
COD *(mg/l)*	-	319	-	100-200	-	-	-	375

In theory, GW as any other water source can be utilized for any purpose provided it is treated to match the required quality standards (Liu, et al., 2010), but the lack of appropriate water quality standards or guidelines has restricted appropriate GW reuse (Lazarova et al., 2003). The possible level of human contact with the water in its end use will verify what level of treatment is required (CIWEM, 2006). Exposure related with GW reuse can be through two routes: physical contact with GW and eating fruit or vegetables irrigated with GW (CSBE, 2003). The use of GW in toilet flushing poses some health risk associated with splashing, i.e. when the toilet is flushed (Christova-Boal et al., 1996).

At present, there are no international guidelines that specify the quality of treated greywater for reuse. Because of the potential risk to human health, many countries have their own regulations based of microbial contents. For example, Germany has adopted the EU bathing water standard for toilet flushing and the WHO (World Health Organisation) has recommended a higher microbial standard for the unrestricted use of reclaimed water for irrigation. In the UK there are no specific regulations concerning re-use. Table 2.2 shows the guidelines for wastewater reuse in different countries. Following consideration of all of the standards around the world Pidou et al. (2007) recommends that definite targets of BOD < 10 mg/l, turbidity <2 NTU and a non- detectable level of faecal coliforms per 100 ml provide a reasonable conservation level.

Table 2.2 Standards for wastewater reuse in different countries (Al-Jayyousei, 2003; Pidou et al., 2007).

Country	Application	BOD_5 *(mg/l)*	TSS[1] *(mg/l)*	Turbidity *(NTU[2])*	Faecal coliforms *(cfu/100 ml)*	Total coliforms *(cfu/100ml)*	PH
Japan	Toilet flushing	10	_	5	<10	<10	6-9
Germany	Wastewater reuse	20	-	1-2	500	100	6-9
Israel	Wastewater reuse	10	10	_	<1	_	
Spain	Wastewater reuse	10	3	2	_	2.2	
USA, California	Unrestricted water reuse	10	_	2	_	Not-detectable	6-9
USA, Florida	Unrestricted water reuse	20	5	_	<240	_	
Australia, Queensland	GW reuse for garden	20	30	2	<4	100	
Canada, British Columbia	Unrestricted urban reuse	10	5	2	2.2	_	
1:Total Suspended Solids, 2: Nephelometric Turbidity Unit, 3:Not Detectable							

2.4.2 GW treatment technologies

The design of GW treatment system varies based on the site conditions and GW characteristics. GW treatment technologies must be robust to handle variations in organic and pathogen concentration in GW influent, and to consistently produce effluent of an appropriate and safe quality to meet required standards for reuse (Winward, 2008). In theory, GW can be used for any purpose provided it is treated to match the required quality standards (Liu et al., 2010). However consideration should be given to the different reuse applications which require a range of water quality standards and thus demand requirements. As mentioned previously the lack of water recycling standards has contributed to the proposal and development of an abundance of technologies which vary greatly both in complexity and performance. A wide variety of technologies have been used or are being developed for GW treatment and reuse (Pidou et al., 2007). Below is a brief description of GW treatment techniques.

2.4.2.1 Simple treatment

Simple treatment technologies are usually two-stage systems; first stage is large solid removal by either coarse filtration or sedimentation, followed by disinfection as second stage (Jefferson et al., 2001). Simple systems are the most common treatment technology that has been used in UK for domestic reuse because it is relatively inexpensive to install and operate and easy to use.

2.4.2.2 Chemical treatment

For chemical treatment there is less information available in the literature. Most of the chemical treatments for GW include photo catalytic, coagulation and ion exchange followed by filtration and/or disinfection (Pidou et al., 2007).

2.4.2.3 Physical treatment

Physical treatment options for GW are sand filters or membranes with/without disinfection. Sand filters are very similar to simple technologies and do provide a limited treatment option for GW (i.e. there are no complete barriers to suspended matters) although they are followed by disinfection. The literature shows that these treatment options are not sufficient to satisfactorily reduce the organics, nutrients and surfactants in GW. Therefore, they are not recommended for GW recycling (Liu et al., 2010). Particularly where long storage times are required (Dixon, 1999; Ghunmi et al., 2008; Winward et al., 2008)

2.4.2.4 Biological treatment

Biological processes are the most suitable unit processes for treating GW based on the characteristic of water (Pidou et al, 2007; Jefferson et al., 2001). However, they have higher energy demands and fouling problems which increases the cost of operation. All methods with a biological stage can achieve excellent organic and solids removal but low organisms removal (Pidou et al., 2007). In most of the cases from literature biological treatments were rated highest followed by physical pre-treatment and/or followed by disinfection. The most common configuration is membrane bioreactors (MBR), biologically aerated filters (BAF) (Mendoza-Espinosa and Stephenson, 1999), rotating biological contractor (RBC) (Abdel-Kader, 2012) and sequence batch reactors (SBR) (Lamine et al. 2007). MBRs combine an activated sludge reactor with a microfiltration membrane, and have been successfully employed in Japan for GW recycling in office blocks and residential buildings (Kishino et al., 1996). Due to the excellent and stable effluent quality, high organic loading rate, compact structure as well as low excess sludge production, the MBR appears to be an attractive technical solution for GW recycling, particularly in collective urban residential buildings (Lazarova et al. 2003; Friedler & Hadari, 2006; Fane, 2005; Liu, et al., 2009).

The MBR has two main configurations which involve either submerged membranes or side-stream configuration. The submerged MBRs configurations are most frequently applied in municipal wastewater treatment (Figure 2.2).

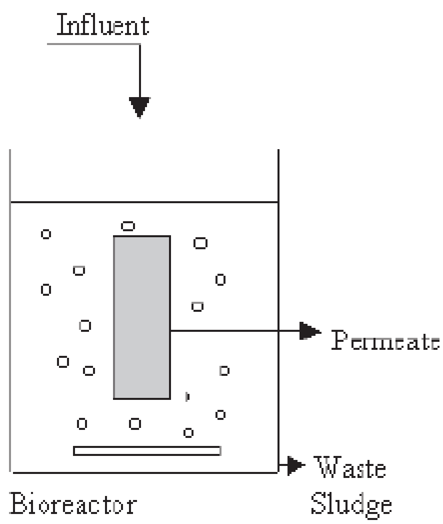


Figure 2.2 Configuration of submerged MBR system (Meline et al., 2006)

In most points of application it was difficult to justify the use of such a process because of the high cost of membranes, low economic value of the product (tertiary effluent) and the potential rapid loss of performance due to membrane fouling (Jefferson et al., 1999). Membrane fouling can be dealt with chemicals removing technique in the tank but requires professional maintenance to take place regularly. MBR based treatment plants have the advantage to be compact; therefore they require only a small amount of land and can be fitted inside a building (Ottoson and Stenstrom, 2003). This is a distinct advantage in urban areas.

2.4.2.4 Extensive technologies

Extensive technologies for GW treatment usually include constructed wetlands that achieve treatment through physical sedimentation in order to remove large particles, followed by sand filtering to remove any particles or media in water, and then bacterial metabolism. Constructed wetlands (CW) replicate natural wetlands in the sense that the wastewater runs through shallow substrates (vertically or horizontally) and is filtered through reeds (aquatic plants) that are artificially established (Wood and Dixon, 2001). The substrata in which the reeds are established provide a solid substrate for plant growth, steady surface area for microbial attachment, and works directly in the cleansing of the wastewater via physical and chemical processes (Cooper et al, 1996).

The examples of CW application in the literature show an excellent ability of this technology to treat GW and remove biological organic substances. Overall, all wetland configurations were able to effectively treat low strength GW but only the vertical flow system (Figure 2.3) maintained its robustness when high strength GW was treated. Analysis of the systems reveals this was due to the fact that aerobic metabolism is a more suitable treatment pathway for GW.

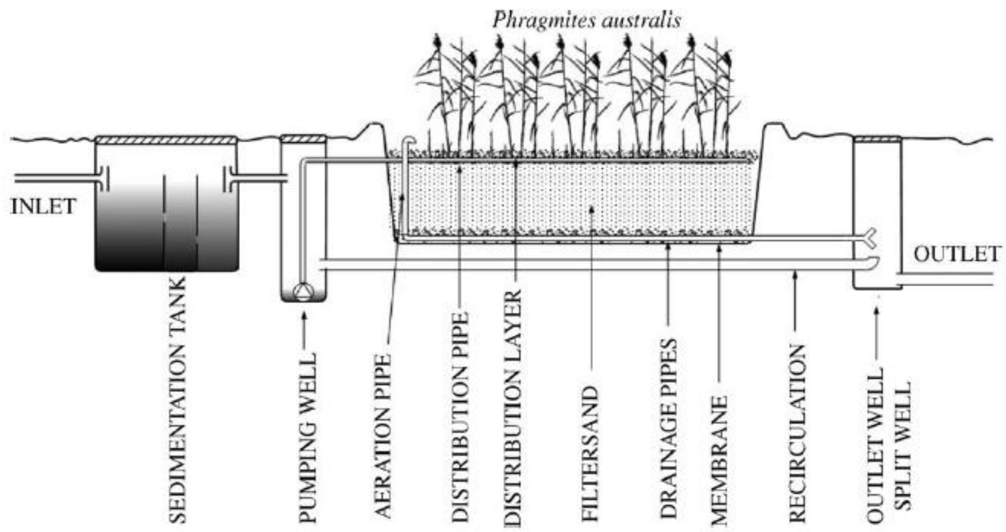


Figure 2.3 Layout of a vertical flow constructed wetland system for a single household (Arias and Brix, 2005)

The CW system configuration (to be horizontally or vertically) depends on the treatment objective and location conditions like population size, climate, cost of land, funds availability, and etc. They are considered as the most environmentally friendly and inexpensive technologies for GW treatment (Friedler and Hadari, 2006; Dallas et al., 2004; Shrestha et al., 2001). However it demands large space and for this reason alone people think that it is not suitable for urban areas (Liu et al., 2010), although this requires subtle arguments as to where land spaces should be allocated for such purposes.

2.4.2.5 Summary of GW recycling treatment technology

There are some factors that have an effect on the choice of the most appropriate treatment technology such as: end users type, site characterisation, scale of development, cost of water, regulatory requirements, and users behaviour (Landcom, 2006; Jefferson et al., 2004). The method and complexity of treatment in a GW systems normally differs with the size of application. For single houses GW systems are normally restricted to coarse filtration and disinfection due to the cost issues. Examples for larger scales like colleges (e.g. Loughborough) and small offices have focused on physical (or simple biological) systems (Surrendran, 2001). Larger scale systems like Millennium Dome operate several distinct stages of treatment and use both biological and membrane technologies. In each case, successful application of the selected technology will depend on a many local factors, priorities and conditions such as politics, land availability, community understanding, technology cost, and economic and environmental restrictions (EKTN, 2008; Wilderer, 2004). In Table 2.3 the performance of 5 categories of treatment technologies for GW are presented.

The common GW treatment systems are biological systems with basic two-stage system with coarse filtration and disinfection (membrane bioreactors (MBR), biologically aerated filters (BAF) and rotating biological contactor (RBC), and constructed wetlands (Al-Jayyousi 2003; Jenssen and Vrale 2003; Madungwe and Sakuringwa 2007). The quality of effluent from these treatment technologies shows that they are capable of achieving most domestic recycling water standard regulations (Nolde 1999; Al-Jayyousi 2003; Winward et al. 2008; Zhang et al., 2009) (See Table 2.3).

For the purpose of this research membrane bioreactor (MBR) and vertical flow constructed wetland were chosen as the treatment technology for further consideration as part of a GW recycling system within this study. The reason for this selection was the robustness and reliability of these two treatment technologies compared with other treatment options based on the available information and data from previous studies within literature.

In light of the information given in section 2.4.1 it was decided that water quality would not be explicitly considered in the thesis. In line with the previous recommendations it was assumed that adequate quality can be achieved for non-potable uses when GW undergoes treatment.

Table 2.3 Summary of 5 different types of GW treatment techniques

Treatment	Simple	Chemical	Physical		Biological	Extensive
Example	Coarse filtration or sedimentation	Photocatalysis, electro-coagulation and coagulation	Sand filter, adsorption	Membrane	Biological aerated filter, membrane bioreactor	Constructed wetlands, ponds, reed beds
Scale	Preferably small scale (single households)	Especially for single household	Common in small-scale	Common in small-scale	Commonly used in bigger buildings	Suitable for large scales
Performance	Remove large solids. Little or no removal of the chemical and biological pollution	Able to reduce suspended solids, organic substances and surfactants	Limited treatment, low solids removal	Limited organisms removal, excellent dissolved and suspended solids	Excellent organic and solid removals	Satisfactory removal of the biological organic substances
Suitable for	Low-strength GW	Low-strength GW	Low-strength GW	Low-strength GW	Medium to high strength GW	Medium to high strength GW
Disinfection	Yes	Yes	Yes	Yes	No	Yes
Purpose of use	Sub surface irrigation, toilet flushing and gardening	Toilet flushing and gardening	Not recommended for GW recycling.		Toilet flushing and gardening	Toilet flushing and gardening
Advantage	Simple to use, not expensive	-	Effective in decreasing the organic pollutant, not expensive	Low turbidity of water	No need for disinfection. Small footprint processes, and producing high quality effluents, compact	Most environmental friendly and cost effective technology for GW treatment
Disadvantage	Limited pollution removal	Failed to meet turbidity values of less than 2 NTU	Not sufficient to an adequate reduction of the organics, nutrients and surfactants.	Fouling, high energy demand	Should follow physical pre-treatment, high energy demand.	Requires large space, not favourable in urban area.
*References: Brewer et al., 2000; Friedler et al., 2006; Hills et al., 2001; Jefferson et al., 1999; Jefferson et al., 2004; Lazarova et al., 2003; Liu et al., 2010; Nodle et al., 1999; Pidou et al., 2007; Surrendran and Wheatley, 1998.						

2.5 Types and configuration of GW recycling systems

GW systems were categorized according to (1) untreated GW diversion systems and (2) treatment systems. Most uses of GW requires some form of treatment, although untreated GW can be used where there is a very low risk of human contact and short storage requirement. Sub-surface irrigation is an example of untreated GW use. This direct application of GW requires only simple storage, with a coarse filter to remove any large debris, hair and other particles. Most systems are relatively simple, incorporating storage and pumped (or gravity fed) hoses or dip feeds for irrigation systems. Irrigation using GW is very popular in the USA, where a greater percentage (7-13%) of water is used for irrigation and other outdoor purposes than in the case in the UK (BSRIA, 1997; Roesner et al., 2006).

Another very simple idea for the direct use of GW within a building is a basin which fits directly over a low-level toilet cistern (Figure 2.4). When water is used in the basin for hand washing, it drains directly into the cistern and can then be used to flush the toilet. There is thus no need for complicated pipe networks or additional storage. It is assumed that water treatment is unnecessary as the GW in generally used very quickly and originated only from hand washing.

Figure 2.4 Direct use of GW from basin to toilet flushing (DigsDigs, 2012)

There are several systems on the market worldwide which reuse GW and recycle it to flush toilets and outdoor uses at three different scales:

(a) Individual scale schemes or packaged systems

The individual household GW recycling scheme has been an appealing scheme for GW installation and there are already many sites around the world where these systems are operating. These systems consist of very basic equipment including GW collection from baths, showers and handbasins, followed by simple filtration, and disinfection (Figure 2.5). Most of the individual household GW systems on the market specify that the treated GW can be used for gardening and toilet flushing which results in 30-50% reduction in water consumption and a reduction in water bills. They are generally less suitable for use in office and commercial buildings due to low productions of GW and high use of WCs (with high water demand) in this type of buildings.

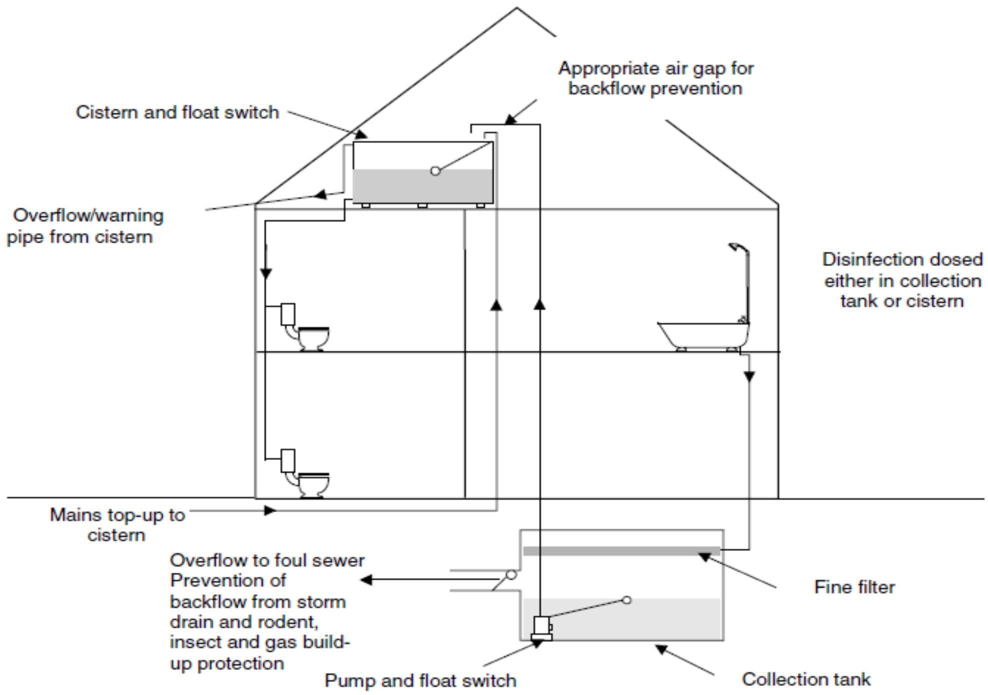


Figure 2.5 A simple GW recycling system for individual household (Leggett and Shaffer, 2002)

The preference in domestic properties is that the system is very low maintenance. However, one shortfall is that all the risks and maintenance requirements are the owners responsibility unless they have a maintenance agreement. There is a risk also where householders might attempt modifications to the system without the sufficient skills and there would subsequently be a likelihood of cross connection (Legget et al., 2011). If a water company chose to offer the maintenance service they would have a legal responsibility to report any cross-connection. Even though this would add to the water company’s liability; it would also provide higher comfort for the rest of the water companies customers. Most of the previous researches on GW recycling systems have focused on the individual house scale, while multi-residential or communal scales are less-evident within the literature.

(b) Multi-residential buildings system

Multi-residential buildings are those with a mixture of self contained dwellings or rooms for residential purposes or with communal facilities. Student halls of residence, key worker accommodation, sheltered housing, and other multi-residential buildings which contain a mix of residential accommodation are all valid examples of multi-residential buildings. This type of buildings is usually located in urban areas with high population concentrations. Research into GW recycling in multi-residential buildings shows higher benefits in terms of saving more water with reduced costs (Friedler & Hadari, 2006; Ghisi and Ferreira, 2006).

(c) Communal schemes

A very few examples of communal scale reuse schemes exist worldwide. One example is the Inkerman D'Lux in Australia (Goddard, 2006). Communal scale reuse schemes require less infrastructure than centralized schemes and have increased benefits through more water savings compared to individual schemes therefore they have the potential to be more economically viable.

The research by Harnett and colleagues in 2009 shows that individual household GW reuse schemes are not the most sustainable way of implementing GW reuse. They suggest that cluster scale residential reuse schemes provide a significantly more sustainable solution than individual schemes based on cost and energy assessment criteria; GW is shared amongst several houses and more water can subsequently be saved through this system. On the other hand technical failures of communal scheme systems result in of greater impact as more people will be affected, however they are less in frequency.

2.6 Components of GW recycling system

Generally GW recycling systems can consist of a number of different components, some specific only to the GW recycling and some which are related to the buildings in which they operate. Generally the GW systems may have the following components (CIRIA, 2001):

- Collection and distribution pipework
- Collection tank
- Filters
- Treatment unit
- Disinfection units
- Pump and associated components
- Storage tank/Cistern
- Back-up water supply

- Electronic controls/ management systems.

2.6.1 Collection and distribution pipework

The collection pipework is the network of pipes used to deliver GW from sources to the collection tanks or, in some specific cases, directly to the end user. Distribution pipework is required to transport water from the storage tank to the point-of-use. There are a wide range of available pipes that are suitable for this purpose. As GW contains high level of salts such as sulphates and chloride that can prove corrosive, copper and galvanized steel pipes are not recommended. Generally the pipe used is low-pressure PVC (Polyvinyl chloride) (for collection pipe work), high-pressure PVC (for distribution pipework) or ABS (acrylonitrile butadiene styrene) plastic waste pipe (CIRIA, 2001). These pipes are long-lasting and usually have about 20 years of service life if installed properly (Leggett et al, 2001a; Roebuck, 2007). Care must be taken to avoid cross-connection of reclaimed water and main water pipework during installation or subsequent works on property (as happened in Amsterdam where numerous people were infected and subsequently use of reclaimed water was band). Further information on appropriate pipe materials and installation protocols can be found in the WRAS (1999a) and Leggett et al (2001b).

2.6.2 Collection tank

As the generation and demand of GW varies throughout the day having storage tank is essential to the running of this system. One of the issues that may favour GW systems for houses is that the collection tank is relatively small (based on daily supply requirements) since supply is not dependent on the seasonal variations or natural events like rainwater storage tanks and it achieves an improved coincidence of supply and demand.

The GW tank capacity can be estimated by comparing the GW supply and the GW demand at end-use (Ghisi and Ferreira, 2007). The tank should dimension to store the least volume between the GW supply and the GW demand. The tank does not need to store more GW than the amount of daily demand and it should be considered that GW should not be stored more than 48 hours and preferably 24 hours (Dixon, 1999). The installation and purchase cost of tank are related to its capacity (Fewkes, 1999) and so it is important to select a tank with an appropriate volume.

Storage tanks come in a variety of shapes and sizes and can be constructed from a range of materials including plastics, e.g. glass-reinforced plastic (GRP), polyethylene or polypropylene, concrete, ferrocement, bricks, and steel (Leggett et al, 2001b; Fewkes, 2007; BSI, 2010). Generally constructed materials for tanks should be from watertight structures without heartening microbial growth (BSI, 2010). In the developed world the most commonly used storage device is the underground tank (Hassell, 2005). Although above ground tanks are particularly cost effective for retrofit cases and are widely utilised in countries like Australia. Installing tanks underground has a number of advantages likes preventing algal growth by shielding the tank from daylight (Konig, 2001), protects the tank from extreme weather conditions at the surface such as freezing spells (Leggett *et al*, 2001b) and helps to regulate the water temperature in the tank, keeping it cool and limiting bacterial growth (Fewkes & Tarran, 1992). However the risk of contaminating ground water from GW tank failure (leakage) should also be considered, especially where the water table is high (CIRIA, 2001). The use of storage devices other than underground tanks appears to be limited in the UK, particularly within the domestic market (Roebuck, 2007).

2.6.3 Filters

GW requires robust filtration due to the presence of soaps, grease, hairs and particulate matters in this type of wastewater. Filtration helps reduce sludge accumulation in the collection tank by reducing suspended loads, reduces pollutant loads and improves its cleanliness, and reduces the chances of clogging in the pipe work and fouling in membranes. There are two types of filters in market: fine filtration and course filtration. Course filtration usually applies before (or in) collection tanks and there are two types of manually cleaned filters or self-cleansing filters. The GW that comes out of this filter has a cloudy appearance (Butler and Memon, 2005). If the filter is too coarse, debris may pass through it causing the pump to work harder reducing its life span and, possibly, causing it to burn out; or it may cause damage to downstream valves, and potentially compromise final water quality by reducing disinfection efficiency. Generally filters should be easily accessible to replace or clean the filter element or media (Thomas and Martinson, 2003).

2.6.4 Treatment

A complete set of treatment technologies for GW were described in section 2.4.2.

2.6.5 Disinfection units

The final stage of treatment often consists of disinfection. Since bacteria can quickly multiply to dangerous levels if not controlled disinfection is recommended for GW systems (Winward et al. 2008). Disinfection is applied to deal with any microbial contamination in all GW systems apart from the sub-surface irrigation. The method of disinfection depends on the end use of water. Table 2.4 shows three types of disinfection methods proposed by BSRIA with their related advantages and disadvantages. If GW is to be used for toilet flushing it must be disinfected in some way. This is because diseases carried by untreated GW can be transmitted by splashing, other human-contact, and cross-contamination with the main potable water supply.

2.6.6 Pumps

Where the system does not distribute the GW by gravity, a pump should be used to ensure its continual availability. Usually in GW recycling systems, pumps were either used to pump treated GW to the point of use (direct systems) or to a header tank located at least 1m above the point of use (indirect systems). Pumps need to be sized properly so that each pump is able to overcome the static lift as well as the friction losses in the pipework and valves. For choosing the appropriate pump the following considerations should be given: energy use and noise, prevention of air (and cavitation) in the system (BSI, 2010).

Table 2.4 Different types of disinfection methods

Method	Advantages	Disadvantages
Chlorine	Very powerful and fast acting; significant residual cleaning effect, Appropriate for point entry treatment.	Can react with some organic material in water to from acids which can leads to corrosion of metallic fittings. Therefore, not suitable for domestic scale. There is a link between dosage rate and water volume. Less cost than other methods
UV	Achieves very high waterborne bacteria and viruses kill rate, ease of use, no chemical requirement, no effect on the chemical characteristics, no risk from excessive use	No residual effect; the water has to have very low BOD and turbidity, demanding the use of fine filters, energy consume, Adds to capital and operation cost of system, requires replacement for every six months
Ozone	Achieves rapid kill; effective against many micro-organisms; reduces to oxygen; can be produced in situ	Lack of residual; not very effective in an open system; turbid water may diminish effectiveness
McGhee, 1991; BSRIA, 1997; Butler and Memon, 2005; Roebuck ,2007; Parsons & Jefferson, 2006; Leggett et al, 2001b; Shaffer et al, 2004		

2.6.7 Storage tank/Cistern

A storage tank or cistern is required for collecting GW after treatment. The volume of storage tank is usually smaller than collection tank. It should be placed in loft and away from heat emitting sources. The water in cistern should not be stored for more than 24 hours, since the residual disinfectant concentration will decline over time. The cistern will have a high level switch or other means to stop the collection tank pump when it is full, and a low-level switch (or float valve) to enable makeup from the mains water when the collection tank is empty.

2.6.8 Back-up water supply

A mains top up supply line must be provided to serve the cistern in case of treated GW shortage. Although GW is not dependent on seasons or related events, but sometimes the GW supply is not enough to meet the demand (usually in offices and commercial buildings) therefore it is advisable to have a top-up arrangement which can supply enough mains water to meet this (Woods-Ballard *et al*, 2007). If the storage cistern is to be provided with a mains water supply, it must be fitted with an appropriate air gap arrangement between the spill over level and the main water inlet and an unrestricted overflow to prevent the water level in the tank reaching the mains inlet under fault conditions of though back siphoning from the mains (requirement of the *Water Fittings Regulations* 1999). Top-up controls can consist of simple mechanical valves controlled by floatation devices or more complicated systems involving float activated switches coupled with solenoid valves.

2.6.9 Electronic controls/ management systems

Many existing GW recycling systems have an electronic control and management unit. Electronic controls will add costs and extra electricity consumption to the system, but it is important to use in order to have visual check of the system such as reporting disinfection failure, filter blockage, pump failure, and water levels in the tank (Konig, 2001). They have a finite lifespan and will likely need replacement after 15-20 years (Roebuck, 2007)

2.7 Barriers to the uptake of GW recycling systems

Several barriers to the uptake of GW recycling systems were pointed to in the literature and listed as follows:

- Cost of system: The main barrier to the wide uptake of these systems is economic feasibility (Jeppeson, 1996; BSRIA, 1997; Leggett and Shaffer, 2002; Memon et al., 2005; Zhang et al., 2009). The cost/benefit of GW use is largely unproven and people are unconvinced that they will get back their expenditure through reduced water bills (Leggette, 2001).
- Water quality standards and health concerns: Probably the main concern with such systems results from the possible health implications of using GW. There is a great challenge to community confidence in the reliability and trustworthiness of GW recycling system. The lack of appropriate standards against which systems can be evaluated leaves uncertainty over the health risks they may pose. The actual question is "How much does using GW system increase the risk (illness) compared to a normal lifestyle with mains water?"
- Public perception: The demand for this water depends on acceptance of GW (Asano and Miller, 1990). Decision to have wider uptake of GW system has much to do with perception rather than health associated risk. Probability of contracting infection is relatively low, probability of death due to that infection is further down, and significantly less than death of a person driving a car.

- GW content: The fact that care has to be taken concerning what goes into GW at source may act as another barrier to implementation. As this depends on user behaviour which ultimately is difficult to legislate against.
- Treatment requirements: Depending on the end-use of the recycled GW, relatively high level of treatment may be required, and so both the resulting cost and high maintenance requirements could restrict the use of systems.
- Water companies' response: A possible barrier to the use of GW system may be the resulting changes in the volume and concentration of sewage effluent discharges to sewer (Bertrand, 2008). Therefore, there may be subject to specific local conditions, positive or negative implications for the operation of the treatment works (BSRIA, 1997).
- Lack of guidance on system: The low uptake of GW in the recent past has, in part been attributed to a lack of guidance for specifies and designers. No guidance discusses the components of system and, assists in detailed design. Currently, where there is no formal arrangement for maintenance it is often the responsibility of the building owner or occupier to undertake maintenance. As the majority of systems require ongoing maintenance and are subsequently not 'fit and forget', a lapse in this can cause problems with water quality and/or water supply from the system and may adversely affect the economic viability of the system (Leggette and Shaffer, 2006).

2.8 GW recycling system and Sustainability assessment

In the report by Brundtland commissions, sustainability is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). The definition of sustainable sanitation system is stated by Ujang and Henze (2006) as "a sanitation system, which is technically manageable, socio-politically appropriate, systematically reliable, economically affordable that utilises minimal amounts of energy and resources with the least negative impact and recovery of useable matters".

A review of literature reveals that indicators for sanitation system sustainability evaluations can generally be grouped into the following categories: economic feasibility, public health, environmental impact, socio-cultural, and technical performance (Larsen and Gujer, 1997; Balkema et al., 2002; Lundin and Morrison, 2002; Kvarnstrom et al., 2004; Bracken et al., 2005). These were illustrated in Figure 2.6.

GW recycling as a sanitation system can contribute to the sustainability resources in reducing water demand through using water more than once. However, this systems requires the material, for construction (e.g. tanks and pipework, etc) and operation (e.g. electricity for pumping, chemicals, etc), which will contain embodied energy and directly use resources. Economic is considered as another important sustainability issue for this system. The economics of GW systems was identified as one of the major considerations in the widespread uptake of this system. As stated by Leggett and Shaffer (2002) if the construction and operation costs of GW systems are greater than mains water costs, then they do not present an economically sustainable solution to water supply and demand.

There are few examples in literature that evaluates the sustainability of GW recycling systems. Single or multiple indicators are frequently used in order to do this analysis. However, the cost evaluations of operation and maintenance were not given appropriate consideration.

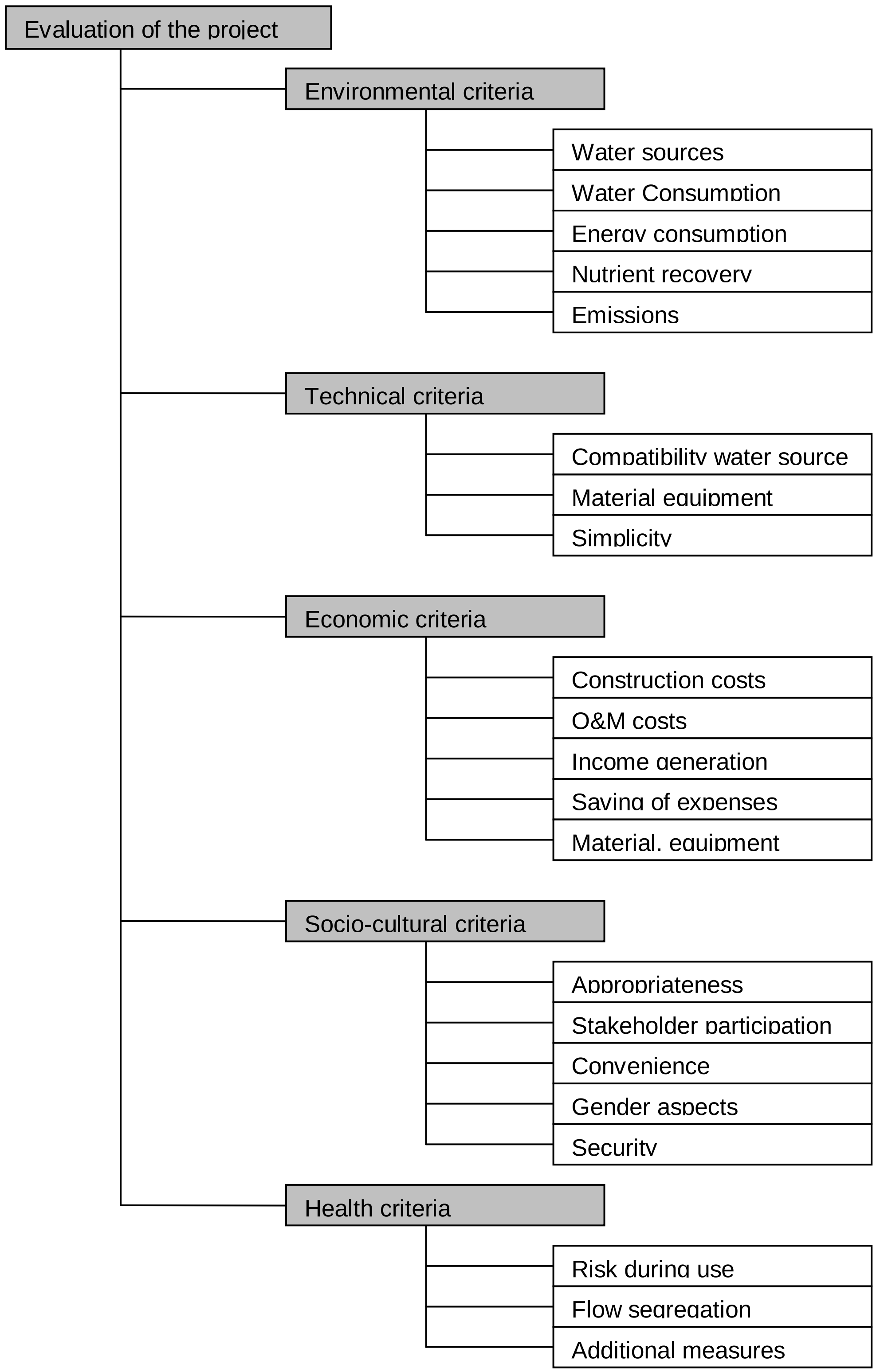


Figure 2.6 Criteria and sub-criteria for sustainability evaluation of sanitary systems (Ashley et al., 2003; Freiberger, 2007).

Most of the sustainability evaluations for GW system in literature focus on water quality, water saving potential and/or cost of the system without any consideration of operation and maintenance, embodied energy, impact of user behaviour, technology change and occupancy rates. The list of previous research on economic assessment and energy assessment of GW recycling systems are considered in Table 4.2 in Chapter 4, and Table 5.1 in Chapter 5

2.9 Literature gaps addressed by this research

In order to control water usage and improve the conservation of water resources many techniques and technologies have been developed, tested and implemented. These have to be implemented as a primary step toward sustainable water use.

GW recycling projects have the potential to reduce the demand on sensitive water bodies by substituting GW for non-potable purposes (Dimitradis, 2005), in addition they lower the cost of developing new water supplies, reduce wastewater volume and reduce the risk of sewer flooding during storm events (Bertrand, 2008; Penn et al., 2013), lessen the discharge of pollutants to the environment, provide water to serve a variety of beneficial uses (Atwater, 1998), and provide regular supplies without depending on external phenomena and seasonal variations in water volume (Zhang, et al., 2010).

However, GW recycling schemes currently have a lower level of acceptability than rainwater systems, due to poor aesthetic water quality (cloudiness), cost (high payback period), lack of choice of systems, maintenance issues, unclear water saving potential ,and concern over their environmental impact.

The literature review shows that most of the studies on GW recycling systems focused on the performance of existing systems at individual scales. Very few studies addressed technical performance of GW systems (e.g., meeting capacity requirements, ease of operation and maintenance) which seems to be one of the barriers for the wide uptake of this system. In the UK, GW systems mainly supplement or reduce the use of mains water, but in a few instances provide independence from mains supply. This results in less profit from system and reliance on mains water. As far as the author is aware there is a lack of the literature relating to improving the sustainability of GW recycling systems through improving technical performance.

Within this study the economic and energy sustainability of new shared GW recycling systems were compared with existing individual block GW recycling systems in order to achieve more sustainable GW recycling system which is more favorable for stakeholders and end users to adopt. The effects of key parameters were also examined based on previous works within in literature. The results from this study will provide into a unique conclusion that helps developers or any other organizations that are interested in applying GW recycling system as part of sustainable urban water management.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

In this chapter a new concept for a GW recycling system in urban mixed-use areas is introduced. As outlined in the introduction Chapter, the small financial benefits and long payback periods compromise the sustainability credentials of GW systems. Moreover, the materials needed for construction of GW systems will contain embodied energy and other natural resources that are required for operating the system such as electricity or chemicals for disinfection. These make it difficult to see these systems as environmentally friendly and cost-effective, especially for small-scale systems.

This chapter describes in detail the methodological approach with analysis conducted through use of a computational spreadsheet package for assessing the mass-balance analysis, financial performance, and CO_2 emission of shared GW recycling systems by explaining the input data requirements. Assessment of its financial performance, environmental, technical and social performance, under a range of operating conditions and configurations are described in detail in Chapters 4, 5, 6, and 7.

3.2 Methodology

A five-step methodology is presented for calculating the mass-balance, financial performance and CO_2 emission for GW recycling system within two high-rise buildings in an urban mixed-use area; one with domestic dwellings (i.e. flats) the other consists of offices.

Step 1: Office and domestic building dimensions, their cross-connection distances and occupancy rates are described in detail (Section 3.4).

Step 2: Water demands within these buildings are investigated (per resident and per employee) in order that the availability and likely consumption of GW supplies can be calculated and mass-balance of system were assessed (Section 3.5).

Step 3: Five scenarios (1 baseline and 4 GW options) are introduced and respective water flow balances therein calculated (Section 3.6).

Step 4: The input data for financial and energy assessments were identified, the data were gathered and in some cases they were estimated or appropriate assumptions made. The detail for financial input data are presented in Chapter 4. Energy input data is discussed further in Chapter 5.

Step 5: Results are subsequently discussed for each of these scenarios and a parametric study for changes in relevant parameters were studied

The GW recycling system performance includes: the amount of potable water and wastewater savings that can be achieved through this system, and the final cash flow from the investment. There are numerous methods available for evaluating the performance of GW recycling system from very simple methods (e.g. 'rule-of-thumb') to complex methods like computer programs. These techniques are also different at various scales. Computer based methods offers a number of benefits compared to manual methods like simulation of design under different conditions, capability of handling complicated data, higher speed and flexibility etc. In this thesis a computer-based method is used for calculations in order to increase understanding of a financial cost of given GW recycling system and extrapolate to situations beyond those originally described in the model in order to go beyond what is already known from direct investigation of the phenomenon being studied and to simulate the system behaviour under a range of different conditions so that system performance (hydrological, financial performance and CO_2 emission) could be predicted and compared with individual block GW recycling system.

3.3 Model overview

The model has been implemented as a spreadsheet application using Microsoft Excel and is a deterministic model based on discrete time steps of one day. The spreadsheet developed during this research is a mass-balance transfer model that represents individual block and shared GW recycling systems which collect GW from a range of sources (e.g. bath, shower, etc) at residential and/or commercial buildings in order to supply toilet/urinal flushing demands within the same buildings. The initial purpose of the application is to provide the mass-balance analysis and financial performance assessment of GW recycling system at individual block and shared scale. An environmental assessment (CO_2 emission) is also included within the model and this will be discussed in detail in Chapter 5.

The model simulates and compares 5 scenarios (Section 3.6). This allows the user to judge the relative cost effectiveness of the proposed GW recycling system compared to relying solely on mains-only water supplies.

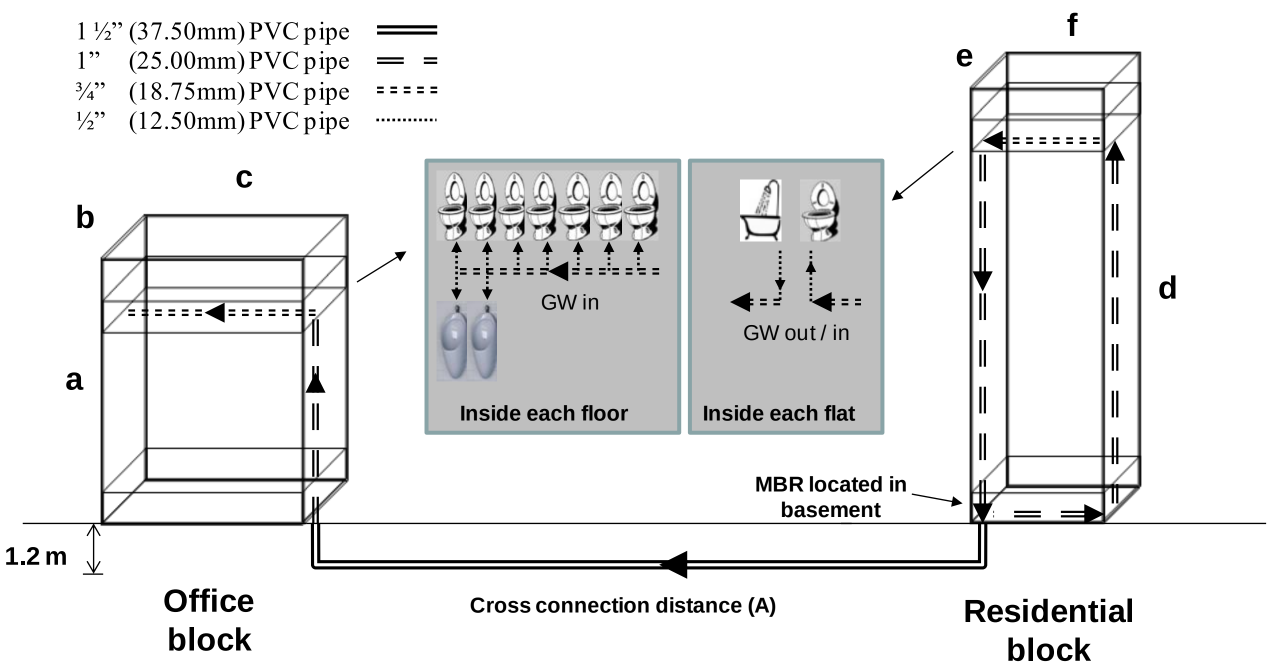


Figure 3.1 Dimensions of mixed-use building(s) under analysis (Schematic for pipe work within Scenario 3a (see later) is shown).

A range of key input parameters have been identified and most are user-definable, for example storage tank capacity, pipes, water demand profiles, pump and treatment technology characteristics (including electricity costs). Both new-build and retrofit buildings can be modelled, although this thesis only considers new-build buildings.

Operating costs can be entered on a yearly basis and these include water supply and sewerage charges, electricity costs and the discount rate. This allows gradual long-term changes in costs to be taken into account. For instance there is a general trend of increasing water supply and sewerage charges in real terms. The same is also true of energy costs (see sections 3.10.1 and 3.10.5). These increases were modelled in detail and the prices are not assumed to be remain static over time, a feature that was considered to be one of the limitation of many of the existing models subsequently reviewed in Chapter 4. Maintenance activities and related costs can be modelled on a temporal scale of at least one month, although costs for a given year are aggregated to give an overall annual expenditure. Maintenance activities can be programmed so that they occur only once or repeatedly at a specified time interval, e.g. once at every month, once every 10 years. It is possible to exclude a given financial cost from the analysis if it is not required, e.g. decommissioning cost.

The application is modular in design and broadly consists of three types of modules: input, analysis and computational. The input modules which can be divided into mass-balance, financial and energy input model are where the user enters the data required by the program to perform an analysis and each has its own set of associated parameters that require user input. The data required for mass-balance and financial analysis were explained in this chapter and energy input data were described in Chapter 5.

In the following section the data for input model and the method for evaluating the mass-balance and financial assessment of five defined scenarios are explained.

3.4. Building descriptions

To develop a generalized model, this thesis firstly adopts then analyses a newly constructed multi-storey residential building and office building (Figure 3.1), selected from within the Eastside mixed-use urban regeneration area, Birmingham, UK (Porter and Hunt, 2005, Hunt et al., 2008).

The high rise residential building consists of:

- 10-storey building (with 3 m floor heights), d = 30 m;
- 10,240 m^2 total floor area;
- 1,024 m^2 per floor, e = 32 m, f = 32 m;
- 18 flats per floor (57 m^2 per flat);
- 432 occupants (assuming 2.4 occupants per flat);
- 180 toilets (See 3.5.1).

The area of each flat (57 m^2) is within the range of average UK room sizes in high rise buildings (LHDG, 2010). [The minimum standard space requirement for one bedroom flats for two people is 50 m^2 and for a two bedroom flat for 3 people is 61 m^2.]

The high rise office building consists of:

- 7-storey building (with 3m floor heights), a = 21 m;
- 13,860 m^2 total floor area;

- 1,980 m^2 per floor, b= 30 m, c = 66 m;
- 924 employees (assuming 1 employee per 15m^2);
- 54 toilets and 19 urinals (see 3.5.2)

It is assumed that the cross-connection distance (A) between office block and residential block is 100 m and without intervention it is assumed that both buildings would be connected to the municipal central water supply and wastewater treatment plant. The various dimensions adopted within this study were adapted directly from the Birmingham Eastside mixed-use development in UK. Sizing of pipes (Figure 3.1) is based upon BS EN 806-4 (guidelines for piping in buildings) and BS6700 (recommended design flow rates). For more detail on sizing the pipes see Appendix 2. The impact of changing three important variables (cross-connection distance, number of floors and floor area) are subsequently examined for both buildings in Chapter 4, section 4.5 for their impact on system financial performance and in Chapter 5, section 5.4.2 for their impact on system CO_2 emission.

3.5 Water demands and GW production in the UK

In order to estimate likely GW volumes produced and consumed in domestic residencies and offices we need to consider the breakdown of total water demands by end-use. Non-potable demands in offices and domestic dwellings are highly dependent on WC type (e.g. water flush, air flush and composting), size of cistern adopted (i.e. 9 to 0 litres/flush) and changes to user behaviour. The associated impact of changes to these input parameters on supply demand requirements, financial performance and carbon costs were examined in Chapters 6 and 7.

The value of the mains water that is substituted by GW has been used as the primary indicator of financial performance of GW recycling systems. It is essential that reliable data be gained on the quantity of available GW flows for reuse, and the potential reclaimed water demand. Inappropriate water consumption/demand data could mislead the planning and designing processes and the financial assessment results (Tchobanoglous et al., 1991).

In this research data on domestic and non-domestic water usage to calculating water usage for residential and office buildings in urban mixed use areas is obtained from the literature. The urban mixed use in question may contain the following use types: residential, office, commercial, retail, hotel, student accommodation, restaurants, sport halls, and hospitals. The water demand breakdown for each of these users has been shown in Appendix 1. Different regions in UK have various water demands. However in this study the regional variation is not considered in water demand assessment and the standardised water use benchmarks of water demand in different building types are used. It was beyond the scope of this research to include all these building types for the analysis and therefore only residential and office buildings were selected as a case study for financial analysis.

Generally toilet flushing is the most frequently cited application for urban GW recycling (Revitt et al., 2011; Leggett and Shaffer, 2002; Lazarova et al., 2003; Liu et al., 2010). As the focus of this study is on urban areas it is assumed that the residents in apartments do not have any water demand for gardening and therefore the recycled water only uses for toilet flushing. Laundry is the other application for the GW recycling but very few studies were on this area (Aalbers and Sietzema, 1999) and there are still some uncertainties regarding laundry application with GW therefore it is not included in this study. Moreover, only the light GW (from bath, shower, and handbasin) were used in the simulation in order to do the economic assessment with the lowest expectations from system, although with the selected treatment technologies (MBR and CW) previous researchers have shown a very good quality effluent with dark GW. Notwithstanding this shortfall is decided to focuses on the lower expectations which is better quality GW and higher standard of treatment in order to omit possible risk costs.

3.5.1 Water demands in residential (domestic) dwellings

Domestic water consumption can be extremely variable due to a range of factors including water price, population density, number of occupancy, type of property, size of property, occupant characteristics, number and type of water saving devices, individual demands, culture, income and climate (Bryant and Tillman, 1988; Agthe and Billings, 2002; Martinez-Espineirra, 2002; Liu et al., 2003; Butler and Memon, 2006; Wong and Mui, 2008).

Forecasting the water demand is difficult due to the lack of empirical data on domestic water consumption (Gleick et al., 2004). However, the current policy regulations in UK, with a preference towards 'smart metering' results in almost 40% of households been metered. As stated by Herrington (1987) demand forecasting results obtained from basic extrapolation or rule of thumbs have been shown to deviate radically from what happened in reality. These methods do not allow for changes in economic or social situations, or for technical improvements, each of which can exert a considerable influence on water demands. UKWIR (1997) recommends two related forecasting methods using micro-component analysis and micro-component group analysis. A micro-component approach to water demand forecasting is often recommended by Environment Agency (2001b) as well. Examining the information of household appliance ownership, volume of water per use and frequencies per use can help to understand the nature of domestic water demand (Downing et al, 2003).

