Cranfield University

Nathalie Marie-Ange Bertrand

Impacts of scaling up water recycling and rainwater harvesting technologies on hydraulic and hydrological flows

Centre for Water Science

PhD

Cranfield University

School of Applied Sciences

PhD

2008

Nathalie Marie-Ange Bertrand

Impacts of scaling up water recycling and rainwater harvesting technologies on hydraulic and hydrological flows

Supervisor: Dr Paul Jeffrey

Academic Year 2005 to 2008

ABSTRACT

In recent years, the increasing awareness of scarcity of water resources, indications of likely climate variability, and the increasing pressure to use available fresh water resources more efficiently have together reinforced the need to look at infrastructure solutions with due regard to environmental considerations and social impacts, present and future. There is a vital need to apply an integrated approach to catchment management to implement sustainable solutions to resolve issues such as water supply and sewerage, drainage and river flooding. Many potentials solutions are available to control water demand and manage flood problems. Greywater recycling and rainwater harvesting are novel technologies. However, their catchment scale impacts on hydraulic and hydrological flows are poorly understood. The research aim is to identify the hydrologic and hydraulic impacts of scaling up such technologies at catchment scale. For this particular study, a computer simulation model will be used to evaluate how increasing urbanisation, climate change and the implementation of greywater recycling and rainwater harvesting may alter the water balance within a representative catchment. To achieve these aims data from the Carrickmines catchment in Ireland have been collected; a simulation model has been adapted to carry out the study, the model has been calibrated and validated, results have been analysed, and finally, a sensitivity analysis has been carried out. The results show that rainwater harvesting systems are comparatively more effective than greywater recycling techniques in reducing flood frequency and intensity. Under five year return period rainfall events, the implementation of rainwater harvesting at any scale and number of units is a useful technique to control river flow and floods. However, the study also shows that under extreme conditions the efficiency of rainwater harvesting systems decreases. The study concludes that implementing the two technologies within a single catchment is not a solution to several forms of hydrological problem. The study shows that implementing rainwater harvesting or re-use technologies are a very useful way to protect local freshwater reserves and therefore conserve our environment.

Keywords: Water network modelling, greywater recycling, rainwater harvesting systems, Water management, catchment scale.

ACKNOWLEDGEMENTS

First of all, I will like to thank my supervisor Dr P Jeffrey for his excellent supervision, help and advice throughout this project. I also thank him for offering me the chance to accomplish a PhD and for sharing his sloe berry “juice” recipe.

Dr Mélanie Muro who actively contributes to the correction of this thesis, I will always been very grateful to your precious help.

I am also very thankful to the EPSRC who funded the WAND project. I also acknowledge HR Wallingford and especially Richard Kellagher, Juan Guitierrez Andres (hope this is the correct spelling☺) and Helen Udale-Clarke for providing all the useful data and technical support to achieve the project.

Thank to the Dun Loaghaire county council and to my “Irish paddy” who gave me a two days tour of the Carrickmines catchment, it has been an unforgettable experience and an amazing introduction to Irish culture! And also many thanks to Samuel D and his wife Bénédicte for their warm welcome during my visit to Dublin.

I also would like to thank all the people in the Centre for Water Science and all the PhD room 1 residents it’s been a pleasure working with you most of the time. I would like to acknowledge my friends: Runi (hunting snake with you is with no doubt my best souvenir of my time at Cranfield), Mel the First (the only queen ever who had to change a tire twice now), Cyncyn (I’m still wondering how you managed to drag me to Las Ventas), Geraldine and John (for sharing your amazing British culture and enthusiasm to French cuisine), Nick the Greek (Thanks for the olive oil/fish soup liquid-liquid extraction training! and where is my walnut liquor gone?) and Karine (without your questions Cranfield would not be the same). And a special thanks for Karine, Dodo and Marcin for being the most amazing neighbours ever.

Many thanks for all the supports I have received from the outside world and especially from Marie, Sève, Yannou and Vanes.

Pour finir, un immense merci à mes parents, pour m’avoir soutenue et encouragée pendant toutes ces années. Intense année pour vous deux (entre le concours brillamment réussit par Laët et la finition de cette thèse). C’est promit on arrêt de vous ennuyer avec tout ça ! Docteur Laët Beber, ma chère petite sœur, bon courage pour ta thèse tu vas voir c’est une expérience unique. Yes, you can !

Avec un peu d’acharnement et beaucoup de conviction tout est possible dans la vie.

On ne voit bien qu’avec le cœur, l’essentiel est invisible pour les yeux.

(Le Petit Prince, Antoine de Saint Exupéry)

A ma tante Maïté,

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TABLE OF EQUATIONS

Abbreviations

CatchMod	Integrated Catchment Water Modelling
CFMPs	Catchment Flood Management Plans
CS	Collection System
DoEHLG	Department of Environment, Heritage and Local Government
DWF	Dry Weather Flow
Ens	Nash-Sutcliffe efficiency index or coefficient
EPA	Irish Environmental Agency
Et	Evapotranspiration
FRC	Fixed Runoff Coefficient
GCM	Global Circulation Model
GDSDS	Great Dublin Strategic Drainage Study
GWP	Global Water Partnership
HadRCM2	Hadley Centre Climate Model
IMP	Impermeability
IRBM	Integrated River Basin Management
IWRM	Integrated Water Resources Management
LS	Inital Loss
M	Return Period Event
MBRs	Membrane Bioreactors
MDSF	Modelling and Decision Support Framework
Ofwat	The Water Services Regulation Authority
OPW	Office of Public Works
PFC	Peak Flow Coefficient
PIMP	Percentage Impermeability
PR	Percentage Runoff
RBD	River Basin Districts
RPA	Return Period Analysis
RRV	Runoff Routine Value
RTC	Real Time Control
RVC	Runoff Volume Coefficient
SOIL	Water holding capacity
SUDS	Sustainable Urban Drainages Systems
SVC	Sewer Volume Coefficient
TSRsim	Time Series Rainfall Simulations
UCWI	Urban Catchment Wetness Index
UKCIP	United Kingdom Climate Impacts Programme
UVQ	Urban Volume and Quanlity
VRC	Volume of Re-use Coefficient
WFD	Water Framework Directive
WwTW	Wastewater Treatment Work

Chapter 1 Introduction

1.1 Drivers for developing sustainable water management strategies

Nowadays, we are aware that traditional approaches to urban water management (such as when traditional approaches refer to centralised supply and wastewater treatment facilities and systems), contribute to the degradation of waterways, facilitate the wastage of valuable water resources and no longer respect the environmental values of society (Brown et al., 2006). Moreover, against the background of the pressures on water resources and the growing trend for a better management of wastewater, governments can no longer afford to employ a end-of-pipe approach to wastewater treatment (Tjandraarmadja *et al.*, 2005).

Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of fresh water resources in terms of quantity and quality and occurs in both extreme and moderate climates. Growing population and climate change exert stress on water supply and increase the frequency of floods. The problem is expected to worsen with urban populations predicted to rise by up to 60% over the next 20 years (UN, 2005).

Population growth will provoke an increase in demand while water available for abstraction is clearly limited. Furthermore, excessive abstraction of freshwater from available sources may cause additional environmental damages, such as low river flows and higher pollution levels eventually leading to a deterioration in habitats available for flora and fauna.

New housing developments will also generate a change in land use patterns and involve an increase in impermeable surfaces. As a result, runoff volume and flash flooding are likely to increase while the recharge of freshwater to groundwater might decrease. Thus, changes in land use patterns will not only reduce the volume of available freshwater resources, particularly in urban areas where water demand is highest, but will also significantly increase the risk of experiencing floods.

The occurrence of water stress and flood problems will be worse in the future due to the expected effects of climate change. The climate change scenarios developed by the United Kingdom Climate Impacts Programme (UKCIP) predict a general increase in temperature. UKCIP has forecast a 50% reduction in rainfall events and an increase of between 1 to 6° C of the average temperature by the summer of 2100, eventually provoking a net increase in water consumption (Hulme *et al.*, 2002). As a result, water demand is likely to increase whilst available water resources are decreasing. Additionally, an increase in effluent discharged into watercourses is expected during summer times potentially resulting in river floods. At the same time, a 30% increase in rainfall during the winter period has been predicted by UKCIP eventually leading to more frequent sewer flooding and storm overflows from sewage works (Hulme *et al.*, 2002).

To conclude, population increase, urban development and climate change are expected to severely impact water quantity and water quality and heighten the risk of floods. There is a vital need to apply an integrated approach to catchment management to achieve sustainable solutions to provide sufficient clean water for human consumption as well as reduce the risk of both river and sewerage based flood events.

1.2 Response options

Over recent years, many technological, regulatory, market and educational mechanisms have been designed, tested and implemented in order to promote water conservation and improve the efficiency of water use. The following paragraphs review and compare the effect of a number of tools and measures: public education and media campaigns, increasing water tariffs, installing water meters, using new domestic appliances, creating new sources of freshwater such as desalination, recycling and re-using of water in the form of greywater and rainwater harvesting and controlling runoff by implementing Sustainable Urban

Drainage Systems (SUDS) and green roofs to enhance water conservation to limit the impact of water stress and floods.