In micro-component group analysis, residential units are classified into different groups in order that each group consists of the residential units showing similarities in terms of appliance consumption rate, usage frequency etc. The group classification criteria are decided considering the factors having a direct or indirect influence on water consumption patterns. Some of the criteria suggested are: socio-economic (indicating the income and of a particular household), type of house (e.g. flat, detached, semi-detached, and terraced) and composition of household (e.g. retired, single adult, families with more than two children). Figure 3.2 shows the household micro-components that most likely have been affected by types of individual and household variable.

Difficulties are more complex when forecasting water demands for new housing developments that do not exist when planning developments based on socio-demographic and socio-economic information for the future inhabitants. The most reliable information available for new households during planning typically includes the location, density and architectural type (e.g. number of bedrooms) of the properties themselves (Fox et al., 2009). Fox and colleagues suggested that a simpler set of physical property characteristics might be sufficient proxies to forecast water demand for new developments to be made regarding the potential inhabitants of new housing stock. Therefore in this thesis micro-component analysis was applied for predicting water consumption (and GW supply/demand) by multiplying frequency of appliance(s) use by volume of water consumption (per use) by the number of occupants. This assumes a linear relationship between frequency of water use and occupancy. Such an approach has been successfully adopted by many authors including Butler (1991), Roebuck (2007) and Hunt et al, 2012.

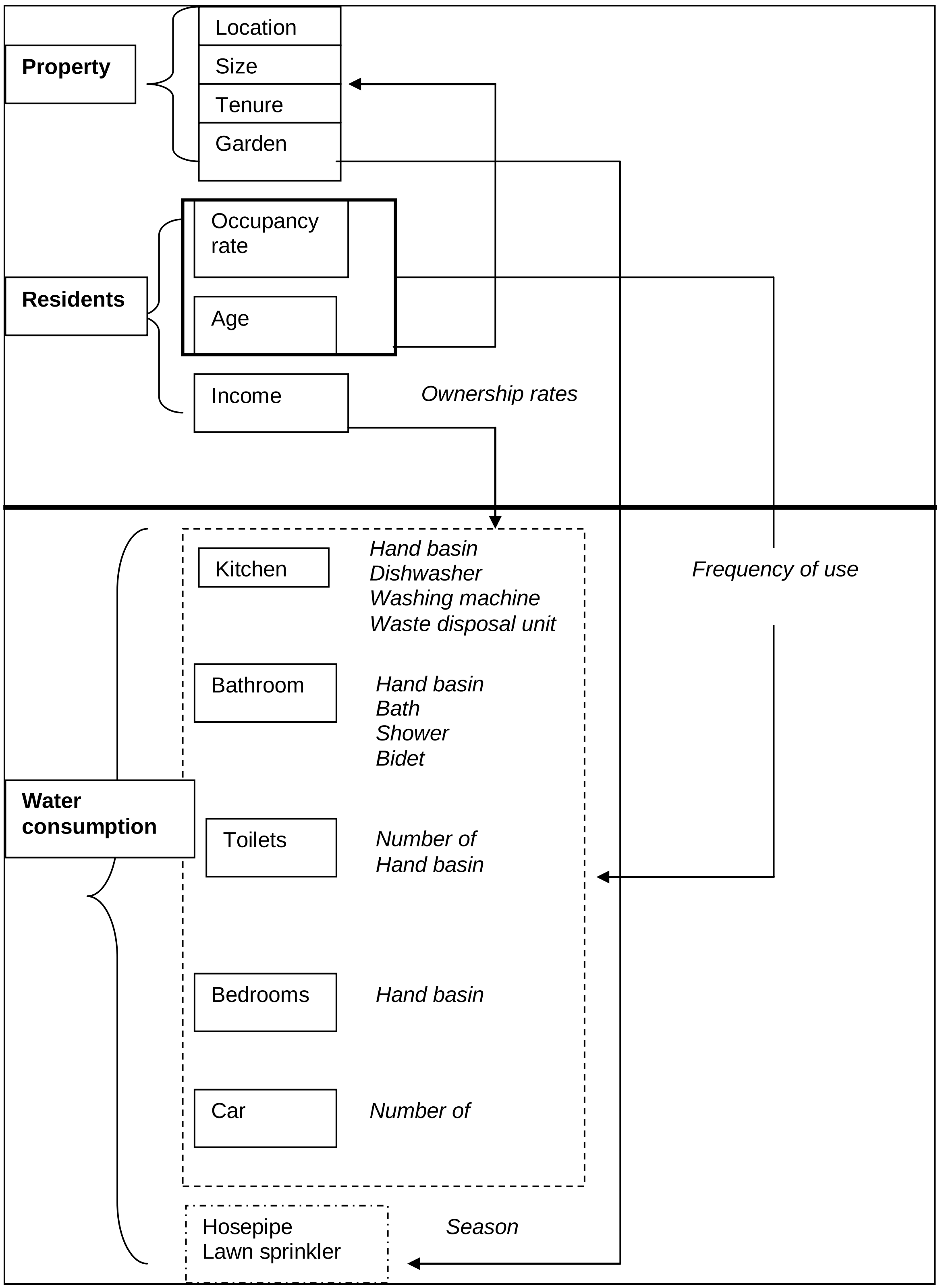


Figure 3.2 Factors that affect household water consumption (Clarke et al., 1997)

In Figure 3.3a the percentage breakdown of daily domestic water usage per capita in the UK for the last decade are presented (EA, 2001) This figure shows that 33% of per capita daily water use is for toilet flushing and only 24% for personal washing which includes showers, baths and handbasins.

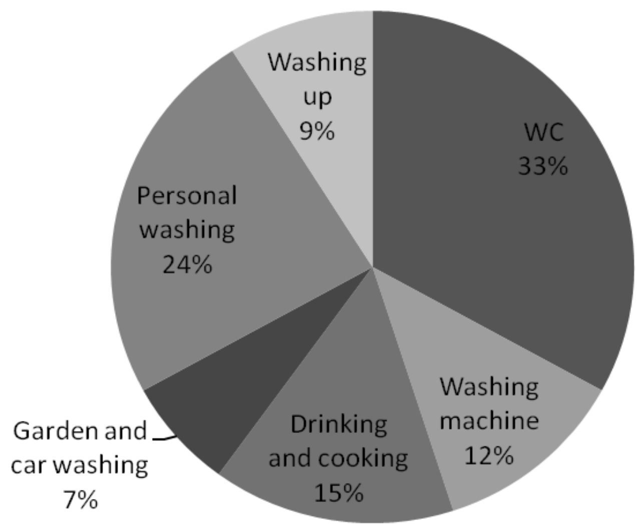


Figure 3.3a Percentage of domestic daily water usage breakdown per capita in the UK for 2001 (EA, 2001)

By assuming 150 lit/capita/day of water consumption this figure shows that 45 lit/capita/day is for toilet flushing (33% of 150) and based on average 4.8 number of flush per person per day (Chambers et al., 2005; DCLG, 2007) it is not inappropriate given the reference date to assume that the size of toilet cistern is 9 lit/flush. However, as from January 2001, all new toilets installed in the UK had to have a maximum flush of 6 litres. According to this the percentage breakdown of daily domestic water usage per capita that presented by EA in 2010 showed a significant difference (Figure 3.3b).

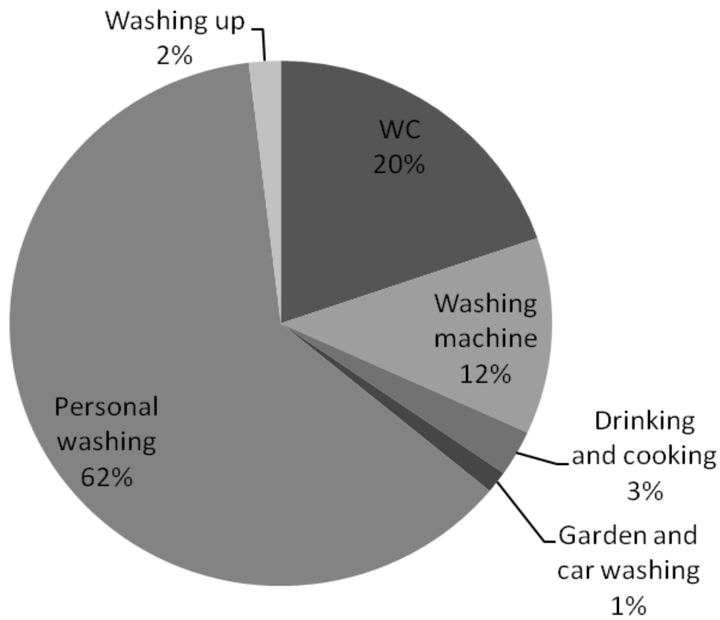


Figure 3.3b Percentage of domestic daily water usage breakdown per capita in the UK for 2010 (EA, 2010)

The percentage of toilet flushing reduced to 20% in this figure due to the updated UK regulation. As it is stated by EA in 2007 (EA, 2007) "in new houses shower and baths now accounts for around 45% of the water use, and taps around 20%). The percentage of personal washing shows significant increase compared to Figure 3.3a - this could be due to increasing duration of showers.

Based on this information the water demands for a typical new residential dwellings can be seen in Table 3.1 and Figure 3.3c. The data for predicted frequency (and duration) of uses and volume of water per use are based on past monitoring studies (SODCON, 1994; Butler, 1991; Chambers et al., 2005; DCLG, 2010; EA, 2010; BREEAM, 2011). The calculated water demand value of 148 litres / person / day reflects the average per capita water use in the UK domestic sector (EA, 2010).

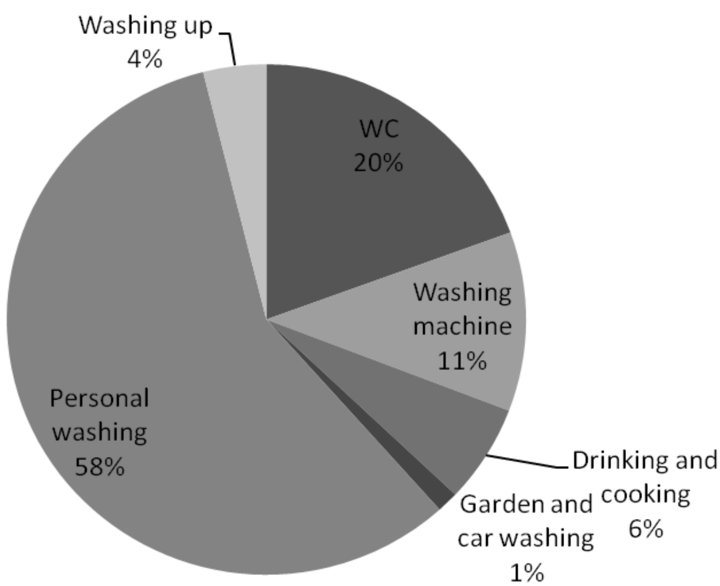


Figure 3.3c Percentage of domestic daily water usage breakdown per capita in the UK assumed within this study

Table 3.1 Per capita water usage breakdown in new residential dwellings within this study

Water use	**Water consumption (Unit)**	**Duration of use (minutes/usage)**	**Frequency (per day & person)**	**Total water use (Lit/day/person)**
WC flushing	6 *(lit/usage)*	-	4.8	28.8
Hand basin	8 *(lit/minute)*	0.33	3.5	9.2
Washing machine	80 *(lit/load)*	-	0.21	16.8
Shower	12 *(lit/minute)*	8	0.6	57.6
Bath	116 *(lit/usage)*	-	0.16	18.6
Kitchen sink	8 *(lit/minute)*	0.33	3.5	9.2
Dishwasher	24.9 *(lit/usage)*	-	0.23	5.7
Other	2 *(lit/day/person)*			2
Total daily water consumption (l/person/day)				148

It is evident that properties with garden have higher water consumption than those without. The data that given by Environment Agency in 2001 shows that up to 7% (around 10.5 lit/ person/ day) of household water consumption is for outdoor uses including gardening. This figure can be affected by variables like garden size, rainfall, species selection, temperature, and user attitudes (Martinez-Espineira, 2002; Syme et al., 2004). As the focus of this study is on residential and office buildings in urban mixed use areas it is anticipated that there is no garden water consumption per occupancy in these building types and it has been neglected from total daily water consumption. It is also assumed that GW is only substituted for WC flushing demand.

For the purpose of this study it is assumed that each flat has one toilet and one shower. Occupancy rates are based on UK average values (Average occupancy rate of 2.4) as previously adopted by Roebuck, 2007; EA, 2010; Hunt et al., 2012. Operation is assumed to be for 365 days per year.

3.5.2 Water demands in offices

There are few studies that have been done in the UK and overseas on water usage in large commercial and service institutions. This section presents some of the studies that have been done on non-domestic water usage in UK and around the world.

Six factors have been stated by CIRIA in 2006 which has an influence on office water use:

- Occupancy

- Size of office
- Age of property
- Type of systems and fittings installed
- Maintenance and management behaviour
- User/employee behaviour.

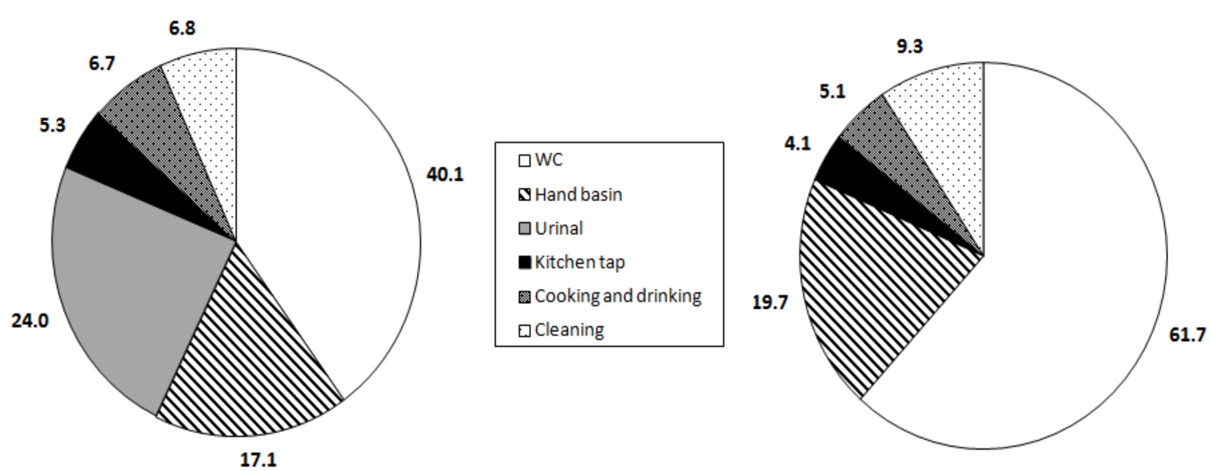
The statistical analysis of the Watermark web-based benchmarking (CIRIA, 2006) tool indicated that occupancy was the primary driver in water consumption in the offices. Although other drivers including floor area, opening hours and building age were considered, they had a very low influence and high risk of unavailable information. In respect to this the indicator for office water consumption was determined to be water consumption in m^3 per person per year.

A number of fittings and systems that can be installed in some offices may influence water consumption in offices, including the following:

- Presence of catering facilities including restaurants
- Type of sanitary ware including showers
- Use of wet air conditioning systems

At present there is no database of such information. However, the investigation by watermark shows that none of the above are likely to have significant correlation in water consumption. Therefore these were not included in this study.

The water demands for a typical office resident can be seen in Table 3.2 and Figures 3.5a and 3.5b. The data for predicted frequency of uses and volume of water per use are based on past monitoring studies (Hills et al., 2001; Waggett and Artosky, 2006). The calculated value of 15 litres / person / day for male employees and 19.4 litres / person / day for female employees reflects the average per capita water use in the UK offices (Waggett and Arotsky, 2006). Based on the findings of Waggett and Arotsky (2006) there is assumed to be 1 occupant for every 15 m^2 and ratio of male and female employees is 1:1 (MTP, 2008).



(a) Male (b) Female

Figure 3.4 Water usage breakdown in UK offices

Frequency of WC flushing in female toilets is assumed to be 2 times higher than in male toilets. This is based on the fact that male urinals are included resulting in less water demands for WC use. Male urinals have a certain flush volume per urinal bowl (i.e. there is typically one water cistern that will service multiple bowls – when it flushes all bowls are flushed simultaneously). The bowls are then (typically) flushed at set time intervals during the day. Urinals are assumed to operate 12 hours per day, 5 days per week (assuming water saving timers are fitted) and not 24/7 based on Water Regulations (1999). Frequency of hand basin use is assumed to be higher in female toilets than in male toilets based on the monitoring study by Thames Water's "Watercycle" project at the Millennium Dome, UK (Hills et al., 2001). For cleaning purposes, it is assumed that each toilet flushes twice and each hand basin runs for 5 seconds per day. The respective water usage breakdown for both male and female employees in the UK is presented in Table 3.3. The number of toilets, urinals and hand basins for offices is assumed to be 1 per 25 males and 1 per 14 female employees, plus an extra one for persons with disability (MTP, 2008). Offices are assumed to be in operation 261 days per year.

Table 3.2 Water usage breakdown for male and female office employees (*Italics* shows where female water usage differs)

Water use	**Water consumption (Units)**	**Duration of use (minutes/usage)**	**Frequency (per day & person)**	**Total water use (Lit/day/person)**
WC flushing	6 (lit/flush)	-	1 *(2)*	6 *(12)*
Urinal	3.6(lit/employee)[1]	-	1 *(0)*	3.6 *(N/A)*
Hand basin	8 (lit/min)	0.2	2 *(3)*	2.6 *(3.8)*
Kitchen sink	8 (lit/min)	1	0.1	0.8
Canteens	12.6 (lit/clean)	-	-	1.0
Cleaning	1(lit/day/person)	-	0.08 *(0.143)*	1.0 *(1.8)*
Total daily water consumption (l/employee/day)				15 *(19.4)*
1.Based 7.5 lit/bowl/hr and number of urinals in the assumed office block				

From Figure 3.5 it can be seen that GW production (85.4 litres / person / day) in domestic dwellings is much higher than demands (28.8 litres / person / day). Whilst in an office the levels of GW production per male and female employee (6.4 litres / employee / day) are significantly less than demands (21.6 litres / person / day).

Domestic dwelling GW systems are expensive compared to the price of fresh water in most countries (and certainly in the UK), and the material, energy and other resources required to construct and operate them are proportionately higher than those required for a mains water system. For the typical office, the opposite is true: GW demand exceeds that produced, thus creating a deficit of GW; the uptake of GW systems in offices is low due to both the small percentage of freshwater displaced and the unfavourable economic cost-benefit analysis of the system (Zadeh et al., 2010). From Figure 3.5 it can be seen that excess domestic GW generation is much higher than the deficit produced in office GW generation and therefore cross-connection appears to be a sensible approach based on flow volumes at individual scale. The ability of supplies to meet demands at block (i.e. building) scale will ultimately depend on occupancy and employee rates in each block. These are investigated further in Chapter 6.

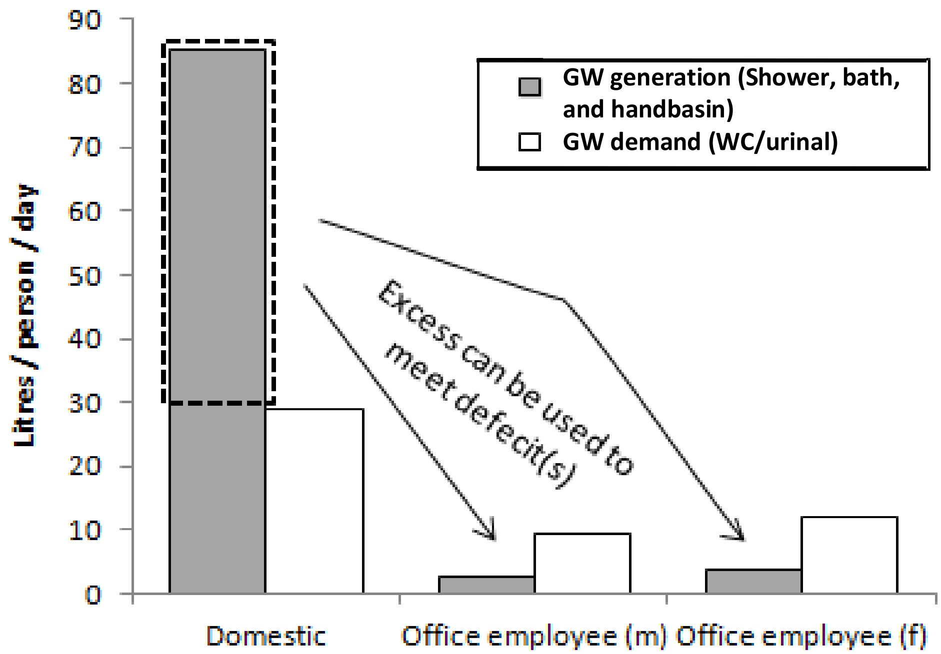


Figure 3.5 Greywater production and consumption for a single domestic resident and office employees (male – m, female – f)

3.6 Defining GW recycling scenarios

The initial step before doing any analysis was to define the five scenarios analysed in this project which was listed below and a short description follows.

- Scenario 1: Baseline scenario (no GW)

- Scenario 2a: Individual Block GW system (MBR)
- Scenario 2b: Individual Block GW system (CW)
- Scenario 3a: Shared GW system (MBR)
- Scenario 3b: Shared GW system (CW)

In Scenario 1 (Figure 3.6a) it is assumed that current practice for water supply and wastewater removal occurs, i.e. centralised supply and treatment, with no GW recycling and / or re-use.

In Scenario 2a and 2b (Figure 3.6b) distinction is made between potable and non-potable water. Within a residential building it is assumed that GW is collected from all showers (12 lit/minute) and used for flushing standard toilets (6L per flush). Initial mass-balance assessment (Figure 3.4) shows that supply more than meets demands therefore GW from basin and baths is not required.

In office buildings the only source of GW is from hand basins, which is subsequently used to flush standard toilets (6L per flush) and urinals (7.5 L /bowl /hour). In Scenario 2a it assumed that a Membrane Bioreactor (MBR) is used to treat GW whilst in Scenario 2b a Constructed Wetland (CW) adopted. The treatment performances and brief description of each were explained in Chapter 2.

In Scenario 3a and 3b (Figure 3.6c) GW is collected from residential showers and treated at one shared treatment unit, then recycled for toilet and urinal flushing in both office and residential blocks. In Scenario 2a it assumed that a Membrane Bioreactor (MBR) is used to treat GW. In Scenario 2b a Constructed Wetland (CW) is used to treat GW.

In all scenarios it is assumed that GW is substituted only for WC flushing demand in residential and office blocks. Whilst GW can be used for other purposes (e.g. gardening, car washing), these are beyond the scope of this current project. In terms of water utility infrastructure requirements, all scenarios are consistent with the 2011 UK Building Regulations, which specify metering for all new properties, 6L per flush for toilets and no more than 7.5 litres per bowl per hour for urinals.

3.7 Summary

The information presented here as well as that from chapter two was used as the basis for a new computer modeling tool for financial evaluation and CO_2 emission of GW recycling systems with the ability of performing a robust and rigorous and more detailed financial analysis than tools that currently exist.

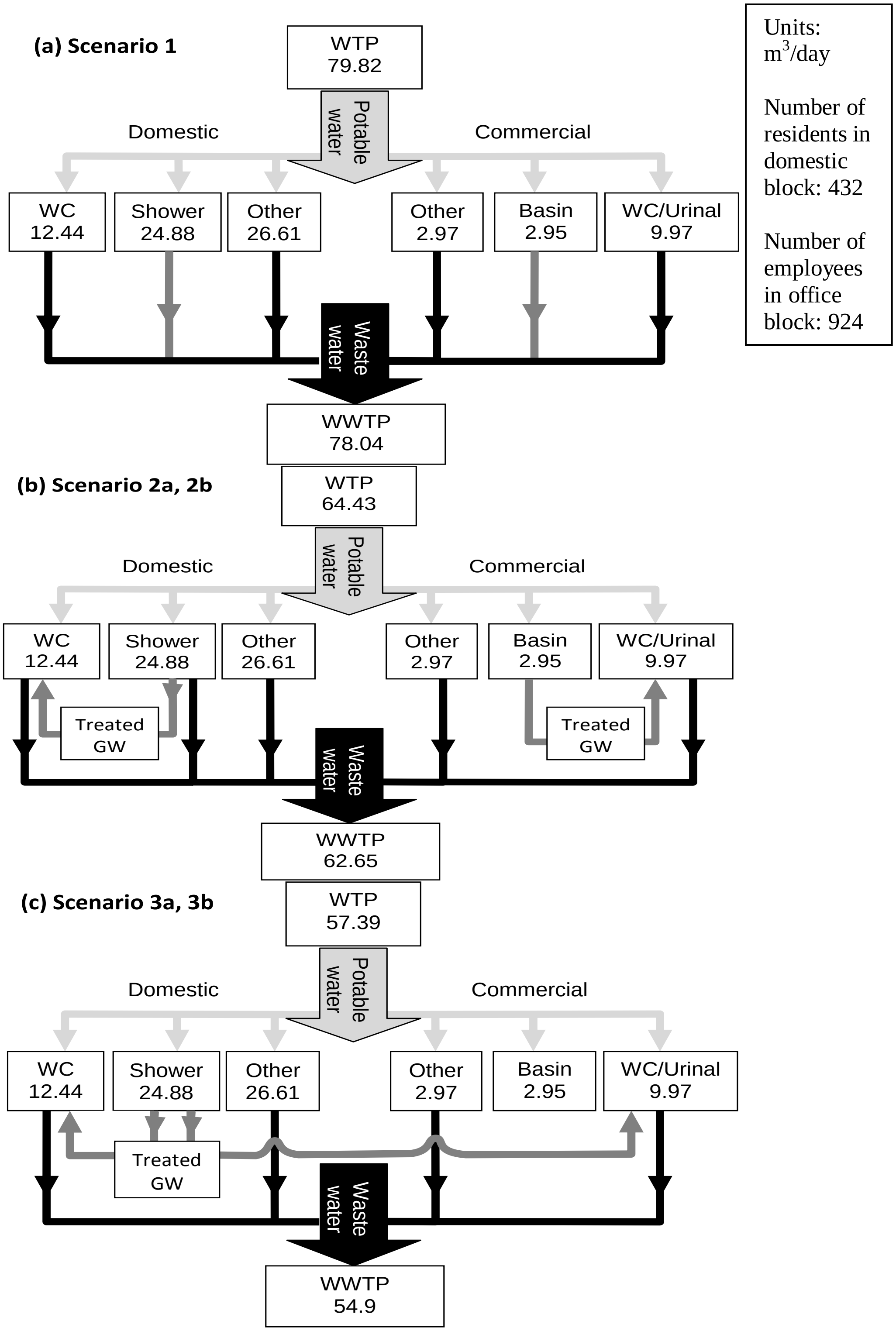


Figure 3.6 Volume balance in m^3 / day for various water supply options (WTP – Water Treatment Plant, WWTP – Waste Water Treatment Plant)

CHAPTER FOUR

FINANCIAL ASSESSMENT

4.1 Introduction

This chapter investigates the financial assessment of shared GW recycling systems installed in new-build residential and office buildings. The water saving potential and financial performance of individual and shared GW recycling system for selected residential and office buildings are presented and compared together. The purpose of this investigation was to provide data on the long-term economic feasibility of both shared and individual GW recycling systems adopted within new-build high-rise residential and office buildings in urban mixed use areas. This chapter determines whether they present an economically sustainable investment and, if so under what circumstances.

The data presented in this chapter coupled with financial information were used as the basis for investigating the financial performance of shared and individual GW recycling system. It was necessary to acknowledge that not all stakeholders will have the same assessment criteria, especially with regards to the selected discount rate and discount period. Moreover, the price of water, wastewater and electricity charges will vary considerably both within and outside the UK. Information presented within this chapter, and appendixes one and two demonstrate that a range of possible values exist and the selection of the different values will be influenced by the context of the investigation. The influence of the change in some of these parameters were also investigated and presented in this chapter. Table 4.1 summarises the parameters that were considered and assessed in the simulations and shows how the different values for each parameter could be assigned to different financial performance of system.

Table 4.1 Parameters used for financial sensitivity analysis

Parameter	Description
Water and wastewater charges	Changes in water and wastewater charges have a direct effect on financial performance of GW recycling system due to water and wastewater savings in this system. It is also has indirect impact on costumer water usage behaviour as increasing the charges will increase the willingness to save water and users become more interested in reuse options. But these influences did not considered in this study.
Energy charges	Changes in energy prices have impact on the operation and maintenance cost of the GW recycling system especially for the system with MBR due to high energy demand.
Discount rate	Reducing or increasing the inflation rate has an effect on the Net Present Value of system. Discount rates from 0% to 12 % were analysed in this study.
Service life	Changes in service life for 5, 10, and 20 years were examined in this system to see if the profits can overcome the capital and operation and maintenance cost of system
Building description	The impact of changing three important variables (cross-connection distance, number of floors and floor area) are subsequently examined for both buildings.

4.2 Financial assessment

Economic assessment as a sustainability tool, estimates whether the system can pay for itself with cost not more than benefits (Balkema et al., 2002). Businesses may use several methods for evaluating economic worth of various projects in order to select the best investment alternative. The next section describes a range of financial assessment methods that are relevant to the water industry with the purpose of recognizing the most suitable technique for performing a financial assessment of GW recycling systems.

An economic assessment includes internal and external costs and benefits of system. The internal costs consist of capital costs (CAPEX) as well as operational and maintenance costs (OPEX). Externalities are either impossible or difficult to monetise but nevertheless may still be regarded as important enough to warrant consideration. According to Sheikh et al. (1998), water reuse/recycling projects are often underrated when compared to other projects due to the failure to appropriately quantify external benefits of reuse such as environmental benefits, local economic development, and improvement of public health. Indeed CAPEX and OPEX of water reuse/recycling systems often bring a negative conclusion in terms of economic feasibility. As a result, the true benefits and costs of many water reuse/recycling projects have never been correctly assessed. In fact, if the external benefits (social and environmental benefits) could be measured, the benefits of many water reuse/recycling projects would exceed the costs and would become positive business case (Miller, 2006).

4.3 Existing financial assessment works

A review of existing studies was accomplished in which the financial performance of GW recycling systems has been explored at the single building and communal scale. There has been a lack of academically research on economic assessment of GW recycling systems in the past several years. As shown in Table 4.2 a number of authors has tried to do the cost assessment of this system at various scales. However, these studies concentrated primarily on hydrological performance, treatment technology performance and GW quality not financial, and most of them omitted to consider operation and maintenance costs or discount rates. Moreover, in those cost assessment examples stable values for water, wastewater and electricity charges were typically used for the whole lifespan of system which in terms of long-term planning is a shortfall. However, a review of past price data shown that these prices change year to year and in fact are likely to increase in real terms (Ofwat, 1999-2012; DTI, 2007b).

One item that was missing from all of the reviewed works was a thorough consideration of the replacement of treatment technology components. The components that were considered in previous literature studies were usually pumps, and UV lamps, though treatment technology components also require replacement in order to continue to work properly. Therefore in this study through previous works done by Roebuck (2007) on service life of RWH components and also contact with some MBR and CW suppliers it was possible to gain more realistic operation life expectancies of many common system parts of GW recycling system.

Table 4.2 Overview of financial assessment of GW recycling systems in literature

Reference	Purpose/overview of study	Financial assessment details	Comments
Humeau, et al., 2012	Technical-economic analysis of on-site GW treatment by non filtration or by Submerged membrane process. With 50 and 500 occupancy residential building in France.	Financial assessment: Capital costs and operation and maintenance costs. Assessment method: Cost of treated water. No discount rate.	Desktop study: The fixed cost only includes the cost for treatment and excludes the collection and distribution system. Results related to France and are not directly applicable to UK.
Mourad et al., 2011	The economic analyses for two potential treatment systems for GW recycling system in typical flat design in Syria for toilet flushing.	Financial Components: excavation, civil work and material Assessment method: payback period	Desktop study: No operation or maintenance cost. No discount rate. Results related to Syria and are not directly applicable to UK.
Zhang et al., 2010	Investigated the feasibility of rainwater harvesting and GW recycling in densely populated semi-urban area in China. Light GW form Tianxiu Garden project (10 m^3/ day) were selected for toilet flushing. The results found that the small plant in not economical or cost-effective.	Financial components: capital costs (purchase and installation), water saving per year, money saving per year Assessment method: ROI (return on investment) in years.	Desktop study. No operation or maintenance cost. No discount rate. Results relate to China and are not directly applicable to UK
Godfrey et al., 2009	GW treatment and reuse system in urban household in India. The GW system was designed for 5 persons. Light GW recycled and was used for toilet flushing and to irrigate the vegetable. Cost benefit analysis was undertaken for GW by considering internal and external costs and benefits. The payback period was 1.6 years.	Financial assessment: capital cost of construction. Assessment method: CBA method, average annual financial savings on water supply and simple payback period	Empirical monitoring study. Assumed no operating or maintenance cost. Results related to India and not applicable to UK. No discount rate.

Table 4.2 Continued…

Reference	Purpose/overview of study	Financial assessment details	Comments
Glick et al.,2009	Life cycle cost method used for GW recycling system for toilet flushing on both new and retrofitted individual housing scheme in Colorado. The NPV of both systems have results in net costs. For the LCC portion of the study, the associated costs for the GW recycling system construction, use and maintenance as well as the water use and treatment costs were estimated using local prices.	Financial components: Capital costs (purchase and installation), operating costs (energy costs, chemicals cost), money saved Assessment method: Life Cycle Cost (NPV)	Desktop study including a discount rate (5%). No maintenance costs. Results related to US and are not directly applicable to UK
Merciret, 2008	Economic assessment of communal GW recycling system in Cambridge region in UK.	Financial components: capital costs (purchase and installation), operating costs (energy costs, chemicals cost), water and wastewater saving, maintenance costs. Assessment method: NPV and payback period	Desktop study including a discount rate (4%). Applied for communal scale system. No replacement cost
Ghisi & Oliveira (2007)	Created a computer model to evaluate the potential for potable water savings by using rainwater and GW in two houses in southern Brazil for uses in toilet flushing and laundry. Economic analysis performed to determine the benefits of using rainwater and GW separately and in combination.	Financial components: capital costs (purchase and installation), operating costs (electricity for pump). Assessment method: NPV and pay-back period methods.	NPV method allowed a range of discount rates to be investigated. No maintenance costs. Results relate to Brazil and are not directly applicable to UK

Table 4.2 Continued…

Reference	Purpose/overview of study	Financial assessment details	Comments
Friedler and Hadari, 2006	They analyses the economic feasibility of GW reuse for toilet flushing in multi-story apartment flat. RBC and MBR treatment technologies were selected for the economic analysis. Typical family size in Israel of 3.4 persons, assumed one family per flat and four flats per floor. Payback period method with interest rate have been used n they analyses. Considering water charges in Israel of 1.16 US$/$m^3$ and sewage charges of 0.3 US$/m3.	Financial assessment: Capital cost (storage tank, pump, and plumbing), operating costs (energy ,chemicals, and labours) Assessment method: The net annual costs saving due to GW reuse. Payback period	Interest rate (5.5 %). No maintenance cost of replacing components like pumps or MBR filters. Results related to Israel and not applicable to UK.
Memon et al., 2005	The Whole Life Costing (WLC) methodology had been applied to evaluate long-term costs and benefits of the light GW recycling system in UK. The analyses were run for new build five bedroom house and full-scale plant installed in student hall with 40 residents. The model was run to obtain the WLC for the base case scenarios (for both scales). Then the influence of different factors on WLC was investigated to find a best option with least WLC.	Financial components: Capital costs (site preparation, purchase and installation, pipework), operating costs (energy costs, chemicals cost), water and wastewater saving, maintenance cots Assessment method: WLC method with considering total capital cost and the net present value (NPV) of operation and maintenance (O&M) cost and decommissioning cost earned at the end of the service life of the system.	Desktop study including a discount rate (4%).

Table 4.2 Continued…

Reference	Purpose/overview of study	Financial assessment details	Comments
March et al., 2004	The paper describes the GW recycling system for toilet flushing in a hotel in Spain. About 23% of total water consumption of hotel (5.2 m^3/d) was recycled and reused. A maintenance program and economic assessment was reported.	Financial assessment: Capital cost (storage tank, pump, and plumbing), operating costs (energy ,chemicals, and labours) Assessment method: Simple payback period	Empirical monitoring study. No maintenance cost (e.g. appliance replacement) constant electricity and water/wastewater charges. No discount rate
Briks et al., 2003	They study the performance of light GW system for WC flushing in five individual two to three bedroom houses in UK. They study highlighted the price of potable water is relatively low, and the payback period of GW recycling systems at individual housing scale is 50 years.	Financial assessment: Water and sewerage charges (£/m3), volume of water saved, Assessment method: Cost benefit analysis, basic payback period	Empirical monitoring study. No maintenance, no discount rate, no replacement cost, no operation cost
Dixon ,1999	PhD research project. Monitored performance of a combined domestic GW/rainwater system for WC flushing and garden irrigation. Empirical monitoring study used to model a number of domestic water demand options such as water conservation, GW, rainwater, and combined GW/rainwater.	Financial components: capital costs (purchase and installation), operating costs (pump and aerator energy costs, disinfection tablet costs) Assessment method: discount rate and simple payback period	Empirical monitoring. Included discount rate (6%) No maintenance costs (e.g. pump replacement). Constant electricity costs and water/sewerage charges.
Surrendran and Wheatley,1998	Reported the water balance and quality of GW recycling system and cost benefit analyses of retrofitted student hall for 40 students. The result shows the payback period of 8-9 years. The payback period reduces to 4-5 years if it applied for new buildings.	Financial components: Capital costs (instrumentation, installation), operating costs (energy costs, labour, consumables) Assessment method: Cost-benefit analysis	Pilot study. Costs figures dated 1998. No maintenance cost (components replacement). No discount rate.

4.4 Economic assessment methods in the water sector

Herrington (2006) stated that an economic appraisal method for any water demand management practice should include economic, social, environmental and technical aspects. Cost benefit analysis (CBA), social cost benefit analysis (SCBA) and cost effectiveness analysis (CEA) were the three economic assessment methods identified by Ashley et al (2004) as suitable economic evaluation methods in water sector. Other financial methods like net present value (NPV), payback period, internal rate of return (IRR), and whole life costing (WLC) were other financial assessment methods used within the literature (see Table 4.2). An average incremental cost (AIC) and unit cost approach has also been used for comparing the cost effectiveness of various water demand management options (Grant, 2003; Fane et al., 2003; MJA, 2007). A brief definition of these financial assessment methods are given in Appendix 2.

In the past, comparisons of asset alternatives have been based mainly on initial capital costs. As stated by Kishk & Al-Hajj (1999) it is now generally acknowledged that economic evaluation of projects based on their initial costs (i.e. purchase and installation) is not acceptable and it is required to taking into account the costs that arise during the life time of system (i.e. operation and maintenance costs). Therefore it is required to consider capital, operational and maintenance costs for asset management decisions involving costs.

Observation studies have found that GW recycling systems are subject to regular costs (Leggett et al., 2001a; Brewer et al., 2001). With regards to economic assessment of GW recycling system a number of recent research projects have concentrated on the Life Cycle Cost Analysis (LCCA) method (Gleick et al., 2008; Ghisi & Oliveira, 2007). LCCA is an economic assessment technique that finds out the total cost of owning and operating a facility over a stipulated period of time. LCCAs strength lies not in the determination of a total cost of a project alternative, but in the ability to compare the cost of project alternatives and to determine which alternative provides the best value per money spent. Therefore, according to the scope of this project it is judged that LCCA is the most appropriate method for assessing the financial performance of GW recycling system in order to achieve the first aim of this research project.

4.5 Life Cycle Cost Analysis method

According to the definition by Woods-Ballard & Kellagher (2004) "*whole life costing is about identifying future costs and referring them back to present day values using standard accounting techniques. It is recognised as an appropriate technique for use in valuing total costs of assets that have regular operating and/or recurrent maintenance costs, based on formalised maintenance programmes"*. Relevantly, the LCCA is an analysis method used to estimate the total cost of a product or system over its service life (ASTM 1999). It accounts for "all relevant costs over all life cycle phases of a product or process, adjusting for differences in the timing of those costs" (US Department of Commerce 1980).

In general LCC are those costs associated with construction, operation and maintenance of the system; while whole life costs includes non construction costs, incomes, and external costs and benefits as well. The Figure 4.1 illustrated the difference between LCC and WLC.

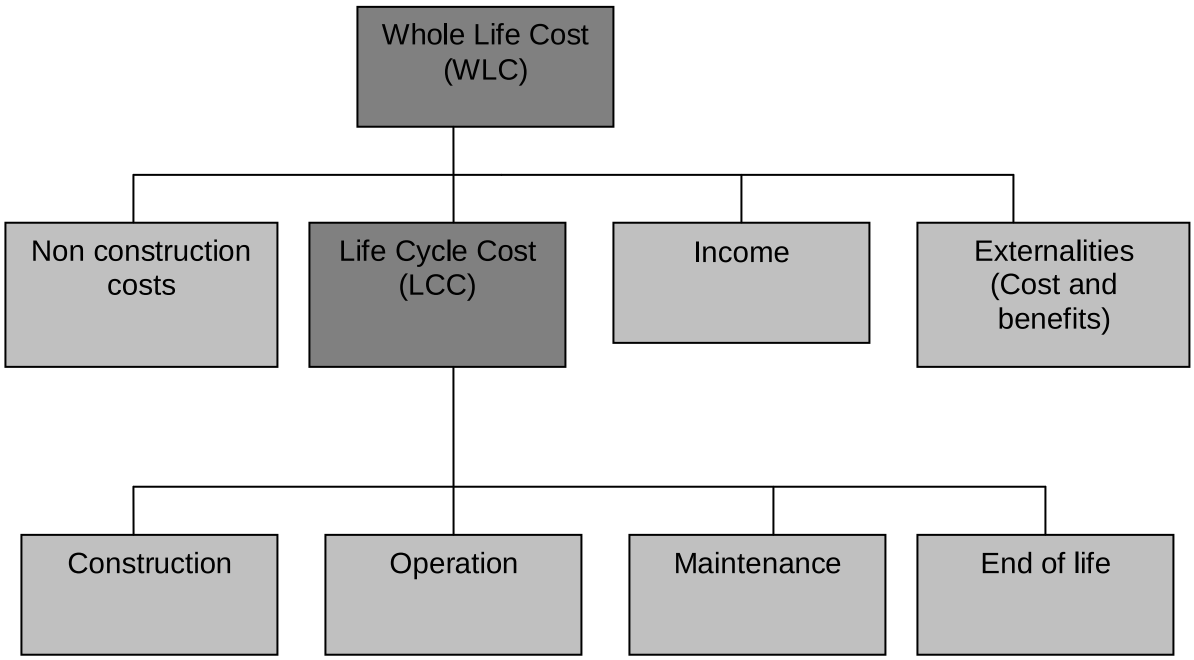


Figure 4.1 the difference between WLC and LCC (Woods-Ballard & Kellagher, 2004; BS ISO 15686-5)

A number of commercially available models can be used for LCCA. However the LCC model should (NSW, 2004):

- Represent the characteristics of the system , for example, intended use, maintenance routines requires, operation support and any limitations;
- Be broad enough to contain and emphasize the factors related to the LCC of system;

- Be easily understood and allow future updates and modifications;
- Provide particular LCC evaluation for each element independently of other elements.

The purpose of the analysis and the required information should also be identified before selecting any model for LCC analysis. In this study The Net Present Value (NPV) model was employed to do the LCC approach.

In the report by Ashley et al (2004) it is indicated that WLC is being progressively more supported by the UK government as a way of ensuring the implementation of cost effective options. It also meets the Ofwat's requirements of serviceability goals that it provides a holistic and robust basis for asset management, consider both cost and performance over total service life of system and can include issues related to resource use and impacts on the environment and society (Byatt, 2000; Heywood et al, 2002).

4.5.1 Net Present Value (NPV)

In view of the fact that investments are typically designed over a number of years, normally the financial assessment methods used will take into account the time value of money by including interest rates in the calculations of future cash flows. These methods are referred to as discount cash flow (DCF) methods. The NPV is a DCF method which is one of the most commonly used tools to compare the amount of invested capital today to the present value of the future cash receipts from the investment (Swamee and Sharma, 2008). Generally, Net Present Value (NPV) is the present value of an investment's future net cash flows minus the capital investment. A positive NPV designates a satisfactory project and a negative one shows the project should not be considered. In this study, the related costs of GW recycling systems, such as capital, operational and maintenance costs are balanced beside any benefits (such as reduction in water and wastewater supply charges). The NPV analysis requires a rate at which costs and benefits are reduced over time, known as the discount rate (MJA, 2007).

$$NPV = \left(\sum_{n=1}^{n} \frac{C_n}{(1 + r/100)^n} \right) \qquad \text{Equation 4.1}$$

where r =economic discount rate, n = life of the project (taken as 15 years), and Cn= cash flow of evaluated scenario minus the cash flow of Scenario 1 for year n.

4.5.2 Discount rate

The system component costs for varying options occur at different times throughout the system life span; they can only be compared by reducing them to costs at a common base date. This is the process of discounting to present value and involves applying a factor called the discount rate, to the flow of projected costs or income, in order to change for the expected impact of price inflation and investment return. In other words the Discount

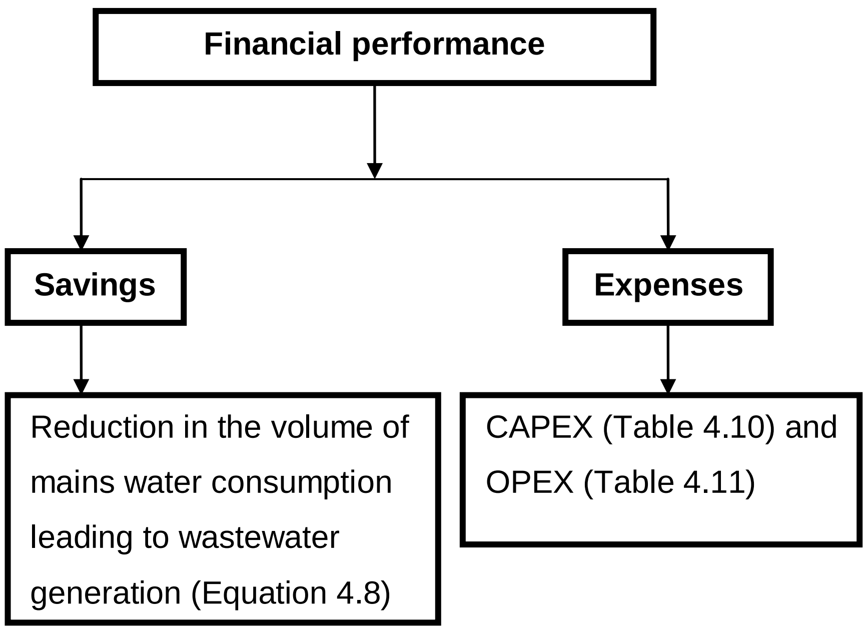
Rate imitates the real rate of interest at which money is borrowed or lent discounted for the effects of inflation. Consequently, the terms interest rate and discount rate are equivalent.

In the literature it is recommended that choosing an appropriate discount rate highly depends on who are the key stakeholders and will be dependant firstly on the goal of the key stakeholders (what are the primary aims and objectives) and secondly on the perspective within which the system is being established. Generally, individuals or a small business that may emphasis the short-term financial benefits should use higher rates than organizations or large established company which in turn look for long-term financial investment so would be more likely to choose a discount rate closer to the rate of return that it could obtain from investing in the open market (Voinov and Farley, 2007). Governments, institutions and societies apply the lowest discount rate of all as this reflects their responsibilities to society, both present and future (Ashley et al., 2004; Sumaila & Walters, 2005).

Usually discount rates between 3 to 8% have been used by many water utilities around the world. In this project a 4% discount rate was used for base analysis based on the 8 years discount rate used in the United Kingdom for evaluating projects (HM Treasury 2010) regardless of considering who is the responsible stakeholder for the system. The effect of different discount rates on the results were examined and explained in Section 4.9.3.

4.6 Input module and associated parameters

In general the aspects that need to be taken into account when evaluating the financial performance of a GW recycling system are the savings and expenses (CAPEX and OPEX).



Data and information in this research was obtained from a variety of sources including:

- Literature (e.g. Journal papers, conference papers, manuals)
- Other researchers currently active or previously active in the field
- Private sector companies

It is important to state that quantification of some of these factors may be subject to substantial uncertainty. It is assumed that economic conditions are similar through the life time of system. In reality events like global recession or wars will significantly affect the world economy. Electricity or water prices have been assumed to change in the predicted manner rather than rapid and disordered (section 4.6.1 and section 4.6.2). These could affect the CAPEX and OPEX of GW recycling systems.

4.6.1 Water flow module

Models that include a financial factor typically use the cost savings in mains supply replaced with recycled water as the main indicator of financial performance (known as avoided costs) as this is the primary way in which GW recycling systems are potentially able to save money. For example see Coombes et al (2003); Ghisi & Oliveira (2007) and MJA (2007), amongst others.

The simulation results from water flow module provided input for quantifying water saving potential and cost calculations in GW recycling system. The module has two components: GW supply and GW demand.

The GW supply component is assumed to be only made of showering from the residential block and from hand basin at the office block but other sub components from bathing, or washing machines can also be added by user if desired as the module structure is flexible. Equations 4.2 and 4.3 were used to calculate the volume of GW supply in residential (GWS_R) and office block (GWS_O).

$$GWS_R = V_s . F_s . R . T \qquad \text{Equation 4.2}$$

Where GWR_R is the annual GW supply in residential block (litre/year), V_s=total shower volume (litre/use), F_s=frequency of shower (uses/person/day), R=number of residents, and T=number of days per year.

$$GWS_O = V_B.F_B.E.T \qquad \text{Equation 4.3}$$

Where GWR_O is the annual GW supply in office block for male employees (litre/year), V_B= total hand basin volume (l/use), F_B=frequency of hand basin use (uses/male/day), E= number of employees (male or female), and T= number of days per year. The same equation used for measuring the GW supply from female employees as well. The data for the parameters in these equations were shown in Table 3.2 and 3.3.

The second component of the water flow module is for GW demand. It is assumed that GW is only used for toilet/urinal flushing. The total GW quantity required for toilet flushing in residential (GWD_R) and toilet and urinal flushing in office (GWD_O) is calculated by using Equation 4.4 and Equation 4.5.

$$GWD_R = V_T.F_T.R.T \qquad \text{Equation 4.4}$$

Where GWD_R is the annual GW demand in residential block (litre/year), V_T=volume of toilet flush (l/flush), F_T= frequency of toilet (uses/person/day), R=number of users, T=number of days per year.

$GWD_O = (V_T.F_T.R+V_u.N.H).T$ Equation 4.5

Where GWD_O is the annual GW demand for male employees in office block (litre/year), V_u= Volume of urinal (lit/bowl/hr), N=number of urinals in building, H= hours of use. Equation 4.5 can be used for measuring the toilet flushing demand for female employees without considering urinal flushing.

The net volume of saved water (W_s) and wastewater (WW_s) was then calculated using Equation 4.6 or Equation 4.7.

If $GWS > GWD$ *then* $W_s = GWD$, *and* $WW_s = GWD$ Equation 4.6

If $GWS < GWD$ *then* $W_s = GWS$, *and* $WW_s = GWS$ Equation 4.7

The value of water saved (S) is calculated as a function of water price (WP) of the mains water saved that would have been used for toilet flushing (W_s) and consequent reduction in the wastewater disposal cost (WWP) resulting as a consequence of reduced volume of wastewater (WW_s). The total savings can be calculated using Equation 4.8.

$S= (W_s*WP) + (WW_s*WWP)$ Equation 4.8

4.6.2 Water and wastewater charges

There are ten privatised water and sewerage companies and 12 water only companies currently operating in England and Wales. The historic data of mains water and wastewater charges for over 22 years are available in OFWAT reports (OFWAT 1989-2014). These data shows that the annual average household bills have increased since privatisation occurred in 1989 (Figure 4.2).

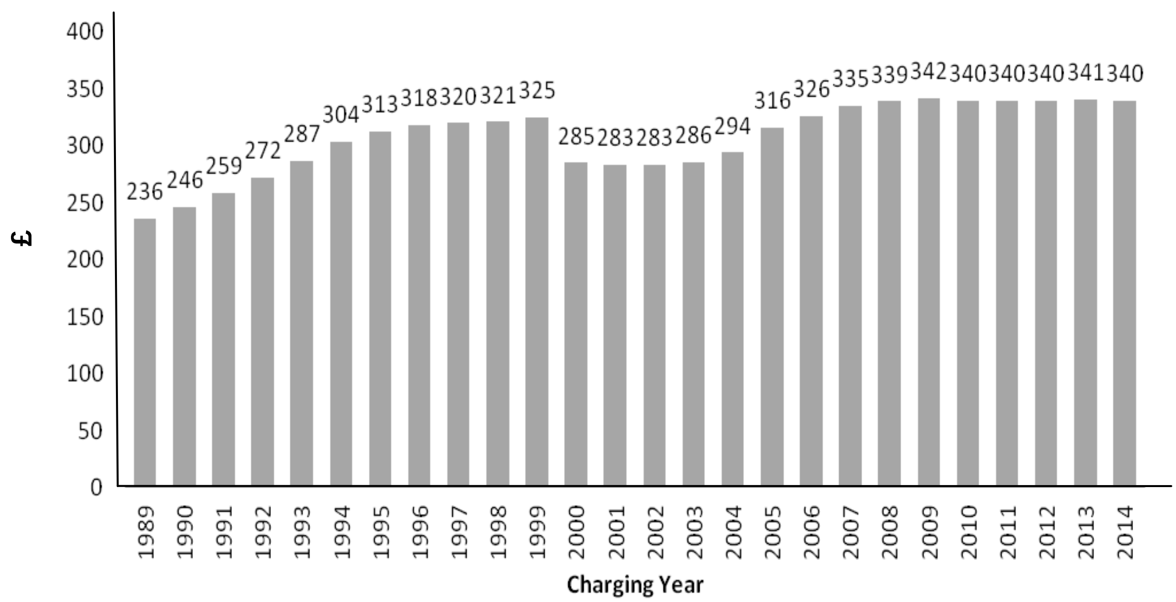


Figure 4.2 Annual average household bills from 1989- 2014 (www.ofwat.org)

In this research the future mains and sewerage charges were predicted for the Birmingham area (Severn Trent Water Company) by using the historic data to extrapolate these forward. The historic data shows that the water and sewerage charges are increasing each year. The predicted future charges in this study and further information on factors affecting water and sewerage costs are presented in appendix one.

The water and sewage charges since privatisation (1989) show about 43% increase excluding inflation. The price cap that was set for the predicted future prices in this study is not more than twice the rates expected in 2015 this price cap has been set to prevent an unrealistically high future prices (Figure 4.3) . This figure is not far away from the reality as other countries in Europe like Germany already have water and sewages charges rates twice as high as the UK (Kraemer et al., 2007).

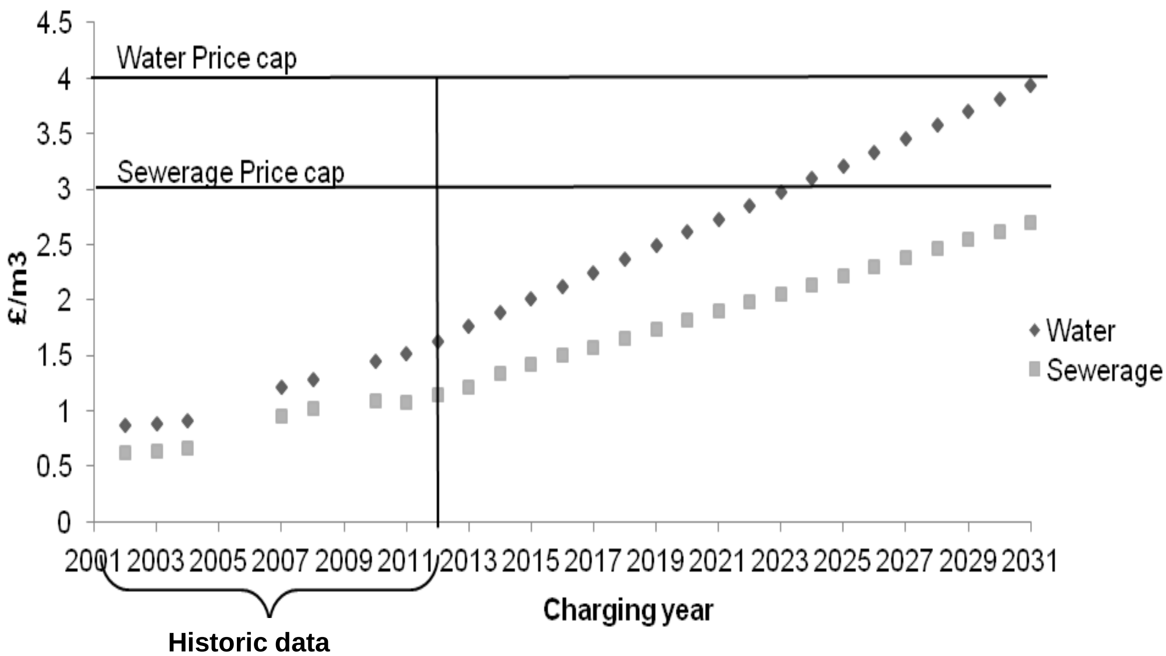


Figure 4.3 Predicted volumetric water and sewerage charges

4.6.3 Cost quantification module

This module calculates the cost of a GW recycling system by taking into account the capital cost, operation costs, and maintenance costs. The total costs are expressed as a function of capital cost, annual operation and maintenance cost and cost of system component replacement costs occurring at irregular time intervals (defined by the model use) throughout the design life of the system.

4.6.3.1Capital cost

The items that were considered for the capital cost of GW recycling system in the literature were:

- Planning costs
- Site preparation cost
- Purchase cost of components
- Collection and distribution pipework
- Installation and commissioning
- Cost of land-take

For GW systems installed in new-build developments a number of these items may be mostly unrelated. For the new build situations the planning, site investigation, design management, land preparation, excavation, supervision and other work preparation does not considerably affect the overall cost of the GW recycling system as some of them are already available on-site, consequently these costs are likely to be minimal (Leggett et al., 2001). Therefore these costs were not considered explicit for the financial assessments part of this research.

Material costs for the GW recycling system are the costs that relates to component purchase, installation and delivery costs. Components for distribution and collection system are: pipes for collection and distribution of GW, pump(s) for delivery of the GW to the toilets in the highest floor of the building, storage tanks for storing GW before and after treatment, filters to remove hair and other particles from GW before it enters the treatment unit, and electronic management system. The cost of these components and treatment technologies includes the purchase cost, installation cost and delivery cost through various UK manufacturers. This information was obtained from private companies, and previous research. Most of the data were based on 2011 the rest were converted to 2011 by considering the Retail Price Index (RPI) of 3% (ONS, 2011). The list of cost data for these components can be found in Appendix 1. The cost data for MBR and CW were obtained from private sector. A total of 15 companies (4 MBR providers and 11 CW providers) were contacted and asked to supply cost information based on the information about the case study. The CW companies were selected from Constructed Wetlands Associates website and only 5 companies responded. None of the companies name is referred to by their actual names. Most of the price data for MBR and CW were gathered in 2011 and so did not require adjustment for inflation.

The sizing of piping systems (pipe diameters, valves, etc.) has followed well-known conventional procedures based on the most common hydraulic engineering principles. The correct size, or diameter, of pipe depends on the pressure at the start of the particular run, the flow required at its end (i.e. the pressure required at fixtures), and whether the pressure is sufficient to overcome the head loss in its path due to friction in the pipe, turns and fittings, and any rise in height - and still deliver the required flow at the desired point of end-use. The probability that all sanitary fixtures use simultaneously is very rare. Therefore, previous research by British Standard (BS6700) has provided a system to estimate probable demand based on Loading Units for domestic and commercial uses. These take into account the flow rate, frequency and length of use of common sanitary appliances (Appendix 2). The pipe size is correct provided that the progressive head does not exceed the actual head and the velocity does not exceed 2 m/s in cold water pipework. The details of the sizes for each pipe at each scenario simulation were presented in Appendix 2. Pipe materials selected for the water supply system are based on the local water authority's adopted practice.

Prices per metre of pipes with various diameters sizes were collected from British pipe manufacturers. This includes the cost for materials only. The diameters of pipes were selected based on the British standard and the required length for each were measured based on the size of buildings and number of toilets. In the system with MBR treatment the whole system can be supplied at the basement of each building but in the CW treatment system the treatment is located within a distance from buildings which causes extra cost to the pumping costs for this system. The assumed distance between CW and the buildings in the case study were inspired by the Eastside Park in the eastside regeneration area in the Birmingham, UK.

As stated by Legget et al (2001) installation costs consists of the fitting of pipe works, excavation for tank and other preparation requirements, wiring electricity, and testing.

These costs are very site-specific and dependent on some key conditions. None of the contacted companies were willing to give installation estimates, based on the fact that installation cost is very site specific and required consideration on a case-by-case basis and cannot be generalised. In the study by Roebuck (2007) it is stated that some companies claimed that from their experience it is possible to assume that installation cost would be same cost as the component costs but this idea did not academically proved. In the literature the £1000 was usually assumed for the installation costs in each new build domestic system (Smerdon et al, 1996; Leggett et al, 2001; Roebuck, 2007). Therefore the same amount was also assumed in this study.

One of the advantages of MBR technology is its low space requirement. The usual place for applying GW recycling system with MBR is the building basement. The cost of land taken is closely relevant to CW treatment method which requires a plan area for the system. As the aim of this study is to work on urban areas the land availability and land cost have a significant effect on the implementation and cost of the GW recycling system with CW treatment technology. As stated in Chapter 2 vertical flow CW were suggested to be the best option in urban areas as they required less land and achieved higher effluent quality for light GW. The required specific surface area is usually 3-4 m^2/p.e. in cold regions and 1-2 m^2/p.e. in warm regions (Reader and Kamau, 2010). However, this may also vary depending on the reuse option and local legislation. Literature reports good experiences with designing vertical flow in warm climates with about 1.2 m^2/per person (Platzer et al., 2007). Different European studies (Austria, Germany, Norway and UK) that applied vertical flow CW for GW treatment were adopted the area of 1 m^2/person

(Jensen, 2004; SuSaNa case studies, 2009; Frazer-William, 2008). Therefore the 1 m^2/person were choose as an appropriate design criteria for vertical flow CW within this study. Based on this criteria and the number of people that connected to the system the bed size for CW were calculated. The land price were estimated to be 65 £/m^2 base on the annual guide to the property market across England in 2011.

4.6.3.2 Maintenance requirements and associated costs

GW recycling systems are not 'fit-and-forgot' technologies and require periodic checking and maintenance if they are to continue to operate reliably (Leggett *et al*, 2001b; Shaffer *et al*, 2004). Routine inspections and annual testing should be carried out in accordance with the manufacturer's instructions. Table 4.3 shows indicative maintenance requirements recommended by British standard.

As stated by Roebuck and Ashley (2006) though capital costs can be calculated with a reasonable degree of precision, operating and maintenance costs are harder to predict. Woods-Ballard and Kellagher (2004) categorise maintenance activities in to two types: regular (e.g. filters cleaning or weeding the plants in CW) and unplanned (e.g. pump failure, MBR filter fouling).

Table 4.3 Recommended regular maintenance activities and frequencies of GW systems (British standard, 2010)

System components	Comments	Maintenance Frequency
Manually cleaned filters and membranes	Check the condition of filters and clean or change if necessary	Monthly
Disinfection or other consumable chemical	Check if operating or any chemical supply needed	Monthly
Storage tank/cisterns	Drain down and Clean tank	Annually
Pump and pump controls	No leak, and no corrosion	Annually
Back-up water supply	Functioning and air gap are maintained	Annually
Control unit	Operating appropriately	Annually
Water level gauge	Check gauges response correctly to water level	Annually
Pipework	No leaks, overflows are clear	Annually
Markings	Check that warnings and signs are visible and in place	Annually
Support and fixing	Adjust and tighten	Annually
Wiring	Visually checking the wires and make sure of safety	Annually
Backwash	Check functionality	Annually

The total maintenance cost (C_M) is given by Equation 4.9. Depending on the level of details available on the maintenance cost, the user can add other additional cost elements to this equation.

Equation 4.9

$$C_M = C_{Consumables} + C_{Monitoring\ cost} + C_{Labour} + C_{Sludge\ disposal} + C_{Electricity} + C_{Equipment\ renewal\ cost}$$

Where $C_{Consumables}$ is Consumable costs; $C_{Monitoring\ cost}$ is monitoring and water quality analyses costs; C_{Labour} is labour costs for system maintenance; $C_{Sludge\ disposal}$ is sludge disposal cost; $C_{Electricity}$ is Electricity cost for distribution and treatment of GW and finally $C_{Equipment\ renewal}$ is cost for system equipment renewal.

Table 4.4 to Table 4.9 describes sources and methods used to calculate the required data for each of the parameters in Equation 4.9. The data that were not for 2011 was converted to present value ‘relative worth’ using a currency converter that used the GDP deflator index to account for inflation.

System performance and water quality are the two types of monitoring activities that are related to GW recycling systems. System performance is part of maintenance requirement of system (Table 4.5) and most of the GW recycling system providers were offered a contract of checking the system performance. Usually modern systems are set with automated monitoring devices that report faults like pump failure via a control panel.

Table 4.4 Consumable costs for GW recycling system maintenance

Description		Data estimation	Units	Reference	comments
Chemical for membrane maintenance	Membrane maintenance costs of chemicals	3 0.5	Lit/cartridge £/lit	Author personal communication with leading MBR manufacturers	
Remote control monitoring	Connection fee	50	£/month	Mercoiret, 2008(From Aquality)	
Chemical for disinfection in CW	Quantity needed per cubic meter of recycled GW	0.003	Kg of chlorine/m^3 of GW	Friedler and Hadari, 2006	Liquid chlorine disinfectant with chlorine concentration in solution=11%
	Chlorine solution price	3	£/litre	UK manufacturers	

Table 4.5 Monitoring costs for GW recycling system maintenance

Description		Data estimation	Units	Reference	comments
Frequency of water quality analysis	Chemical analyses frequency Microbiological analyses frequency	1 4	Times/year Times/year	CIRIA,2006 ; Shaffer et al., 2004	
Chemical analyses prices	Dissolved Oxygen Turbidity (NTU)	13.93+VAT 10.73+ VAT	£ £	School of Water Sciences Cranfield University, (2007), Routine Analysis Tests and Charges	
Microbiological analyses prices	Total+ Faecal coliforms	58.85+ VAT	£		

Table 4.6 Labour costs for GW recycling system maintenance

Description		Data estimation	Units	Reference	comments
Maintenance of the collection and distribution systems	Hourly rate of pay	10.41	£/h	Spon's, 2011	UK specific standard wage that matches the level of qualification required for maintenance
	Maintenance of pipelines and storage tanks	% of the capital costs per year	2	Asano, 1998	No specification of effluent type and technology used.
Maintenance of the MBR treatment system	Routine inspection frequency	2	times/year	Mercoiret, 2008, Author personal communication with leading MBR manufacturers	This routine inspection includes membrane maintenance and membrane cleaning
	Routine inspection duration	4	hr		
	Number of staff needed for routine inspection	2	persons		
	Membrane maintenance frequency	1	Number Of maintenance events/year		For chemical cleaning
Maintenance of the CW treatment system	Frequency for weeding Duration for weeding	Fortnightly 0.08	 hr/m^2	Personal communication with 2 CW companies Author assumption	Based on the CW bed area the duration for weeding and harvesting can be measured
	Frequency for harvesting Duration for harvesting	1 0.08	times/year hr/m^2	Personal communication with 2 CW companies Author assumption	
	Cleaning inlet pipes frequency Cleaning inlet duration	1 2	Month/year hr	Garcie-prez et al., 2007;	

Table 4.7 Sludge disposal costs for GW recycling system maintenance

Description		Data estimation	Units	Reference	comments
Sludge management	Sludge production	4	m^3 every 3 to 5 years	Mercoiret, 2008, Author personal communication with leading MBR manufacturers	Sludge removal is only applies for GW recycling system with MBR treatment
	Sludge disposal cost	120	£+VAT		
	Desludging Frequency	3	year		

Currently there is not any legislation or regulations regarding the quality of recycled GW and there is no stringent legal requirement to monitor the quality of treated GW from such a system. Previous studies show there is a low risk to human health from GW recycling system especially for toilet flushing uses. Therefore, as suggested by Mustow *et al* (1997), different unit types (e.g. BOD, COD, TCC) are carefully tested by an independent body and when a system receives official approval then it can be installed without water quality monitoring. WRAS (1999) and Legget et al (2001) both recommend that it is better to run frequent tests especially for multi-residential buildings. For individual housing systems this act probably would be too expensive due to the low water savings in this type of system.

Table 4.8 Electricity costs for GW recycling system maintenance

Description		**Data estimation**	**Units**	**Reference**	**comments**
Treatment demand	Energy demand per cubic meter of treated GW with MBR	1.5	KWh/m^3 of treated GW	Mercoiret, 2008; Friedler and Hadari, 2006; Nolde, 1999	
	Energy demand per cubic meter of treated GW with Vertical CW	0.014	KWh/m^3 of treated GW	Dillon, 2002; Personal communication with reed-bed company	The intermittent batch loading in vertical flow CW enhances the oxygen transfer and leads to high aerobic degradation activities. Therefore, vertical filters always need pumps
Pumping (collection and distribution demand)	Energy demand per cubic meter of collected GW	0	KWh/m^3 of collected GW	0	The gravity-fed nature of the collection system is considered as a case study condition
	Energy demand per cubic meter of distributed treated GW	-	KWh/day	Author calculation from Equations 3.10- 3.12	

As stated by Leggett *et al* (2001) the pump unit from distribution system and from treatment system are the items that have a constant expense in GW recycling system which relates to the cost of electricity consumed (Table 4.8). The energy requirement for solenoid and electronic control was not considered in the financial assessment, as the energy requirement of these items were not cited anywhere in the literature.

The energy requirements for the pump were estimated using the standard pump power equation:

$$P_{Consumed} = \frac{\gamma.Q.TDH}{\eta} \quad . \qquad \text{Equation 4.10}$$

where P is the powered consumed by the pump (W), Q is the flow rate (m^3/s), η is the pump overall (mechanical and hydraulic) efficiency (Equation 4.13) , γ is the specific weight of water (N/m^3):

$$TDH = H_p + \Delta Z + \Delta H_f \qquad \text{Equation 4.11}$$

where H_p is the operating head (pressure required by fixture), ΔZ is the elevation difference between pump and the fixture in the last flat at highest floor., ΔH_f is the head lost in system which is due to friction in pipes and fittings and varies according to the flow rate (Q) of the water, length (L) and diameter (D) of the pipe and material ($C_{H\text{-}W}$) of the pipe, which can be calculate for each pipe in the building using the Hazen-Williams equation:

$$\Delta H_f = 3.134 \times 10^6 \left(\frac{Q}{C_{H-W}} \right)^{1.852} D^{-4.87} L \qquad \text{Equation 4.12}$$

For simplification instead of measuring the head lost at each pipe, the average head lost (0.762 metre (2.5 ft) per 30.48 metre (100 ft) of pipe) used by many building installation designers were also assumed within each scenario of this study.

A pump is never 100% efficient and therefore the pump efficiency (η) must be included to calculate total energy consumption of pump. The efficiency of pump in this study was considered based on the manufacture recommendation (65%). The pump algorithm used in the thesis model assumes that the power consumption and flow rate are constant for a given head. In practice variable speed pumps are available in which the power consumption versus flow rate can vary but this level of detail was not considered necessary for the model.

4.6.3.3 Replacement cost

The design life is the minimum expected time-span for the structure or scheme to perform its task (Woods-Ballards & Kellagher, 2004). The design life was divided in two categories:

1. Service life: the limiting term of the infrastructure during which they maintain the required operating qualities and performance. A service life of 15 years was assumed for GW recycling system in this study with both type of treatment techniques (Memon et al, 2005; Friedler and Hadari 2006). Other possible service lifes for 5, 10 and 20 years were also examined in section 4.9.4.
2. Component life: The period of acceptable usage after which the chance of failure significantly increases and before which the components of infrastructure are removed to maintain the reliability of operation.

It is crucial to understand the design life of each component for accomplishing an economic assessment. The need to repair or replace the components will have effect the long-term cost effectiveness of GW recycling system. Data for the expected component life for GW recycling systems was collected from literature review. It is assumed that if only part of a component required replacement then the whole unit was changed. Table 4.9 presents a service life of GW recycling system components that have been assumed in this research. Expanded details and references for these assumptions are shown in Appendix 1.

Based on these assumptions when the service life of each component were over the cost for purchasing a new one was added to the total maintenance cost of the GW recycling system on that year. For simplification the purchase cost that was assumed for each component was based on the purchase costs in 2011 although these costs might increase or decrease in the year that components need to be changed.

Table 4.9 Assumed life expectancy of GW recycling system components

System components	Life expectancy (year)
Storage tank	20
Pump	10
Filter	10
Membrane module	2
Electronic control	20
Pipework	50^{+}
Valves	10
CW bed	6

With time, the gravels in CW will become clogged with accumulated solids and bacterial film therefore the material may have to be replaced every 6 years.

4.6.4 Electricity costs

Historic average electricity costs for domestic properties were available for the years 1998-2011 (DECC, 2011). Assessment of this data shows that prices remained quite stable at the range of 6-7 pence/kWh between 1998 and 2003. Since 2003 prices have ascended significantly. The average unit cost for domestic electricity use is 15.2 pence/KWh for 2011 (Figure 4.4).

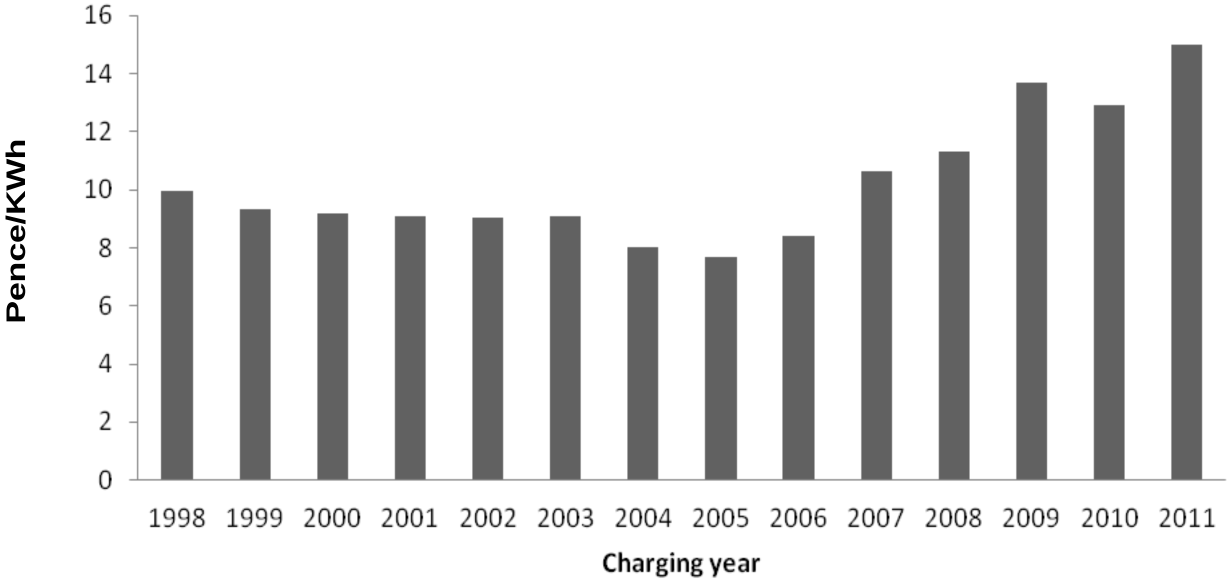


Figure 4.4 Average domestic unit price of electricity in UK form 1998- 2011 (DECC, 2011)

Ofgem have stated that future costs are unlikely to fall below the price levels witnessed in the 1998-2003 period (Ofgem, 2007). The recent increase in prices has been recognized to influence by a number of factors including the steadily rising wholesale gas and oil prices, and reduced availability of gas supplies on the open market in general.

Historic data trends were analysed and extrapolated in order to predict the average future unit costs. Limitations on the maximum price were set to prevent predicted future prices from becoming unrealistically high. Direct intervention by Central Government and other organisation and research sectors have invested in alternative energy sources and methods on demand reduction to prevent the price rises. Therefore, the price cap set for this analysis was assumed to be at twice of peak value of historic dataset in order to permit adequate headroom for a realistically increasing future costs. The annual future electricity charges are presented in Figure 4.5.

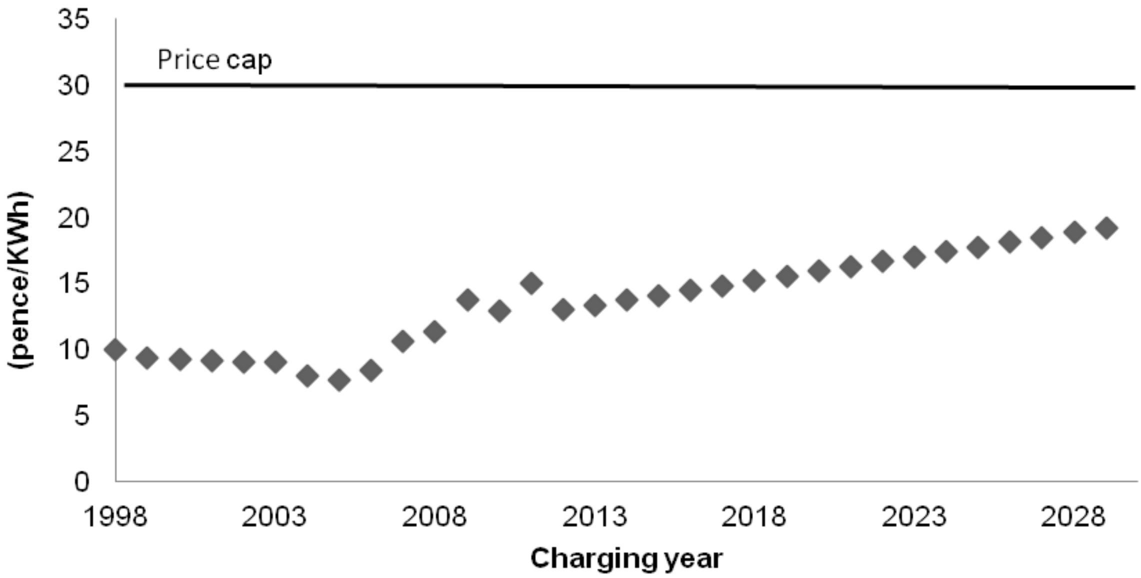


Figure 4.5 Predicted electricity charges in the UK

The range of predicted future unit costs of electricity for the next 15 years are presented in Appendix one. Other multiples for average annual price changes for electricity charges were examined and the results are presented in section 4.9.2.

4.7 External costs and benefits

In recent years, technological progress in the field of GW recycling has been very important, as the feasibility of GW recycling projects is subject mostly to economic aspects and social acceptance and not so much to the achieving of satisfactory quality effluent. Regarding to this it is important to have a detail cost analysis of the GW recycling projects.

However, perhaps the economic aspect is the least studied in GW recycling research topic, since in general only private costs are considered (see Table 3.1), while the external costs and benefits were highly neglected and just demoted to a series of statements about the advantage or disadvantage of GW recycling.

GW recycling systems do have impacts on society and the environment in terms of sustainable water resource management. Examples of these are health benefits and especially environmental benefits (e.g decrease diversion of freshwater from sensitive ecosystems, see EPA, 1999). Regardless of the complications involved in the quantification of externalities, caused by the lack of market to adjust their prices, in the perspective of wastewater reuse there is a growing interest in the monetary valuation of them. For example the study by Godfrey and colleagues (2009) focused on the cost benefit analysis of GW recycling in a school in India with considering the monetary values of environmental and health benefits. In the study by Segui and colleagues (2009) the technique of travel costs were used to establish the environmental benefits from wastewater reuse in the perspective of a wetland reinstallation project.

Usually the environmental implications of product/systems are often investigated using Life Cycle Assessment (LCA) which is a way of evaluating the environmental impacts associated with product/system throughout its life (ISO 14040, 1997). LCA is a well established, standardised method which also includes an impact assessment phase (LCIA) where potential impacts are aggregated and quantified (ISO 14040, 1997; ISO 14042, 2000). LCA has been used for estimating environmental loads from urban water systems, usually wastewater systems (Tillman et al., 1998; Lundin et al 2000; Machado et al., 2006; Ortiz et al., 2007; Stoket and Horvat, 2009; Pasqualin et al., 2009).

For example Stokes and Horvath (2009) used the LCA method to compare three water supply alternatives in California. These alternatives were: desalination, importing, and recycling. Energy use, air emissions associated with energy generation, vehicle and equipment operation, and material production were quantified for these water supply options. The study revealed that the environmental effects of energy and air emissions caused by infrastructure is considerable, and in some cases, significant relative to the economic cost of water. In the study recycled water is shown to be more environmentally caring than desalination and should be adopted provided that there were customer satisfaction for non-potable water use.

Lundie et al (2004) carried out all LCA study to examine the potential environmental impacts of Sydney Water's total operations in the year 2021. The base cases system were modelled to represent current operating assets as augmented and upgraded to 2021. Results provided for a base case were used to compare alternative future scenarios and for conclusions to be drawn regarding potential environmental improvements. The result shows that the desalination scenario produced a significant increase in greenhouse gas emissions due to electricity generation for a small increase in water supply. Water demand management, on-site treatment, and centralized biosolids treatment indicates significant environmental improvements are possible relative to the assessment of a conventional system of corresponding scale.

There has been limited research into the life cycle impacts of GW recycling systems and that which exists is not particularly favorable (See section 2.9). LCA was used in the study by Van der Hoek et al (1999) to measure the environmental impacts of some of the possible water supply options for a new sustainable housing development that accommodates around 45,000 people in Amsterdam. Using GW recycling and rainwater harvesting were one of the water supply options for this development but they were found to be the higher life cycle impact due to the energy consumption. The optimum scenario was found to be a dual supply system using surface water from local lake for toilet flushing and laundry.

Memon et al (2007) employed an LCA approach with two assessment methods to compare the environmental impacts (e.g. climate change, acidification, human health, etc) of four different GW recycling treatment technologies for WC flushing at the 500 household scale. The study results indicate that the technologies based on natural treatment processes like green roof or CW has lower environmental impact.

In 2009 Benetto and colleagues carried out a study to calculate the LCA of ecological sanitation scenarios at an office building in Beckerich (Luxembourge). The aim for they study was to provide a data and information to decision-makers and stakeholders about advantageous and disadvantageous of different sanitation scenarios including GW recycling with reed bed as compared to traditional central wastewater treatment systems. The result shows that GW has lower requirements than the conventional treatment process.

On the other hand, Dixon & McManus (2006) show that the environmental benefits from reducing mains water demand may be reduced or even eliminated altogether, due to life cycle impacts of construction and operation of the system. The environmental costs related with manufacturing GW recycling system components, delivery to site, excavation for the tank, installation, operational burdens (e.g. energy usage for pump) as well as maintenance requirements are all additional impacts that occur as a result of installing a system. This phenomenon is called “trade-off” or “rebound effect”. The underlying principle here is that a reduction in the environmental impact of one part of a system (e.g. reducing water demand) can lead to unplanned and unexpected increases in the environmental impact of another (e.g. increase of carbon emission).

Determining a method to measure the environmental cost and benefits is one of the main difficulties that limit the inclusion of these alongside commonly used economic indicators. To do this efficiently different economic evaluation methodologies have been developed by economists. For example Cheng & Wang (2009) suggested a net benefit value model for cost-benefit valuation of reuse projects in residential areas in China. The environmental benefits were estimated by applying a mathematical equation developed by the Ministry of Environmental Protection of China. Another method is known as contingent valuation method (CVM) (Ashley *et al*, 2004). This method estimates the willingness-to-pay for a change in the quantity or quality of an environmental service by using the results from sample survey and questionnaires. Many authors consider that conventional methods like contingent valuation, travel cost, hedonic prices, etc, of economic valuation as consolidated techniques because they are supported by plentiful empirical applications, in the scientific community (Diamond & Hausman, 1994; Shabman & Stephenson, 2000; Getzner, 2000). There is no settled agreement on the validity of these methodologies because they are difficult to implement by the authorities, moreover they require significant investment in terms of money and time. Notwithstanding results may be subjective to some extent (Woods-Ballard & Kellagher, 2004).

As stated by Ashley et al., (2004) variant costing is another approach for monetisation of environmental costs. This method is based on identifying negative environmental impacts and identifying methods in which these can be avoided, followed by estimating the costs required to mitigate these negative environmental effects. The preliminary point for this method is an Environmental Impact Assessment (EIA).

LCA can be used to estimate the environmental impact of construction and operation of GW recycling system but the results are highly case specific. This is due to the fact that in each case system configuration which has effect on the installation of pumps or tank type or UV units may be varied. Also the building type and the location that GW system applied have different impacts. Moreover, GW system components may be manufactured in different countries with various energy productions techniques. The same would also be appropriate to any monetary costs allocated to negative impacts. Possibly generalisations can be made but at the current time there is not any research to support this.

Regarding to the reasons mentioned above environmental costs and benefits have not been included in the cost analysis. Although as part of the sustainability assessment the embodied and operational energy consumption and CO_2 emissions related to them were calculated. The results were presented in Chapter 5.

4.8 Results and Discussion

4.8.1 Water saving

The water savings for GW recycling systems depend on the dynamics of water use within buildings over short periods of time like a day. The size of GW recycling systems were designed to satisfy a proportion of daily demand. The demand that can be met is determined as much by the timing of events that yield collected water (typically showering and bathing), the rate of treatment, and the timing of demand events (typically toilet flushing) as by the storage capacity of the system. In the GW recycling in residential block the GW from showers is higher than demand therefore it is assumed that the extra collected GW will spilled back to the sewer and this volume of surcharge is added to the calculation. In the sensitivity analysis at some cases the GW only from shower was not enough in shared GW recycling system for the demand therefore the GW from handbasin and/or washing machine in residential building, and /or handbasin from offices were also added to the source of GW. In both cases a minimum of 5% reduction in GW yield were considered for functions like filter backwash where treated water is at regular intervals flushed back through the filter to help keep the filter clean, and also for other water losses through treatment. The GW yields and demands were based on the benchmarks and sources previously set out in Tables 3.2 and 3.3.

4.8.2 CAPEX and OPEX cost

The component requirement for the individual and shared system were described in Chapter 2 and Chapter 3. As stated in British Standards the optimum storage capacity for treated GW should be determined by the following factors:

- The peak capacity treatment rate;
- The demand, usage or behaviour patterns.

It is recommended that storage of treated GW be minimized to that needed for immediate use. It is also required to not store treated GW for more than 24 hours (Dixon, 1999). In this study the storage capacity sized is based on whole day GW demands which varies in each scenario. All other components and costs, including maintenance activities, were assumed to be the same for each GW recycling system. These are summarised below in Tables 4.10, 4.11and 4.12. Note that all prices are for the 2011 period. Pumps were selected based on the total head that pump should provide which is equal to operating head required by toilet fixtures (25 psi) ,elevation difference between pump and toilet fixture, and friction lost in system.

Some research assumed the economic life to be 20 years (NAPHCC 1992, Brown 2007), while others used 15 years (Memon et al, 2005; Friedler, Hadari 2006). Lundin and Morrison (2002) recommend that the sustainability of wastewater systems be considered over period of 50-100 years. However Emerson and colleagues in 1995 reports that 15 years is the span considered as a useful life of a plant by Anglian Water, although this suggestion might not extend to other UK utilities. In this research the 15 years service life were selected for initial assessment and the other possible service life (5, 10, and 20 years) were examined as part of sensitivity analysis.

Table 4.10 Flow rates and related cost savings across scenarios

Various flows (units m^3/day unless stated otherwise)	Scenario				
	1 (*Domestic, Office*)	2a	2b	3a	3b
Potable mains water demand [a]	79.8 *(63.9, 15.9)*	64.4	64.4	57.4	57.4
Domestic GW demand	0.0	12.4	12.4	12.4	12.4
Office GW demand	0.0	10.7	10.7	10.7	10.7
Domestic GW generation	0.0	24.9	24.9	28.9	28.9
Office GW generation	0.0	2.9	2.9	0.0	0.0
Total GW recycled and used	**0.0**	**15.4**	**15.4**	**23.1**	**23.1**
Wastewater generation [a]	78.2 *(62.6, 15.6)*	62.6	62.6	54.9	56.2
WTP and WTTP charges *(£K/yr)* [b, c]	**74.9 *(63.6, 11.3)***	**61.2**	**61.2**	**53.3**	**53.3**
Total savings *(£K/yr)*	**0.0**	**13.6**	**13.6**	**21.5**	**21.5**

[a] Based on data from Table 3.1 and 3.2, [b] Assuming a price of £1.62per m^3 for potable water supply and £1.13 per m^3 for sewerage charges (bases on OFWAT, 2011-2012 tariffs), [c] Assuming offices are in operation 261 days/yr and domestic flats are in operation 365 days/yr

Table 4.11 Generic CAPEX compared across scenarios

Various costs (£K)	Scenario				
	1	2a	2b	3a	3b
Pipe work [c]	-	14.5	15.4	11.8	12.5
Pump(s) [d]	-	0.31	0.29	0.31	0.31
Storage tank(s) [e]	-	2.8	2.8	3.1	3.1
Filter(s)	-	0.23	0.14	0.58	0.58
Installation [f]	-	1.0	1.0	1.0	1.0
Treatment system	-	65.8[g] Domestic = 41.2 (12.4 m^3/d) Office = 24.6 (2.96 m^3/d)	44.2[h] Domestic = 33.8 (12.4 m^3/d) Office = 10.4 (2.96 m^3/d)	49.2[g]	66.3[h]
Total CAPEX	**-**	**84.6**	**63.8**	**65.9**	**83.8**

[c] Collection and distribution pipe sizes are based on author calculations - sizes range from 100mm (inter building connection) to 12.5mm (internal connections within flats); [d] Prices are based on PVC pipes supplied through UK manufactures in 2012, [d] CombiBloc (40-250) Centrifugal pump (Johnsons pump company, 2012), [e] The storage tank is sized based on the greywater volume used per day in each scenario; prices for underground storage tank are adapted from Roebuck and updated to 2012 using an average rate of inflation, [g] Based on volume of greywater treated - the price includes purchase, delivery and installation from leading UK MBR manufacturers, [h] Based on volume of treated greywater and effluent quality requirement - the price includes excavation, materials, and installation and is based on data from leading UK CW companies, plus land purchasing prices in Birmingham city centre area in the UK (£65/m^2) and considering 1m^2/PE

Table 4.12 Annual OPEX compared across scenario

Various costs (£K)	Scenario				
	1	2a	2b	3a	3b
Water quality analysis [a]	-	1.38	1.38	0.69	0.69
Energy (distribution system) [b, c]	-	0.07	0.07	0.144	0.144
Energy (treatment system) [b, d]	-	1.06	0.08	1.81	0.017
Equipment renewal (distribution system) [e]	-	0.027	0.027	0.023	0.023
Equipment renewal (treatment system) [f]	-	0.487	0.058 [*17.7*]	0.265	0.08 [*26.6*]
Consumable cost [g]:	-	0.160	0.762	0.243	1.239
Labour cost [h]:	-	0.753	2.614	0.824	3.556
Sludge disposal [i]:	-	0.08	-	0.04	-
Total OPEX	**-**	**4.02**	**4.99**	**4.04**	**5.74**

[a] 1 time per year for chemical analyses and 2 times per year for microbiological analyses at each system(The price reduces by 50% after 3 years of system operation); [b] 13 Pence/KWh (average UK electricity charge from 2012) ; [c] Based on CombiBloc (40-250) centrifuge pump performance data [50] and assumes 12 hours of pump operation per day; [d] adopted form Nolde [48] and Freidler and Hadari (2006) for MBR and from Dillon and leading UK CW companies; [e] Includes the cost for replacing the pumps every 10 years, and filters every 5 years, plus considering 2% of capital costs per year for general repair costs for other distribution system; [f] In scenarios with MBR (2a and 3a), membrane modules (3 MBR modules for scenarios 2a and 5 MBR modules for scenario 3a) were replaced every 2 years – There is no decisive criterion that triggers end of membrane life , 2 years (730 days) is not inappropriate based on maintaining at least a 98% threshold from the original manufacturers permeability rating. [N.B. Membranes can be, and are, used for longer however with a reduction in permeability performance, i.e. a 50% reduction is estimated by 3400 days. Price of each MBR modules is £200 (UK MBR manufacturers, 2012). In scenarios with CW (2b and 3b) the reeds in bed requires harvesting and weeding while the whole bed should be replaced with new material and plants every 6 years (depends on site condition and greywater quality) the italicised values in brackets indicate the costs on Year 6 when bed replacement is required for VFCW; [g] Chemicals for membrane maintenance (NaOH (3kg/ m^3 of greywater treated), and NaOCl (0.67 kg/m^3 of greywater treated), and chemicals for greywater disinfection (0.003 kg of Chlorine per m^3 of greywater) in CW treatment; [h] Routine inspection: 2 hour per week for general system, 2 times per year, for 4 hours with 2 persons for MBR system and; for CW includes weeding every 2 months for 10 minutes per m^2 of bed, plus harvesting 2 times a year with 10 minutes per m^2 of bed. Labour cost 11.7 £/h (Spon's, 2011); [i] Based on the price to empty 4 m^3 of sludge every 3 years .

Figure 4.6 shows the NPV for all six Scenarios when considering 15 years of operation from where it can be seen that there is a higher (positive) NPV for shared GW systems. This is due to higher savings related to potable mains water supply and wastewater discharge, as compared to individual GW systems. The highest NPV belongs to Scenario 3a (a shared GW recycling system with MBR treatment). The NPV for Scenario 3b (a shared GW recycling system with VFCW treatment) is almost 30 % lower than Scenario 3a, although still positive in value.

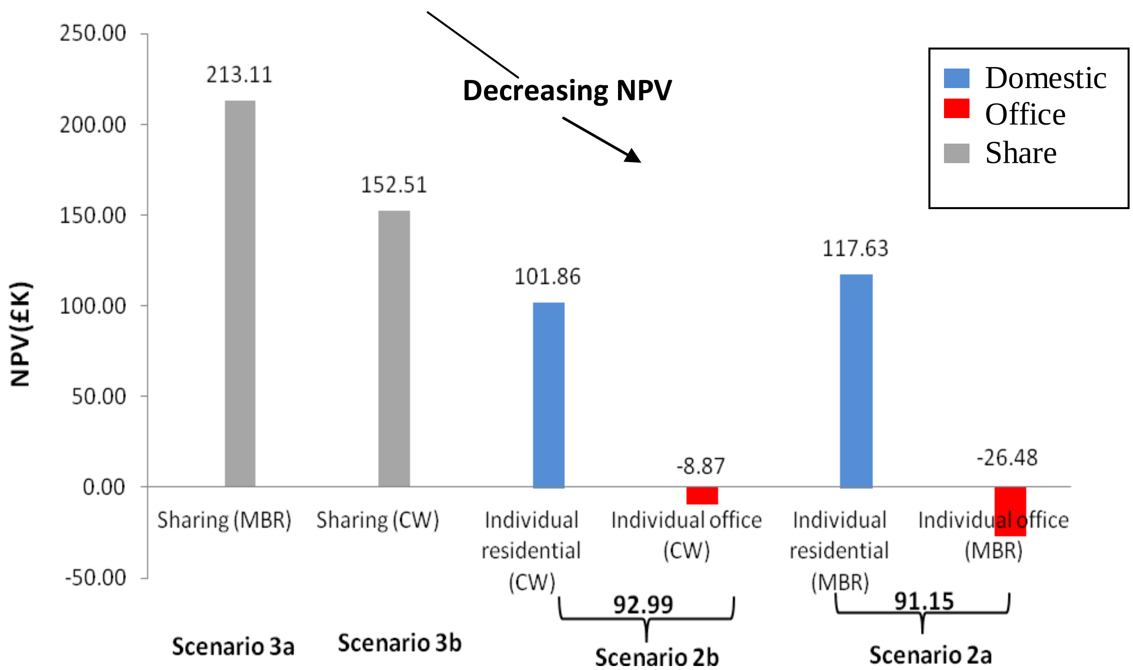


Figure 4.6 Total cost of scenarios for a typical residential and office building over a 1 year lifetime (from here onwards this is referred to as ‘Base’)

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A comparison between the two treatment options shows that the overall OPEX of a VFCW is higher than MBR treatment system mainly because labour and consumable cost compensate the low energy requirements of the VFCW (Table 4.10 and 4.11) the CAPEX for a shared VFCW is also much higher (Table 4.12). This is because the economy of scales does not apply for this type of system, in other words the costs of site mobilisation and demobilisation (i.e. to get the contractor to start allocated works and ultimately clear the site) would be the same independent of the size of the system adopted. In countries with lower labour cost or using different sterilisation method other conclusions may hence be reached. Whilst Scenario 2b does show a positive NPV for individual domestic systems there is a negative NPV for individual office systems, however, the cumulative NPV is positive. In Scenario 2a the influential factor is the negative NPV value for offices. In all cases it can be seen that a cumulative positive NPV can be achieved (i.e. NPV for offices and domestic added together). In other words money would be saved as compared to Scenario 1 (the 'mains only' scenario).

These results were based on the typical UK residential and office water usage and the capital costs and operation and maintenance costs will depend on the daily GW flow. Most of the assumptions and cost data for CAPEX and OPEX were based on UK cases. In the following sub sections a sensitivity analysis of different parameters that might have effect on the results were examined and compared together.

4.9 Sensitivity analysis of the financial model

The sensitivity analysis of the financial model was performed in order to determine the level of variation in predicted GW recycling system performance to change in key financial parameters. In this part of analysis sensitivity to changes in five parameters were investigated (Table 4.1). These were the main water supply and sewerage charges, electricity charges, discount rate, service life, and building description. The effect of altering the technology adopted in building, user behaviour, and occupancy rates are considered in more detail later in the next chapters.

NPV of each scenario were calculated with respect to the cash flows of scenario 1 (mains only scenario) using the Equation 4.1. Reporting changes in GW recycling system NPV would not have been logical by themselves since these results are do not provide information on GW recycling system cost effectiveness. They require comparison with the NPV of the equivalent mains-only system before any significance can be attached to them.

4.9.1 Annual changes in Water supply and wastewater charges

Whilst it is acknowledged that any predictions about future costs will contain an inherent degree of uncertainty, the historic data and likely future resource pressures indicate a number of probable increases in main water supply charges and sewerage charges.

As described in 4.6.2, 22 years of historic data for main water and wastewater charges for West Midlands region (Severn Trent Water Company) from OFWAT reports (OFWAT

1989-2015) were extrapolated in order to predict the average increase in water and wastewater charges for the next 20 years. The price cap that was set to be not more than twice the rates expected in 2015 this price cap has been set to prevent an unrealistically high future prices.

In order to carry out the sensitivity analysis for the future changes in water and wastewater charges in the UK on the cost effectiveness of GW recycling system scenarios, the average percentage changes annually for both water and sewerage unit costs (£/m3) for 0%,1%,1.5%,2%,...up to 10% increase were considered in the analysis. Note that the associated supply and sewage standing charges were not included in the analysis. Price cap of no more than 100% increase in the price of 2015 was considered in order to prevent any overestimations. All the data for mains water supply and sewerage supply charges were presented in Appendix 1.

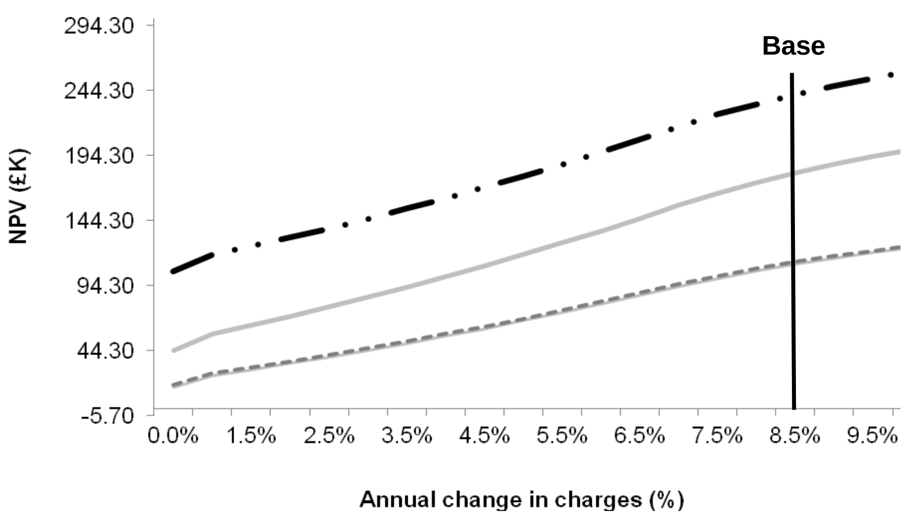


Figure 4.7 Sensitivity results on changes in main water and wastewater charges on NPV

Note that the results presented in Figure 4.7 refer to both the supply and sewerage unit costs of water (£/m^3) and exclude the associated supply and sewerage standing charges. These were not altered in all scenarios.

4.9.2 Electricity charges

The historical electricity prices in UK for the past 10 years were extrapolated and used to predict the prices from 2011 for up to 20 years. Energy and climate change policies are likely to have a significant impact on consumers across the UK through changes in prices for goods and services. This part of project assessed the sensitivity of changes in electricity prices due to these Energy and climate change policies on the NPV of the GW recycling systems scenarios that were assumed in this study. The possible changes in prices from policies assumed were based on those policies already in place or that have been planned to a sufficient degree of detail (i.e. with quantified estimates of costs and benefits) (DECC 2011). The ranges of price changes due to polices were assumed to be from 5% to 55% based on the DECC's latest assessment of the impact of energy and climate change policies on electricity prices and bills. The ambition of the policies once rolled out might increase over many years, but in this study the changes in prices were assumed to be constant over the years.

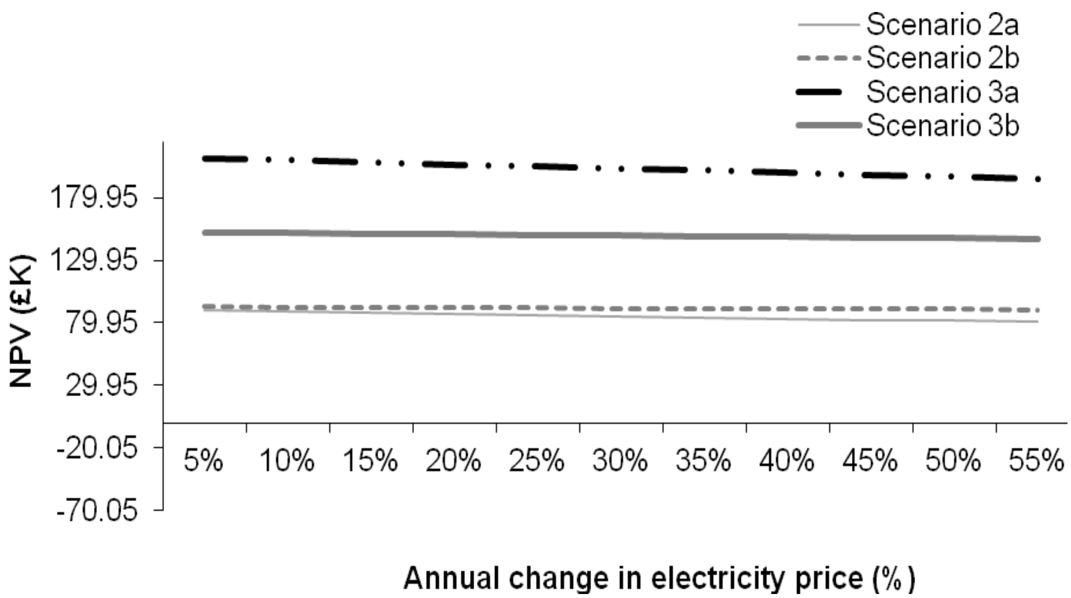


Figure 4.8 Sensitivity results on increase in electricity prices on NPV

As presented in Figure 4.8, the resulting graph displayed a negative gradient, indicating that the cost effectiveness of the assumed GW recycling systems scenarios were slightly decreased by increase in the electricity prices. Linear relationships were apparent for variation in electricity prices. The NPV for all scenarios remains positive for even 55% increase in electricity price. The impact of changing electricity charges on scenarios with MBR (3a and 2a) were more as the result of higher electricity demand in these scenarios.

4.9.3 Discount rate

The discount rate defined as "*the difference between the rate of return on the open market and inflation*" (Lampe et al., 2005). The choice of discount rate can have a significant impact on the NPV of the system and so there should be a rational basis for selecting a particular value.

Many water utilities around the world use a discount rate equal to the interest rate or the current cost of capital of between 6 and 8%. Over the last 8 years or so the United Kingdom has been using a discount rate for evaluating projects of 3.5% and declining to 1% between 30 and 301 years (Simpson, 2009). The influence of discount rates from a range of 0% to 15% were examined on the NPV of the system as part the of sensitivity analysis in this section.

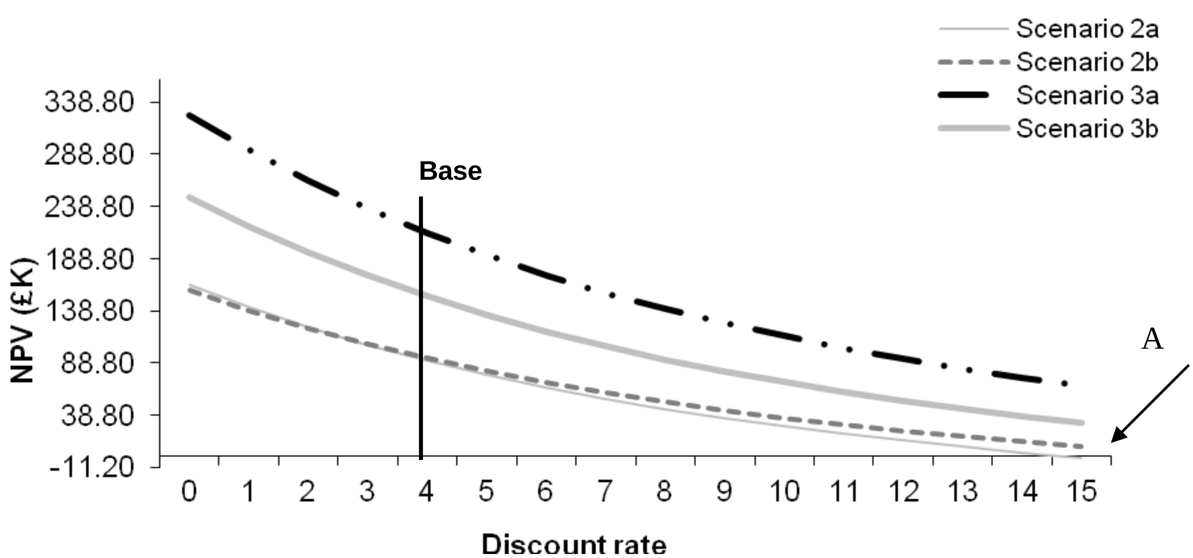


Figure 4.9 Sensitivity results for changes in discount rate on NPV (%)

Changes in discount rate showed exponential decay pattern relationship with cost effectiveness of GW recycling system scenarios (Figure 4.9). Increase in discount rate resulted in decrease of the NPV of all scenarios becoming close to zero. The NPV for individual GW recycling system scenarios became negative at 15% discount rate for scenario 2a (point A).

4.9.4 Service life

The impact of service life on financial feasibility of GW recycling system scenarios was considered for 5, 10, 15 and 20 years. From the simulation results it can be concluded that longer discount periods led to an increase in the NPV of each scenario (Figure 4.10).

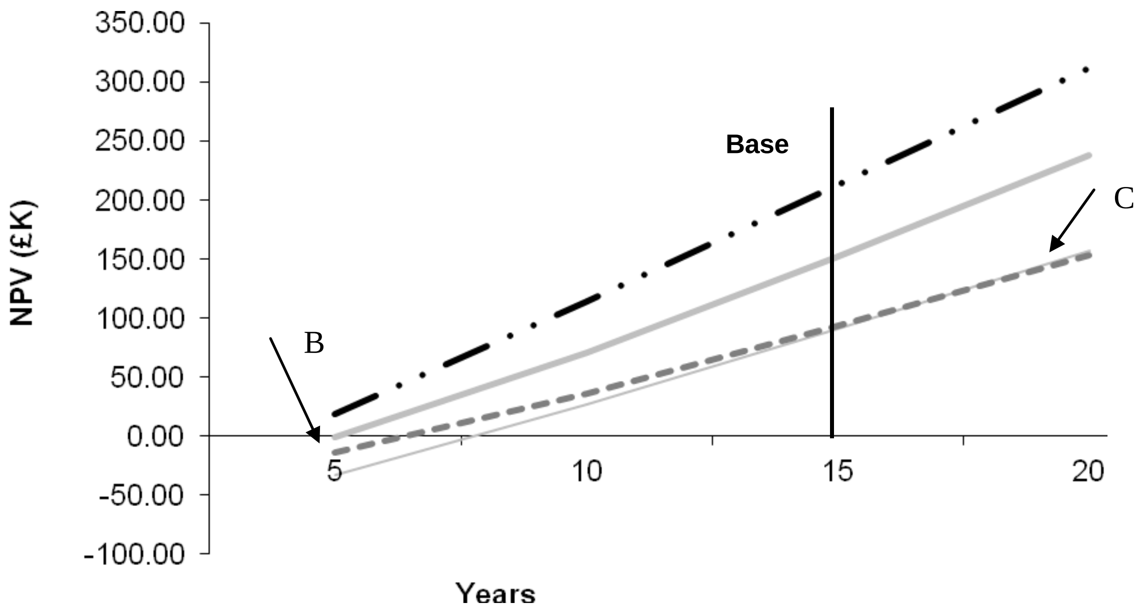


Figure 4.10 Sensitivity results for changes in system service life on NPV

This general trend supports the fact that a longer service life will result in a more income generated from water and wastewater savings which in turn covers more of the capital cost of systems. Likewise when service life is reduced to 5 years (or less) the NPV for all scenarios (excepting scenario 3a) becomes negative due to insufficient accumulation of savings (from water and wastewater) to offset expenses (point B). Subsequently an increase in service life to 20 years results in significantly greater value of NPV for all scenarios. In addition the NPV for Scenarios 2a and 2b become positive (with transitions at 6 and 7yrs respectively) with values being broadly similar (point C). This was likely due to the costs being dominated by maintenance requirements (OPEX) for VFCW treatment in Scenario 2b, which is assumed that bed and reeds be replaced every 6 years and increase in service life results in more cost due to maintenances while for individual GW recycling system with MBR treatment it is assumed that components do not require to be replaced at year 20 as they were replaced at year 10.

4.9.5 Building description

As part of the sensitivity analysis the impact of floor numbers, floor area, and the cross-connection distance between the two buildings (A in Figure 3.1) on the economic feasibility of shared and individual GW recycling systems with MBR and CW are examined and presented in this section.

4.9.5.1 Floor number

The impact of floor numbers on NPV was considered via two analysis options: In the first option, the height of office high-rise is assumed unchanged (i.e. 7 floors) and only the height of the residential high-rise (as in Figure 3.1) is varied between 5 floors (15 m) and 40 floors (120 m). The impact on NPV is shown in Figure 4.11. Linear increases in total NPV with floor number can be seen in all 5 scenarios.

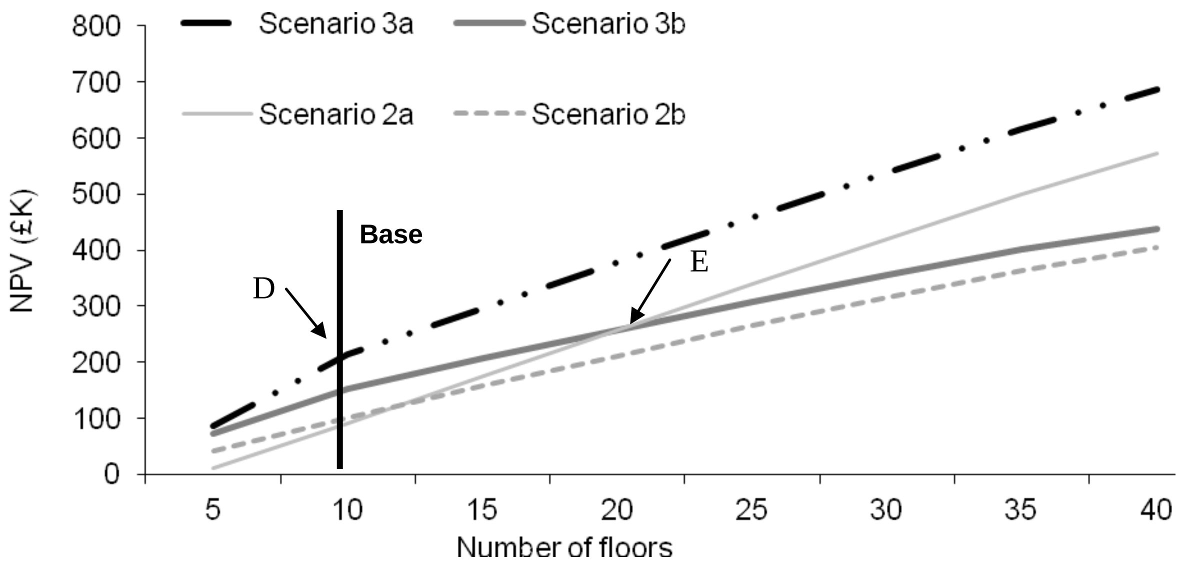


Figure 4.11 Sensitivity results for changes in number of residential floors on NPV

For any floor number, domestic GW supplies are enough to meet domestic GW demands, however at and below 5 floors they are insufficient to fully meet shared GW demands and this reduces NPV in Scenarios 3a and 3b. Therefore, by increase in the number of floors to 10 the NPV for these two scenarios were dramatically increases (point D).

When the residential floor area reaches 20 floors or more the financial savings for individual GW recycling system with MBR treatment (scenario 2a) becomes higher than shared GW recycling system with CW and individual GW recycling system with CW (point E). This can be justified that increase in number of floors relates to more occupancy and as the CW bed size is directly related to number of people connecting to the system the cost for GW recycling system with CW increase by increase in number of occupancy. This can be justified by the fact that CW systems do not have economy of scale therefore water savings from residential and offices in scenario 3b cannot overcome the higher savings from individual GW recycling system with MBR (scenario 2a).

The second option assumes the height of residential high-rise is unchanged (i.e. 10 floors) and only the height of the office high-rise (D in Figure 3.1) is varied between 5 floors (15 m) and 40 floors (120 m). By changing the number of floors in office block the gross area automatically changes and relatively number of employees are related to the gross area of office (15m^2/employee). Table 4.13 shows the estimated office gross area based on the assumed number of floors and the related number of employees.

Table 4.13 Assumed number of floors, and estimated gross area and number of employees

Building height	Gross area	Number of employees
4	7920	528
7 (Base)	13860	924
10	19800	1320
15	29700	1980
20	39600	2640
25	49500	3300
30	59400	3960
35	69300	4620
40	79200	5280

The impact on NPV is shown in Figure 4.11. There is a linear decrease in NPV as the number of office floors increases. However, when the number of office floors increase from 4 to 7 floors (point F) the NPV increases. This change is related to the fact that when offices have 7 floors or less there is sufficient surplus domestic GW production to meet office GW demands up to 7 floors.

Conversely, when the office high-rise is > 7 floors the surplus GW supply from the residential showers is insufficient to meet shared GW demands (indicated by a marginal decrease in slope at this point). Once again alternative sources of GW are not considered and hence demands must be met through mains water top-up, thereby decreasing associated savings. In contrast with the results showed in Figure 4.6 by increasing the number of floors in offices scenario 3a and 3b were still more cost effective than scenario 2a and 2b. In addition Scenario 2a becomes a more cost effective option than Scenario 2b at point G (20 floors) due to increase in CW bed size and increase in capital costs of scenario 2b.

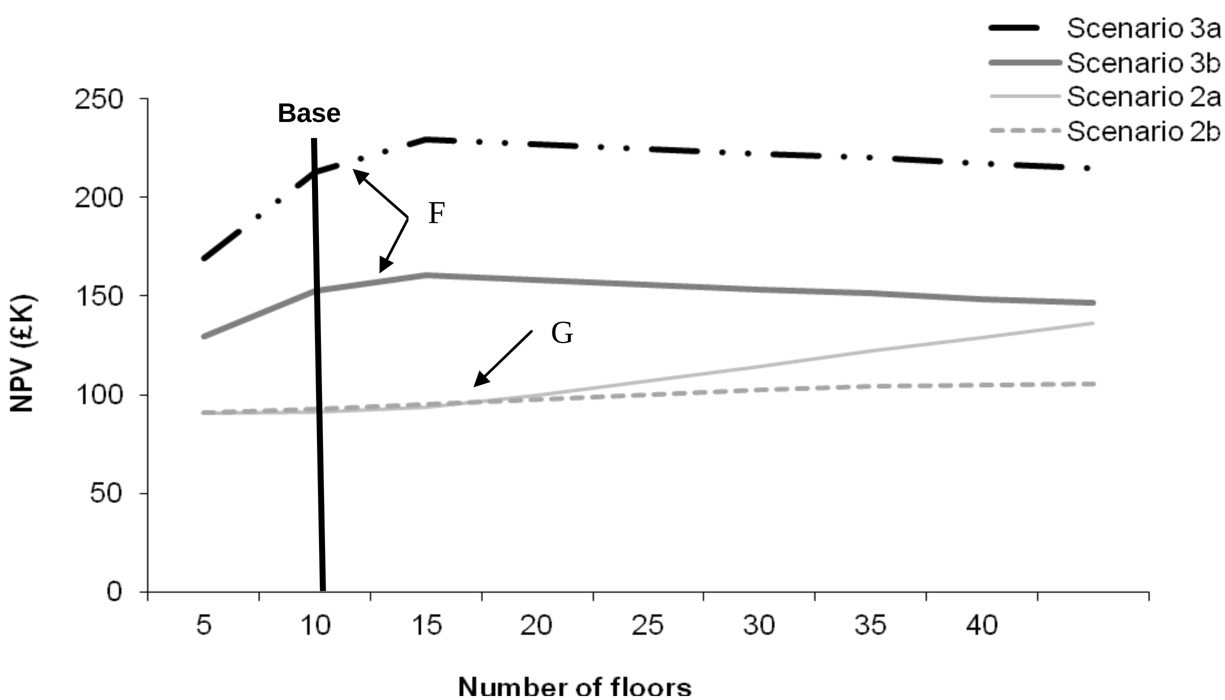


Figure 4.12 Sensitivity results for changes in number of office floors on NPV

In the cases that GW supply could not meet the demand due to decrease in residential floor (or increase in office floors) other sources of GW supply could have been added by considering the following options in order to meet the demand:

1. Add GW from washing machines in residential block. This solution would require extra piping that connects the washing machines to the collection GW water piping network in the block. The quality is another issue that might be considered as the GW from washing machines is more polluted because of the cleaning products and it might have an effect on the treatment technology and ultimately require a more advanced system. These changes were considered out of the scope of this research.

2. Add GW from handbasins in office block. Extra piping costs would be added to the system but it is not changing the quality of GW.

3. Option one and two.

When the residential floor is 5 floors adding only washing machine (option 1) or only handbasin (option 2) from offices does not meet the demand in both buildings therefore in this case it is requires adding both GW from showers and washing machines in residential and handbasins in offices (option 3).

Increasing office floor areas also resulted in an increase in demand for GW supply from considered residential block because it could not meet the increasing demand. The hydrological simulation results shows that when office floors becomes 20 or more adding all the source (i.e. shower and washing machine in residential block and handbasin in office block) were not enough to meet the toilet flushing demand in both buildings.

4.9.5.2 Floor area

The impact of floor area on NPV was considered via two analysis options in which: In the first option, only the total residential floor area (hence number of flats) is varied between 2,000 and 30,000 m^2 (i.e. ef = 200 to 3000 in Figure 3.1), the height of both high-rises and total office floor area (13,860 m^2) is assumed unchanged. Based on the assumptions on the range of average UK room sizes in high rise residential buildings (57 m^2) (LHDG, 2010), the number of flats per floor and the size of the residential block were simulated for each assumed floor area (Table 4.14). As the number of occupancy per floor and accordingly the volume of GW that need to pass through the pipes were changes, pipes were sized based on load values assigned to fixtures by National Standard Plumping Code, BS 6700 recommended maximum of 2m/s standard velocity of water in pipes. The details of calculation and results for pipe size were described in Appendix 2.

Table 4.14 Assumed floor area and building size in residential block

Total area	Flat per floor	Length	Width	Each flat area
2000	3	20	10	66.6
4000	7	20	20	57.14
7000	12	35	20	58.33
10000 (Base)	18	32	32	55.11
15000	27	43	35	55.74
20000	36	40	50	55.55
25000	45	50	50	55.5
30000	54	60	50	55.5

Figure 4.13 shows that NPV increase linearly with residential floor area. However, When the total residential floor area is reduced below 7000 m^2 (approximately half of the office floor area) shared GW supplies are insufficient to meet shared GW demands (i.e. Scenario 3a and 3b) and therefore additional mains water supplies are required and this significantly reduces NPV.

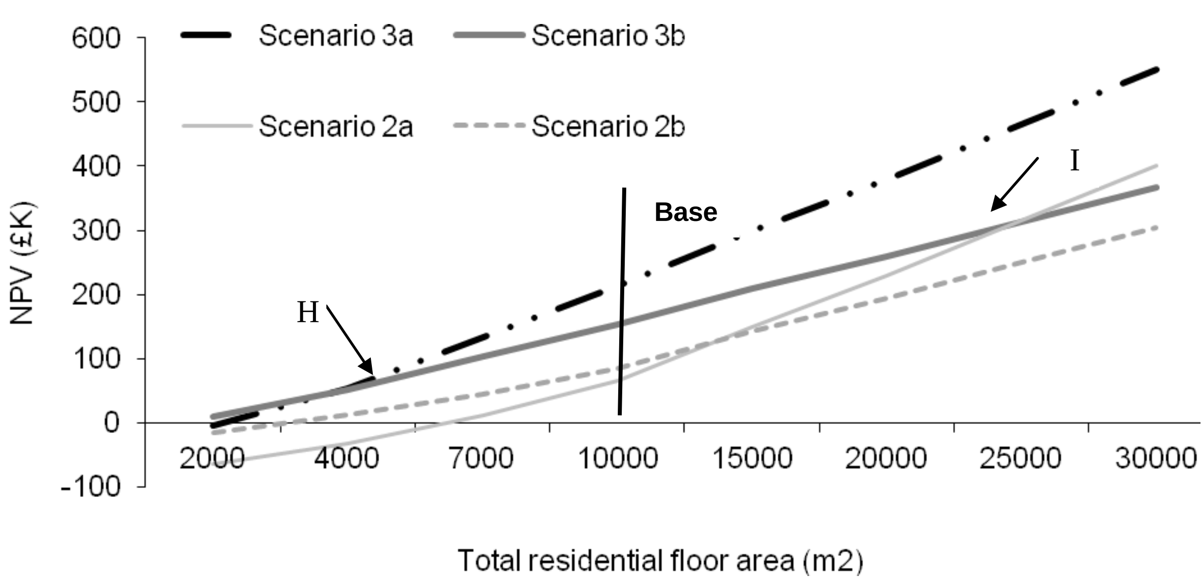


Figure 4.13 Sensitivity results for changes in total residential floor area on NPV

Subsequently at 4000 m^2 (point H) Scenario 3a and 3b becomes more cost effective (with positive NPV) than scenario 2a and 2b (with negative NPV). At 2,000 m^2 the NPV of scenario 3b were higher than all other scenarios and scenario 3a and 2b were broadly similar. At 15,000 m^2 the NPV of scenario 2a becomes higher than 2b as increase in the residential floor area and relatively increase in volume of GW to be treated requires bigger CW bed, therefore the capital cost for scenario 2b becomes higher than scenario 2a. Increasing the total floor area by 20,000 m^2 and higher, results in more potable water and wastewater savings in all scenarios, however results in bigger bed requirement for scenarios with CW treatment options. Therefore, at this point (point I) scenario 2a becomes more cost effective than scenario 2b and 3b.

In the second option only the total office floor area is varied between 2,000 and 30,000 m^2 (i.e. bc = 286 to 4,286 in Figure 3.1), the total residential floor area (10,240 m^2) and building heights are assumed unchanged. Number of employees and the size of office block at each simulation options are showed in Table 4.15.

Table 4.15 Assumed floor area and building size in office block

Total area	Length	Width	Number of employees
2000	20	14	131
5000	51	14	333
7000	50	20	467
10000	57	25	665
13860 (Base)	66	30	924
15000	74	29	1001
20000	71.5	40	1335
25000	83	43	1666
30000	91	47	1996

The impact on Net Present Value is shown in Figure 4.14. At 2,000 m^2 (office to resident floor ratio 1:5) the NPV of Scenario 2b is less than scenario 2a showing that at this ratio individual MBR GW recycling system is more cost effective than using CW treatment. Although, the NPV value for both is negative. As this ratio decreases, the NPV increases and Scenario 2b become more cost effective than scenario 2a but still with a negative value. Scenario 3a has the highest NPV value among all scenarios considered. The NPV value for both shared scenarios increases by increasing office floor area as more GW demand from offices results in higher volume of water saving.

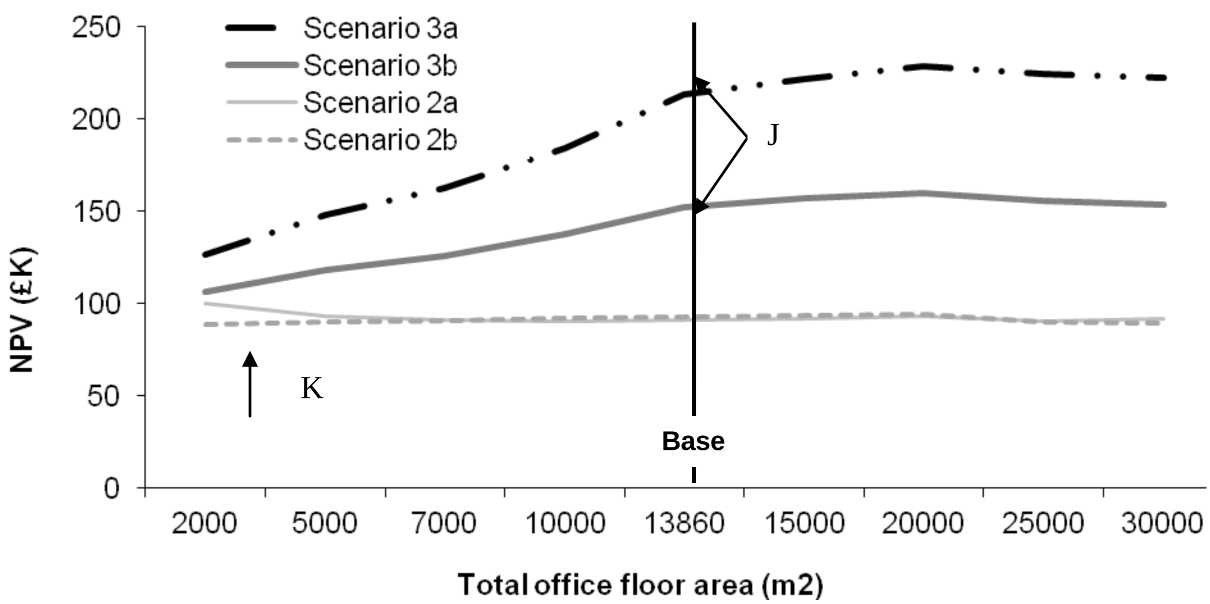


Figure 4.14 Sensitivity results for changes in total office floor area on NPV

However, at 13,860 m^2 (office to resident floor ratio of approximately 3:2) a maximum value of NPV of is achieved. This reduces as the office floor area increases. This is not surprising given that GW production from residential assumed sources becomes insufficient to meet shared GW demands shortly after 13,860 m^2 therefore mains top-up is subsequently required.

As mentioned in previous section there are other options to increase the GW supply in cases that the supply does not meet the demand. For example when the floor are in residential block is less than 7,000 m^2 or when in office blocks is more than 20,000 m^2. The results for hydrological model shows that adding GW from both washing machine in residential block and handbasin from office block is not enough for demand when the residential block is just 2000 m^2. However when the residential floor area increase to 4000 m^2 these two sources can almost meet the toilet and urinal flushing in both buildings. In the case that the office block is 20,000 m^2 by adding only the GW from washing machines is sufficient for the system, but when the floor area in this building increases to 25000 m^2 to 30,000 m^2 it is required to add GW from washing machine from residential users and handbasins from office users to GW source in order to meet all the demands.

4.9.5.3 cross-connection distance

For all analyses it has been assumed that the cross-connection distance between the residential block and office block is 100 metres (A in Figure 3.1) based on the examples in urban mixed-use areas in UK. As part of the parameter study the effect on changing the distance between buildings from 50 meters to 1000 meters on the NPV, is assessed. All remaining parameters were unchanged. The result shows that 50 meter increase in the distance between buildings only decrease the total NPV by 0.2%.

4.10 Examination of sensitivity analysis results

Table 4.16 shows the gradients associated with each of the key parameters from the different scenarios perspectives. Note that for the non-linear curves these results represent the average gradients. The steeper the gradient the more sensitive GW recycling systems savings were to change in the associated parameter. The maximum gradients (most sensitive) have been highlighted in red.

Table 4.16 Sensitivity analysis results: associated gradients

Parameter	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b
Water and wastewater charges	0.036	0.036	0.05	0.05
Electricity price	-0.0054	-0.0004	-0.0087	-0.0003
Discount rate	-0.04	-0.04	-0.10	-0.07
Service life	0.068	0.068	0.16	0.11
Building height Residential block Office block	 0.522 0.002	 0.25 -0.007	 **0.54** -0.006	 0.25 -0.005
Building floor area Residential block Office block	 0.1 -0.01	 0.21 -0.003	 0.47 0.02	 0.23 0.006
Cross-connection distance	-	-	-0.0004	-0.0004

From the table 4.16 it can be seen that the least change in GW recycling system financial savings was associated with variation in cross-connection distance between buildings. After that electricity prices were the parameter that scenarios were less sensitive to its changes. Sensitivity to changes in residential number of floors and floor area were the most significant. This shows that for these four scenarios the savings were directly correlated with the residential building description as the main source of GW supply. If the size of residential block increase/ decreases by a given percentage then there is an almost equal corresponding decrease/increase in the NPV of GW recycling system. After residential building, changes in service life and water and wastewater charges were the parameters that mostly affect the results.

CHAPTER FIVE

CARBON EMISSION ASSESSMENT

5.1 Introduction

Traditionally, feasibility analysis in the construction sector is limited to financial considerations. As the concept of sustainability becomes increasingly important, the methods used in a feasibility analysis have to be reconfigured in a way that incorporates elements of sustainability (Zhang et al., 2009). In the previous chapter the financial feasibility of shared and individual GW recycling system at the considered residential and office block were examined. As part of sustainability assessment in this part of the study, total carbon emissions of shared and individual GW recycling systems are assessed and compared together.

A carbon footprint is a measure of the greenhouse gas emissions related with an activity or a product. The most important greenhouse gas produced by human activities is carbon dioxide (CO_2). Reducing greenhouse gas emissions is one of the key challenges in many countries. The UK government has recognised the necessity for significant reductions. The water industry contributes 0.8 per cent of annual UK greenhouse gas emissions therefore, the water and wastewater sectors fall within these initiatives. Many large scale resource development options such as desalination, pumped storage reservoirs and effluent re-use are recognised as relatively energy intensive both in terms of operation and construction. Demand management may result in lower energy use, which could offset future energy pressures and reduce carbon emissions.

Average UK water consumption is 148 lit/capita/day. The supply of this volume of water and its subsequent treatment by the water companies is equivalent to 38.6 kg CO_2/person/year. As a result water consumption by itself does not significantly affect CO_2 emissions (Hackett and Gray, 2006). However, due to improved building regulations and energy saving initiatives it is expected that improvements in household design are implemented.

In this chapter a literature review on energy assessment and CO_2 emission of different water demand management strategies is described (Section 5.2). Then a methodology is presented for assessing the energy consumption and carbon emission (embodied and operational) of two different types of GW technologies (Membrane Bioreactor - MBR and a Constructed Wetland - CW) adopted on an either or basis as part of an individual (or shared) GW urban supply system for assumed domestic and office high-rise buildings (Section 5.3). The resulting energy consumption and CO_2 emission are presented in Section 5.4 from where the influence of cross-connection distances, building heights and floor plate areas are shown. Conclusions are subsequently drawn in Section 5.5.

5.2 Literature review

Existing research on energy consumption of water infrastructure has primarily focused on large-scale centralised systems. For example a study by Stokes and Horvath in 2009 compares the energy and emission of three water supply alternatives (importing, desalination, recycling) in California State in USA (See section 2.9). However, there is currently considerable interest in new urban scale water infrastructure, including development-scale water recycling plants, stormwater harvesting systems, household rainwater tanks and household GW reuse systems. To date, very little evaluation of these systems has been carried out and the actual operating energy consumption and even water savings of these systems has been the subject of limited investigation. Some of the examples on energy assessment on the water demand reduction technologies are presented in Table 5.1.

Table 5.1 Literature review on environmental assessment of GW recycling system

	description	scale	considered	Comment
Memon et al, 2007	Full Life cycle impact assessment of four GW treatment technologies at residential households in the UK. Treatments were reedbed, MBR, MCR, and green roof.	20 development scales	Physical components in each technology, energy and materials used for the technology maintenance and operation	The geographical installation location and transportation phase and waste disposal phase was excluded. No assessment for distribution network was considered. No carbon saving through saving water.
Halcrow, 2008 (seen in EA,2008a)	Greenhouse gas emissions (carbon impacts) of a range of water supply and demand management (reducing water demand) options including individual and communal grey and rainwater systems over 60 year of life time.	1,000 homes at household and community scales	Carbon embodied in materials and during manufacturing of the product; the carbon emitted during installation of the product; and the carbon associated each time the option is replaced and the end of its life span.	Not clear which treatment technologies were used for GW recycling system and if they do considered the emissions from operation and maintenance of treatment technologies.
Glick et al., 2009	Economy and LCA of GW recycling system for new and retrofitted homes in USA.	Individual home with 5 occupancy	Environmental impacts associated with the material acquisition and transportation from the manufacturer to the site. Emissions associated with electricity and water supply were also calculated	Carbon saving through water saving were considered, replacement of components were also considered in the analysis.
Harnet et al., 2009	Discussed the economic (NPV) and environment (total energy) of cluster scale GW recycling system over 50 year life time at different scales in Australia	From individual up to 47 houses	Embodied energy of the materials and energy for operating	Not clear which treatment technologies were used for GW recycling system and if they do considered the emissions from construction and operation of treatment technologies.

Table 5.1 Continue…

	description	scale	considered	Comment
Retamal et al. ,2009	Energy intensity of rainwater harvesting system at different households in Australia were compared in they study.	From 1 to 5 occupancy houses	Only operational energy intensity for pumping and pressure vessels in rainwater harvesting system	No embodied energy for construction and maintenance , no carbon saving
EA, 2010	Energy and carbon implications of rainwater harvesting and GW recycling systems that supply water for non potable use in buildings in UK were calculated over 15,30 and 60 years of lifetime.	Individual houses, flats, hotel, office and school	Cradle to gate embodied and operational use minus emissions saving from offsetting mains water supply and foul water pumping	MBR treatment system was part of the analysis but not CW treatment
Ward et al., 2010	They carried the study on the energy demand for pumping the rainwater for use in toilet flushing at office building in UK. They finding's show that overall energy consumption associated with RWH systems is very minor fraction of total office building energy consumption.	Individual office building	Pumping electricity consumption and embodied energy related to electricity consumption	No embodied energy for construction or maintenance of rainwater system. No carbon saving through water saving
Anad and Apul, 2011	Compared to the cost, energy and carbon of standard sanitation technology with some alternative water demand management options like rainwater harvesting, low flush toilets and composting toilets	Individual higher education buildings in USA	Only manufacturing (material extraction and processing) and operational phase were considered	No GW recycling system were considered in, no carbon saving.

As shown in Table 5.1, accounting for operational and embodied energy of any conventional GW system is relatively unexplored especially for systems with CW treatment option, except for a few notable publications. Moreover for the shared GW system suggested in this study this is completely unexplored. As such there is a requirement to explore in detail the related carbon emissions of this potential new supply source within this supply configuration.

5.3 Methodology

The same five-step methodology for mass-balance and financial assessment as explained in Chapter 3 (section 3.1) was applied for the energy consumption and CO_2 emission assessment in this study. The only difference was in step 4 (input data) which is described in this section. In order to do the assessment there is a division between the construction and use phase. Total energy consumption and carbon emissions are assumed to be the summation of embodied energy (5.3.2), operational energy (5.3.3) and carbon savings (5.3.4).

5.3.1 System boundary

The system boundary determines the process involved in the assessment. The system analysis boundary adopted within this part of the study in all 5 scenarios is presented in Figure 5.1.

Since the aim of this study is to compare the performance of two GW systems in the new buildings the influence of carbon emissions related to transport, delivery, distribution, system assembly and site installation are not included. The water from each of the GW technologies (MBR and CW) will ultimately enter the wastewater system and will have different water quality characteristics and in theory would require different levels of water treatment downstream. The detailing of the cleaning processes for specific waste water management / treatment is beyond the scope of this current research.

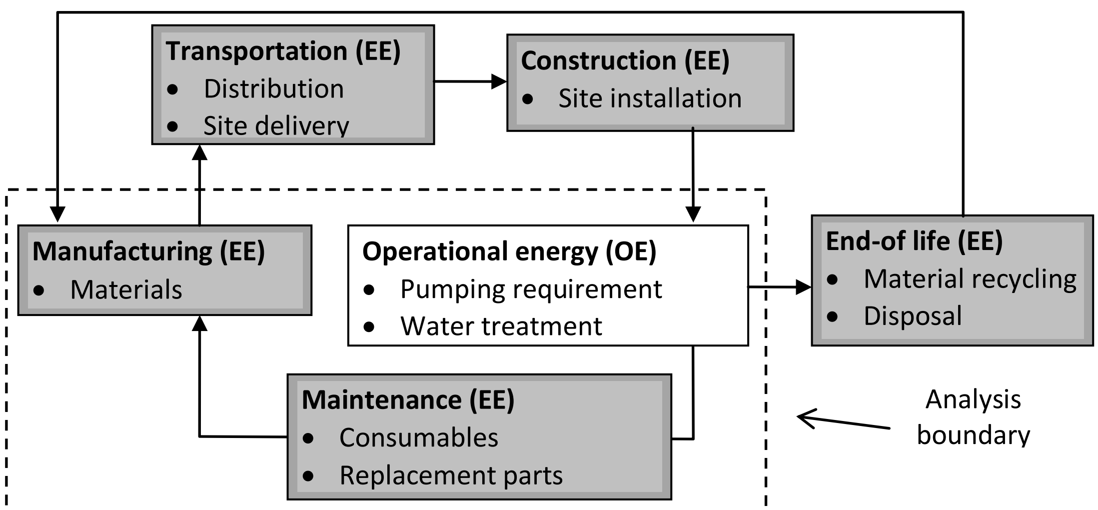


Figure 5.1 Carbon accounting boundary for GW systems (grey shows embodied energy - EE).

5.3.2 Embodied Carbon

Generic embodied energy and carbon of components and related parameters used within this study are detailed within Table 5.2a (MBR) and 5.2b (CW). The total embodied carbon is calculated by multiplying respective unit weights by volumes required. The resulting embodied energy and carbon calculated for Scenarios 2a and 3a (after 15 years operation) are shown on the right side of Tables 5.2a, and those for Scenarios 2b and 3b are shown in Table 5.2b. In both tables the respective total embodied carbon is shown in the bottom rows. There was no manufacturers' information on embodied carbon of system components and it was out of the scope of this study to collect the accurate mass and material inventories. Therefore, a rough estimation for mass and material inventories of system components were based upon existing literature and contact through un-named suppliers. Data concerning the cradle-to-gate energy and carbon emissions of these materials is taken from the University of Bath Department of Mechanical Engineering, Inventory of Carbon and Energy (Jones and Hammond, 2011). In the following sub sections the detail of estimating the mass and material inventories for MBR (section 5.3.2.1) and CW (section 5.3.2.2) are described.

Table 5.2a Embodied energy (and related CO_2) for MBR system by component type over 15 years operation

Generic parameters used within all MBR scenarios				Application to Scenario 2a			Application to Scenario 3a		
Component	**Material**	**Unit weight**	**Energy (MJ/kg) *(KgCO₂e/kg)***	**Amount required**	**Net weight (kg)**	**Energy (TJ) *(MTCO₂)***	**Amount required**	**Net weight (kg)**	**Energy (TJ) *(MTCO₂)***
Tanks[1]	PVC	1.3 g /c m^3	77.2 *(3.1)*	320,000 litre	416	0.032 *(1.29)*	338,461 litre	440	0.034 *(1.36)*
Membrane[2]	Polypropylene	63 g / cartridge	95.89 *(3.43)*	95 cartridges	6.02	0.0006 *(0.02)*	143 cartridges	9.04	0.0009 *(0.03)*
Pumps[3]*	Cast iron	-	24.62 *(1.91)*	-	84	0.002 *(0.16)*	-	48	0.001 *(0.09)*
	Bronze	-	69.34 *(6.07)*	-	42	0.003 *(0.25)*	-	24	0.002 *(0.15)*
	Stainless steel	-	56.7 *(6.15)*	-	516	0.03 *(3.17)*	-	302	0.017 *(1.86)*
Pipes[3]	PVC (12.50mm)	0.24 kg/m	67.5 *(3.23)*	10,324 m	2458	0.165 *(7.92)*	8394 m	1999	0.135 (6.31)
	PVC (18.75mm)	0.47 kg/m	67.5 *(3.23)*	390 m	110	0.007 *(0.36)*	-	-	-
	PVC (25.00mm)	0.64 kg/m	67.5 *(3.23)*	352 m	237	0.016 *(0.75)*	352 m	167	0.011 *(0.53)*
	PVC (31.25mm)	0.76 kg/m	67.5 *(3.23)*	180 m	115	0.008 *(0.37)*	125 m	80	0.005 *(0.25)*
	PVC (50.00mm)	1.01 kg/m	67.5 *(3.23)*	33 m	33	0.002 *(0.11)*	33 m	33	0.002 *(0.11)*
	PVC (62.5mm)	1.59 kg/m	67.5 *(3.23)*	97 m	154	0.01 *(0.5)*	97 m	154	0.010 *(0.5)*
	PVC (100.0mm)	2.99 kg/m	67.5 *(3.23)*	58 m	73	0.005 *(0.24)*	-	-	-
				Total	3182	0.214 *(10.27)*	Total	2434	0.164 *(7.86)*
Chemicals[2]	NaOH	39.99 g/mol	11.87 *(3.38)*	-	27.7	0.0004 *(0.11)*	-	41.6	0.0005 *(0.14)*
	HCL	36.46 g/mol		-	5.89	0.0001 *(0.04)*	-	8.85	0.0001 *(0.03)*
					TOTAL	*0.282 (15.29)*		**TOTAL**	*0.219 (11.52)*

[1] Sized according to GW production and demand - m^3/day, assuming 1mm thickness of PVC. [2]Added according to design guidelines and recommendations from leading British manufacturers [3] Sized according to flow rates (m^3/day) and building dimensions [The Engineering tool Box, 2011]. *Based on a Johnsons CombiBloc pump.

Table 5.2b Embodied energy (and related CO_2 emissions) by component type for a CW system over 15 years operation

Generic parameters used within all MBR scenarios				Application to Scenario 2b			Application to Scenario 3b		
Component	**Material**	**Unit weight**	**Energy (MJ/kg) *(KgCO₂e/kg)***	**Amount required**	**Net weight (kg)**	**Energy (TJ) *(MTCO₂)***	**Amount required**	**Net weight (kg)**	**Energy (TJ) *(MTCO₂)***
Tanks[1]	PVC	1.3 g /cm^3	77.2 *(3.1)*	160000 litre	208	0.016 *(0.65)*	169230 litre	220	0.017 *(0.68)*
CW Bed[2]*	Sand (0-0.3 m) [5]	1992 kg/m^3	0.008 *(0.005)*	401 m^3	798792	0.006 *(4.07)*	602 m^3	1199913	0.01 *(6.12)*
	Gravel fine (0.3-0.4 m) [6]	2002 kg/m^3	0.3 *(0.017)*	152 m^3	305829	0.09 *(5.19)*	229 m^3	459405	0.14 *(7.78)*
	Gravel med (0.4-0.65 m) [7]	2002 kg/m^3	0.3 *(0.017)*	382 m^3	76457434	0.22 *(12.99)*	573 m^3	1148511	0.34 *(19.51)*
	Cobbles (0.65-0.75 m) [8]	2550 kg/m^3	0.3 *(0.017)*	134 m^3	340850	0.102 *(5.79)*	201 m^3	512011	0.15 *(8.70)*
Pumps[3]**	Cast iron	-	24.62 *(1.91)*	-	84	0.002 *(0.16)*	-	48	0.001 *(0.09)*
	Bronze	-	69.34 *(6.07)*	-	42	0.003 *(0.25)*	-	24	0.002 *(0.15)*
	Stainless steel	-	56.7 *(6.15)*	-	336	0.019 *(2.06)*	-	168	0.009 *(1.03)*
Pipes[3]	PVC (12.50mm)	0.24 kg/m	67.5 *(3.23)*	10324 m	2458	0.165 *(7.93)*	8394 m	1999	0.135 (6.45)
	PVC (18.75mm)	0.47 kg/m	67.5 *(3.23)*	352 m	110	0.007 *(0.36)*	-	-	-
	PVC (25.00mm)	0.64 kg/m	67.5 *(3.23)*	352 m	531	0.036 *(1.72)*	983 m	713	0.048 *(2.31)*
	PVC (31.25mm)	0.76 kg/m	67.5 *(3.23)*	350 m	224	0.015 *(0.72)*	175 m	112	0.008 *(0.36)*
	PVC (50.00mm)	1.01 kg/m	67.5 *(3.23)*	84 m	85	0.006 *(0.28)*	84 m	85	0.006 *(0.28)*
	PVC (62.5mm)	1.59 kg/m	67.5 *(3.23)*	84 m	134	0.009 *(0.43)*	84 m	134	0.009 *(0.43)*
	PVC (100.0mm)	2.99 kg/m	67.5 *(3.23)*	58 m	343	0.002 *(1.11)*	82 m	492	0.033 *(1.59)*
				Total	3886	0.26 *(12.55)*	Total	3536	0.238 *(11.42)*
Chemicals[4]	Chlorine	0.003 kg/m^3	11.87 *(3.29)*	-	0.69	0.024 *(6.89)*		1.04	0.045 *(12.58)*
					TOTAL	0.73 *(43.74)*		**TOTAL**	*0.913 (55.53)*

[1] Sized according to GW production and demand - m^3/day. [2] Based on Memon et al., 2007; Stefanakis and Tsihrintzis, 2009, [3]Sized according to flow rates (m^3/day) and building dimensions [The Engineering tool Box, 2011], [4]Added according to design guidelines and recommendations from leading British manufacturers, [5]0.5 mm, [6]6 mm, [7]24.4 mm, [8] 90 mm, * A CW bed area of 1 m^2 / person is required for effective water treatment [Frazer-Williams, 2007] **Based on a Johnsons CombiBloc pump.

5.3.2.1 MBR embodied carbon

The GW recycling with MBR treatment technology consists of GW tank (chamber), membrane including membrane cartridge, aeration device, pump and pipe network. The chamber is made of PVC and assumed to be the same volume as GW and green water tank at each scale. As the density of PVC is 1.3g cm^{-3} (Omnexus, 2011), the weight of tanks were calculated.

Two pumps (one circulation and one suction pump) made of stainless steel, cast iron, and bronze are applied to provide aeration for the chamber below the membrane and recirculation loop. 1 pump for distributing is employed in this MBR system, which is made of stainless steel. The number of cartridges required depends on the flow GW rate of to be treated. The information is adopted from author communication with two leading MBR manufacturers. The related weights of each cartridge were adopted from Goodfellow Company. It is assumed that the pipes applied in distribution and collection is made of PVC (polyvinyl chloride). According to the product information from The Engineering Tool Box (i.e. pipe weights for PVC) the embodied emission for required pipes were measured. During operation, 6 monthly cleaning with NaOH and yearly cleaning with HCl are required, based on the pilot scale system in Cranfield University and Kubota recommendations. As the life span of the MBR system is 15 years, the mass of NaOH and HCL used during operation is calculated.

5.3.2.2 CW embodied carbon

As described in Chapter 2, vertical flow constructed wetland was considered as the other treatment technology option for GW recycling in this project. The proposed design principles for vertical flow constructed wetland differ among European countries. Guidelines in Denmark refer up to 3.2 m^2 /PE (Arias and Brix, 2005), in Austria 5 m^2 /PE (Vymazal, 2006), in the United Kingdom 1–2 m^2 /PE (Frazer wilimas, 2007), in Belgium 3.8 m^2 /PE (Rousseau et al., 2004), and in Germany 2–3 m^2 /PE (Bahlo and Wach, 1995). In the study by Frazer-William, the bed areas for treating GW from residential users were assumed to be 1 m^2 /PE and the quality from outflow were satisfactory. In this study, the same figure from Frazer-William which was a UK based study is used to find the bed area requirement for each GW recycling scenario and the results shown in Table 5.3. As it can be seen from table below the bed are requires for shared scenario is bigger than individual scenario as due to higher volume of GW that required to be treated in this shared scenarios.

Table 5.3 CW surface bed area in GW recycling system scenarios

Scenario	**GW flow rate (m^3/day)**	**Surface bed area (m^2)**
Individual Residential	12.2	432
Individual Office	2.95	103
Shared scenario	28.88	864

The depth of the bed is usually 0.8-1 m (Garcia-Perez et al., 2007; Arias and Brix, 2005; Memon et al., 2007), in which growing medium consists of cobbles, gravel, sand and compost. The type of filter material in CW depends on the regional conditions and the skills and knowledge of the design engineer. Normally, sand and gravel is used and recommended to be the most suitable to construct the filter body of wetland for wastewater of GW treatment (Stefanakis and Tsihrintzis, 2009; Hoffmann et al., 2011).

At the base of the bed there are a drainage pipes which are covered with 15 cm cobbles (D_{50}= 90 mm). At the top of this cobbles layer, there is a 25 cm thick layer of medium gravel (D_{50}= 24.4 mm), followed by 10 cm thick layer of fine gravel (D_{50}= 6 mm), and a 30 cm thick layer of sand (D_{50}= 0.5 mm) with total bed thickness of 80 cm. On top of the sand layer there is a carbonate medium gravel layer (about 10cm), in order to avoid water accumulating on the surface. The top gravel layer does not contribute to the filtering process and usually 50% mixed with zeolite (mixed D50 = 13.0 mm) or with bauxite (mixed D50 = 17.5 mm) (Stefanakis and Tsihrintzis, 2009). The mass of sand, gravel and cobbles were measured using Equation 5.1.

$$m = \rho \times V \qquad \text{Equation 5.1}$$

Where m is Mass, ρ is density and V is Volume.

The distribution piping network at the top of the bed assumed to be 1 inch diameter PVC lateral pipes and later pipes are placed no more than 0.7 m apart (Hoffmann et al., 2010). Across the bottom of the wetland, there will be a drainage system which collects the treated GW with a 4 inch PVC perforated pipe. A 4 inch PVC pipe was also placed at both the inlet and outlet of the gravel to distribute and then collect the effluent after it travelled through the gravel layer at the bottom of the wetland.

It is assumed that common reeds were used in wetlands. As reeds are likely to have no impact on the energy consumption; therefore their contribution is excluded from the inventory. The storage tanks for storing untreated GW and for storing treated GW were also made of PVC, and the density is 1.3g/cm^3 (Omnexus, 2005); the mass of grey and green tanks at each scenario were measured using the same equation as for pipes. It is assumed that 2 pumps made of stainless steel, cast iron and bronze will be employed in vertical flow CW system (Johnson Pump Company, 2005), and 1 stainless steel pump for distributing. The mass of each material is collected from previous study by Liu. 2007.

The additional embodied carbon related to the following items, which are replaced at a time consistent with effective service-life (listed from shortest to longest), are included within calculations:

- Chemicals - added according to volume of GW treated (Table 4)
- Filters - replaced after 5 years (Kirk and Dell'Isola, 1995);
- CW beds - replaced (i.e. new sand, gravel and plants) every 6 years (CW leading companies in UK).
- MBR membranes - replaced after 10 years of operation (Mercoiret, 2008).
- Pumps - replaced after 10 years (Kirk and Dell'Isola, 1995);

5.3.2 Operation energy

In all scenarios there is an energy requirement related to (pipeline) delivery of mains water and removal of wastewater (P_1) as shown in Equation 5.2.

$$P_1 = (V_w.E_w) + (V_{ww}.E_{ww}) \qquad \text{Equation 5.2}$$

Where V_w is the volume of potable water delivered (m^3), E_w is the energy requirements per m^3 of potable water delivered (Table 5.4), V_{ww} is the volume of wastewater removed (m^3) and E_{ww} is the energy requirements per m^3 of wastewater removed (Table 5.4). The energy requirement for pumping water through the treatment process and from the final storage tank to point of end-use (P_2) was estimated using the Equations 3.10 to 3.12 from Chapter 3.

The energy requirements for treating GW via MBR and CW are calculated using Equation 5.3 and 5.4 respectively.

$$P_3 = (V_{GW}.E_{MBR}) \qquad \text{Equation 5.3}$$

$$P_4 = (V_{GW}.E_{CW}) \qquad \text{Equation 5.4}$$

Where VGW is the volume of GW treated (m^3) and E_{MBR} and E_{CW} are the energy requirements per m3 of GW treated when using MBR or CW respectively (Table 5.4).

Total operational energy is the summation of P1, P2 and P3 (for MBR) and P1, P2 and P4 for CW.

Carbon emissions are subsequently calculated using UK emission factors from energy generation rated at 0.55 $KgCO_2$ /kWh of energy used (DECC, 2011). This is based on the following mix of UK fuel supplies (35.7% coal, 48.9% natural gas, 5.2% nuclear, 6.5% renewable, 3.7% of other fuels; DECC, 2011).

Table 5.4.Operational energy parameters used within analyses

Operational energy	**kWh/m^3 *($kgCO_2$/ML)***	**Assumption**	**Reference**
Mains water delivery (Equation 1)	E_w = 0.73 *(0.41)*	Median carbon intensities for delivered mains water.	Water UK (2009) seen in EA 2010
Mains wastewater removal (Equation 1)	E_{ww} = 0.19 *(0.10)*	Median carbon intensities for wastewater removal (For sewage pumping only and excludes treatment).	Water UK (2009) seen in EA 2010
On-site water pumping (Equation 2, 3)	Varies with building dimensions and cross-connection distances	Pumping is required for re-distribution of treated GW. GW collection is assumed gravity fed.	Cengel and Cimbala (2005)
On-site MBR Treatment (Equation 4)	E_{MBR} = 1.5 *(0.825)*	Based on previous studies and related to volumes of GW treated.	Nolde (1999); Friedler and Hadari, (2006); and Mercoiret (2008)
On-site CW Treatment (Equation 5)	E_{CW} = 0.014 *(0.0077)*	Based on previous studies and related to volumes of GW treated. Energy use is associated with use of blowers for aeration of system. This is particularly true for vertical flow wetlands.	Dillon (2003); Personal communications with leading CW companies within UK

5.3.3 Carbon savings

Water companies at a global scale comprise of 2% to 5% of greenhouse gas emissions (Parson et al., 2012). In the UK about 0.8% of total yearly emissions are by the water industry which accounts for 4.15 million tonnes of CO_2 equivalents (Sarwar, 2008). Pumps were used in extracting water from its source, aeration and mixing wastewater and they also used for distribution of drinking water and collection of wastewater. Pumping is the main energy driver in the water sector and the carbon dioxide emissions from electricity used by pumps and compressors were the main carbon foot print of water supply and wastewater treatment (Reynaud, 2008).

Water conservation is seen as a key aspect both in ensuring sustainability of water supplies but also in saving energy and thus reducing CO_2 emissions (ICWE, 1992; POLIS, 2005; Brandes, 2006; McMahon et al., 2006; Australian Government, 2007; Gray, 2008). The results attained using the UK water industry research spreadsheet revealed linearity between energy and flowrate of wastewater treated, suggesting potential cuts in carbon emissions through water saving (EA, 2010). However this needs to be study for GW as there is a debate that GW recycling results in increasing the pollutant concentration in sewerage and might requires more energy for treatment in central wastewater treatment plant.

The carbon saving of GW recycling is due to the reduction in demand for potable water and the volume of wastewater being pumped to central treatment plants, but it is assumed that the GW system does not change considerably the total pollutant charge to wastewater treatment, and therefore has limited impact on the carbon emissions for wastewater treatment process (Equation 5.5).

$$Carbon\ saving = (R_{water}\ x\ E_{water}) + (R_{sewage}\ x\ E_{Sewage}) \qquad \text{Equation 5.5}$$

Where R_{water} is reduction in potable water demand, E_{water} is emissions per unit of water delivered, R_{sewage} reduction in sewage pumped to treatment, and E_{Sewage} is emissions rate per unit of sewage being pumped.

Emissions from using mains water vary depending on the nature of the regional or local supply network. If local water sources were highly energy insensitive (like desalination), then GW use would decreases the total energy consumption in the building. On the other hand, if local water sources and wastewater treatment processes are not energy intensive, e.g., if water is treated via a septic system or is not currently treated then GW reuse may slightly increase household energy requirements. The median energy (0.73 kWh/m^3) and carbon intensities (0.34 $kgCO_2e/m^3$) for delivered mains water and the energy (0.187 kWh/m3) and carbon emission (0.104 $kgCO_2e/m^3$) for foul water pumping (0.7 $kgCO_2/m^3$ for wastewater treatment) component of wastewater treatment used in this study were from UK water companies data in 2009/10 (Water UK, 2010). The results for energy and carbon saving for individual and shared GW recycling system scenarios are shown in Table 5.5.

For Scenario 2b (CW) and Scenario 3b (CW) it is assumed that growing reeds act as a carbon sink, thereby reducing carbon emissions by locking away atmospheric carbon in their structure. The rate at which they do this is estimated as 3.3 kg/m^2/year with an accuracy of +/- 15% (Dixon et al., 2003). The results for carbon saving through the reeds in CW for these two scenarios are presented in Table 5.5.

5.4 Results and discussion

5.4.1 Influence of scenario choice on carbon emissions

Table 5.5 shows embodied carbon emissions for all 5 Scenarios over 15 years of operation. When considering the total carbon emissions, in absence of any carbon savings (iv in Table 5.5), the order of scenarios (highest to lowest emissions) is: Scenario 3a (+25% compared to Scenario1) > Scenario 2a (+21%) > Scenario 3b (+9%) > Scenario 2b (+7%) > Scenario 1 (0%). In other words MBR systems are the most carbon impacting option at this scale (shared and individual high-rise basis) followed by CW systems. The least carbon impacting option is conventional mains supply. However, when carbon savings are included within the analysis (vi in Table 5.5), the ordering and therefore carbon impact changes significantly: Scenario 3a (+25%) > Scenario 2a (+21%) > Scenario 1 (+0%) > Scenario 2b (-5%) > Scenario 3b (-10%). In other words MBR systems would significantly increase carbon impacts at this scale, whereas CW systems would marginally reduce carbon impacts. The reduced requirement for water and wastewater treatment (ii in Table 5.5) is an influencing factor here; saving 41 $MTCO_2$ (15 m^3 / day, see Figure 3.6) in Scenarios 2a and 2b and 56.47 $MTCO_2$ (22 m^3 / day, see Figure 3.6) in Scenarios 3a and 3b. The introduction of a carbon sink (i.e. CW) in Scenario 2b and 3b further reduces carbon emissions by 10 $MTCO_2$ and 20 $MTCO_2$ respectively (v in Table 5.5). This indicates that MBR might be considered an applicable localised solution for reducing mains water demands, however with significant impacts on carbon emissions. Whereas CW, when adopted on a shared-high-rise basis, would equally reduce mains water demand whilst reducing emissions by up to 10% (if adopted on a shared GW system basis).

However, space requirements may be an influential factor here, particularly in urban areas where available land is scarce and expensive. Although the land requirements within the example used here are less than the building footprint for each high-rise, i.e. 432 m^2 for the residential and 103 m^2 for the office - when using individual systems. Therefore location of the CW on the roof space might be considered (with the requirement for additional pumping).

Table 5.5 Carbon emissions within scenarios

Units: Carbon *(MT CO_2)*	**Scenarios (after 15 years of operation)**							
	1		**2a**		**2b**		**3a**	**3b**
	Residential	Office	Residential	Office	Residential	Office	Shared	Shared
Embodied carbon (i)	N/A	N/A	*9.13*	*6.16*	*37.83*	*12.81*	*11.52*	*68.12*
			15.29 (combined)		*50.6 (combined)*			
Operational carbon (ii):	*179.25*	*31.59*	*144.27*	*25.65*	*144.27*	*25.65*	*154.37*	*154.37*
Mains water delivery and wastewater removal	*210.84*		*169.92 (combined)*		*169.92 (combined)*			
Operational carbon (iii):	-	-	*59.42*	*10.49*	*4.08*	*0.91*	*97.85*	*6.88*
GW treatment and distribution	-		*69.91 (combined)*		*4.99 (combined)*			
Total (iv) = (i) + (ii) +(ii)	***210.84***		*255.14*		*225.54*		*263.74*	*229.36*
Carbon saving (v)	*0.0*		*0.0*	*0.0*	*21.38*	*5.08*	*0.0*	*39.76*
Total (vi) = (iv) - (v)	*210.84*		*255.14*		*199.08*		*263.74*	***189.61***

5.4.2 Sensitivity analysis

5.4.2.1 Building description

The impact of floor numbers on carbon emissions as part of changing the building descriptions for sensitivity analysis was considered via two analysis options: In the first option, the height of office high-rise is assumed unchanged (i.e. 7 floors) and only the height of the residential high-rise (a in Figure 3.1) is varied between 5 floors (15 m) and 40 floors (120 m). The impact on total carbon emissions is shown in Figure 5.2. Linear increases in total carbon emissions with floor number can be seen in all 5 scenarios however, relative changes in carbon savings are broadly similar, i.e. Scenario 3b achieves

4% savings (compared to Scenario 1) at 5 floors and 8% savings at 40 floors. For any floor number, domestic GW supplies are able to meet domestic GW demands, however below 5 floors they are insufficient to fully meet shared GW demands and this reduces the carbon savings in Scenarios 3a and 3b. In such cases GW supplies could have been increased through incorporating hand basins and / or washing machines (see Chapter 4, section 4.5.5).

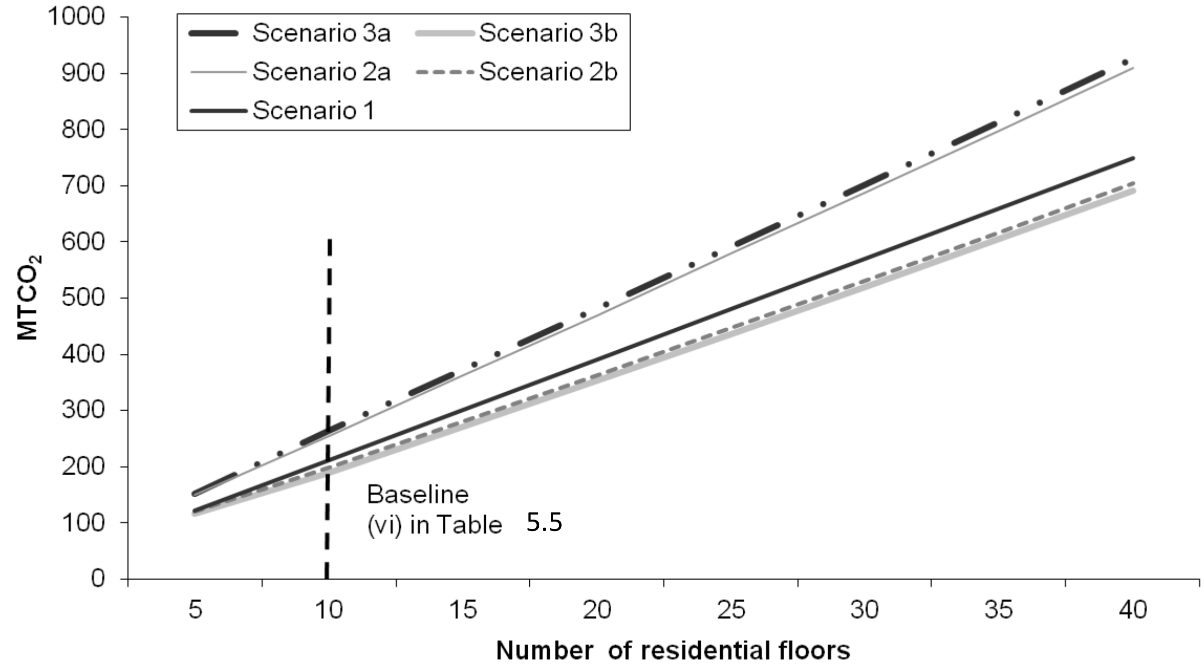


Figure 5.2 Influence of residential block height on carbon emissions (MT= Metric Tons).

The second option assumes the height of residential high-rise is unchanged (i.e. 10 floors) and only the height of the office high-rise (d in Figure 3.1) is varied between 5 floors (15 m) and 40 floors (120 m). The impact on total emissions is shown in Figure 5.3. There is a linear increase in carbon emissions as the number of office floors increases however the slope is much shallower than in Figure 5.2. This change is related to the fact that offices have significantly lower daily flushing requirements per employee (Table 3.2) than domestic residents (Table 3.3). In addition, there is still sufficient surplus domestic GW production to meet increasing office GW demands up to 15 floors. However, when the office high-rise is > 15 floors the surplus GW supply from the residential showers is insufficient to meet shared GW demands (indicated by a marginal increase in slope at this point).

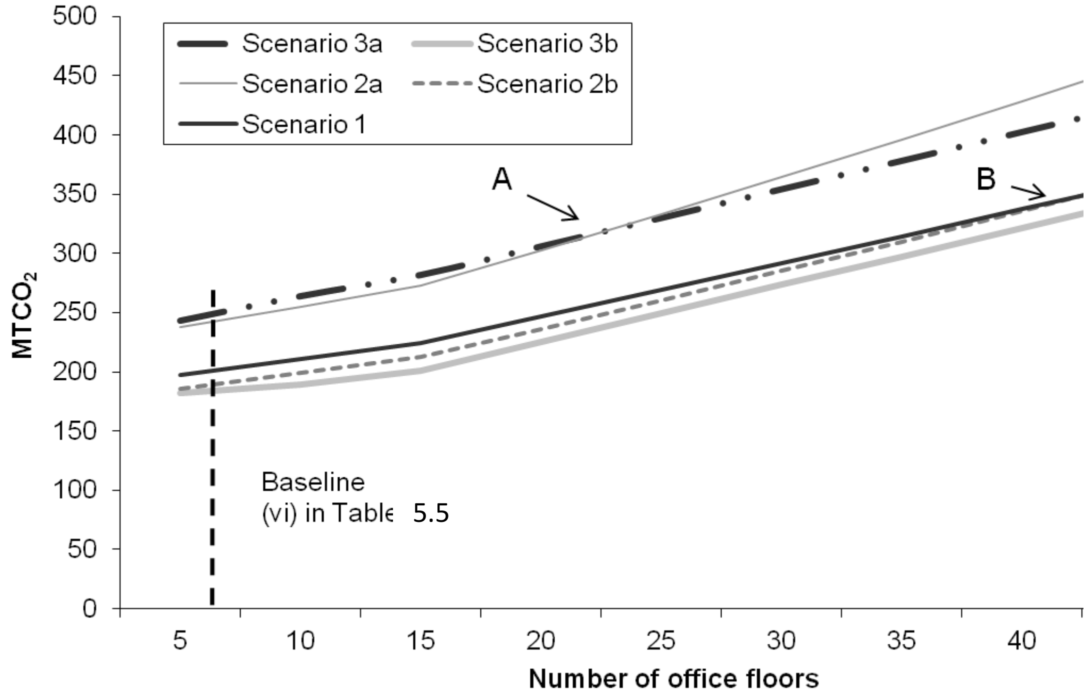


Figure 5.3 Influence of office block height on carbon emissions (MT= Metric Tons).

When office floor numbers are increased from 5 to 9 to 40 the carbon savings of Scenario 3b (as compared to Scenario 1) increase from 6 % to 11 % and then decrease to 4 % respectively. The maximum saving corresponds to an office to residential height ratio of approximately 3:2. This shows significant contrast with the first option and shows greater sensitivity between carbon savings and office height when adopting a mixed use system CW system. In addition Scenario 2a becomes a less carbon impacting option than Scenario 3a at point A (22 floors) and has 27% higher carbon emissions at 40 floors. At the same number of floors (point B) Scenario 2b becomes more carbon impacting than Scenario 1.

The impact of floor area on carbon emissions was also considered via two analysis options: In the first option, only the total residential floor area (hence number of flats) is varied between 2,000 and 30,000 m^2 (i.e. ef = 200 to 3000 in Figure 3.1), the height of both high-rises and total office floor area (13,860 m^2) is assumed unchanged. Figure 5.4 shows that carbon emissions increase linearly with residential floor area.
However, when the total residential floor area is reduced below 7000 m^2 (approximately half of the office floor area) shared GW supplies are insufficient to meet shared GW demands (i.e. Scenario 3a and 3b) and therefore additional mains water supplies are required and this significantly reduces carbon emission savings.

Subsequently at 4000 m^2 (point C) Scenario 3b becomes more carbon impacting than Scenario 1 and Scenario 2b and at 2,000 m^2 the emissions from all 5 scenarios are broadly similar. At 30,000 m^2 the relative changes in Scenario 3a (+22% compared to Scenario 1) and Scenario 3b (-10% compared to Scenario 1) are broadly comparable with that found at the baseline.

In the second option only the total office floor area is varied between 2,000 and 30,000 m^2 (i.e. bc = 286 to 4,286 in Figure 3.1), the total residential floor area (10,240 m^2) and building heights are assumed unchanged. The impact on total emissions is shown in Figure 5.5.

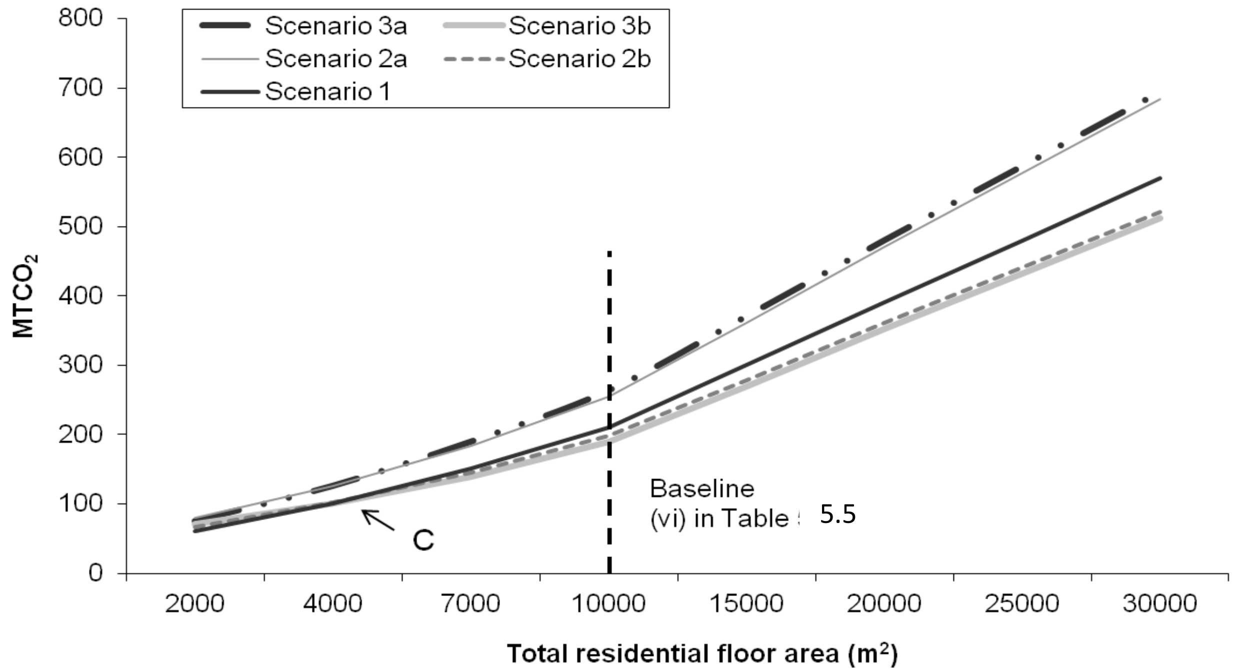


Figure 5.4 Influence of total residential floor area on carbon emissions (MT= Metric Tons).

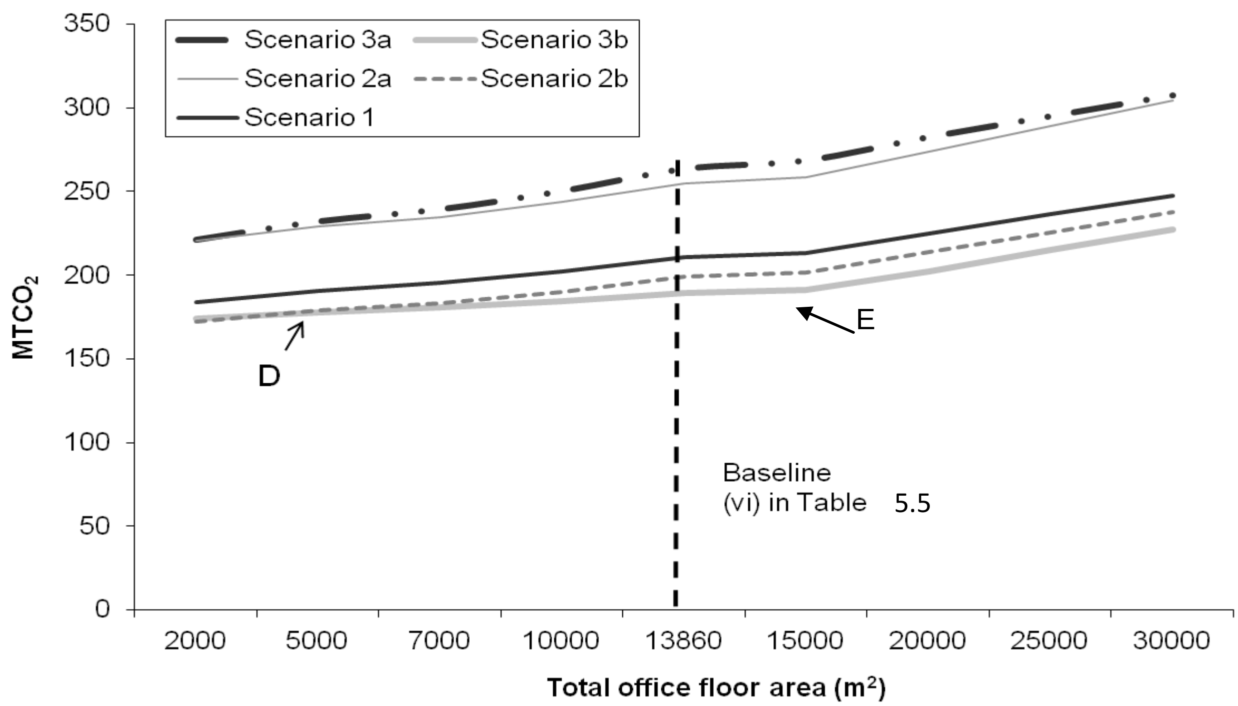


Figure 5.5 Influence of total office floor area on carbon emissions (MT= Metric Tons)

At 2,000 m^2 (office to resident floor ratio 1:5) the carbon savings of Scenario 2b and 3b (6 % compared to Scenario 1) become broadly similar and the added advantage of a mixed-, rather than single-, use GW system with MBR treatment (Scenario 3b) is less pronounced. However, as this ratio decreases the carbon reduction advantages of Scenario 3b become more apparent. For example, at 15,000 m^2 (office to resident floor ratio of 3:2) a maximum reduction in emissions of 11 % is achieved (point E). This reduces to 9 % at 30,000 m^2. This is not surprising given that GW production from residential showers becomes insufficient to meet shared GW demands at 15,000 m^2 therefore mains top-up is subsequently required.

For last part of building description analysis the cross-connection distance between the two buildings (A in Figure 3.1) was increased from 50 to 500 m and the remaining parameters were unchanged, thereby influencing operational energy (due to changing head losses and related energy requirement for pumping) and embodied energy (due to changes in pipe length – carbon costs due to trenching are ignored here, see Hunt et al., 2012). A 50 m increase of cross connection distance produced a marginal increase in carbon emissions of 0.01%.

5.4.2.2 Service life

The impact of service life on carbon emission was analysed for 5, 10, 15 and 20 years of operation. The results for the analyses showed an escalating trend on carbon emission by increasing the service life (Figure 5.6).

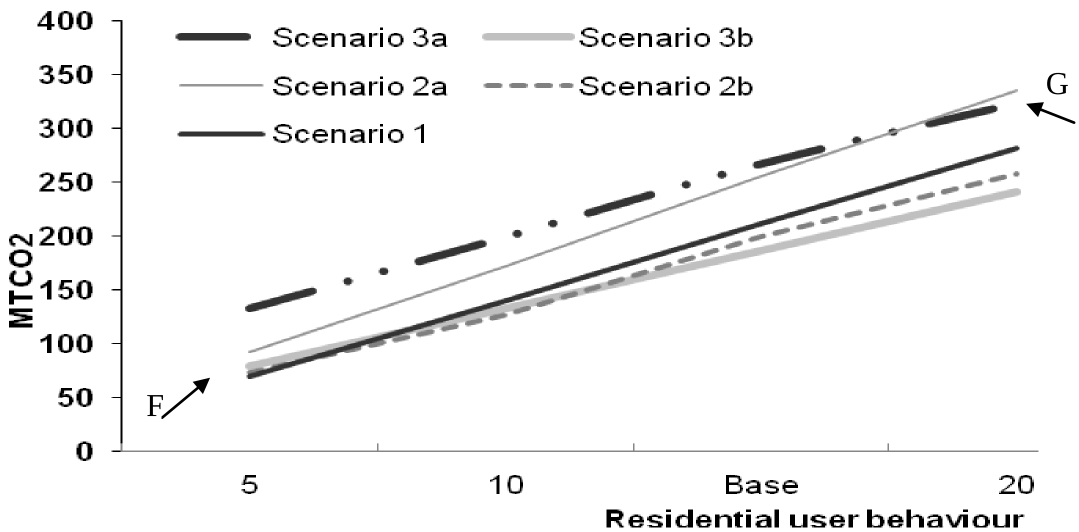


Figure 5.6 Influence of service life on carbon emission (MT= Metric Tons)

This can be accomplished by the fact that when increase the service life it requires changing some of the system components as the service life is less than the system service life (e.g. filters, pump, membranes, etc; see Table 3.11). Although the longer the system operates then more potable water will be saved but the embodied emissions from component replacement will increase the total carbon emissions for the whole system. The results for 5 year operation showed that total carbon emission of scenario 3b becomes higher than scenario 1 and scenario 2b (point F). This is because of the fact that system operates for short amount of time and carbon savings from potable water saving during this 5 year of operation cannot offset the emissions from bigger bed and higher energy requirement in this scenario. Point G in Figure 5.6 shows that total carbon emission of scenario 2a becomes higher than scenario 3a for 20 years of operation. The reason for this is, 20 years of operation means more potable water and more wastewater savings that can help to reduce total carbon emissions in the scenario. Consequently the carbon saving from more potable water savings in scenario 3a results in lower total carbon emission than individual GW recycling scenario with MBR treatment (Scenario 2a). This makes shared GW recycling system less carbon intensive than individual GW recycling systems.

5.5 Conclusion and recommendation

Current legislation requires the sustainable management of rivers and groundwater. In some cases this means reducing water abstraction to ensure a sustainable water environment which results in a reduction in the availability of water for supply. To balance this effect, companies are investigating alternative sources of water. Additionally both the Environment Agency and Energy Saving Trust's corporate strategies recognise the need to act to reduce climate change and its consequences and to use resources in a sustainable manner.

Based on the analysis performed within present chapter and Chapter 4 conclusions were made. Initially it is found that surplus domestic GW from one resident can approximately meet the GW demands of four office employees therefore cross-connection appears to be a sensible approach based on flow volumes at individual scale. The combined inflow/outflow for the domestic and office high-rise examined can be reduced by 19%

when GW systems are adopted in isolation. This can be improved to almost 30% when GW is shared.

Usually there are trade-offs and conflicts that needs to be considered in sustainable design, which are not always apparent when looking at specific design options for separately improving performance on energy, cost, water, materials use, etc. The same trade-offs between CO_2 emission, water consumption, and financial performance of GW recycling system were found in this study particularly with MBR systems. As the result for carbon emission study for individual and shared GW recycling system with MBR treatment shows that GW recycling system in both systems increase CO_2 emissions compared to using mains water while both systems reduce potable water consumption by up to 19% in individual system and 30% in shared systems (Figure 5.7). The GW recycling system with MBR treatment achieved highest NPV while on the other hand has the highest CO_2 emission compare to other scenarios (Figure 5.7).

When considering a 15 year operation period it is shown that shared CW treatment achieved the lowest carbon emissions, saving up to 11% (compared to conventional mains) whereas a shared MBR increased carbon emissions by up to 27%. This can be justified by the fact that CW requires far less energy for operation and by the fact that the reeds in wetland beds lock in CO_2 (see section 5.2 and Table 5.5). Most carbon savings for the shared GW system occur when the ratio (height or floor area) of office building to residential building is approximately 2:3. Below this value there is insufficient domestic GW supply to meet shared GW demands. In contrast to the carbon emission results, shared GW recycling system with MBR treatment showed highest NPV (1.18 £Million) than other scenarios, while the shared CW treatment achieved almost half of this value (0.62 £Million).

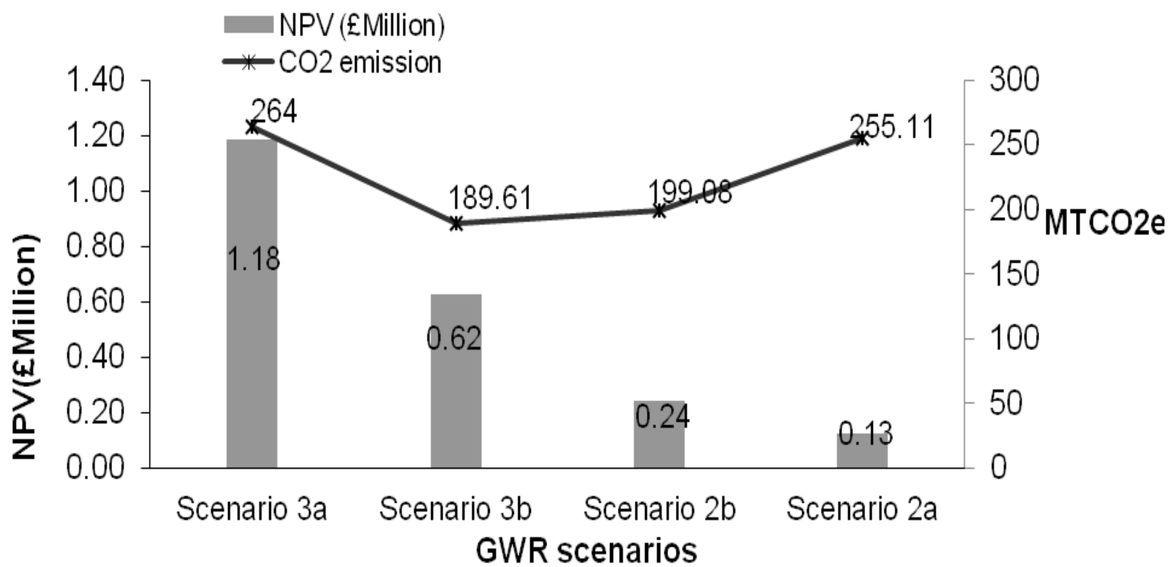


Figure 5.7 Net Present Value and CO_2 emission of all scenarios from a 15 year analysis

This shows that the choice of GW system can influence greatly both water savings and energy (and related carbon emissions) savings highlighting the delicate balance that exists between each. The worst choice an urban planner could make do is to seek the adoption of GW systems (individual or multi-use) that unwittingly cause a rebound effect on carbon emissions. However a shared GW (CW treatment) system does appear to hold significant potential to reduce carbon emissions, although these are significantly behind the 80% required at UK levels for 2050. Increase in resilience to water shortage is the other benefit that these systems have which might attract the developer's attention to become more interested in applying GW recycling systems in mixed-use buildings.

There is a possibility to reduce this trade-off between potable water saving and carbon emission within new configuration of shared GW recycling system in mixed use buildings. Mixed-use buildings were the building that uses for more than one purpose. In the case that domestic users (residential or hotel) were located at the top of the building and the commercial or retail users were located at the bottom of building (Figure 5.9) GW can be collected from possible sources (shower, bath, handbasin) via gravity and stored in the GW tank which is located in the middle of the building were the residential and commercial units were separated. The treatment units and clean water tank were also located in this floor. Treated GW then will delivered to WCs in domestic users via pump and to WC and urinals in commercial users via gravity. As the GW for commercial users will be delivered via gravity and does not required any electricity for pumping the overall energy and carbon emission for the whole system reduces compares to the shared GW recycling systems within separate residential and office buildings.

In order to carry out the analysis, the individual residential block that was considered for previous analysis (Chapter 3, Section 3.3) assumed to be mixed-use building. This assumption was adopted from mixed-use buildings in the UK. The mixed-use building consists of 6 floor residential flats, 4 floors of offices, and 1 floor of mechanical plenum (with 3m floor height). The results for mass-balance analyses for this building show that the GW from showers in residential floors is enough for demand in both residential and office toilets.

The analyses results for this system shows the water saving is up to 30 %, same as in shared GW recycling system within separate buildings, while the increase in CO_2 emission were 17% (247.09 $MTCO_2$) which is almost 10% lowers than shared GW recycling system in separate buildings.

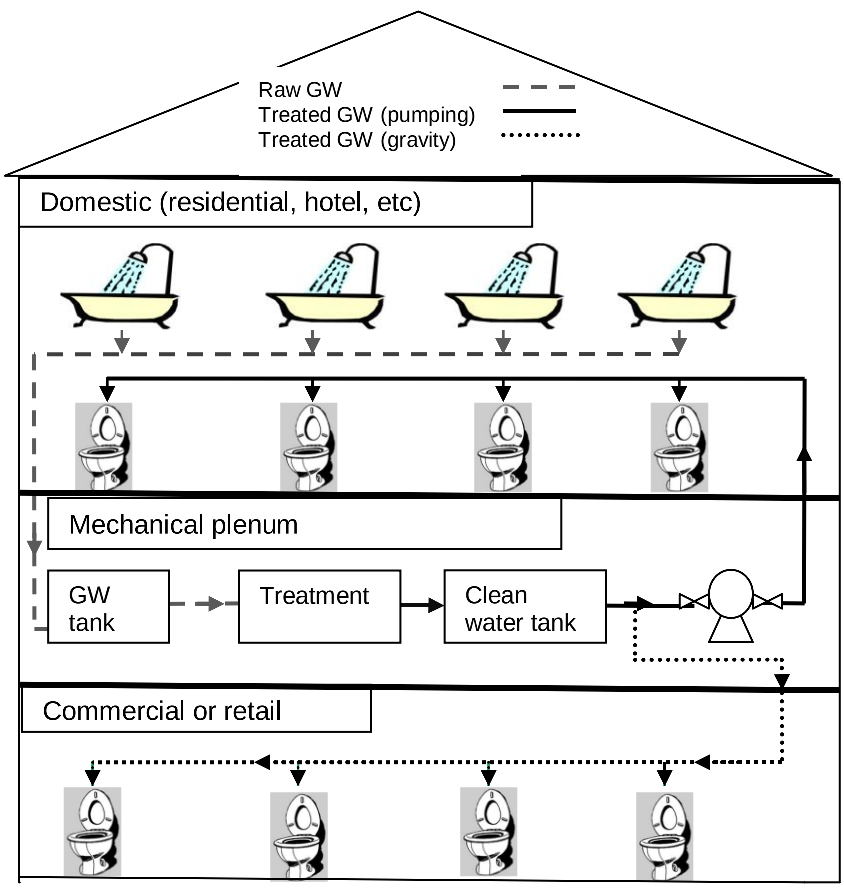


Figure 5.8 GW recycling system configurations in mixed-use building with MBR treatment

Although there is an increase in the building greenhouse gas emission but for example this increase in the shared GW recycling system with MBR treatment is about 5 $MTCO_2e$/year which is probably equal to the emission from average car emission per year (3.3 MT CO_2/year). The efficiency of MBR systems has been improved significantly over the last ten years (6-8 kWh/m^3 to 1.5 kWh/m^3) and reducing this further through research and development will lessen the trade off with CO_2 emission which needs to be made currently when adopting a shared GW recycling system with MBR treatment. Meanwhile a better reduction of carbon footprint may be achieved through the optimization of pump operation.

Future research should now look to investigate the influence of inter-building GW shared when considering users from within other building types and perhaps investigate its impact at a larger city scale. Allied to this is the influence of changes to consumer demands (i.e. through technology and user behaviour see Chapter 6 and 7) that might bring us closer to or perhaps even move us further away from this 80% carbon reduction target.

CHAPTER SIX

SOCIAL ASSESSMENT AND PUBLIC PERCEPTIONS

6.1 Introduction

The mass-balance, financial and CO_2 emission assessment for the individual and shared GW recycling system for new build residential and office blocks were assessed by considering 5 scenarios and the results were presented in Chapters 4 and 5 . In order to calculate the volume of water used by each occupant in the residential block and each employee in the office block the technologies adopted in each building were multiplied by a factor related to user behaviour (Table 3.2 and Table 3.3). However, for it to truly reflect societal trends it would also require to consider in two key drivers of change for water demand: 'social' (occupancy rate and user behaviour) and 'technological'. In this chapter the role of social (user behaviour) is examined within the considered residential and office block. The role of technological changes will be examined within the UK policy drivers framework and presented in Chapter 7.

In the initial part of this chapter the changes in number of occupancy and user behaviour in residential and office block are examined. The second part of this chapter focuses on the social acceptance of GW recycling systems via previous works done in the literature.

6.2 User behaviour

6.2.1 Residential behavior

Daily per capita water consumption varies widely across the globe. The way of life, age, gender, environmental education, income, located region and living standards have a strong influence on how much water is used (EU, 2008; Elizondo and Lofthouse, 2010). Ethnicity, religion, and psychological circumstances are also three factors that play a role towards water consumption patterns (Smith & Ali, 2006). Table 6.1 shows an example on tap water consumption within different age bands, social groupings, gender and region in England and Wales.

Table 6.1 Tap water consumption for drinking in England and Wales (MEL Research, 1996)

Age band	l/c/d	Social group	l/c/d	Gender	l/c/d	Region	l/c/d
0-5	0.503	Professional	1.104	Male	1.127	North	1.228
6-15	0.603	Clerical	1.154	Female	1.149	Midlands	1.087
16-25	0.974	Skilled manual	1.171			South	1.118
26-35	1.199	Semi-skilled	0.989				
36-45	1.277	Economically inactive	1.142				
46-55	1.493	Retired	1.315				
55+	1.353						

The average total per capita consumption in European countries is ranged between 135 to 160 litre per capita per day (Denmark: 114 l/c/d, France: 156 l/c/d, Netherlands: 145 l/c/d, Germany: 136 l/c/d). In USA per capita consumption is usually more than 300 l/c/d. Socio-economic, technical and climate were the factors influencing the difference in water consumption in these countries (Kresig, 1996). A number of factors that act as barriers to behaviour change have been identified, including price and pricing attitude (Syme et al., 2004; Renwick and Archibald 1998), garden importance (Syme et al., 2004), perceptions of others behaviour (Corral-Verdugo et al. 2003), income, household size and other household characteristics and home ownership (Renwick and Archibald 1998; Gregory and Di Leo 2003; Syme et al. 2004).

The ranges of user behaviour on micro-components uses in domestic properties are presented in Table 6.2 based on past monitoring international studies around the globe.

Table 6.2 Range of frequency (F) and duration (D) of domestic micro-components use

WC (number of flush)	Washing Machines	Taps		Showers		Bath	Dishwasher
		F (times/day)	D (min)	F (times/day)	D (min)	(times/day)	(times/day)
6.3[19]	0.81[19]	3 [11]	0.3	0.6 [6]	5 [3,6]	0.34 [6,9]	0.71[19]
5.25 [1,17]	0.34 [5]	2.25 [7]	6	0.6[11]	10	0.12[12]	0.4[21]
4.8 [5,3,21]	0.18 [1]	3.5[21]	1	0.65[12,16]	8 [16]		0.14[12]
4.3 [6,18]	0.16 [2]			0.6 [14]	7		0.214[7]
4[9,10]	0.157 [6]				10		
3.7 [2,15]	0.37[12]				15 [21]		
3.3 [4]	0.05[19]				3 [19]		
2.8[19]					30		
2.2[19]							

Reference: 1.SODCON, 1994; 2.Butler , 1991; 3.Chambers et al., 2005; 4.Thackray et al., 1978; 5.DCLG, 2007; 6. EA, 2001; 7. Butler and Memon, 2006; 8. Mays, 2010 ; 9. European Commision, 2009; 10. EU Eco-Lable, 2011; 11. Green building store, 2011, 12.Aquacraft, 2003; 13.Loh and Coghlan, 2003; 14. Shimokura et l., 1998; 15. Otaki et al., 2008; 16. Barreto, 2000; 17. Gleick et al., 2011; 18.DCLG, 2010; 19. Hunt et al., 2012; 20. DeOreo et al., 2011

There is no prediction that these frequencies and durations will differ significantly from those occurring at present and so the existing data was used as an acceptable indicator of future behaviour. The only difference is the showers and bath usage (i.e. the frequency of bathing has declined considerably and frequency of shower usage has increased). The duration of showers varies from 3 to 30 minutes and there were assumed to be no significant differences between shower durations for normal or efficient showers. In reality, however one may prefer to take a longer shower where user experience is more pleasurable; this requires further research to be undertaken.

In order to assess the effect of water usage behaviours on mass-balance, financial performance and CO_2 emission of the considered scenarios (see Figure 3.6); a set of six design cases were assumed based on the various behaviours shown in Table 6.2. The benchmarks adopted within each design case are shown in Table 6.3. This section discusses how these benchmarks can be achieved simply through changes to user behaviour while other factors were kept unchanged. In this list CSH stands for the code for sustainable homes, and reductions within Typical UK are relative to 2010/2011 levels.

When considering the design cases for residential users (Table 6.3 and 6.4) it can be seen that changes in demand (as compared with the Typical cases (D_3) have been achieved as follows: D_6 adopts a lowest possible frequency and duration of use for each appliance. D_5 adopts the second lowest frequency and durations as presented in Table 6.2 with the same dishwasher frequency as in D_6. In D_4 showers were assumed to run for 10 min for each time and toilet flushing were same as in D_3 case. D1 adopts the same shower duration as D_2 excepting the adoption of a higher frequency in handbasin, washing machine and dishwasher.

Table 6.3 Water benchmarks and demand assumed within domestic users

Consumer type	Water benchmark adopted	Demand level (lit/person/day)	% change from D3
(D1)	Typical UK+65%	250.0	65%
(D2)	Typical UK+30%	188.0	30%
(D3)	Typical UK	148.0	0
(D4)	CSH level 1,2	122.2	-17%
(D5)	CSH level 3,4	102.4	-30%
(D6)	CSH level 5,6	69.8	-52%

The detail of each scenario with considered frequency and duration of use were shown in Table 6.4.

6.2.2 Results

The impact of six different domestic water user behaviour (see Table 6.3) on the NPV and CO_2 emission of considered GW recycling scenarios (Figure 3.6) was examined (Table 6.5). The user behaviour in non domestic users and other parameters were kept unchanged in this part of analysis.

Table 6.5 NPV (£K) and related carbon emission (*$MTCO_2$*) within scenarios.

Domestic User behaviour Design case	**Scenarios (after 15 years of operation)**				
	1	**2a**	**2b**	**3a**	**3b**
	Mains only	Individual	Individual	Shared	Shared
(D1)	N/A (*334.83*)	146.96 (*386.97*)	132.16 (*314.48*)	269.86 (*395.86*)	191.11 (*304.96*)
(D2)	N/A (*259.87*)	91.15 (*302.14*)	92.99 (*250.27*)	213.11 (*310.72*)	152.51(*240.84*)
(D3)	N/A (*210.85*)	91.15 (*255.11*)	92.99 (199.07)	213.11 (*263.74*)	152.51 (*189.63*)
(D4)	N/A (*179.60*)	50.92 (*218.10*)	63.09 (*174.13*)	171.64 (*226.56*)	116.48 (*164.73*)
(D5)	N/A (*155.55*)	18.77 (*189.33*)	38.90 (*155.24*)	114.66 (*193.91*)	88.50 (*149.36*)
(D6)	N/A (*115.95*)	-2.01 (*146.59*)	23.02 (*119.08*)	48.69 (*143.76*)	46.64 (*120.01*)

Table 6.4 Assumed design cases by changing user behaviour (frequency (F) times per day and duration (D) per minute) in domestic buildings

Residential		Design cases											
	Technology	Typical UK +65% (D1)		Typical UK +30% (D2)		Typical UK (D3)		CSH level 1&2 (D4)		CSH level 3&4 (D5)		CSH level 5&6 (D6)	
		D	F	D	F	D[1]	F[2]	D	F	D	F	D	F
WC flushing	6 (lit/usage)	-	6.3	-	4.8	-	4.8	-	3.7	-	2.8	-	2.2
Hand basin	8 (lit/minute)	0.33	3.0	0.33	3.0	0.33	3.5	0.33	2.0	0.33	2.0	0.33	2.0
Washing machine	80 (lit/load)	-	0.81	-	0.34	-	0.21	-	0.16	-	0.16	-	0.05
Shower	12 (lit/minute)	15	0.6	10	0.6	8	0.6	7	0.6	5	0.6	3	0.6
Bath	116 (lit/usage)	-	0.16	-	0.3	-	0.16	-	0.16	-	0.16	-	0.11
Kitchen sink	8 (lit/minute)	0.33	3	0.33	2	0.33	3.5	0.33	2	0.33	2	0.33	2
Dishwasher	24.9 (lit/usage)	-	0.7	-	0.4	-	0.23	-	0.23	-	0.23	-	0.23
1. Duration of use in minute, 2. Frequency of use per day													

The impact on NPV is shown in Figure 6.1. At the design case D6 and D5, where user behaviour are at its highest assumed efficiency, the NPV of all GW recycling scenarios drops and at Scenarios 2b (individual GWR with CW) it becomes negative in case D6 (Table 6.5 and Figure 6.1).

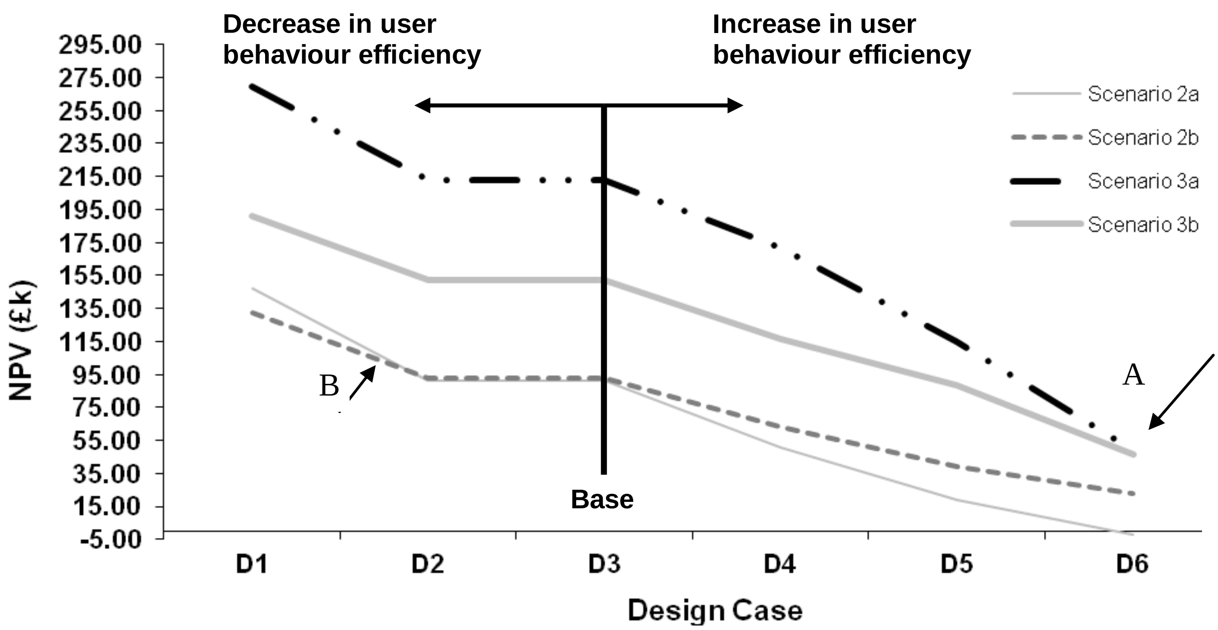


Figure 6.1 Sensitivity results on changing in domestic water user behaviour on NPV

This is because in these design cases the volume of GW production, which is highly dependent on user behaviour, was decreased dramatically as it is assumed that users spend less time in showers and use washing machines less frequently etc (see Table 6.4 for more details on changes in user behaviour within these design case). In shared cases it results in a deficit of supply for toilet flushing demand in both buildings even when the frequency of toilet use in residential building were assumed to be less than the normal. In the D6 case the NPV of scenario 3b becomes very close to scenario 3a which is due to a reduced volume of GW treated and results in smaller bed requirements for CW in this case; see point A in Figure 6.1.

In the D4 design case the NPV of all scenarios was positive, with the same order (scenario 3a>scenario 3b> scenario 2b> scenario 2a) as in the Based case (D3). The result in case D2 was similar to D3 as the same frequency for toilet flushing (4.8 times/day) was assumed in both design cases. In the final assumed design case (D1) the NPV in all GW recycling scenarios increases (almost by 20% in shared scenarios). This is because of the fact that there is more GW supply and demand due to the changes in user behaviour in this scenario, and therefore results in more water saving from GW recycling for toilet/urinal flush use. As it shows in Figure 6.1 (point B), the NPV of scenario 2a in this design case is higher than scenario 2b because an increase in volume of raw GW results in bigger CW bed and as CW does not have the economy of scale the capital cost in this scenario increases.

Figure 6.2 shows carbon emissions by changing the residential user behaviour for all 5 Scenarios over 15 years of operation. Changing the residential user behaviour towards more efficient use of micro components, results in reduction of total carbon emission of GW recycling system in both individual and shared scales.

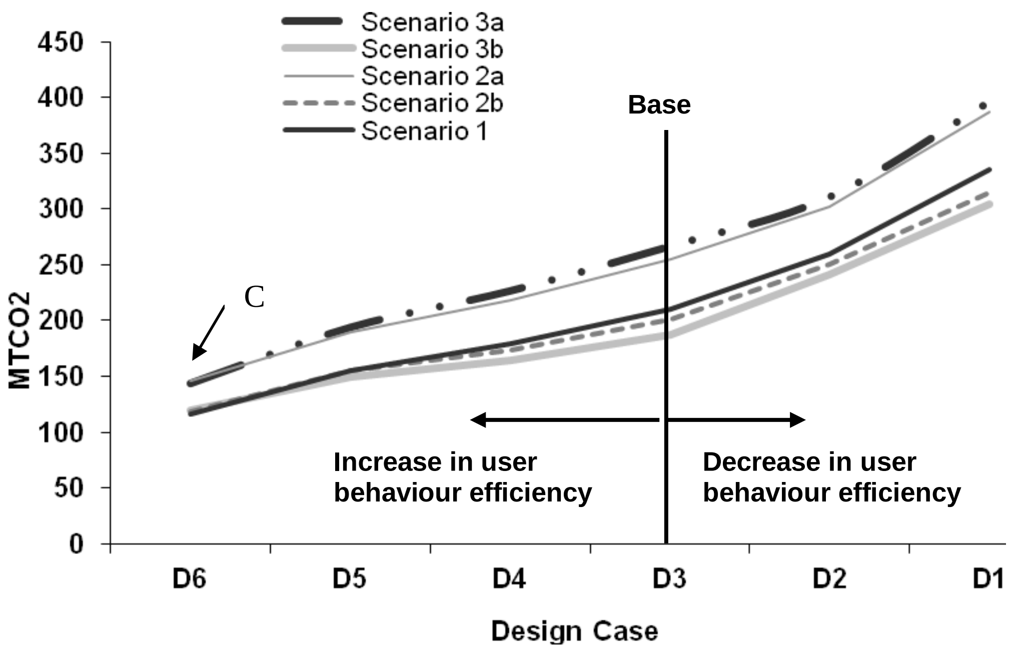


Figure 6.2 Influence of residential user behaviour on carbon emissions (MT= Metric Tons).

The order of scenarios (highest to lowest emissions) is same as Base case (D3). This means MBR systems are still the most carbon impacting option for both shared and individual scenarios followed by CW systems. There is exclusion in D6 case that scenario 1 has the lowest carbon emission than other scenarios. Also the total emission of scenario 2a is higher than scenario 3a (point C) at this design case. This can be justified by the fact that in this case it is considered that residential water user behaviour is at its lowest possible option therefore even reducing the carbon by saving potable water via GW recycling and carbon reduction by reeds in CW does not cover the emission from construction and operation of GW recycling system in this case. The reason that total emission in individual GW recycling scenario with MBR is higher than shared GW recycling is that toilet flushing demand within residential users in this case is significantly lower than other assumed cases therefore less potable water saving can be achieved by GW recycling in individual building while in shared GW recycling although there is deficit in the GW supply for the demand in both buildings but the saving through this systems results in reduction in total carbon emission than individual GW recycling system.

6.2.3 Office behavior

In offices the frequency of appliance uses were divided in male and female groups as it is assumed that there is a notable difference in the frequency of washroom appliance usage between genders. This assumption is supported by the findings of Thames water's "Watercycle" project at the Millennium Dome in London. The observation of the study for public washroom shows that on average 23% of males used WCs and 76% used urinals when they visited the washroom compare to females that 86% of them using WCs when visits washrooms. Interestingly 81% of females use the handbasin after the toilet use while only 73% of males use the handbasin (Hills, 2001).

The user behaviour on frequency of toilet flushing, duration and frequency on hand basin and kitchen tap usage in offices were changed in order to achieve the assumed design cases within this study (Table 6.6).

There was a lack of information regarding frequency of micro components use in commercial buildings, therefore most of the frequency of uses for considered design cases were assumed by author (Table 6.7). For example in Typical UK-64% it is assumed that there is no WC flushing in male toilets and only one visit per female employee. This might be too ambitious as during typical working hours (8 hours) humans need to use toilet likely (although not definitely) more than one time. The design case assumptions were based on the benchmarks adapted from CIRIA (typical use, best practice use, and excessive use) report on water usage within offices in UK and the benchmarks recommended by Hunt et al., 2012. These assumptions were also supported by the BREEAM (Building Research Establishment Environmental Assessment Method) rating for water usage within Offices depending on the predicted annual water consumption per person per year based on a standard assessment procedure. These range from 1 credit for water consumption of 4.5-5.5 m^3/person/year, 2 credits for water consumption of 1.5 to 4.4 m^3/person/year to 3 credits for water consumption of less than 1.5 m^3/person/year.

Table 6.6 Assumed design cases by changing user behaviour in office block (frequency (F) times per day and duration (D) per minute) (*Italics* shows where female water usage differs)

Office		**Design cases**											
	Technology	**Typical UK +65%**		**Typical UK +30%**		**Typical UK**		**Typical UK-20%**		**Typical UK-40%**		**Typical UK -64%**	
		(O1)		**(O2)**		**(O3)**		**(O4)**		**(O5)**		**(O6)**	
		D	**F**	**D**	**F**	**D[1]**	**F[2]**	**D**	**F**	**D**	**F**	**D**	**F**
WC	6 (lit/usage)	-	*2(3)*	-	*2(3)*	-	1 *(2)*	-	1*(2)*	-	1*(2)*	-	0*(1)*
Urinal	3.6 (lit/person)	-	*2(NA)*	-	1*(NA)*	-	1 *(N/A)*	-	1*(NA)*	-	1*(NA)*	-	1*(NA)*
Hand basin	8(lit/minute)	0.3	1*(3)*	0.2	1*(3)*	0.2	2 *(3)*	0.1	1*(1)*	0.1	1*(1)*	0.1	1*(1)*
Kitchen tap	8(lit/minute)	0.2	*2(2)*	0.2	1(1)	0.1	1*(1)*	0.1	1*(1)*	0.0	0.0	0.1	1*(1)*
1. Duration of use in minute, 2. Frequency of use per day													

Table 6.7 Water benchmarks and demand assumed within case study for male and female office employees (*Italics* shows where female water usage differs)

Consumer type	Water benchmark adopted	Demand level (lit/person/day)
(O1)	Typical UK+ 65%[a]	25.6 *(31.2)*
(O2)	Typical UK+30%[b]	20.6 *(26.1)*
(O3)	Typical UK [a]	15 *(19.4)*
(O4)	Typical UK-20%[b]	13.2 *(16.4)*
(O5)	Typical UK-40%[b]	11.6 *(15.6)*
(O6)	Typical UK-64%[a]	7.1 *(11.2)*
(a) Benchmarks adapted from Waggett and Arotsky (2006) and BREEAM (b) Interpolated		

6.2.4 Results

The impact of six different commercial water user behaviour (see Table 6.7) on the NPV and CO_2 emission of considered GW recycling scenarios (Figure 3.6) was examined (Table 6.8). The user behaviour for domestic users and other parameters were kept unchanged in this part of analysis.

Table 6.8 NPV (£K) and related carbon emission (*$MTCO_2$*) within scenarios.

Commercial User behaviour Design case	Scenarios (after 15 years of operation)				
	1	2a	2b	3a	3b
	Mains only	Individual	Individual	Shared	Shared
(O1)	N/A (*231.65*)	105.94 (*280.42*)	104.90 (*216.19*)	230.42(*287.37*)	161.67(*207.92*)
(O2)	N/A (*222.29*)	82.56 (*265.54*)	83.79 (*211.37*)	230.42 (*278.01*)	161.67 (*198.56*)
(O3)	N/A (*210.85*)	91.15 (*255.11*)	92.99 (*199.07*)	213.11 (*263.74*)	152.51 (*189.63*)
(O4)	N/A (*206.39*)	83.55 (*246.80*)	77.17 (*197.79*)	213.11 (*262.03*)	152.51 (*182.61*)
(O5)	N/A (*204.90*)	83.55 (*245.31*)	77.17(*196.31*)	213.11 (*260.54*)	152.51 (*181.13*)
(O6)	N/A (*195.24*)	87.99 (*235.65*)	81.61 (*186.64*)	158.78 (*239.39*)	122.09 (*182.02*)

The impact on NPV for considered design cases on office water user behaviour is shown in Figure 6.3. In both O1 and O2 cases that the efficiency of user behaviour decreases the NPV in shared GWR scenarios increased due to higher demand for GW however the GW supply from residential block was not enough for the whole demand in these two cases. The NPV in individual GWR scenarios increased in O1 compared with the base case due to assumed higher generation of GW within offices due to behaviour change. Conversely in O2 the NPV in individual GWR scenarios decreases compared to O3 (base case) as a result of increase in toilet flushing demand and assumed same handbasin consumption in both cases. Increasing the efficiency office water use behaviour resulted on the constant NPV within all design cases except the O6 (point D). This is because changing the user behaviour in offices does not have any effect on the GW supply as the GW is supplies from residential building and it is only changes the GW demand in offices. The O6 design case is the only design case that frequency of toilet flushing in both female and male toilets were assumed to be reduced (see Table 6.6) and therefore it results in less demand for GW and less savings in potable water and consequently reduces the NPV in this case.

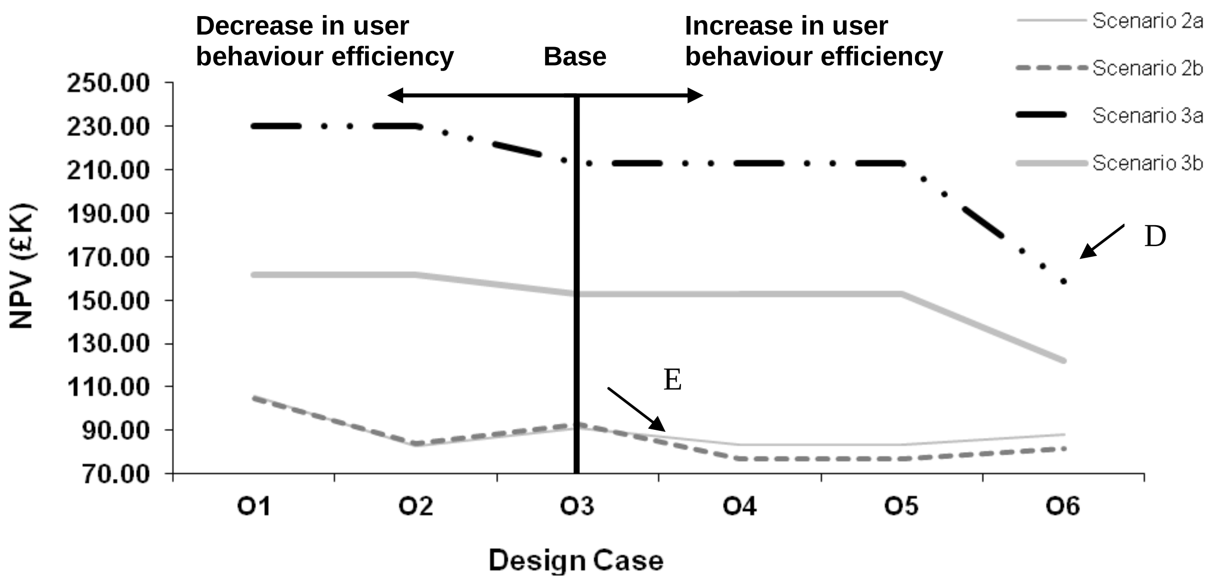


Figure 6.3 Sensitivity results on changing in office water user behaviour on NPV

The NPV in individual GWR scenarios reduces by increasing the efficiency of user behaviour. This is attributed to the fact that increasing the efficiency in user behaviour results in less demand for toilet flushing and results in lower savings. In the O6 case the zero toilet demand for male employees and only one toilet demand for female employees per day assumed. Therefore the deficit between supply and demand in individual GWR system in office block was reduced in this case compare to O5 and O4 and results in higher NPV in both scenario 2a and 2b. But reduction in toilet flushing demand means lower savings and therefore lower NPV in this case achieved compared to other cases (point E).

The results for analysis show that changing the office water use behaviour has minor impact (less than 10% changes) on the total carbon emission in considered scenarios. The reason for this reaction is because in shared scenarios changing the office user behaviour only impacts on the demand of GW which might lead to an increase or decrease respectively, therefore the operational energy for pumping were relatively unchanged.

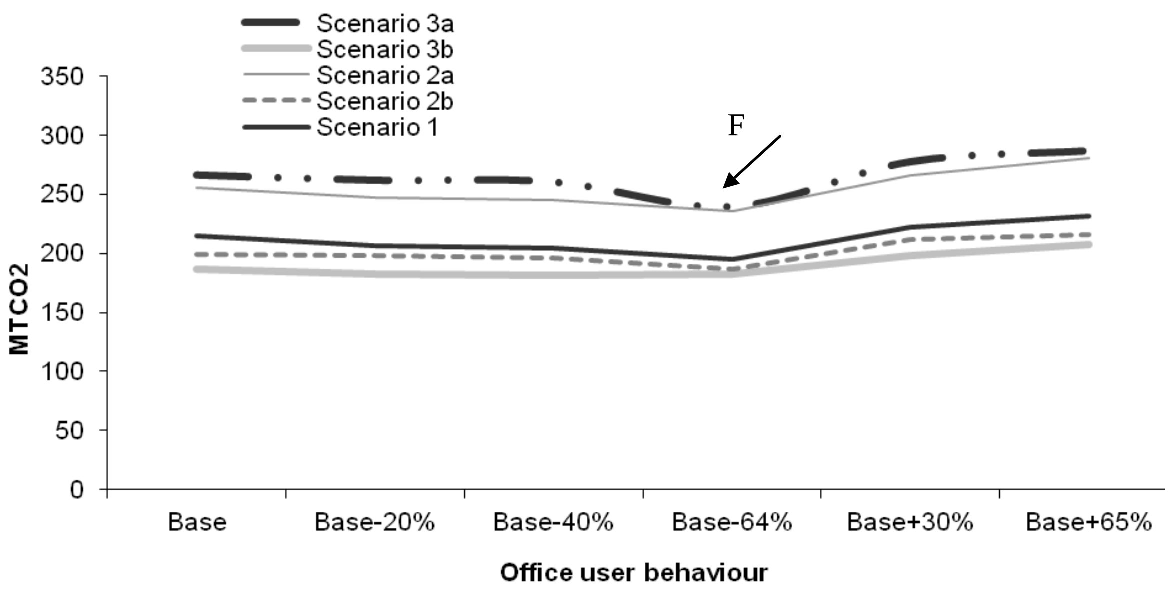


Figure 6.4 Influence of office user behaviour on carbon emissions (MT= Metric Tons).

In individual scenarios as the volume of GW supply is very low changing the user behaviour slightly increases or decrease the GW generation which consequently increase or reduce the energy requirement for treatment and distribution of GW in the system. As is shown in Figure

6.4 increasing the efficiency in water use reduces the total CO_2 emissions and reduces the efficiency of water use in offices resulting in increases in the total carbon emissions. The scenarios order within assumed cases is: Scenario 3a> Scenario 2a> Scenario 1> Scenario 2b> Scenario 3b. In the O6 case the total carbon emission of scenarios 2a and 3a were very close to each other (point F) due to the fact that the carbon savings from higher volume of potable water saving in shared scenario can nearly offset the higher energy demand for construction and operation in this scenario compare to individual scenario therefore the total carbon emission in both scenarios becomes broadly similar.

6.3 Occupancy rate

The number of occupants can dramatically affect water demands. The study by Butler (1991) showed a linear relationship between household occupancy and frequency of WC flush and washing machine usage therefore an acceptable approach for calculating the household usage is to multiply the per capita usage frequency by the household occupancy rate (Roebuck, 2007). The effect on changing the occupancy rate in residential and office blocks on mass-balance, financial performance and CO_2 emission of shared and individual GW recycling system within assumed buildings examined in this section.

6.3.1 Residential occupancy

The number of occupants in residential properties has been found to have a direct influence on the total water demand within a dwelling (Butler, 1991; Jeffrey & Gearey, 2006; Butler & Memon, 2007). Increasing the number of occupancy results in more available GW in a selected scale and might increase the efficiency of the system, while reducing the number of occupancy has an opposite results, which likewise reduces the hydrological performance and economic feasibility of system due to insufficient supply of GW .

In order to find out whether the trend towards more sustainable GW recycling system (higher NPV value and less carbon emission) continues, reverses or plateaus as the occupancy rate changes, the practical average UK household occupancy range between 1 to 5 were tested in this study. The minimum occupancy rate assumed to be 1 as the system is designed for urban mixed-use areas, that is at least 1 person is assumed to be living in each apartment. Household occupancy rate is in the range of 2-4 in most countries of the world (Appendix 3).

In single household occupancy, which has a growing trend today, the water consumption per capita increases compare to two occupancy (DEFRA, 2006). Two-person household consumes 300 litres of water per day (150 litres each), whereas a single occupancy household consumes 210 litres per day (SODCON, 2000; DEFRA, 2006; DEFRA, 2007; Memon, Ton-That, & Butler, 2007). This increase is related to changes in user behaviour. Although the using behaviour for toilet flushing, shower, bath and sinks are unlikely to change. However, the main behaviour changes is for washing machines and dishwashers as single occupant might be more likely to use a half full dishwasher and half full washing machines. Although, based on this description there is also likely to be a change in average water consumption for single occupancy houses this change was not considered in this study and the daily water consumption of 148 lit/person/day was assumed for all occupant levels.

6.3.2. Results

Figure 6.5 shows the impact of residential occupancy change on NPV. As it shown in the figure when the number of occupancy in residential flats is lower than 2.4 (average UK residential rate) the NPV for individual GW recycling scenarios were negative as the results in the deficit of GW supply. The mass-balance analysis for shared scenarios was also showed insufficient supply in these occupancy rates.

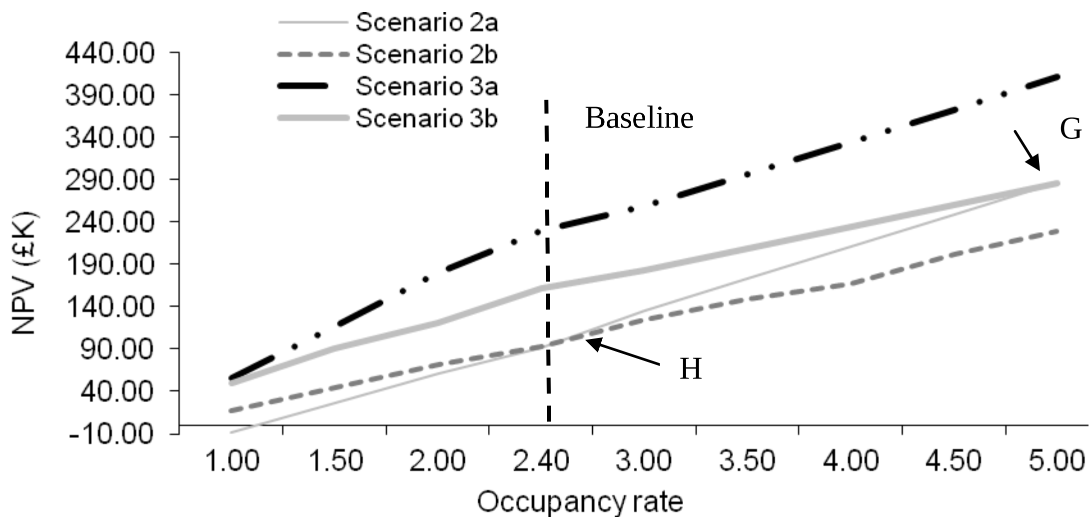


Figure 6.5 Influence of change in residential occupancy rate on NPV.

Increasing the number of occupancies results in an increase in the NPV of all scenarios until the point H in Figure 6.5 when scenario 2a becomes higher than scenario 2b again because CW technology does not have the economy of scale and any increase in number of occupancies means requirement for a larger CW bed size. This increase in NPV on scenario 2a continues until the number of occupancies in residential flats is as high as 5 people per flat. At this level the NPV which in this scenario becomes even higher than the shared scenario with CW treatment technology (scenario 3b); see point G. This is a rare occurrence for an individual scenario to have a higher NPV than a shared scenario.

Linear increases in total carbon emissions with increase in residential occupancy rate can be seen in all 5 scenarios however, relative changes in carbon savings are broadly similar, except the occupancy rate below 2.5 residents per flat. For any occupancy rate, domestic GW supplies are able to meet domestic GW demands, however below 2.5 occupancy per flat they are insufficient to fully meet shared GW demands and this reduces the difference between carbon emissions in all scenarios.

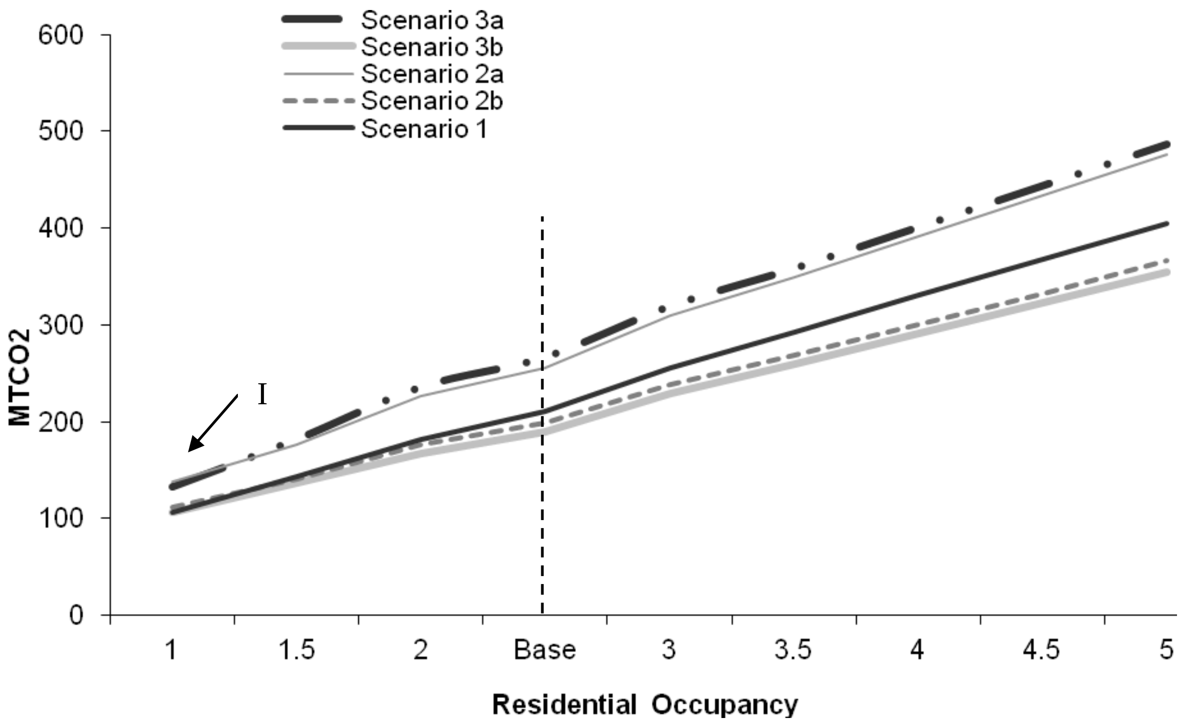


Figure 6.6 Influence of residential occupancy rate on carbon emissions (MT= Metric Tons).

The carbon emission within scenarios becomes very close when the occupancy rate is as low as 1 person per flat (point I). Total carbon emission for scenario 1, 2b, and 3b were almost similar in this case as there is deficit between supply and demand in this option due to low number of residents within the residential block. This makes the potable water saving through GW system to minimum and results in individual and shared GW recycling system have similar emissions. The total emission in all scenarios decreases when the occupancy rate decreases due to reduce in total water consumption and wastewater generation in buildings.

6.3.3 Offices occupancy

Office occupancy rates were usually defined by specific working conditions which affects the space requirement per employees. There are many national building and employment codes which set up standards for an office occupancy rate. Generally the average area per office employee is ranges between 9.3 to 25.5 square meters depending on the style and type of the business (Table 6.9). The standard of office space per employee (in m^2) was relatively stable over time, except in Italy and Japan, where the amount of office space per person is slightly increasing (OEDC, 2004).

With the intention of examining the effect of changing office occupancy rate on the financial and environmental performance of shared and individual GW recycling system, the average area of 5 to 40 m^2 per employee were chosen in this study to cover the broad range on average area around the world as showed in Table 6.9.

Table 6.9 Standard of average space requirement per office employees

Country	Average area per employee (m^2)	References
Central London	16.8	Van Meel, 2000
San Francisco	16.25	(International Facility Management Association, 1997
Italy	23	OECD,2004
Denmark	9.3	Van Meel, 2000
Frankfurt	25.5	Van Meel, 2000
Amsterdam	24.0	Van Meel, 2000
Brussels	24.0	Van Meel, 2000
New South Wales	15	Work Safe Victoria, 2008
UK	15	Employment land review, 2005

6.3.4 Results

The impact of office occupancy change on NPV in 4 considered GW recycling scenarios is shown in Figure 6.7. In the shared scenarios the NPV slightly increases as the occupancy rate increases from 5 to 15 square meters per employee. Following that increase the occupancy rate for more than 15 square meters per employee results in a decrease in NPV value, not least in shared scenarios 3a and 3b. This is because when the average area for office employee decreases the number of employees in the same building increases consequently leading to a deficit in GW supply (i.e.GW from the residential building is insufficient to meet toilet flushing demands in offices). Conversely increasing the average area per employee means fewer employees in the building therefore there is a reduction in demand for GW and less potable water saving therefore the NPV decreases also.

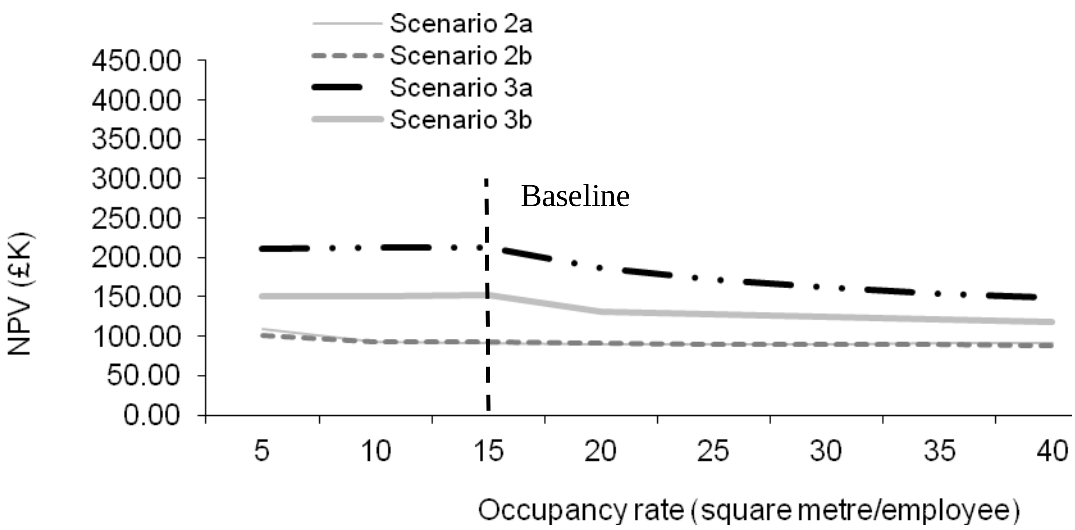


Figure 6.7 Influence of change in office occupancy rate NPV

The NPV on scenario 2b increases as the number of employee per area increases from 5 to 15. In this case there is more GW supply per employee. However, increasing the number of employees beyond 15 employee/m^2 results in a relatively constant NPV. The same trend was seen in scenario 2a except in the 10 employee/m^2 range the NPV dropped because of the deficit in supply and related high construction costs for an individual MBR.

In the carbon emission assessment study by changing the office occupancy rate the pipe diameters were also considered to be changing as the number of toilets and urinal per floor were dependant on assumed number of employees per floor. Therefore any changes to office occupancy resulted in flow changes in pipes and required smaller or bigger pipe diameters.

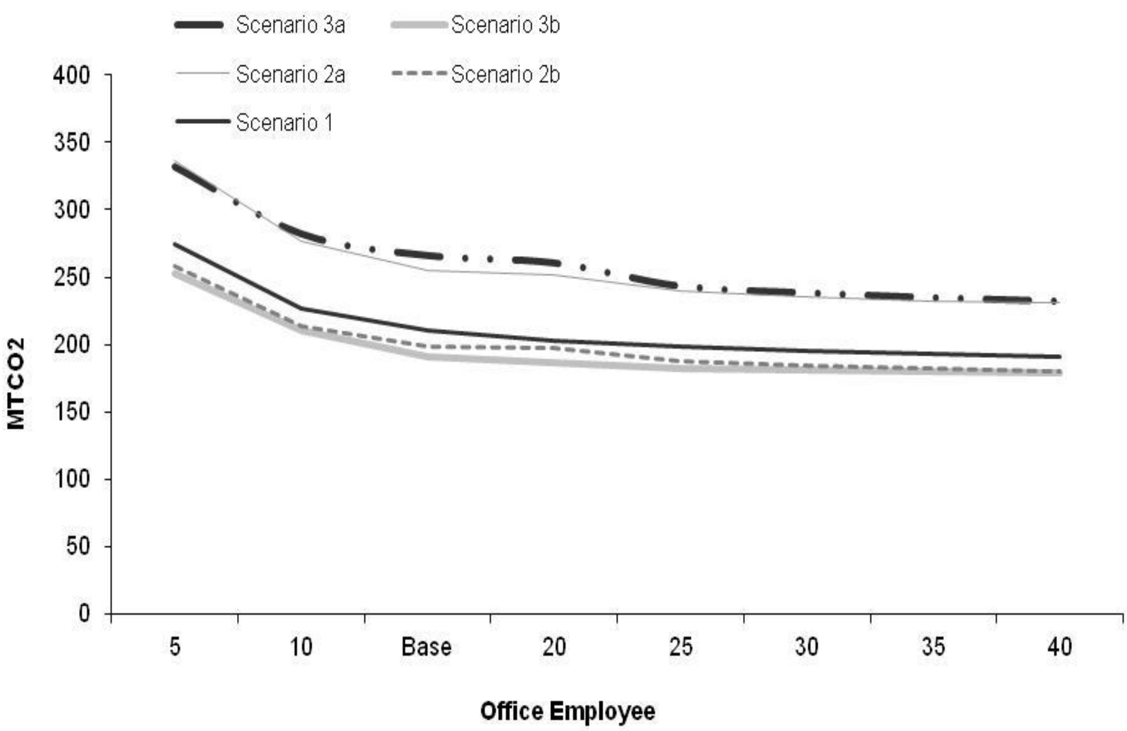


Figure 6.8 Influence of change in office occupancy rate (m^2 per employee) on carbon emission (MT= Metric Tons).

As shown in Figure 6.8, increasing the area required per employee reduces the total carbon emission in all scenarios. This is because of the fact that less employees required GW within the office block.

6.4 Social acceptability

When considering the implementation of GW reuse, it has been shown in many cases that the importance of environmental and economic feasibility of GW systems is not well supported by general public (Okun, 1991; Wegner-Gwidt, 1991; Jeffrey and Temple, 1999). An understanding of the public vision of GW recycling systems and what is satisfactory (or reasonable) to them to consider, are primary aspects of supporting installation and consequent appropriate use of such systems (Sefton, 2009). In other words, public support is essential for successful implementation of GW reuse projects. A major obstacle for implementation of GW reuse is public perception that it is unsafe or unhealthy, or a more general reluctance to the idea of reusing wastewater. The results from the study by Brown and Davis (2007) in Australia, the study by Domenech and Sauri (2010) in Spain, and the study by Jamrah et al. (2008) in Oman, shows that the key reasons for the poor acceptance of GW reuse are: concerns about health risk, religious concerns, perceived costs and financial benefits, operation regime, difficulty of use, environmental awareness and a idea that using recycled water decreases the living standard. In the UK, apart from these mentioned obstacles , another barrier for accepting GW is the misperception that the UK does not have any water supply problems because of the regular rainfall, which means people are less willing to accept the need to value water highly (Jeffrey and Jefferson, 2003).

However, some studies have shown that public acceptance of GW reuse for certain activities can be fairly high where water is valued highly (Russell & Hampton, 2006; Atkinson, 2005). The survey studies that carried out in Australia (Denlay and Dowset, 1994; Brown and Davies 2007; Mankand and Tapsuwan, 2011) Amsterdam (Van der Hoek et al., 1999), Canada ((Stenekes et al., 2006), Oman (Jamrah et al. 2008), and Israel (Friedler et al, 2006) were revealed that public's aversion to support reuse was augmented by increases to the level of physical contact with the water, by 97% supporting reuse for irrigation, 96% supporting for toilet flushing, 80% supporting for clothes washing, and 20-30% for potable reuse. According to these studies using GW for toilet flushing has in general terms high support from the public. Nevertheless, the public perception for reusing GW that have been previously used by others (rather than themselves) reduces in an unfavourable manner for reuse. This might be a drawback point for shared GW as the source is shared between different users.

Another important factor in the acceptance of GW reuse was identified to be public trust in local water authorities. Surveys focusing on Australia and USA have pointed that a main reason for public willingness to use wastewater reuse is a high level of trust in the local water authority (Po et al. 2003; Khan and Gerrard, 2006). For example, it is stated by Hennesy (2009) that it appears that some opposition to GW reuse implementation may be experienced in Canada due to a lack of public trust in local authorities regarding concerns about tap water quality and rapid growth in bottled water sales (Krewski et al., 1995; Environics research group, 2000). In contrast with this idea, the UK consumers fail to fully value water because the water service is reliable with a very high standard and compared to other bottled water is cheap. Therefore, there is no interest in implementing a GW recycling system as the yearly savings are unlikely to be large enough to make financial sense in terms of 'payback' periods. The current 'payback' period for an individual GW recycling system in UK has been estimated to be in the region of tens of years.

Previous studies shows that socio-economic features most probably influence public perception and acceptance of GW recycling is correlated with a high level of education, followed by a younger age category, while income and gender appeared significant in only one third of the studies (Po et al., 2003; porter et al., 2005; Ryan et al., 2009; Demenech and Sauri, 2010).

Further, within the social science literature there appears to be a distorting views towards focusing on acceptance of centralised wastewater reuse systems. Although some research outcomes can be generalizable to the GW reuse context, it is clear that there is a significant gap in the knowledge base of social drivers specific to the acceptance of GW recycling systems and the factors contributing to its widespread use. GW recycling systems are typically owned by property developers, homeowners, or other private entities, whereas centralized wastewater treatment systems usually are publicly owned. Consequently, the investor has a direct encouragement to invest in the GW recycling system, as this investment can enhance the value of the property, or generate cash flows by saving on the operation and maintenance costs of the water systems. It is recommended that future research focus on examining public attitudes relevant to GW recycling systems, as well as adoption behaviours among current users of these systems. This will assist in developing policies specific to domestic GW recycling system.

In order to improve public acceptance on GW reuse it is important to look at successful water sector projects that have changed policy, behaviour, or public acceptance. Strategies to change public perception include campaigns that educate the public, engage the community, and activate the media. Baumann (1983), Gibson and Apostolidis (2001), Hartling (2001), March et al.(2004), and Stenekes et al. (2006) were all agreed in the three main ways that if implemented correctly may ensure public acceptance of wastewater reuse schemes: 1) Publicity (including advertisement in the media), to be clear and disclose all the facts about the project; 2) to talk to the public clearly in a language they understand, and in an interesting way; 3) to have the public participate whether as ratepayers, taxpayers or stakeholders in the decision making process.

People will have to see an explicit value of using recycled water if they are to spend their own money on a system. Therefore, if the developer is paying for construction who is going to pay for the maintenance activities and what is the benefit for them? In shared mixed use GW recycling system there is a risk that responsibilities are unclear or not well-defined between municipalities (i.e. who generally is responsible for water provision?), property owners (i.e. who may invest in GW recycling systems?), technology suppliers (i.e. who provides the equipments?), and service providers (i.e. who operate and maintain these equipments). It follows that accountability and responsibilities have to be clearly defined from the outset of the project. In addition to this developers, which are the key decision makers with brownfield development, are tasked with providing projects that people want to buy or rent and that investors will be willing to finance. Developers may not be convinced that there is a demand for sustainable buildings, which they believe rightly or wrongly, to cost more. According to one national developer, businesses seek to reduce cost through smaller premises and more efficient use of space, not through energy and water efficiency (Dair and Williams, 2006).

The result of this research project has shown that shared GW recycling system in mixed use buildings reduces potable water, and has a financial benefit at 15 years (i.e. positive NPV). According to these results it is now vital to know what stakeholder's perspective about this shared GW recycling system is and what is stopping them from implementing such systems. In this respect, further work is needed to examine and identify supporting mechanisms that are suitable for overcoming the key reasons for lack of inclusion of GW recycling system in single and multi-use buildings.

Future research could look into the effectiveness of government rebates in facilitating adoption of GW recycling systems, as well as ease of public access to these forms of financial support. Further research could improve understanding of why residents choose to buy into housing developments that have decentralised water systems including rainwater harvesting or GW recycling. The successful implementation and strong public acceptance of decentralized systems can play an important role in the future of water resource management worldwide.

CHAPTER SEVEN

TECHNOLOGY ASSESSMENT AND POLICY IMPLICATIONS

7.1 Introduction

Replacing old water-using technologies with those that allow the same desired goals with less water have been helped to improve the efficiency of water use for many years. This chapter looks at the implementations of various water efficient appliances (technology) within buildings for the assumed scenarios to assess the effect of these changes on the performances of individual and shared GW recycling systems. By making changes only to technology efficiency while keeping other variables like (e.g. user behaviour, water charges, or occupancy rate) constant will help find a rigorous analysis of the direct impact of technology change on the NPV and CO_2 emission.

Following the results on the assessment of technology changes this chapter also looks at the roles of the policies in GW adoption around the world and in the UK.

7.2 Water efficient technology ranges

There are various ranges of technologies that can be applied in buildings such as low flush toilets, low flow shower heads, low flow taps, efficient washing machines, etc. Usually the first devices that people are more willing to implement and the political agencies will choose for conservation programs are showerheads and toilets, as they are relatively easy to manage and install and have a short payback period (Gleick et al., 2003). There is growing use of high-efficiency washing machines and dishwashers since 1990s and they are now increasingly available and popular (Gleick et al., 2003). The range of technologies adopted and their related performances have been taken from appropriate literature and are described below. The relative water consumption for each technology that can be used in residential and office buildings is shown in Table 7.1.

7.2.1 Toilets

Low flush toilets are specially designed to decrease the volume of water consumed during flushing. From 1st January 2001 the Water Supply (Water Fittings) Regulations (1999) specified a maximum flush of 6 litres for toilets in new buildings. Technical innovations in this field have made it possible to reduce the water used by toilets from 9 litres per flush to almost 0 (Table 7.1). The last three items in the table demonstrate the technical lower limit for flush volumes but there is no suggestion that these methods are likely to see widespread implementation in the short to medium term (Roebuck, 2007). Therefore the choice is between flush volumes ranging from 6-litre to 2.5 litres single flush.

7.2.2 Shower and bath

Water use in showers and baths are typically the second largest of indoor residential water use. In UK, as presented in Chapter 3, showers accounts for 12 percent of indoor residential water uses. Showers generally have flow rates ranging from 3 litres per minute to 30 litres per minute. The maximum allowable flow rate in UK for showerheads is 12 lit/min based on EU member states scheme and legal regulations in 2011. Low volume baths are now available and are contoured to the human body to create a comfortable bath at a reduced volume of 140 litres to 66 litres undersized baths. The range of possible shower flow rates and bath sizes that are available in market were shows in Table 7.1.

7.2.3 Taps

Tap flow is harder to link to water use than showerheads because tap use is largely volume based. The amount of water used for brushing teeth while leaving the tap running, however, will be larger with a tap that flows at a higher rate. Thus, a low-flow tap may or may not reduce water needs, depending on the use and individual behaviour. Ranges of tap flow rate were presented in Table 7.1 .The Water Regulations in UK requires that the flow rate of taps does not exceed 3.6 litres per minute.

7.2.4 Washing machines

Since the last decade 77% of households own a washing machine and the growth in ownership seems to be increasing (EA, 2003). In the past few years, increasing attention has been paid to the potential for efficient washing machines to reduce water and energy use (Grant 2006). Water usage for new washing machines varies from 6.2 litres per kilogram to 20 litres water per kilogram. Table 7.1 shows a range of volume of water used by washing machines for a typical cycle. In the study by Butler in 1991a linear relationship between household occupancy and frequency of washing machine usage was found. Therefore in order to determine household usage the per capita frequency can simply be multiplied by the household occupancy rate.

7.2.5 Dishwashers

Dishwashers account for less than two percent of total residential water use (Mayer et al. 1999). Dishwasher ownership continues to rise from 6% of households in 1985 to 28% in 2007 (EA, 2003; DEFRA, 2007). Since water becomes more of a concern, it is expected there will be continued improvement in the water-use efficiency of newer models as the current electrical dishwashers are more efficient than manual dishwashing especially in terms of water consumption (Stamminger et al.2007) .

7.2.6 Urinals

As showed in Figure 3.4a urinal flushing accounts for about 20% of office water use. In practice, urinal flush rates are often adjusted, in an attempt to reduce odour or blockage, and flushing can continue for 24 hours a day, 7 days a week. For some offices and buildings, this may mean that 76% of flushing occurs when the building is unoccupied. Under the Water Regulations (1999), urinals should use no more than 7.5 litres per bowl per hour (10 litres for a single bowl) and should have a device fitted to prevent flushing when the building is not being used. Some office urinals are now fitted with devices that eliminate the requirement for flushing. This has had considerable impact on demands within this sector. Although the impact on the infrastructure (i.e. pipe deposition) and water quality needs to be investigated further.

Table 7.1 Range of existing and modern indoor water using appliances

WC	Washing Machines	Lavatory taps	Kitchen taps	Showers	Bath	Dishwasher	Urinal flush (2 or more urinals)
6 single lit/flush[2,5,6,7]	110 lit/load[8]	15 lit/min[23]	12 lit/min[15]	15 lit/min[23]	230[24]	56.78 lit/load[17]	7.5 lit/bowl/hr
6/4 Dual lit/flush[9]	100 lit/use[1]	12 lit/min[14,15]	10 lit/min	12 lit/min[13,15]	140 [16]	24.09 lit/load	6 lit/bowl/hr
6/3 Dual lit/flush[7,9]	80 lit/use[4]	10 lit/min[12]	9 lit/min[13]	10.8 lit/min[20]	116	20 lit/load[17]	3.5 lit/bowl/hr
4.5 single lit/flush[7]	65 lit/use[6]	8 lit/min	8 lit/min[20]	9.5 lit/min[12]	88[17]	16.75 lit/cycle[15]	1.5 lit/bowl/hr
4 single lit/flush[6,7,9]	55 lit/use[6]	7.5 lit/min[14]	7.5 lit/min [21]	8.5 lit/min	65[17]	14 lit/load[17]	0.75 lit/bowl/hr
4/2 Dual lit/flush[6,9]	49 lit/use[5]	6 lit/min[13,16]	5 lit/min [21]	8 lit/min		13.09 lit/load	0
2-3 single lit/flush[7]	45 lit/use[3,22]	5 lit/min[16,17]		6.43 lit/min		12 lit/load[17]	
2.5 single lit/flush	40-80 lit/use[6,18]	4.7 lit/min		6 lit/min		10 lit/load	
1.5 ultra low flush toilet (ULFT) lit/flush[10]	35-40/ 5 kg[7]	4 lit/min		5.11 lit/min[19]			
1.2 Vacuum toilet[7]	27 lit/kg[2]	3 lit/min[16]		4.5 lit/min			
0 Composting toilet[6,11]	12 lit/kg[16]	1.7 lit/min[16]		3.5 lit/min[21]			

Reference: 1.SODCON, 1994; 2.HMSO, 1999; 3.Lallana et al., 2001; 4.Butler and Memon, 2006; 5.DCLG, 2007; 6. EA, 2001b; 7. Grant, 2006; 8. Mays, 2010 9. Grant, 2003; 10.Milan, 2007; 11. Anand and Apul, 2011; 12. EA, 2003; 13. Australian Eco-Label, 2008; 14. Kaps and Wolf, 2011; 15. EU Eco-Lable, 2011; 16. Green building store, 2011; 17.EU water saving potential, 2007; 18.Bricor, 2010; 19. Friedman, 2009; 20. Aquacraft, 2003; 21. BREEAM, 2009; 22. British standard, BS 8525-1, 2010; 23. Jamrah et al., 2008; 24. MTP, 2008.

7.3 Considered design cases for assessment

In this part of the research the role of technological changes in line with UK policy drivers were examined within the 5 considered scenarios for assumed residential and office building. As shown in Table 7.1 there are various ranges of possible water saving devices available within the current market and examining the effect of each individual technology on the scenarios performance is very complicated and time consuming. Therefore for simplification, instead of testing the effect of each appliance a set of five design cases for domestic demands in UK has been derived using the water efficiency calculator for new dwellings (DCLG, 2010; Hunt et al., 2012). For instance, Code for Sustainable Homes is a non-statutory design standard for new homes including water consumption and it is now set of national standards for the sustainable construction of new homes (Table 7.2). All new Government funded housing is expected to meet Code level 3 (105 lit per person per day) from April 2008 (DEFRA, 2007). The regulatory minimum standards being proposed in this document will underpin the standards of water efficiency at different Code levels which are shown in Table 7.2 and Table 7.3.

Table 7.2 Water performance targets in Building Regulations for Code for Sustainable Homes

Water consumption (litres/person/day)	DCLG mandatory levels
< 120 lit/person /day	Level 1 and 2
<110 lit/person/day	Level 1 and 2
< 105 lit/person/day	Level 3 and 4
< 90 lit/person/day	Level 3 and 4
<80 lit/person/day	Level 5 and 6

In order to calculate the volume of water used by each resident the chosen technology need to be multiplied by a factor related to user behaviour (Table 3.2 and 3.3). It is important to note that user behaviour can have a direct impact on the amount of potable water that is used throughout all domestic homes therefore this is kept unchanged within all the design cases. The technology considered followed by the total water consumption for each design case were shown in Table 7.3.

Table 7.3 Domestic technological efficiency by end-use for each design case

Technology *(units)*	**Design case**				
	Base+30%	Base	CSH 1&2	CSH 3&4	CSH 5&6
	(D1)	(D2)	(D3)	(D4)	(D5)
WC *(lit/flush)*	6	6	4.5	4 .5	2.5
Washing Machine *(lit/load)*	110	80	49	49	35
Lavatory taps *(lit/min)*	12	8	6	5	5
Kitchen taps *(lit/min)*	12	8	6	5	5
Shower *(lit/min)*	15	12	10	8	6
Bath *(lit/capacity)*	230	116	116	88	65
Dishwasher *(lit/load)*	25	25	16	14	14
Total *(lit/capita/day)*	**196**	**148**	**118**	**101**	**76**

Changes in demand compare with base case (148 lit/p/d in Table 7.3) have been achieved as follows: in 118 lit/p/d case reduced flow rate shower and kitchen and handbasin tap, and smaller WC cistern in addition to a more efficient washing machine and dishwasher adopted compare to previous cases. The 101 lit/p/d cases adopt the same WC cistern and washing machine as 118 lit/p/d; however, it increases further the efficiency of the dishwasher and reduces the size of the bath and flow rate of shower and kitchen and handbasin taps. In 76 lit/p/d case the same kitchen and handbasin taps and same dishwasher adopted; however, it reduces further the size of the bath, and shower (for more details see Appendix 4).

Unlike domestic dwellings there is no ‘water efficiency calculator for offices’ or a ‘code for sustainable offices’. The base design case was adopted from Waggett and Arotsky (2006) water usage benchmark in offices. The benchmark for other design cases were adopted from study by Hunt and colleagues (2012) along with the BREEAM assessment codes for offices.

The Changes in water demand in offices compare to base case (Table 7.4) have been achieved as follows: 10.5 lit/employee/day adopts a smaller WC cistern and lower flow taps, with same urinal. For 7.6 lit/employee/day the same technologies as 10.5 lit/employee/day were adopted excepting the adoption of a more efficient single flush WC cistern. 5.7 lit/employee/day adopts the same WC cistern as 7.6 lit/employee/day. However, it increases further the efficiency of urinals (now waterless) and low flow taps. 16.7 lit/employee/day adopts the same WC cistern as base case, while urinal and taps were less efficient and use more water (See Appendix 4 for more detail).

Table 7.4 Office technological efficiency by end-use for each design case (*Italics* shows where female water usage differs)

Technology *(units)*	**Design Case**				
	Base+30%	Base	Base-20%	Base -40%	Base-64%
	(O1)	(O2)	(O3)	(O4)	(O5)
WC *(lit/flush)*	6	6	4.5	2	2
Urinal *(lit/bowl/hr)*	7.5	7.5	3.5	3.5	1.5
Lavatory taps *(lit/min)*	12	8	6	6	4
Kitchen taps *(lit/min)*	12	8	6	6	4
Total *(lit/capita/day)*	**16.7 *(21.8)***	**15 *(19.4)***	**10.5 *(14.8)***	**7.6 *(9.1)***	**5.7 *(7.9)***

It is assumed that changing the technology does not have any significant effect on changing the size of pipes.

7.4 Results

In this section quantification of GW supply and demands, financial performance and CO_2 emission of individual and shared GW recycling systems in the light of technological changes imposed (Section 7.3), is assessed for considered domestic and office block within mixed used urban regeneration areas in UK. Table 7.5 shows that NPV and carbon emission within scenarios by changing the technology in residential (Table 7.5a) and in offices (Table 7.5.b) block.

Table 7.5a. NPV (£K) and related carbon emission (*$MTCO_2$*) within scenarios with residential technology changes.

Domestic Technology Design case	**Scenarios (after 15 years of operation)**				
	1	**2a**	**2b**	**3a**	**3b**
	Mains only	Individual	Individual	Shared	Shared
D1+O2	N/A (*269.4*)	91.15 (*313.67*)	92.99 (*257.63*)	213.08 (*322.31*)	152.48 (*248.18*)
D2+O2	N/A (*210.85*)	91.15 (*255.14*)	92.99 (*199.08*)	213.11 (*263.74*)	152.51 (*189.63*)
D3 +O2	N/A (*122.6*)	47.31 (*152.19*)	60.38 (*126.87*)	174.90 (*155.02*)	125.23 (*122.55*)
D4 +O2	N/A (*153.96*)	47.31 (*161.23*)	60.38 (*149.06*)	134.43 (*164.28*)	103.20 (*144.64*)
D5 +O2	N/A (*174.43*)	-8.77 (*212.41*)	17.76 (*169.53*)	75.20 (*220.85*)	61.93 (*160.14*)

Table 7.5b. NPV (£K) and related carbon emission (*$MTCO_2$*) within scenarios with office technology changes.

Commercial Technology Design case	**Scenarios (after 15 years of operation)**				
	1	**2a**	**2b**	**3a**	**3b**
	Mains only	Individual	Individual	Shared	Shared
D2+O1	N/A (*214.64*)	102.15 (*261.47*)	103.03 (*200.75*)	210.51 (*267.12*)	151.12 (*193.78*)
D2+O2	N/A (*210.85*)	91.15 (*255.14*)	92.99 (*199.08*)	213.11 (*263.74*)	152.51 (*189.63*)
D2+O3	N/A (*202.39*)	89.26 (*246.8*)	90.55 (*191.67*)	182.27 (*251.72*)	129.38 (*184.41*)
D2+O4	N/A (*194.39*)	92.45 (*237.39*)	93.73 (*183.67*)	143.54 (*237.45*)	115.17 (*182.16*)
D2+O5	N/A (*191.56*)	89.70 (*233.25*)	89.00 (*181.90*)	140.35 (*234.82*)	113.55 (*179.15*)

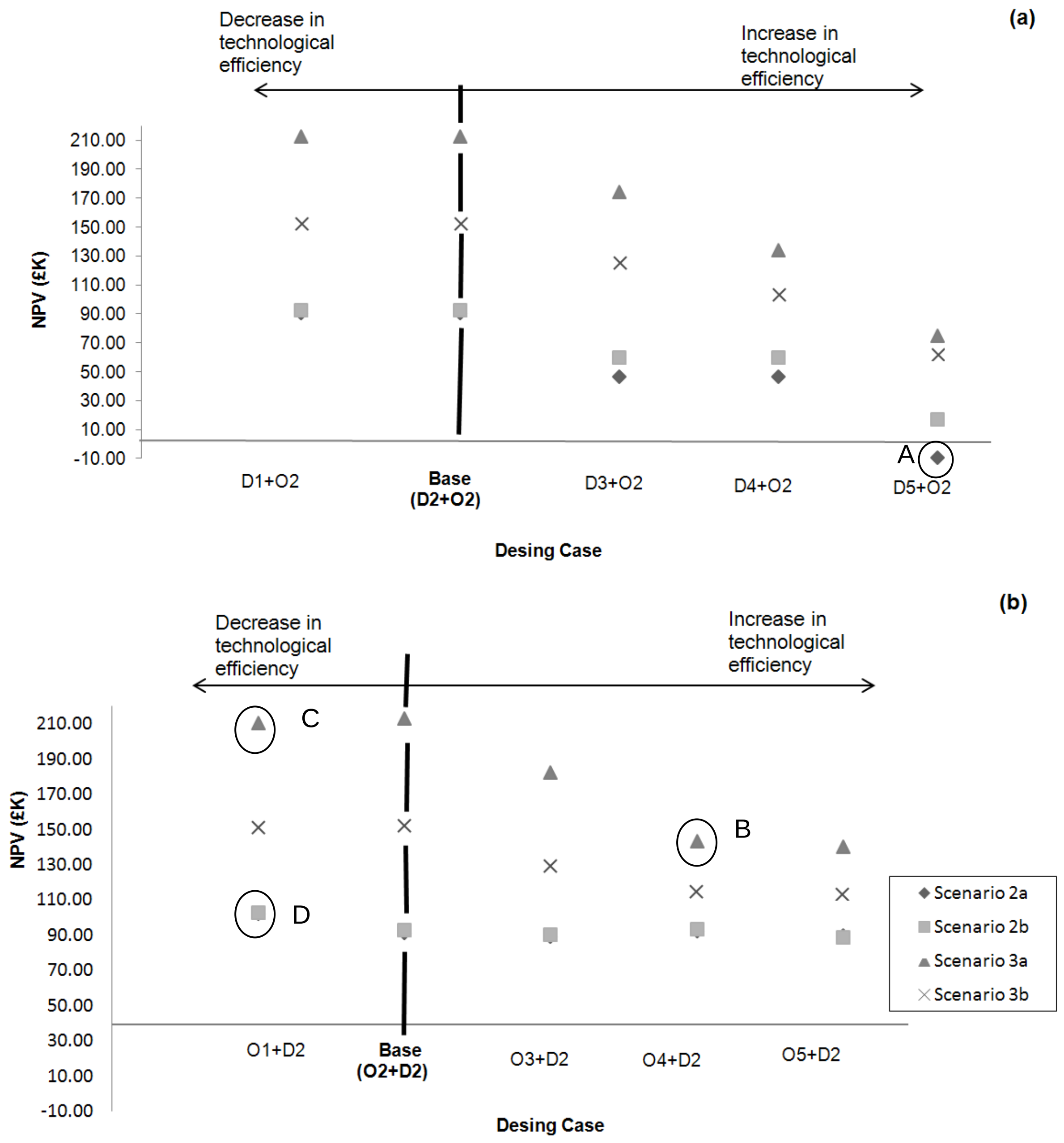
7.4.1 Financial performance

Figure 7.1a and 7.1b respectively shows the financial performance (NPV) of considered GW recycling scenarios (Figure 3.6) over the assumed technology design cases for residential (Table 7.3) and office block (Table 7.4).

In the D1+O2 design case that the total water demand per person in domestic properties increases to 196 lit per day, the NPV in all GW recycling scenarios were same as in D2+O2. This is due to the fact that both cases assume toilet cisterns are 6 lit/flush (the maximum allowable size in new buildings). Therefore, no matter if there is more GW supply in the D1+O2 case (via showers), the amount of water and wastewater savings through GW recycling is same in both design cases. The fraction of unused treated GW in D1+O2 case increases with the introduction of high flow shower heads therefore has limited effect here.

Figure 7.1 (a) Influence of residential technology changes on NPV

(b). Influence of office technology changes on NPV



In the D3+O2 case the volume of water that will be available as GW will reduce the potential for utilising the treated GW. In addition it will reduce according to the adoption of low flush toilets, meaning the financial saving made on GW recycling system will decrease. The same trend was achieved in D4+O2 and D5+O2 cases. The NPV of scenario 2a in D5+O2 case becomes negative (point A). Because the shower flow rate (8 and 6 lit/min) is assumed very low in these cases, even the GW demand for low flush toilets (4.5 and 2.5 lit/flush) cannot be supplied in these cases. In such cases GW supplies could have been increased through incorporating hand basins and/or washing machines. The analysis shows that in both cases adding only handbasin to the GW source is still not enough for the demand so it is required to include the GW from bath or washing machines to the system as well in order to meet all the required demand for GW. As the GW consumption (toilet flush volume) decreased dramatically therefore the volume of the saved water and resulting financial savings were also decrease. These findings were similar to the result of the study by Memon and colleagues in 2005.

The NPV of scenario 2a and 2b were the same in D3+O2 and D4+O2. This is attributed to the fact that the water consumption by WC is constant and only the volume of the GW generated is reduced. In the case that the volume of GW supply decreases, the concentration in pollutants was also increased. This is likely to require more rigorous treatment (or more maintenance) which has an effect on the cost of the system, but these implications were excluded from this study. The difference between NPV between scenario 2a and 2b increase by increase in the technological efficiency in residential block. This can be attributed to the fact that the volume of GW to be treated has linear impact on the bed size in the CW and the cost of this system therefore increase in technological efficiency means less requirement for GW and smaller CW bed. However the relationship between capital cost of MBR and volume of GW to be treated are not linear. Consequently increasing the technological efficiency in residential block results in increase in the difference of NPV between scenario 2a and 2b.

The results for changing the technologies in office blocks showed a descending trend for shared GW recycling scenarios (Figure 7.1b). The technological efficiency increases up to the point B at which the NPVs for the last two cases were almost the same. This is because the same toilet cistern size (2 lit/flush) and different urinal flushing (1.7 lit/employee in O4+D2 and 0.7 lit/employee in O5+D2) were assumed in both cases.

The result for the individual GW recycling scenarios in the office block showed a distinctly different trend than shared GW recycling scenarios. By decreasing technology efficiency (O1+D2) in these more available GW and more savings (point C) were available. By increasing the technological efficiency (O3+D2) mean that less GW supply and less potable water savings. As a consequence this leads to a reduction in NPV. Interestingly, the NPV in the last design cases becomes higher than the base case (point D). This can be attributed to the fact that the considered technology in these cases resulted in less demand in GW. As a consequence the GW supply from only office handbasin could meet most of the demands and leading to increases in profit for these two design cases.

7.4.2 Energy performance

The impact of technology changes on carbon emission was considered via two analysis options: In the first option the technology adopted in offices were assumed unchanged and only the technologies in residential building were varied between 4 considered design cases as described in Table 7.3. The impact on total carbon emissions is shown in Figure 7.2. The order of scenarios for the considered design cases was same as the base case (see chapter 5, section 5.4.1 for more details). The order of design cases (highest to lowest case) is: D1 +O2> D2 +O2> D3 +O2> D4 +O2> D5 +O2. For the first three considered design cases (D5 +O2, D4 +O2, and D3 +O2), the total carbon emission were reduced within all 5 scenarios compared to the Typical UK case (Base) mainly because of the lower volume of water consumed. This was due to the adoption of efficient micro components in these design cases. Smaller toilet cistern use less GW therefore requires a smaller amount of energy for treatment and distribution. There is an obvious sustainability trade-off in the first two design cases (i.e. D5 +O2 and D4 +O2) because although total carbon emission reduces within each case the amount of potable water saving is less, and there is a deficit in GW supply and demand.

In D5 +O2, the total emission in scenarios 1, 2b and 3b were very close to each other with scenario 3b and 1 approximately with the same value (point F). The water saving via GW recycling in this case is very low compare to other cases due to insufficient GW supply; therefore even by considering the carbon reduction potential by adoption of reeds in the CW the total carbon emission in this case is almost similar to the using main water alone (Scenario 1).

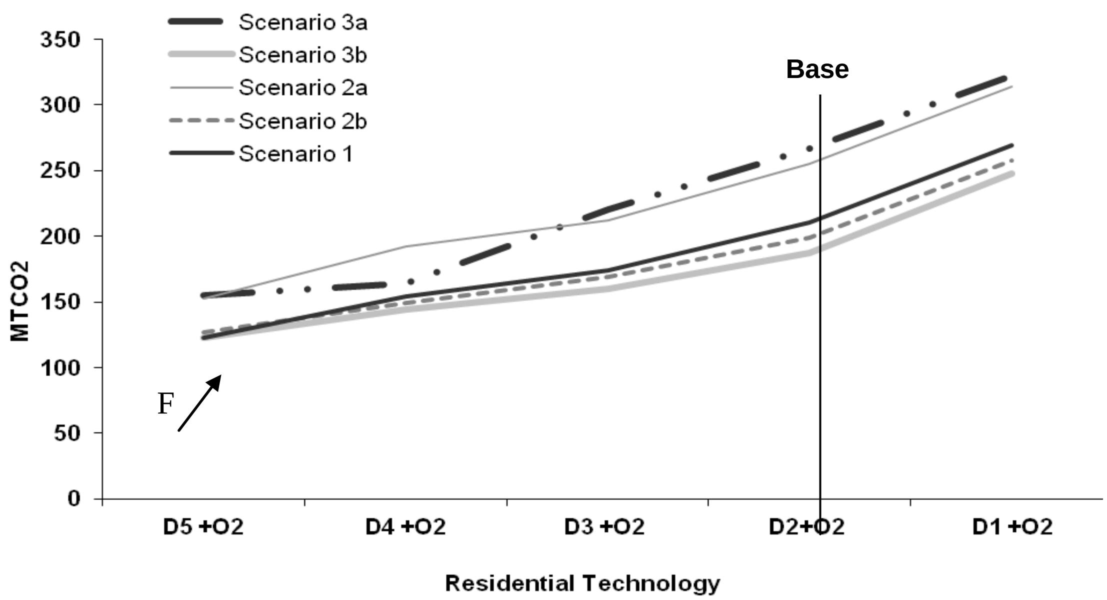


Figure 7.2 Influence of residential technology on carbon emissions (MT= Metric Tons).

Figure 7.3 shows embodied carbon emissions for all 5 Scenarios over 15 years of operation by changing the technology adopted within office block (Table 7.4). The order of scenarios in all design cases was same as the Base case. Increasing the efficiency in the technology adopted in the office block results in decrease in the total carbon emission. The order of design cases (highest to lowest case) is: D2 +O1> D2 +O2 > D2 +O3 > D2 +O4> D2 +O5.

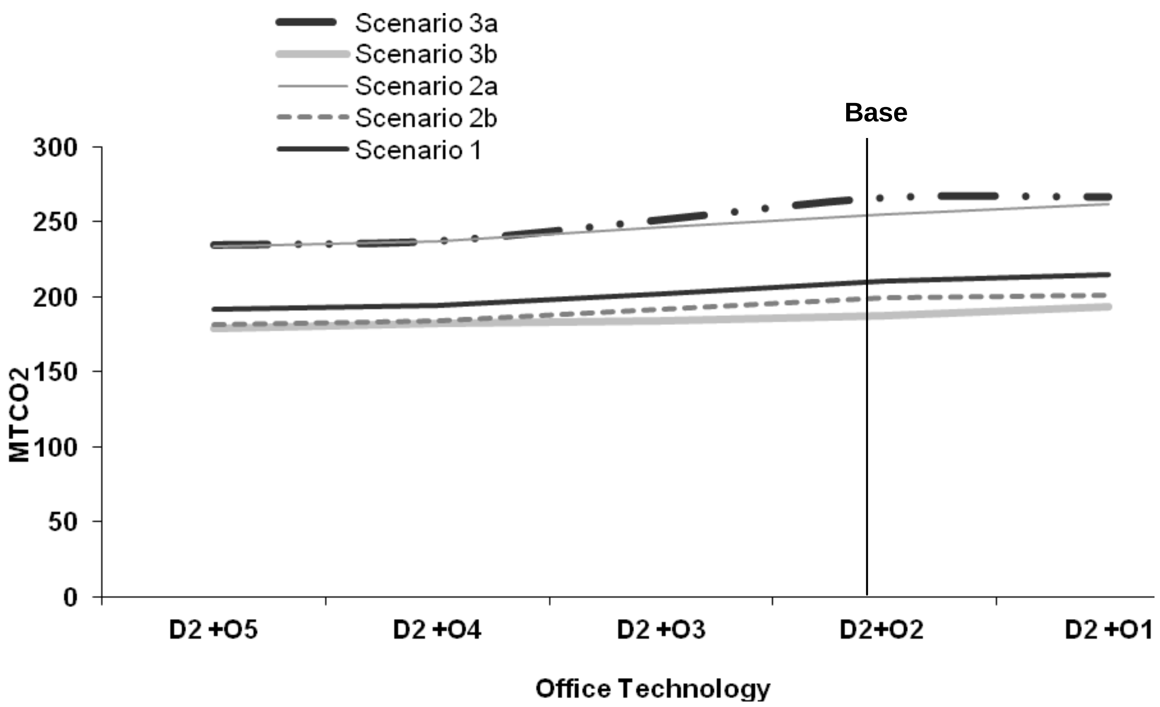


Figure 7.3 Influence of office technology on carbon emissions (MT= Metric Tons).

By increasing the efficiency of micro comments, the difference between total emissions in individual GW recycling systems and shared GW recycling systems were also reduces in considered design cases. This is attributed to the fact that increasing the efficiency of the technologies in the office building results in a reduction in GW demand. Therefore less GW is treated and distributed. In addition to this the potable water saving (and related carbon reduction) within the system also reduces. From these results it can be concluded that although there are trade-offs between financial performance and carbon emission but if he carbon reduction is the priority concern therefore case D5 +O2 with sharing GW is the more sustainable option with less water demand (due to efficient technology adoption) still positive

NPV compare to individual GW scenarios and with less carbon emission that even scenario 3a (MBR treatment) is only 8.19% more carbon intense than mains only scenario.

7.5 Policies and Regulation

7.5.1 Overview of global GW policies, regulations and laws

GW regulations around the world vary from being prohibited in all circumstance to being legal with few restrictions (Prathapar et al., 2005; CSBE 2003). However, GW use is increasing even in areas with no policies or very restricted laws. For example, in Oman wastewater regulations do not distinguish between black and GW and it is required that GW be treated to the potable water standards (Prathapar et al, 2005; Maimon et al. 2010). Nevertheless, many household use untreated GW for home irrigation which is illegal in principle (McIlwaine and Redwood, 2010). Sheikh (2010) also estimated that in California State only 0.01% of GW systems are legally permitted.

In some Middle Eastern countries GW reuse is illegal. Conversely, Israeli recently legalized GW reuse from showers, baths and washing machines for toilet flushing and landscaping (Global Water Intelligence, 2010). Jordan also has a standard regarding GW reuse in rural areas but it does not clarify the requirements for obtaining a permit (McIlwaine and Redwood, 2010).

Currently in Europe GW standards are under review through European and International standard committees (Anglian Water). As stated by the European Council Directive 91/271/EEC “treated wastewater shall be reused whenever appropriate,” though, it is unclear to how to determine its appropriateness (Somogyi et al. 2009). Several cities of Spain have agreed policies to promote GW reuse in multistory buildings (Domenech and Sauri 2010). Among European countries Germany has been a leader in GW use in the Europe and GW reuse is legal but must be registered with the Health Office (Nolde 2005).

In 1989 Santa Barbara was the first district in the US with building codes to separate GW from black water. Since then GW reuse systems in urban areas have been used under the regulation of plumbing codes in the United States of America. This was in response to severe future water shortages in areas such as California and Florida. About 30 of 50 states have some kind of GW regulations (Sheikh, 2012). These vary widely and do not form part of a national GW policy. The state of Arizona is seen as a leader in terms of support of GW reuse in United States and has a more flexible GW policy than many states. Current GW policy in Arizona employed three tiers that have different requirements for systems of different sizes. The three tiers are:

- Tier 1: Systems with a flow of less than 1.5 m^3 per day does not require a permission but need to protect public and environmental health like limiting human contact and cover any storage tanks.
- Tier 2: Systems with a flow of 1.5-11.5 m^3/day must submit their plans to the Department of Environment Quality and apply for a permit.
- Tier 3: Systems with over 11.5 m^3 per day must apply for permit and require written verification from permitting department. For more details of GW policy and regulations in Arizona State see Ludwing, 2002.

With respect to GW policies and regulations, Australia is often considered to be a shining example among other countries due to severe water shortage. Australia has developed national guiding principles for GW reuse which is called “Australian Guidelines for Water Recycling: Managing Health and Environmental Risks”. Regulations once again vary by states. For example in Tasmania, all GW must be treated (Tasmanian Environment Centre Inc., 2009), whereas in New South Wales untreated GW can be used for subsurface irrigation (NSW Office of Water, 2010).

There are several countries that have incentive programs for installation of GW reuse systems, including Australia, Cypress, Korea and Tokyo (Australian Government, 2010; CSBE 2003; CWWA 2002). In Tokyo, (Japan) due to increased rates of urbanization and population growth, not only are there encouragements for setting up GW systems, but they are compulsory for buildings with an area of more than 30,000 m^2, or with a potential to reuse 100 m^3 per day (BSRIA, 2001; Wiltshire, 2005).

7.5.2 UK GW policies and regulations

There are no UK regulations for the use of GW in terms of water quality (Leggett et al., 2001). However, there is regulation in place that affects the installation, use and maintenance of the systems called British Standards GW Systems Code of Practice. Any design and installation need to conform with the requirements of the “Water Supply (water fitting) Regulations 1999 for England and Wales, the Water Quality Regulations 1994” (Alkhatib, 2008). These regulations necessitate that mains water and water supplied is protected against cross connection or backflow by unrestricted air gaps. The same regulations also require pipe marking for the pipes conveying reclaimed water to be easily distinguished.

Currently several water companies (e.g. Anglian, Yorkshire, and Thames) are actively researching non-potable GW recycling mostly on individual domestic and non-domestic buildings and several universities such as Imperial College, Cranfield, Loughborough and Reading are investigating in-house GW recycling for non-potable uses.

In addition research information centres (BSRIA, CIRIA, etc.) and professional bodies (CIWEM, ICE, etc.) are exploring the possibility of using directly or indirectly GW recycling in the UK for domestic and non-domestic users at individual and communal scale.

GW systems are not in wide usage in UK mainly because of problems with maintenance, reliability and costs of these systems (UK Environment Agency 2008). Mainly due to low water and wastewater charges in this country. However, GW reuse is legal, provided that it fulfilled with certain building codes like BREEAM and Code for Sustainable Homes.

BREEAM is one of the leading environmental assessment method and rating system for buildings and is widely recognized measures of a building's environmental performance. It was first launched in 1990. It sets the standard for best practice in sustainable building design, construction and operation by using standard measures of performance which are set against recognized benchmarks. The measures used present a broad range of categories and criteria from energy to ecology. Including aspects related to energy and water use, materials, and etc.

The Code for Sustainable Homes (CSH) is the national standard that was launched in December 2006, by which new homes in England, Wales and Northern Ireland are being judged for their green credentials by rating and certifying they performance. It is a Government owned national standard deliberated to support continuous progress in more sustainable home building and reduce carbon dioxide emissions.

The code covers nine categories of sustainable design: Energy and CO2 emissions, water usage, materials, waste, health, ecology, pollution, and surface run-off. It is awarded a certificate, ranging from one to six star rating systems to communicate the overall sustainability performance on new homes against each of these nine categories. The Code is neither a set of regulation nor obligatory, and there is not any aim to make it mandatory (by 2016 or any other date). The only circumstances where the Code can be required are the following requirements to meet the CSH level 3 (DCLG, 2010):

- All new housing funded by the Homes and Communities Agency (HCA)
- All new housing promoted or supported by the Welsh Assembly Government or their sponsored bodies.
- All new self-contained social housing in Northern Ireland.

The weight factor for water use in CSH is 9% which can encourage the builders or designer to implement more water efficient appliances in the building to improve the CSH credit. GW reuse can earn a significant credits for building by reducing the potable water demand and achieving one of the criteria shown in Table 7.6.

Table 7.6 Water consumption criteria and relevant CSH level

Water consumption (litres/person/day)	Credits	Mandatory Levels
<120l/p/day	1	Levels 1 and 2
<110 l/p/day	2	
<105 l/p/day	3	Levels 3 and 4
<90 l/p/day	4	
<80 l/p/day	5	Level 5 and 6

When compared to other green building standards CSH does not provide as many incentives for GW reuse/recycling. For example, LEED (Leadership in Energy and Environment Design) Green Building Rating System was initially created by the US Green Building

Council in 1998. It is planned as a voluntary standard for developing sustainable buildings. Projects receive points for each "green" practice that they implement. On average, a LEED™ certified building uses 30% less water than a conventional building. Buildings can qualify for four levels of certification and GW reuse/recycling can earn a significant number of LEED points across several categories: Water Use Reduction: 20% Reduction (1 point), Water Efficient Landscaping, No Potable Water Use or No Irrigation (2 points), Innovative Wastewater Technologies (2 points), Water Use Reduction, 30% -40% reduction (2-4 points).

Research by Australia's biggest property website *www.realestate.com.au* has revealed more vendors are seeing green credentials as selling points, and buyers are responding with one in ten people prepared to pay up to 20 per cent more for a "green‟ home. As water supplies and sustainability move up the agenda, properties that are environment friendly are becoming more popular; water tanks rank as *the* feature most likely to add value to a property. In France, rainwater harvesting is the second highest feature regarded by the public as a positive feature of green building, after renewable energy and before renewable materials (although this does not translate in the property value: owners of private houses in France cannot reflect the investment cost into the sale value of the property). These are lessons that the UK market should not overtake on moving forward to a more sustainable future.

7.6 Conclusion

With reference to green building standards (CSH and LEED) and the results that accomplished within this chapter it can be conclude that shared GW recycling system in line with adopting more efficient micro components can significantly reduce potable water consumption and carbon emissions in buildings and consequently results in achieving higher green buildings credits. While, for individual GW recycling systems adopting water saving appliances reduces the potable water saving due to increasing deficit between GW supply and demand. Therefore the financial performance of system also diminishes which is a negative aspect for developers. This result can encourage the planners, builders and designers to consider shared GW recycling system in the developments by achieving higher financial benefits and higher sustainability credit.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

8.1 Introduction

Pressure on freshwater resources increases with increasing global changes such as urbanisation, population growth and climate change, besides existing un-sustainable aspects to usual urban water management. Efforts are underway to discover innovative methods of meeting water needs. GW is one demand management option that has the potential to decrease reliance on mains water supply by substituting freshwater for non-potable uses like WC flushing and gardening. Chapter Two was a broad literature review covering the general aspects of existing GW recycling systems.

Although the use of treated GW can reduce the volume required from the mains water supply, and its replacement for WC flushing and gardening are publicly accepted (Chapter 6, Section 6.4), the uptake of this system is currently very low (especially in the UK) because of the high cost of construction, operation and maintenance (Chapter 4) and the longer payback period than the system lifetime.

In addition, construction (requires raw materials), operation (requires electricity, and chemicals), and maintenance (requires raw materials, and chemicals) of GW recycling system contains embodied and operational energy which results in increased total CO_2 emission compared to the mains water only option (Chapter 5). Indeed the materials required for GW construction, operation and maintenance makes it difficult to see these systems as environmentally friendly and cost-effective, especially for individual systems. A superficial conclusion might therefore be that the natural and financial resources required for construction and operation of individual GW systems make it less sustainable when compared to the mains water supply.

The research presented the evaluation and comparison of financial performance and carbon costing of shared GW recycling system between residential and commercial building blocks with individual GW recycling in each residential and commercial block in urban mixed-use regeneration areas via financial assessment and carbon emissions.

8.2 Summary

8.2.1 Methods of modeling the financial and energy performance of GW recycling system

In Chapter Three the five step methodology for calculating the water mass-balance, financial and CO_2 emission of the GW recycling system were presented. Suitable data for modelling each of these were gathered. A newly constructed multi-storey residential building and office building (Figure 3.1), within the Eastside mixed-use urban regeneration area, Birmingham, UK (Porter and Hunt, 2005, Hunt et al., 2008) were adopted in order to develop a generalized model.

The initial step was to define the five scenarios analysed in this project which was listed below.

- Scenario 1: Baseline scenario (no GW)
- Scenario 2a: Individual GW system (MBR)
- Scenario 2b: Individual GW system (CW)
- Scenario 3a: Shared GW system (MBR)
- Scenario 3b: Shared GW system (CW)

The model simulates and compares these 5 scenarios (Section 3.6) to allow the user to judge the relative financial performance and CO_2 emission of a proposed GW recycling system compared to individual GW recycling system and mains water only system.

With regard to calculating the water mass-balance, water usage breakdown of total water demands by domestic and commercial end-uses in UK were identified. The calculations were based on a micro-component approach. As potable and non-potable demand in offices and domestic dwellings are highly dependent on the type of appliances (e.g. low flow shower heads, infrared taps, and dual flush toilets), flow rate (i.e. WC from 9 to 0 litres/flush) and changes to user behaviour. The associated impact of changes to these input parameters on supply demand requirements, financial performance and carbon costs were examined in Chapters 6 and 7.

In Chapter Four the water saving consistency and financial performance of a potential individual and shared GW recycling system for selected residential and office buildings were presented and compared together. A literature review on various financial assessments of GW recycling systems was conducted in order to establish the state of the art GW recycling system financial assessment modelling. It was found that most of the financial studies were limited in scope and detail and most of them missed considering the operation and maintenance cost or discount rate. Moreover, in the cost assessment examples stable values for water, wastewater and electricity charges were typically used for the whole lifespan of system. The most common method for assessing the financial performance of GW recycling system was by envisaging the cost of recycled water from the GW recycling system and then comparing it to the cost of supplying the same volume of water from the mains system.

A range of financial assessment techniques applicable to the water sector were identified, with a view to determining the most appropriate for the financial assessment of GW recycling system. Of these diverse approaches for financial assessment a Life Cycle Cost Analysis (LCCA) method as part of Whole Life Costing approach was judged to be the most appropriate for assessing the financial performance of GW recycling systems. The NPV were chosen to reporting the LCCA. The range of data required in order to perform a meaningful LCCA is acknowledged; as such a considerable number of supporting data were gathered and presented. However, it was noted that some information will be site-specific and requires collection on a case-by-case basis.

In the report by Leggett and colleagues in 2001 the factors that need to be taken into account as part of rigorous rainwater harvesting system financial assessment were pointed out. It is assumed that the same aspects need to be considered in financial assessment of GW recycling systems as both system were part of SUDS (sustainable urban drainage systems) and were used as demand management strategies. There is a similarity between these aspects presented by Leggett et al. (2001) and to the one presented in Woods-Ballard & Kellagher (2004) relating to the data required as part of a SUDS whole life costing analysis and this synergy was used as one of the reasons for selecting LCCA approach in this study.

The intention of this thesis is to explicitly consider only the physical (technical) and financial aspects of GW recycling system. It was acknowledged that externalities (usually intangible), such as environmental and social costs/benefits, exist but consideration of these aspects was outside the scope of this study. At the present time it would appear that little detailed research is available on the whole life cost aspects of GW recycling systems. This can be one of the contributions that this project adds to knowledge. In addition to this, within the author's knowledge there is no study in the literature that has been looking at the LCCA of construction wetlands for GW recycling. The concepts and information from Chapter Two and Three, with the new data which were presented and discussed in the Chapter Four were brought together in a new spreadsheet-based modelling tool. With regard to the financial performance it was found that shared GW recycling systems are more cost effective than individual GW recycling systems with 57% increase in the NPV with GW system with MBR treatment option (£213.11k in sharing system and £91.9k in individual block system) and 40% increase in the GW system with VFCW (£152.51k in sharing system and £92.99k in individual block system). In addition the combined inflow/outflow for the high-rise domestic and office buildings can be reduced by 17% when GW systems are adopted in isolation whereas this can be improved to 28% when GW is shared (this is irrespective of the treatment system chosen).

The effect of changes in some key parameters on financial assessment results were also examined in this chapter. These parameters were changes in water and wastewater charges, discount rates, electricity prices, service life, and building descriptions. The results for this section shows that results were mostly affected by the residential building description followed by changes in service life and water and wastewater charges were the parameters that mostly affect the results (Table 4.16).

In Chapter Five the information and concepts were brought together with the data presented in previous chapters for the creation of a CO_2 emissions assessing spreadsheet-modelling tool. An academic literature review on energy assessment and CO_2 emission of different water demand management strategies shows that to date very little energy evaluation of GW recycling systems has been carried out and the actual operating energy consumption, and even water savings of these systems, has been the subject of limited investigation. The energy assessment of the shared GW recycling system suggested in this study is completely unexplored. As such there is a requirement to explore in detail the related carbon emissions of this potential new supply source within this supply configuration. The embodied and operational energy for construction, operation and maintenance of all five considered scenarios were calculated and compared together in this chapter. The sensitivity analysis of changes in building descriptions was also assessed. When considering a 15 year operation period it is shown that shared CW treatment achieved the lowest carbon emissions, saving up to 11% (compared to conventional mains water) whereas a shared MBR increased carbon emissions by up to 27%. Most carbon savings for the shared GW system occur when the ratio (height or floor area) of office building to residential building is approximately 2:3. Below this value there is insufficient domestic GW supply to meet shared GW demands.

In addition to this study the financial and energy assessment for shared GW recycling system in mixed-use high-rise building with residential users at top and office users and bottom were conducted. The result shows a similar percentage in potable water saving (30%) in shared GW recycling systems as within separate buildings, while associated CO_2 emission were 10% lower in shared GW recycling systems.

8.2.2 Parametric study

Chapter Six investigates the possible changes in domestic and office water user behaviours and occupancy rate. According to the literature there were a variety of possible user behaviours on the use of micro-components in domestic and commercial users which vary around the globe and are affected by different aspects like culture, climate, quality of life and etc. Six various cases were assumed for water use behaviour in domestic buildings and office blocks.

Two sets of analysis were adopted: First the user behaviour in domestic dwelling was changed while other parameters and office user behaviour remained unchanged. In the second set of analysis office user behaviour changed and domestic user behaviour and other parameters were remained unchanged. Total NPV and CO_2 emission were compared.

Generally the results show that the changes in office water use behaviour and employee density does not have major impact on the NPV and CO_2 emission of individual and shared scenarios. Only in the assumed case with the most efficient water-use-behaviour (Typical UK-64%) does the NPV of shared GW recycling reduce. This is by 25% (£158.78k) when adopting an MBR system and 20% (£122.09k) when adopting a CW system. As a result of less demand for recycled GW in this scenario, reduced CO_2 emission occurred (i.e. a reduction of 9% and 4% in shared GWR system with MBR and CW, respectively). In addition it was found that reducing the employee density in offices reduces the NPV in all scenarios. This is as a direct result of a reduced GW demand within this building type.

The changes in domestic water use behaviour have significant impact on the financial performance and CO_2 emission of considered scenarios. Increasing the efficiency of water use of domestic users to the most efficient water use behaviour (Typical UK-64%) results in negative NPV (-£2.01k) in the individual GW recycling scenario with MBR treatment option. However, in shared GW recycling systems, whilst the NPV reduces due to this change in behaviour (i.e. a 77% reduction associated to the MBR and 69% reduction associated to the CW), they still offer a positive NPV which makes them more favourable than an individual system. Moreover a reduction in total CO_2 emission was also observed due to the reduction in total water demand related to an increase in water usage efficiency (i.e. a reduction of approximately 40% in case D_6).

Increasing the water consumption by 30% due to the changes in domestic user behaviour results in increases to the total CO_2 emission in all scenarios but did not increase the NPV more than what was achieved in the typical UK case. Therefore this case was recognized as the least sustainable case for GW recycling systems. In the case with 65% increase the NPV and total CO_2 emission both increased due to the fact that the demand for fresh water increases and more GW was produced and demands consequently increase the system savings and CO_2 emission.

It was found that increasing residential occupancy rate (higher population density), results in raising the total NPV value in all scenarios. Notably, the NPV calculations show CW do not have economy of scale and increase in occupancy in building results in bigger bed size for this system. The result showed that when the office occupancy rate becomes less than 13 m^2

per employee (1115 employees) the greywater supply from 432 residential is not sufficient for supply.

The effect of changes in technology adopted within domestic and office blocks presented in Chapter Seven revealed that moving towards more efficient micro-components reduces a NPV and total CO_2 emission in all scenarios for both changes in domestic and office blocks. Only in residential blocks, the individual scenarios become negative in NPV (£-8.77k) when the most efficient micro-components were considered in this building, but shared scenarios still remain financially beneficial. In all cases the improvement in technological efficiency reduced the value of NPV, this impact being more noticeable in domestic buildings than offices. Individual GW recycling systems (MBR) in office blocks resulted in lowest water saving potential (20% with no change to technological efficiency) and negative NPV for an MBR system when annual charge < 5.5%, discount rates > 7%, service life < 13 yrs.

These results highlight the importance of considering likely changes in future user behaviour or technology adoption in buildings, which the existing research does not do. It is found that individual GW recycling systems were not cost effective in combination with demand management options that were likely be adopted in new build buildings due to new regulations and policies, whereas shared GW recycling systems still remain highly cost effective and the total CO_2 emission were also reduced in this option as a result of less water consumption. It also raises the point that even for systems where the users have more efficient behaviour and high efficiency technologies were adopted (probably by force of policies) the shared GW recycling system still remains financially viable while the individual GW recycling system does not.

8.5 Contribution to knowledge

The primary contributions of this thesis to the existing knowledge are summarised below:

- A new configuration of GW recycling system in urban mixed used areas between high-rise residential and office buildings (shared GW recycling system) was proposed. The result shows the surplus domestic GW from one resident can approximately meet the GW demands of four office employees.
- Critiqued existing approaches to the financial and energy assessment of GW recycling systems, identified weakness and knowledge gaps.
- Explained and justified how LCCA as part of whole life costing could be used as the basis for a more precise approach to the financial assessment of GW recycling systems. In conclusion the NPV achievable through the adoption of shared systems was greater than individual systems. Moreover the NPV of MBR water treatment was greater than NPV of VFCW water treatment.
- In terms of modelling the financial performance and total CO_2 of GW recycling systems at the development scales for high-rise buildings, a more comprehensive and more inclusive model than existing approaches was developed. To support financial and energy assessment, a range of costing and energy data was gathered, and presented.
- The rigorous considerations of the cost issues and total CO_2 emission of CW for GW recycling was studied. When considering a 15 year operation period it is shown that shared CW treatment achieved the lowest carbon emissions, saving up to 11% (compared to conventional mains) whereas a shared MBR increased carbon emissions by up to 27%. Most carbon savings for the shared GW system occur when the ratio

(height or floor area) of office building to residential building is approximately 2:3. Below this value there is insufficient domestic GW supply to meet shared GW demands. The influence of cross-connection distance is less influential; carbon emissions increase by 0.01% for each 50 m.

- The financial and energy assessment for shared GW recycling system in mixed-use high-rise building with residential users at top and office users at bottom were conducted. The detailed financial and CO_2 emission of GW recycling system in this type of buildings were never studied before. Results show the similar percentage in water saving (30%) as in shared GW recycling system within separate buildings, while the increase in CO_2 emission reduced by 10% compared to shared GW recycling system in two separate buildings.
- Demand management measures (changes in micro-components) and various possible changes to user behaviors based on global examples were considered in combination with GW recycling system and the affect on the financial and energy performance of system was analyzed.

GW recycling is not yet widely accepted in practice, partly because of the low economic benefit, particularly in commercial buildings such as offices. The findings from this research show that a shared GW recycling system can carry lower economic costs in both high and low efficiency buildings compared with GW recycling in individual building block. It also shows that the choice of GW system can influence greatly the energy (and related carbon emissions) savings highlighting the delicate balance that exists between each. The worst choice an urban planner could make is to seek the adoption of GW systems (individual or multi-use) that unwittingly cause a rebound effect on carbon emissions. However a shared

GW (CW treatment) system does appear to hold significant potential to reduce carbon emissions, although these are significantly behind the 80% required at UK levels for 2050.

The same methodology can be extended within the UK to buildings with different uses, including hotels, educational facilities, commercial premises, and malls. In addition it is applicable to country-specific patterns of water use. As the cost of water rises and increasing pressure is placed upon ageing and deteriorating water and wastewater infrastructure solutions that reduce water demand, greywater will become more viable financially. Given that the utility service infrastructure created to support buildings typically has a design life of 20-40 years, adoption of systems that might be marginally more expensive now but deliver considerable benefits in the future should be seriously considered: possibly proving an immediate ‘selling point’ for the development, and a future means to avoid retrofitting costs.

As mixed-use development is in vogue within UK property market (British Council for Offices, 2005) the findings within this study will help the developers and urban planners to more easily consider the adoption of shared GW recycling within the developments in order to increase the sustainability of urban water use with less cost and energy consumption.

8.6 Further work

A number of potential possibilities for further research were recognized during the course of this project:

- Little quantitative work has been conducted among communities who are currently using GW recycling systems for both non-potable and potable use. The work can be done in order to identify people's willingness to pay, and why residents chose to buy houses that have GW recycling systems.
- Research should look into effectiveness of government rebates in facility adoption of GW recycling systems as well as ease of public access to these forms of financial support.
- It is important to find out who is the responsible for this type of GW recycling system? Who is responsible for the maintenance charges?; and whether the people are happy to use the GW from their neighbours.
- Research should establish which stakeholder type (architects, planners, councillors, developers and investors) are more likely to attempt to introduce GW recycling into development projects, which are more successful in meeting their agendas, and what is stopping them from considering and applying GW recycling system in these projects. Some recently completed and some under development projects need to be chosen as case studies. The empirical evidence from the sample cases however makes an important contribution to knowledge by explaining the role of different stakeholders in applying or rejecting GW recycling. This information can be gained by local planning authority, documentation and interview with stakeholders as an open question via focus group.

- Future research should now look to investigate the influence of inter-building GW shared when considering users from within other building types and perhaps investigate its impact at a larger city scale.
- Methane is one of the GHG emissions relevant to urban level policies and is emitted from solid waste decomposition, waste water treatment, food production, land use change, and energy conversion. It would be very useful to know what the GW recycling impact on wastewater treatment emission is. Does it help to reduce this emission by reducing the volume of GW in to sewer systems or increase the emission by increasing the pollution concentration in wastewater?

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APPENDICES

Appendix 1: Additional information relating to Chapter 3 and Chapter 4

1A Water usage breakdown in different type of urban users

As mentioned in Section 2.1 GW includes wastewater from showers, baths, washing machines and hand basins. According to this definition, the main GW producers in urban areas are domestic accommodation and non-domestic accommodations such as hotels, guest houses, student halls and residences.

Figure A1.1 shows the water usage breakdown in non-domestic accommodations in the UK. This chart indicates that about 53% of total water consumption per person (in domestic buildings), 42% of total water consumption per bedspace (in hotel buildings), and 61% of total water consumption per pupil (in student accommodations) can be used as GW sources. In order to estimate the amount of available GW from each one of the above, the primary step is to evaluate the average water consumption (or wastewater production) per person for each of the domestic and non-domestic accommodations. By multiplying the average water consumption per person by the number of people in each building (population), the total water consumption can be approximated. If the selected case study for the research does not have any digital address point or census data, the population of domestic buildings can be applied manually by counting the number of apartments within each building in the area, and multiplying by an occupancy factor (using a representative occupancy factor –2.4 for the

UK– if no more specific occupancy information is available) in order to estimate the population.

For domestic and non-domestic accommodation buildings, the volume of GW water available is much higher than the treated GW demand for toilet flushing (31% GW demand in residential, 10% in hotels, and 33% in student halls). In this case the amount of potable water that might be saved through GW reuse will be relatively small, thus supporting the conclusion that it is likely not to prove beneficial in terms of overall 'sustainability performance' to use materials and other resources to construct and operate a GW system in individual accommodation buildings (Mercoiret,2008).

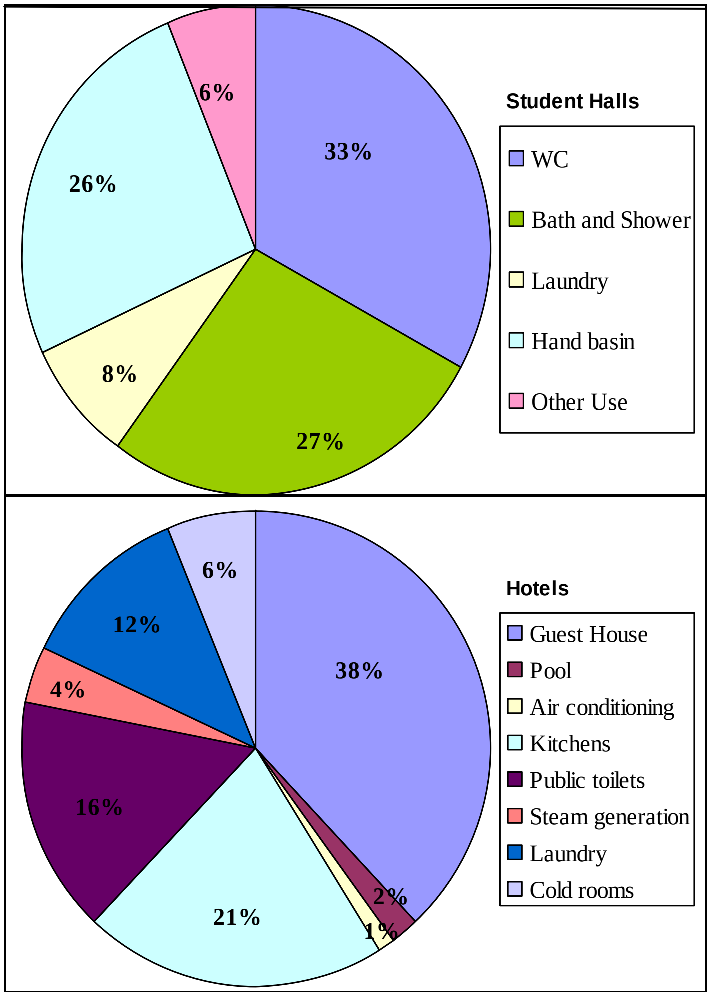

Figure A1.1: Water usage breakdown in hotels (Waggett and Arotsky, 2006), and student halls (Suresh, 2000)

Previous sections stated that the most frequent application for GW reuse is toilet flushing which can reduce potable water demand within water users. The main GW users in urban areas are commercial users (offices, retailers, restaurants, educational, sports, healthcare, etc.) due to their high demand for toilet flushing, relative to their overall water use.

Figure A1.2 presents the average distribution of water consumption in UK commercial buildings. This show 63% (5 litres/employee/day) of office, retail and educational water usage is for toilet flushing, 35% of restaurant water usage is for toilet flushing and 36% of sports water usage is for toilet flushing which can be replaced by treated GW. On the other hand, the volume of GW produced in typical commercial buildings is estimated to be much less than the demand: 27% (or 2.1 litres/employee/day) of office, retail and educational water usage, 5% of restaurant water usage, and 30% of sports water usage from hand washing throughout the day. Based on the water balance for UK commercial buildings, therefore, one may conclude that the limited uptake of GW systems in commercial sections is due to this mismatch in GW supply (that generated) and GW demand (uses suitable for GW).

In order to estimate the volume of GW demand from each one of the above users the initial step, as in the previous section, is to calculate the average water consumption (or wastewater production) per person for each of the commercial users based on information from UK research information centres. In many cases discharge consents are either not applicable or data are not available; however non-consented trade / commercial flows can be significant (for example in town / city centre areas, where a large concentration of small offices or retail premises exists: universities, schools, large hospitals, areas of licensed premises and other concentrations of people).

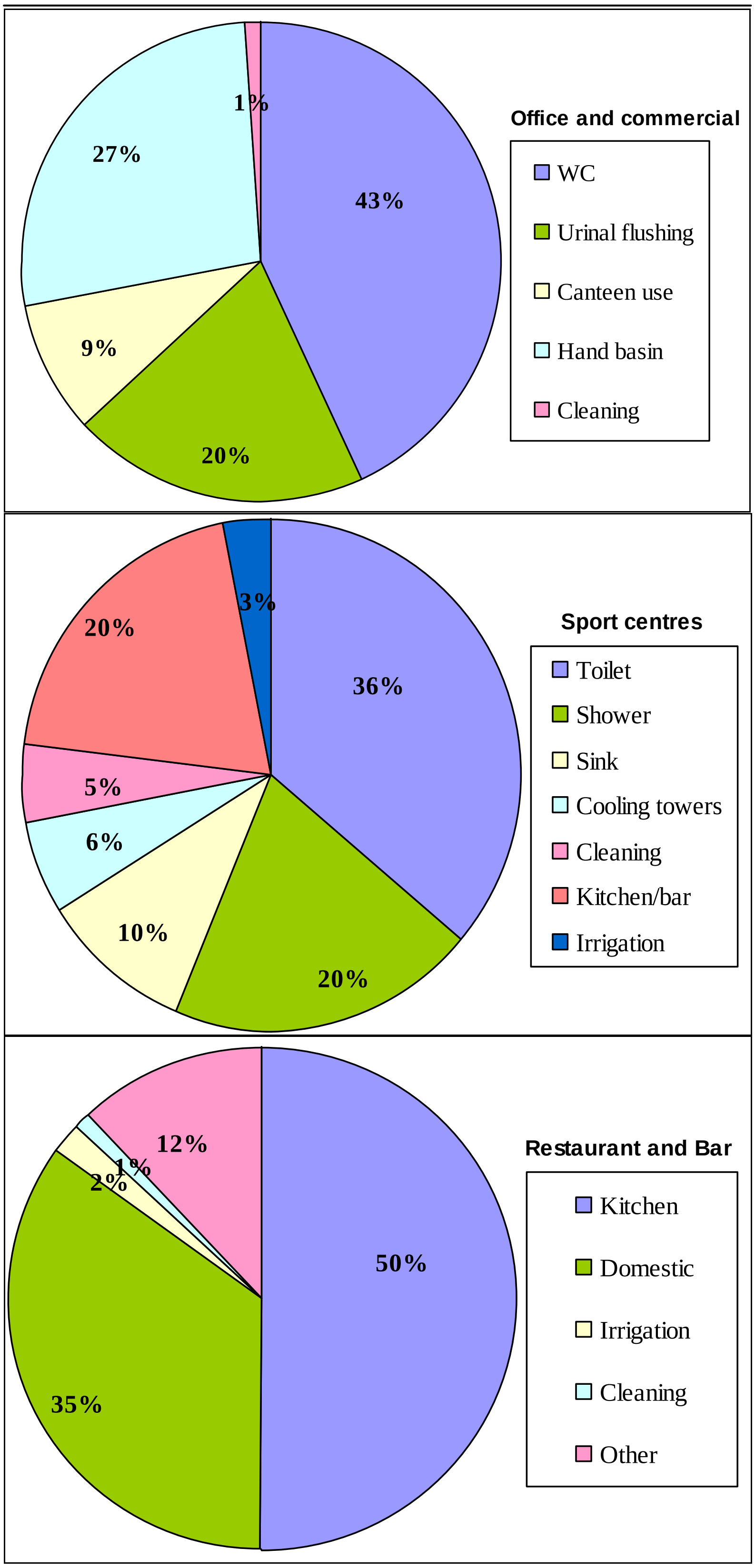

Figure A1.2: Water usage breakdown in office and commercial buildings (Environment Agency, 2001), restaurants (SWMF, 1997), and sports centres (Suresh, 2000)

1B Purchase and delivery costs for individual system components

Table A1.1 Unit cost of GW recycling system components (average UK retail price)

Pipe (Price per meter (£/m))	Pipe size (inch)
1.16	½
1.64	¾
2.49	1
3.31	1 ¼
4.04	1 ½
5.78	2
8.32	2 ½
11.43	3
18.82	4
40.30	6

Tank	Cost (exc. VAT)
Over ground storage tank (lit)	
1500	£232
2500	£465
3000	£610
5500	£990
7000	£1200
10000	£1640
14500	£2360
24500	£3050
30000	£3670
37000	£4500
45000	£5800

Filter area drained(m^2)	Cost (exc. VAT)
150	£127
350	£195
450	£250
700	£515
1,550	£1170
2,400	£2070
3,000	£2220
3,350	£2430
3,500	£2500

Other Items	(exc. VAT)
Electric display unit	£200
solenoid vale	£65
Backflow prevention valve	£150
Float valve	£10-15

Pump (lit/min)	Cost (exc. VAT)
42 (35 m)	£261.45
75 (30 m)	£304
95 (48 m)	£369.33
133 (40 m)	£430

1C Financial support for the GW recycling system

In the economic analysis it should take into account who pays for the system, and who accumulates, the benefits. Other than a reduction in demands for mains water and a reduction in volume of foul water for pumping and treatment, GW water might have other benefits like reduced requirements for additional reservoir in drought conditions and associated impacts on mains water infrastructure. This includes reduced sludge volumes for treatment and disposal, and a change in pollutant charge of foul water for treatment. Some benefits, such as reduced wastewater production from GW systems or savings in water resource development, are not experienced directly. As there is a limited number of research on the probability of pollutant discharges of foul water for treatment the reduction in volume of sludge is rarely recognised or calculated in analyses. Table A1.5 describes the relevant methods of financial support for the capital costs of GW recycling system with the key conditions applicable.

Table A1.5 Methods of financing the capital costs of water reclamation projects (AQUAREC, 2006; Asano et al., 2007).

Type	Expected Benefits	Conditions	Applicable Scale
Subsidies	Allows for the enclosure of non-monitory benefits	Needs to provide best value for money (e.g. Cheaper than regulation)	Individual and Communal
Owner finance	Reduces financial risks	Developers will need to be convinced they will be able to recover their capital costs	Individual
Reclaimed water delivery charges	Increased security of supply for reclaimed water users	Sufficient customers willingness to pay	Communal
Infrastructure Charge	Less potable water supply is needed	Agreement from OFWAT for increase or water company has to meet costs of conventional infrastructure	Communal
Loans	Cost can be spread over time	Stable cash flows	Individual and Communal
Internal funding	“Financing streamlined and easier to administer. Strong incentive for reliable service and system maintenance”	Willingness to pay, Ability to pay, Limited risk	Communal

1D Factors affecting future water and sewerage charges in UK

Historically, water has been priced only to recover the costs of treating and transporting it. The water itself has been free (As remains the case in Southern Ireland) and has sometimes been treated as if it were free (US-Iranian water reuse and management, 2002).

As stated in the yearly reports by Ofwat, the main components of customer's water and sewage bills are: capital charges for improvement and maintaining the system, operating costs and operating profits for lenders and investors. Figure A1.3 shows the amount of these components on the average household bill for 19 years.

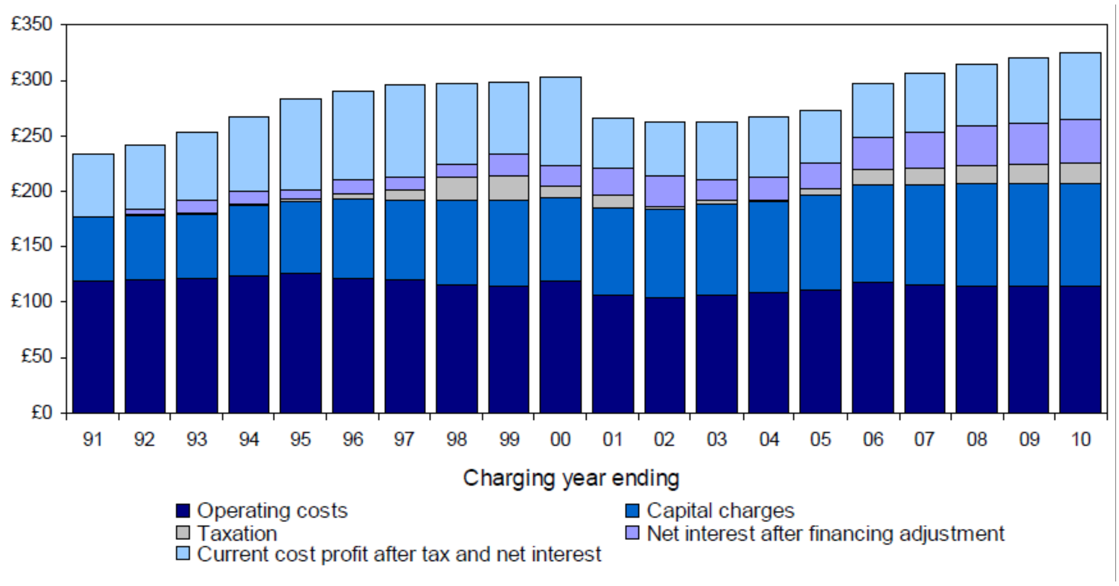

Figure A1.3 Components of the average household bill 1991-2010 (Ofwat, 2008)

Each year water and wastewater companies impose an average increase in charges to Ofwat and based on that Ofwat adjusts water and sewerage charges by setting a limit for the water (and sewerage) companies in England and Wales. This price limit set by Ofwat allows each company to increase or decrease its average charges above (or below) price rises each year to finance its services and meet its legal requirements.

Table A1.6 Assumed future water and sewerage charges

Annual changes (%)		**predicted charges scenarios**																				
		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
Regression analysis	water £/m^3	1.52	1.62	1.76	1.88	2.00	2.12	2.25	2.37	2.49	2.61	2.73	2.85	2.97	3.09	3.21	3.33	3.46	3.58	3.70	3.82	3.94
	Sewage £/m^3	1.08	1.14	1.21	1.33	1.41	1.50	1.58	1.66	1.74	1.82	1.90	1.98	2.06	2.14	2.22	2.30	2.38	2.46	2.54	2.62	2.70
0	water £/m^3	1.52	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
	Sewage £/m^3	1.08	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14
1	water £/m^3	1.52	1.62	1.64	1.66	1.67	1.69	1.71	1.72	1.74	1.76	1.78	1.79	1.81	1.83	1.85	1.87	1.88	1.90	1.92	1.94	1.96
	Sewage £/m^3	1.08	1.14	1.15	1.16	1.17	1.18	1.20	1.21	1.22	1.23	1.24	1.26	1.27	1.28	1.29	1.31	1.32	1.33	1.35	1.36	1.37
2	water £/m^3	1.52	1.62	1.66	1.69	1.72	1.76	1.79	1.83	1.86	1.90	1.94	1.98	2.02	2.06	2.10	2.14	2.18	2.23	2.27	2.32	2.36
	Sewage £/m^3	1.08	1.14	1.16	1.18	1.21	1.23	1.26	1.28	1.31	1.33	1.36	1.39	1.41	1.44	1.47	1.50	1.53	1.56	1.59	1.62	1.66
3	water £/m^3	1.52	1.62	1.66	1.71	1.75	1.79	1.84	1.88	1.93	1.98	2.03	2.08	2.13	2.18	2.24	2.29	2.35	2.41	2.47	2.53	2.60
	Sewage £/m^3	1.08	1.14	1.17	1.20	1.22	1.26	1.29	1.32	1.35	1.39	1.42	1.46	1.49	1.53	1.57	1.61	1.65	1.69	1.73	1.77	1.82
4	water £/m^3	1.52	1.62	1.69	1.76	1.83	1.90	1.98	2.05	2.14	2.22	2.31	2.40	2.50	2.60	2.70	2.81	2.92	3.04	3.16	3.29	3.42
	Sewage £/m^3	1.08	1.14	1.18	1.23	1.28	1.33	1.38	1.44	1.50	1.56	1.62	1.68	1.75	1.82	1.89	1.97	2.05	2.13	2.22	2.30	2.40
5	water £/m^3	1.52	1.62	1.70	1.79	1.88	1.97	2.07	2.18	2.28	2.40	2.52	2.64	2.78	2.92	3.06	3.21	3.37	3.54	3.72	3.91	4.10
	Sewage £/m^3	1.08	1.14	1.19	1.25	1.32	1.38	1.45	1.52	1.60	1.68	1.76	1.85	1.95	2.04	2.14	2.25	2.36	2.48	2.61	2.74	2.87

6	water £/m^3	1.52	1.62	1.72	1.82	1.93	2.05	2.17	2.30	2.44	2.59	2.74	2.91	3.08	3.27	3.46	3.67	3.89	4.12	4.37	4.63	4.91
	Sewage £/m^3	1.08	1.14	1.21	1.28	1.35	1.44	1.52	1.61	1.71	1.81	1.92	2.04	2.16	2.29	2.43	2.57	2.73	2.89	3.06	3.25	3.44
7	water £/m^3	1.52	1.62	1.74	1.86	1.99	2.13	2.28	2.44	2.61	2.79	2.98	3.19	3.42	3.66	3.91	4.19	4.48	4.79	5.13	5.49	5.87
	Sewage £/m^3	1.08	1.14	1.22	1.30	1.39	1.49	1.60	1.71	1.83	1.95	2.09	2.24	2.39	2.56	2.74	2.93	3.14	3.36	3.59	3.84	4.11
8	water £/m^3	1.52	1.62	1.75	1.89	2.04	2.21	2.39	2.58	2.78	3.00	3.25	3.50	3.79	4.09	4.41	4.77	5.15	5.56	6.01	6.49	7.01
	Sewage £/m^3	1.08	1.14	1.23	1.33	1.43	1.55	1.67	1.80	1.95	2.11	2.27	2.46	2.65	2.86	3.09	3.34	3.61	3.90	4.21	4.55	4.91
9	water £/m^3	1.52	1.62	1.77	1.93	2.10	2.29	2.50	2.72	2.97	3.23	3.53	3.84	4.19	4.57	4.98	5.42	5.91	6.45	7.03	7.66	8.35
	Sewage £/m^3	1.08	1.14	1.24	1.35	1.47	1.61	1.75	1.91	2.08	2.27	2.47	2.69	2.94	3.20	3.49	3.80	4.14	4.52	4.92	5.37	5.85
10	water £/m^3	1.52	1.62	1.78	1.95	2.13	2.33	2.56	2.80	3.06	3.36	3.67	4.02	4.41	4.82	5.28	5.78	6.33	6.93	7.59	8.32	9.11
	Sewage £/m^3	1.08	1.14	1.25	1.36	1.49	1.64	1.79	1.96	2.15	2.35	2.57	2.82	3.09	3.38	3.70	4.05	4.44	4.86	5.32	5.83	6.38

1E GW recycling system components life expectancy

There are some factors that affects the service life:

a. Type of collection and distribution network
b. Material of pipes, joints and network affiliations
c. Population growth rate
d. Quality of maintenance
e. Natural disasters
f. Treatment technology

Table A1.7 Life expectancy of GW recycling system components

System components	Life expectancy	Comments	Reference
Underground Storage tank	20-50+	Not been affected by weather or UV light were applied underground	Leggett et al., 2003; Fane et al., 2003; Building Magazine, 2006;Coombes & Kuczera, 2003
Over ground storage tank	15-30	Due to weathering and UV radiations	Building Magazine, 2006, Legget et al., 2001
Pump	5-10	Replacement is depends on the running hours. Pump bearings are the main component that fails and requires the pump to be replaced.	Legget et al., 2001; Building Magazine, 2006; Coomebes & Kuczera; Roebuck ,2007; Kirk and Dell'Isola, 1995
Filter	5-15+	It is depends on maintenance routines	Legget et al., 2001 Kirk and Dell'Isola, 1995; Roebuck ,2007
Membrane	10		Mercoiret, 2008; Lutz Johnen of Aquality, p.c. January 2012
Electronic control	10- 20		Legget et al., 2001; Building Magazine, 2006; Roebuck ,2007
Pipework	20- 50+	For plastic and stainless steel pipes	Legget et al., 2001; DEFRA,2006; Building Magazine, 2006
Valves	5,10,15		Legget et al., 2001
CW bed	6	The whole bed material and plants needs to be removed	Author Personal communication

Table A1.8 Assumed future electricity charges

Annual Percentage change (%)	Scenario and unit cost of electricity (p/kWh)																				
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Regression analysis	0.13	0.14	0.15	0.15	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22	0.22	0.22	0.23
5	0.14	0.15	0.16	0.16	0.16	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.23	0.24	0.24
10	0.15	0.16	0.16	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.23	0.24	0.24	0.25	0.25
15	0.15	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.23	0.24	0.24	0.25	0.25	0.26	0.26
20	0.16	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.23	0.24	0.24	0.25	0.25	0.26	0.26	0.27	0.27
25	0.17	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.23	0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.29
30	0.17	0.19	0.19	0.20	0.20	0.21	0.22	0.22	0.23	0.23	0.24	0.24	0.25	0.26	0.26	0.27	0.27	0.28	0.29	0.29	0.30
35	0.18	0.19	0.20	0.21	0.21	0.22	0.22	0.23	0.24	0.24	0.25	0.25	0.26	0.27	0.27	0.28	0.28	0.29	0.30	0.30	0.31
40	0.19	0.20	0.21	0.21	0.22	0.23	0.23	0.24	0.24	0.25	0.26	0.26	0.27	0.28	0.28	0.29	0.30	0.30	0.31	0.31	0.32
45	0.19	0.21	0.22	0.22	0.23	0.23	0.24	0.25	0.25	0.26	0.27	0.27	0.28	0.28	0.29	0.30	0.31	0.31	0.32	0.33	0.33
50	0.20	0.22	0.22	0.23	0.24	0.24	0.25	0.26	0.26	0.27	0.28	0.28	0.29	0.29	0.30	0.31	0.32	0.32	0.33	0.34	0.34
55	0.21	0.22	0.23	0.24	0.24	0.25	0.26	0.26	0.27	0.28	0.28	0.29	0.30	0.30	0.31	0.32	0.33	0.33	0.34	0.35	0.35

Appendix 2: Additional information relating to Chapter 4

2A Additional methods of evaluating economic of projects

Payback period (PBP) and **Return on investment (ROI)** are two methods of economic analysis that do not consider all relevant values over the service life of project. Therefore they are not fully reliable with the life cycle cost of project. However, they are quick, simple and inexpensive form of measure.

The payback period formula is:

$$PBP = \frac{Initial - Investment - Costs}{Average - Yearly - Inciome}$$ (White et al., 1989)

Higher PBP for a project means it is requires more time to gain the initial expenses via the profit that gain through the years.

The return on investment formula is:

$$ROI = \frac{(GainFromInvestment - CostOfInvestment)}{CostOfInvestment}$$ (Bhatia., 2011)

The amount and timing of the investment income compares directly, with the amount and timing of costs of investment in this method. If an investment has a negative ROI, it should not be undertaken.

The additional four modes of analysis that follow are fully consistent with the LCC approach:

Present worth method (PW); what future money is worth today and what it will be worth in the future when it finally arrives is called its Future Value (FV).

$$PW = \sum_{t=0}^{n} A_t (1+i)^{-1}$$ (White et al., 1989)

Pw = present worth of the investment, n = planning horizon, t = time in years, A_t = net cash flow at the end of period t, i = discount rate

Profitability index or benefit/cost ratio method; the profitability index, or PI, method compares the present value of future cash inflows with the initial investment on a relative basis. Therefore, the PI is the ratio of the present value of cash flows (PV) to the initial investment of the project.

Net present Value (NPV): See chapter 3 for details

Internal rate of return (IRR): An internal rate of return is also a discounted cash flow (DCF) analysis normally used to estimate the interest of investments or projects. "The

IRR is defined as the interest rate that makes the net present value of all cash flow equal to zero" ((Bhatia., 2011).

$$0 = \sum_{t=0}^{n} A_t (1+i^*)^{n-t}$$ (White et al., 1989)

n= planning horizon, t=time in years, A_t= net cash flow at the end of period t, i^*=IRR

2B Sizing the pipes in water distribution system

The idea is to choose the pipe sizes so that the water flows fast enough to fill the bath or the sink in a sensible time without making too much noise. The loading rate was measure by using the recommendations by BS6700 (Table A2.1). Number of toilets was multiplied by chose loading rate from the table and converted to design flow rate by using the Figure A2.1.

Table A2.1 BS6700 Recommended loading rate for water appliances

Appliances	Loading unit
WC	2
1/2" washbasin tap	1.5
3/4" bath tap	10
Shower mixer	3
1/2" sink	3
washing machine	3
dishwasher	3

Based on the calculated design flow rate, the diameter of pipe can be estimated based on the BS 6700 recommendation of maximum of 2m/s for cold water to not likely to create flow noises.

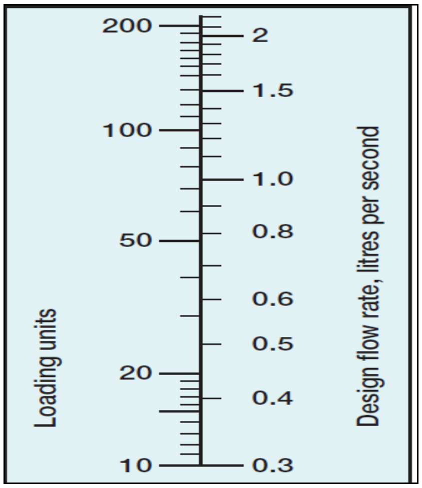

Figure A2.1 converting loading rate to design flow rate chart (lit/sec)

After finding probable flow rate per floor it is now required to use Hazen Williams pipe flow chart (Figure A2.2) to find the suitable pipe size based on the 2 m/s velocity and the first assumption of 3ft head loss per 100 ft of pipe.

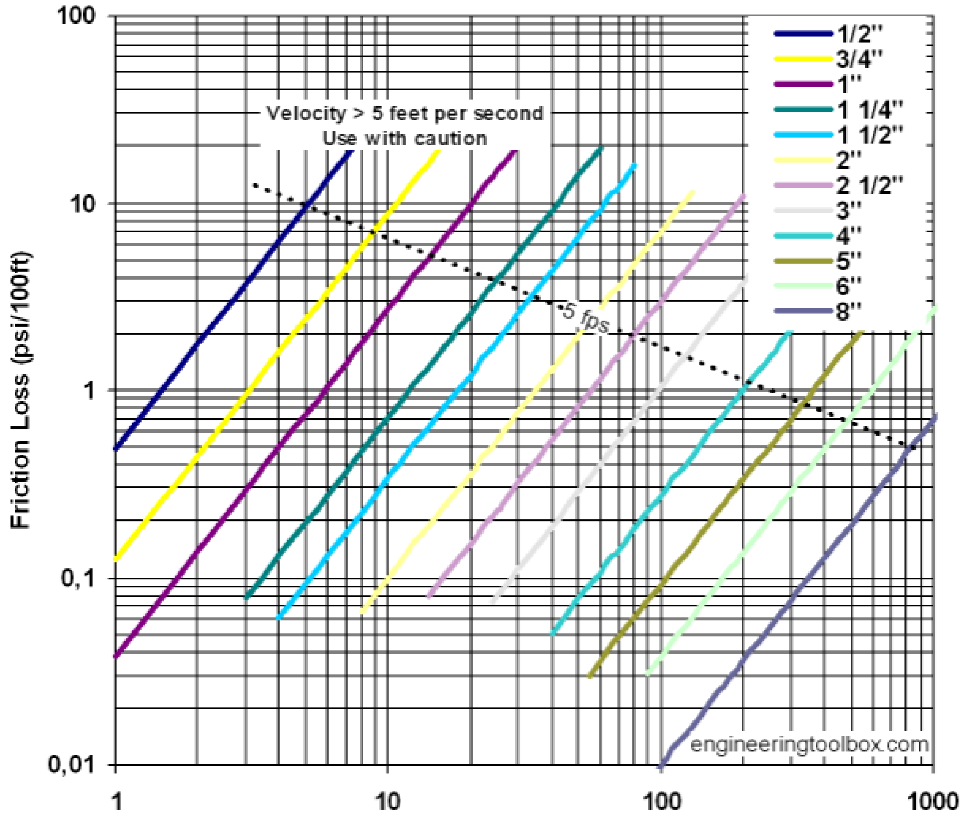

Figure A2.2 Hazen-Williams pipe flow chart (C=140) (Engineering toolbox, 2011)

The result for pipe sizing calculation for the considered buildings in this study based on the different floor area and building height as shown in Tables A2.2 to A2.5.

Table A2.2 Pipe size for distribution and collection network in residential block with assumed various floor area

Different floor area	Distribution (See Figure 1, Chapter 3)			Collection (See Figure 1, Chapter 3)		
flat per floor	Pipe f	Pipe d	To CW	Pipe f	Pipe d	To CW
3	½”	1 ¼”	1 ¼”	½”	1 ¼”	1 ¼”
7	½”	1 ¼”	1 ¼”	¾”	1 ½”	1 ¼”
12	¾”	1 ½”	1 ½”	¾”	2”	1 ½”
18	¾”	2”	2”	1”	2 ½”	2”
27	1”	2”	2”	1”	2 1/22	2”
36	1”	2 ½”	2 ½”	1 ¼”	3”	2 ½”
45	1 ¼”	2 ½”	2 ½”	1 ¼”	3”	2 ½”
54	1 ¼”	2 ½”	2 ½”	1 ¼”	3”	2 ½”

Table A2.3 Pipe size for distribution and collection network in residential block with assumed various building height

Different number of floors	Distribution (See Figure 1, Chapter 3)			Collection (See Figure 1, Chapter 3)		
	Pipe f	Pipe d	To CW	Pipe f	Pipe d	To CW
5	¾”	1 ¼”	1 ¼”	1 ¼”	1.61	1 ¼”
10	¾”	2”	2”	1 ¼”	2.469	2”
15	¾”	2 ½”	2 ½”	1 ¼”	2.469	2 ½”
20	¾”	2 ½”	2 ½”	1 ¼”	3”	2 ½”
25	¾”	3”	3”	1 ¼”	4”	3”
30	¾”	3”	3”	1 ¼”	4”	3”
35	¾”	4”	4”	1 ¼”	4”	4”
40	¾”	6”	6”	1 ¼”	6”	6”

Table A2.4 Pipe size for distribution and collection network in office block with assumed various floor area

Different floor area	Distribution (See Figure 1, Chapter 3)		
	Pipe c	Pipe a	Pipe A (cross connection)
1960	1/2"	3/4"	3/4"
4998	1/2"	3/4"	3/4"
7000	1/2"	1"	1"
9975	1/2"	1 1/4"	1 1/4"
13860	1/2"	1 1/4"	1 1/4"
15022	1/2"	1 1/4"	1 1/4"
20020	1/2"	1 1/4"	1 1/4"
24983	3/4"	1 1/2"	1 1/2"
29939	3/4"	1 1/2"	1 1/2"

A2.5 Pipes sizes for distribution and collection network in office block with assumed various building height

Different number of floors	Distribution		
	Pipe c	Pipe a	Pipe A (cross connection)
4	1/2"	1"	1"
7	1/2"	1 1/4"	1 1/4"
10	1/2"	1 1/4"	1 1/4"
15	1/2"	2"	2"
20	1/2"	2"	2"
25	1/2"	2 1/2"	2 1/2"
30	1/2"	2 1/2"	2 1/2"
35	1/2"	3"	3"
40	1/2"	3"	3"

A2.6 Pipe size for distribution and collection network in office block with assumed various number of employees per floor

Different number of employees per floor	Distribution		
sq meter/employee	Pipe B	Pipe C	Pipe A (cross connection)
5	3/4"	1 1/2"	1 1/2"
10	3/4"	1 1/4"	1 1/4"
15	1/2"	1 1/4"	1 1/4"
20	1/2"	1 1/4"	1 1/4"
25	1/2"	1"	1"
30	1/2"	1"	1"
35	1/2"	1"	1"
40	1/2"	1"	1"

Appendix 3: Additional information relating to Chapter 6

Table A3.1. Assumed frequency and duration of micro-component uses in domestic properties

Typical UK	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	6	-	4.8	28.8
Hand basin	8	0.33	3.5	9.2
Washing machine	80	-	0.21	16.8
Shower	12	8	0.6	57.6
Bath	116	-	0.16	18.6
Kitchen sink	8	0.33	3.5	9.2
Dishwasher	24.9	-	0.23	5.7
Other	-	-	-	2.0
		Total potable demand=		148.0
CSH level 1,2	**Lit/usage**	**Duration (min)**	**frequency of use**	**Total usage (lit/occupancy/day)**
WC	6	-	3.7	22.2
Hand basin	8	0.33	2.0	5.3
Washing machine	80	-	0.16	12.8
Shower	12	7	0.6	50.4
Bath	116	-	0.16	18.6
Kitchen sink	8	0.33	2	5.3
Dishwasher	24.9	-	0.23	5.7
Other	-	-	-	2.0
		Total potable demand=		122.2
CSH level 3,4	**Lit/usage**	**Duration (min)**	**frequency of use**	**Total usage (lit/occupancy/day)**
WC	6	-	2.8	16.8
Hand basin	8	0.33	2.0	5.3
Washing machine	80	-	0.16	12.8
Shower	12	5	0.6	36.0
Bath	116	-	0.16	18.6
Kitchen sink	8	0.33	2	5.3
Dishwasher	24.9	-	0.23	5.7
Other	-	-	-	2.0
			Total potable demand=	102.4

CSH level 5,6	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	6	-	2.2	13.2
Hand basin	8	0.33	2.0	5.3
Washing machine	80	-	0.05	4.0
Shower	12	3	0.6	21.6
Bath	116	-	0.11	12.8
Kitchen sink	8	0.33	2	5.3
Dishwasher	24.9	-	0.23	5.7
Other	-	-	-	2.0
			Total potable demand=	69.8
Typical UK+30%	**Lit/usage**	**Duration (min)**	**frequency of use**	**Total usage (lit/occupancy/day)**
WC	6	-	4.8	26.5
Hand basin	8	0.33	3	7.9
Washing machine	80	-	0.34	27.2
Shower	12	10	0.6	72.0
Bath	116	-	0.3	34.8
Kitchen sink	8	0.33	2	7.9
Dishwasher	24.9	-	0.4	10.0
Other	-	-	-	2.0
			Total potable demand=	188
Typical UK+65%	**Lit/usage**	**Duration (min)**	**frequency of use**	**Total usage (lit/occupancy/day)**
WC	6	-	6.3	37.8
Hand basin	8	0.33	3.0	7.9
Washing machine	80	-	0.81	64.8
Shower	12	13	0.6	93.6
Bath	116	-	0.16	18.6
Kitchen sink	8	0.33	3	7.9
Dishwasher	24.9	-	0.71	17.4
Other	-	-	-	2.0
			Total potable demand=	250

Table A3.2. Assumed frequency and duration of micro-component uses in office buildings

Female employee				
Typical UK	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	2.0	12.0
Hand basin	8.0	0.2	3.0	3.8
Kitchen tap	8.0	1.0	0.1	0.8
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.143	1.8
			Total=	19.4
Male employee				
Typical UK	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	1.0	6.0
Hand basin	8.0	0.2	2.0	2.6
Urinal	3.6	-	1.0	3.6
Kitchen tap	8.0	1.0	0.1	0.8
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.080	1.0
			Total=	15.0

Female employee				
Typical UK-20%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	2.0	12.0
Hand basin	8.0	0.1	1.0	0.8
Kitchen tap	8.0	0.1	1.0	0.8
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.143	1.8
			Total=	16.4
Male employee				
Typical UK-20%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	1.0	6.0
Hand basin	8.0	0.1	1.0	0.8
Urinal	3.6	-	1.0	3.6
Kitchen tap	8.0	0.1	1.0	0.8
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.080	1.0
			Total=	13.2

Female employee				
Typical UK-40%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	2.0	12.0
Hand basin	8.0	0.1	1.0	0.8
Kitchen tap	8.0	0.1	0.0	0.0
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.143	1.8
			Total=	15.6
Male employee				
Typical UK-40%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	1.0	6.0
Hand basin	8.0	0.1	1.0	0.0
Urinal	3.6	-	1.0	3.6
Kitchen tap	8.0	0.0	0.0	0.0
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.080	1.0
			Total=	12.4

Female employee	O3			
Typical UK-64%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	1.0	6.0
Hand basin	8.0	0.1	1.0	1.6
Kitchen tap	8.0	0.1	1.0	0.8
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.143	1.8
			Total=	10.4
Male employee				
Typical UK-64%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	0.0	0.0
Hand basin	8.0	0.1	1.0	0.6
Urinal	3.6	-	1.0	3.6
Kitchen tap	8.0	0.1	1.0	0.8
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.080	1.0
			Total=	7.1

Female employee				
Typical UK+30%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	3.0	18.0
Hand basin	8.0	0.2	3.0	3.8
Kitchen tap	8.0	0.2	1.0	1.6
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.143	1.8
			Total=	26.2
Male employee				
Typical UK+30%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	2.0	12.0
Hand basin	8.0	0.2	1.0	1.4
Urinal	3.6	-	1.0	3.6
Kitchen tap	8.0	0.2	1.0	1.6
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.080	1.0
			Total=	20.6

Female employee				
Typical UK+ 65%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	3.0	18.0
Hand basin	8.0	0.3	3.0	7.2
Kitchen tap	8.0	0.2	2.0	3.2
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.143	1.8
			Total=	31.2
Male employee				
Typical UK+ 65%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	2.0	12.0
Hand basin	8.0	0.3	2.0	4.8
Urinal	3.6	-	1.0	3.6
Kitchen tap	8.0	0.2	2.0	3.2
Cooking and drinking	1.0	-	-	1.0
Cleaning	12.6	-	0.080	1.0
			Total=	25.6

Table A3.3. Household occupancy rate ranges around the world

Countries	Average occupancy rate	References
China	3.95	Jiang and Zeng,1994
Ireland	3.1	UNEC,2001
Japan	2.8	UNEC,2001
Italy	2.7	UNEC,2001
United States, Canada	2.58	USA Census Bureau, 2010
Australia	2.4	Australian Bureau Statics, 2010
Finland, Austria, France	2.5	UNEC,2001
United Kingdom, Belgium	2.4	Fido *et al* (2005)
Netherland, Switzerland	2.3	UNEC,2001
Norway, Denmark, Germany	2.2	UNEC,2001
Sweden	2.1	UNEC,2001
Mexico	2.9	Geo-Mecixo, 2010
Brazil	3.8	Olivia, 2008
India	4.2	NSSO, 2005
South Africa	3.65	Aardt, 2007

Appendix 4: Additional information relating to Chapter 7

Table A4.1. Assumed technology adopted in domestic properties a long with considered design cases.

Base	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	6	-	4.8	28.8
Hand basin	8	0.33	3.5	9.2
Washing machine	80	-	0.21	16.8
Shower	12	8	0.6	57.6
Bath	116	-	0.16	18.6
Kitchen sink	8	0.33	3.5	9.2
Dishwasher	24.9	-	0.23	5.7
Other	-	-	-	2.0
			Total demand=	148.0

Base+30%	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	6	-	4.8	28.8
Hand basin	12	0.33	3.5	13.9
Washing machine	110	-	0.21	23.1
Shower	15	8	0.6	72.0
Bath	230	-	0.16	36.8
Kitchen sink	12	0.33	3.5	13.9
Dishwasher	25	-	0.23	5.8
Other	-	-	-	2.0
			Total demand=	196.2

CSH 1&2	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	4.5	-	4.8	21.6
Hand basin	6	0.33	3.5	6.9
Washing machine	49	-	0.21	10.3
Shower	10	8	0.6	48.0
Bath	116	-	0.16	18.6
Kitchen sink	6	0.33	3.5	6.9
Dishwasher	16	-	0.23	3.7
Other	-	-	-	2.0
			Total demand=	118.0

CSH 3&4	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	4.5	-	4.8	21.6
Hand basin	5	0.33	3.5	5.8
Washing machine	49	-	0.21	10.3
Shower	8	8	0.6	38.4
Bath	88	-	0.16	14.1
Kitchen sink	5	0.33	3.5	5.8
Dishwasher	14	-	0.23	3.2
Other	-	-	-	2.0
			Total demand=	101.1

CSH 5&6	Lit/usage	Duration (min)	frequency of use	Total usage (lit/occupancy/day)
WC	2.5	-	4.8	12.0
Hand basin	5	0.33	3.5	5.8
Washing machine	35	-	0.21	7.4
Shower	6	8	0.6	28.8
Bath	65	-	0.16	10.4
Kitchen sink	5	0.33	3.5	5.8
Dishwasher	14	-	0.23	3.2
Other	-	-	-	2.0
			Total demand=	75.3

Table A4.2. Assumed technology adopted in office buildings a long with considered design cases.

Female employee				
Base-20%	Lit/usage	duration (min)	frequency of use	Total usage (lit/employee/day)
WC	4.5	-	2.0	9.0
Hand basin	6.0	0.2	3.0	2.9
Kitchen tap	6.0	1.0	0.1	0.6
Cooking and drinking	1.0	-	-	1.0
Cleaning	9.5	-	0.143	1.4
			Total=	14.8
Male employee				
Base-20%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	4.5	-	1.0	4.5
Hand basin	6.0	0.2	2.0	1.9
Urinal	1.7	-	1.0	1.7
Kitchen tap	6.0	1.0	0.1	0.6
Cooking and drinking	1.0	-	-	1.0
Cleaning	9.5	-	0.080	0.8
			Total=	10.5

Female employee				
Base-40%	Lit/usage	duration (min)	frequency of use	Total usage (lit/employee/day)
WC	2.0	-	2.0	4.0
Hand basin	6.0	0.2	3.0	2.9
Kitchen tap	6.0	1.0	0.1	0.6
Cooking and drinking	1.0	-	-	1.0
Cleaning	4.5	-	0.143	0.6
			Total=	9.1
Male employee				
Base-40%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	2.0	-	1.0	2.0
Hand basin	6.0	0.2	2.0	1.9
Urinal	1.7	-	1.0	1.7
Kitchen tap	6.0	1.0	0.1	0.6
Cooking and drinking	1.0	-	-	1.0
Cleaning	4.5	-	0.080	0.4
			Total=	7.6

Female employee				
Base-64%	Lit/usage	duration (min)	frequency of use	Total usage (lit/employee/day)
WC	2.0	-	2.0	4.0
Hand basin	4.0	0.2	3.0	1.9
Kitchen tap	4.0	1.0	0.1	0.4
Cooking and drinking	1.0	-	-	1.0
Cleaning	4.3	-	0.143	0.6
			Total=	7.9
Male employee				
Base-64%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	2.0	-	1.0	2.0
Hand basin	4.0	0.2	2.0	1.3
Urinal	0.7	-	1.0	0.7
Kitchen tap	4.0	1.0	0.1	0.4
Cooking and drinking	1.0	-	-	1.0
Cleaning	4.3	-	0.080	0.3
			Total=	5.7

Female employee				
Base+30%	Lit/usage	duration (min)	frequency of use	Total usage (lit/employee/day)
WC	6.0	-	2.0	12.0
Hand basin	12.0	0.2	3.0	5.8
Kitchen tap	12.0	1.0	0.1	1.2
Cooking and drinking	1.0	-	-	1.0
Cleaning	13.0	-	0.143	1.9
			Total=	21.8
Male employee				
Base+30%	**Lit/usage**	**duration (min)**	**frequency of use**	**Total usage (lit/employee/day)**
WC	6.0	-	1.0	6.0
Hand basin	12.0	0.2	2.0	3.8
Urinal	3.6	-	1.0	3.6
Kitchen tap	12.0	1.0	0.1	1.2
Cooking and drinking	1.0	-	-	1.0
Cleaning	13.0	-	0.080	1.0
			Total=	16.7

List of Publications

1. Zadeh, S.M., Hunt, D.V.L., Lombardi, D. R., and Rogers C.D.F. (2013). Carbon costing for mixed-use greywater recycling systems. *Proc. Institute of Civil Engineers*: *Water Management*, **166** (X), 1-15 (*in print*). http://dx.doi.org/10.1680/wama.12.00093

CARBON COSTING FOR MIXED-USE GREYWATER RECYCLING SYSTEMS

Abstract

Urbanisation in the 21st Century is accompanied by higher water demands per unit area of available space. The ability of water providers to meet these demands long term will require sustainable innovations in terms of water supply. Previous research by the authors of this paper has shown that urban mixed-use systems that share greywater (GW) between high-rise domestic dwellings (where GW production > nonpotable demands) and high-rise offices (where non-potable demands > GW production) could overcome these difficulties. This paper explores the carbon costs (embodied and operational) of such an urban arrangement by investigating the influence of: Membrane Bioreactors (MBW), Constructed Wetlands (CW); building heights, floor plate areas and cross-connection distances. Five water supply scenarios are considered: Scenario 1 (Conventional mains treated off-site); Scenario 2a and 2b (Individual GW treatment via CW / MBR); Scenario 3a and 3b (shared GW treatment via CW / MBR). Over a 15 year period it is shown that shared CW treatment had the lowest carbon emissions, saving up to 11% compared to conventional mains, whereas a shared MBR increased carbon emissions by up to 27% - most carbon savings occur when the ratio (height or floor area) of office building to residential building is 2:3.

Keywords: Carbon dioxide emissions, Greywater recycling, Energy requirement, Urban development, Water management

2. Zadeh, Sara M.; Hunt, Dexter V.; Lombardi, D. R.; Rogers, Christopher D. 2013. "Shared Urban Greywater Recycling Systems: Water Resource Savings and Economic Investment." *Sustainability* 5, no. 7: 2887-2912. http://www.mdpi.com/2071-1050/5/7/2887

Shared Urban Greywater Recycling Systems: Water Resource savings and Economic Investment

Abstract

The water industry is becoming increasingly aware of the risks associated with urban supplies not meeting demands by 2050. Greywater (GW) recycling for non-potable uses (e.g. urinal and toilet flushing) provides an urban water management strategy to help alleviate this risk by reducing mains water demands. This paper proposes an innovative cross connected system that collects GW from residential buildings and recycles it for toilet/urinal flushing in both residential and office buildings. The capital cost (CAPEX), operational cost (OPEX) and water saving potential are calculated for individual and shared residential and office buildings in an urban mixed-use regeneration area in the UK assuming two different treatment processes; a membrane bioreactor (MBR) and a vertical flow constructed wetland (VFCW). The Net Present Value (NPV) method was used to compare the financial performance of each considered scenario from where it was found that a shared GW recycling system (VFCW) was the most economically viable option. The sensitivity of this financial model was assessed considering four parameters (i.e. water supply and sewerage charges, discount rate(s), service life and improved technological efficiency, e.g. low flush toilets, low shower heads, etc), from where it was found that shared GW systems performed best in the long-term.

Keywords: Urban mixed-use development, Greywater recycling, Vertical Flow Constructed wetland, Membrane Bioreactor, Water saving devices.

3. Zadeh, S.; Lombardi, D.; Hunt, D.; Rogers, C. Greywater Recycling Systems in Urban Mixed-Use Regeneration Areas: Economic Analysis and Water Saving Potential. In Proceedings of the 2nd World Sustain. Forum, 1-30 November 2012; Sciforum Electronic Conferences Series, 2012. (http://www.sciforum.net/presentation/1021)

Greywater Recycling Systems in Urban Mixed-Use Regeneration Areas: Economic Analysis and Water Saving Potential

Abstract

Greywater (GW) recycling for non-potable uses such as toilet flushing is a management strategy to meet urban water demand with substantial water saving. This paper proposes a system that collects GW from residential buildings and recycles it for toilet flushing in both residential and office buildings. The total cost and water saving of standard sanitation technology were compared with 5 other options requiring less or no potable water use in toilets. Scenarios compare: no GW, individual GW, and shared GW systems with and without low-flush appliances. Typical residential and office buildings in urban mixed-use regeneration areas in the UK were used for these analyses. The results implied that constructed wetland treatment technology with standard appliances is more economically and environmentally viable than other scenarios. By increasing the water and wastewater price, shared GW systems with and without low-flush appliances were viable options within highly water efficient domestic and office buildings.

Keywords: Urban development, Greywater recycling

4. Zadeh SM, Lombardi DR, Hunt DVL and Rogers CDF (2010) Local area greywater symbiosis approach to a more sustainable urban water management. The Sustainable World, Ecology and the Environment 142: 11 (see also IWA World Water Congress, Montreal, 19–23 September 2010).

Local area greywater symbiosis approach to more sustainable urban water management

Abstract

Stress on water resources in some areas is reaching critical levels due to population growth, rapid urbanization, economic development, climate change, and an ageing infrastructure. Greywater reuse has been explored as a more sustainable water resource management option to displace demand for fresh water, largely for residential use on a household or building level. However, the infrastructure needed and the disinfectant required for greywater systems make it difficult to see these systems as environmentally friendly and cost-effective, especially for individual households. The research reported herein tests the hypothesis that greywater reuse shared amongst users in neighbouring residential, office and commercial buildings may improve the feasibility of, and hence make more sustainable, grey water recycling as part of urban water management. The local area symbiosis scheme is designed in 3 stages: first, calculating a balance between greywater supply and demand in the area based on class of use (residential, office, or other); second, estimate shared (local recycling) potentials based on the quantities available and requirements for use; and finally, estimating the sustainability of the proposed system by considering the technologies and infrastructure required for implementation.

Keywords: Greywater recycling; urban regeneration; reuse; sustainable urban water management; urban recycling.

5. Zadeh SM, Lombardi DR, Hunt DVL and Rogers CDF (2012) Reducing the Sustainability Trade-off in the Performance of Greywater Recycling Systems. Sustainable Water Management Conference (see also AWWA 2012 Sustainable Water Management Conference). http://acumen-va-online.com/awwaSWM2012/contents.php?s=MON07

Reducing the Sustainability Trade-off in the Performance of Greywater Recycling Systems

Abstract

Population growth, rapid urbanization and climate change are placing considerable pressure on existing freshwater supplies in many regions worldwide. One of the approaches to considerably reducing this problem is to recycle greywater, GW, (i.e. wastewater from baths and showers) for non-potable uses (i.e. toilet flushing or gardening). Unfortunately, related high energy costs and long payback periods have been the main causes of the low uptake for GW recycling systems, particularly in the UK. Therefore there is a requirement to design systems which are economically and environmentally more sustainable. The paper presents an innovative communal design for improving the efficiency of GW recycling systems within a typical mixed-use building in the UK. In the proposed system GW from residential users on the top floors will be collected, treated and re-used for toilet flushing in offices on the lower floors of the same building. The collection and distribution of GW is gravity fed, requiring little / no pumping. This paper discusses the trade-offs between economic (Net present Value) and environmental criteria (CO2 emissions) over a 15-year life-span when using The Membrane Bioreactor (MBR) technology. The results of the analysis indicate that, for this case study, the proposed design is significantly more sustainable than adopting individual GW recycling systems for residential users and offices.

Keywords: Greywater recycling; urban regeneration; carbon emission; sustainable trade off.