Public education and media campaigns are used to inform the population of the importance of reducing household water consumption and ways in which this can be achieved. In the UK, organisations such as the Consumer Council for Water (CCWater) and Waterwise promote such campaigns as well as water companies, water saving groups and other stakeholders. Defra (2008) highlights in the report "Future Water" that government should continue working on organising campaigns to raise customer awareness of the limit of water resources. For example, a reduction of 30% in water used following a media campaign carried out in the 1980s in Melbourne, Australia demonstrates the potential benefits of educational approaches to water conservation (Beekman, 1998). Campaigns have also been targeted at business and industry, where information on cost-effective water saving procedures is introduced. For example, the Environmental Technology Best Practice Programme (Envirowise) and a scheme to promote optimum use of water for industry and agriculture dependent on direct abstraction (coordinated by the Environment Agency (EA)).

Increasing water tariffs is a second instrument to encourage customers to decrease their water consumption. Examples from Melbourne show that a 10% increase in water prices resulted in a 5.3% reduction in demand by lower income households but only a 1.1% reduction by wealthy households (Renwick and Archibald, 1998). This study supports other work which suggests that the reduction in water demand is more effective for low and medium income households than for wealthy households when pricing is used (Sauri, 2003). However, water prices should stay affordable for all parts of the population. In England, for example, the Water Services Regulation Authority (Ofwat) has the objective of protecting consumers by setting price limits that enable efficient companies to deliver the services customers need.

The installation of water meters encourages indirect water savings by informing consumers about their water consumption. In the UK, water meters are being installed in all new housing developments, whereas existing households are required to pay for their installation. Currently, 30% of houses have installed a water meter in England. A 10% reduction in water consumption has been observed following meter installation (Defra, 2008). Water meter implementation has also been demonstrated to be helpful in identifying and fixing leakage problems, dripping pipes and running toilets in households. Metering water is a useful tool to control water consumption and should therefore be implemented more widely.

Private households can save water by using new domestic appliances. A two-third reduction in water has been achieved over the last three decades with modern machines which use less than 50 litres per wash (Sim *et al.*, 2005). Water saver showers only use between four and nine litres per minute which accounts for approximately half the consumption of a power-shower (Environment Agency, 2001). Waterless or vacuum toilets reduce the daily amount of water used for flushing by 20 % (Environment Agency, 2001). Controlling water temperature devices can also be implemented to control water consumption (Sim *et al.*, 2005). To promote these new water saving technologies, the UK government introduced the Code for Sustainable Homes in April 2007 (Communities and Local Government, 2008). The objective of building sustainable houses is to reduce the daily water consumption from 150l/d/p to 105 when Code Level 3 is achieved.

Techniques such as desalination present an opportunity to tap into ‘new’ or alternative sources of freshwater. However, this approach requires a lot of energy and as sustainable water management seeks to reduce greenhouse gas emissions, this option should perhaps be implemented only when no other solution remains. Currently, Thames Water is building a desalination plant called the Thames Gateway Water Treatment Plant which will have the capacity to supply 150 million litres of water, meeting the demands of approximately 400,000 households (Thames Water, 2005).

From the perspective of this thesis however, decentralised treatment strategies present encouraging options for water conservation and more efficient resource usage, and can play a particular role in providing affordable and sustainable solutions to deal with wastewater treatment and discharge (Tjandraarmadja *et al.*, 2005). The recycling and re-use of water in the form of greywater and rainwater harvesting is an efficient way to reduce demands on water resources. For example, up to 30% reduction in potable demand can be achieved by reclaiming greywater for non-potable applications (Diaper *et al.*, 2001). Rainwater harvesting technologies have been reported to reduce water demand by up to 50% (Villareal and Dixon, 2005). However, so far reuse technology implementation has been mainly driven by the physical limitation of water scarcity rather than by explicit precautionary planning (Brown et al., 2006).

Sustainable Urban Drainage Systems (SUDS) and Green Roofs are also being used to control flood and pollution risks. SUDS are an alternative concept in planning, design and management systems (CIRIA, 2001). It focuses on people and the environment, and gives equal consideration to water quality, quantity and public amenity. Such drainage systems aim to reduce flood risk and pollution and to improve the urban environment. Green roofs comprise a vegetation layer placed on top of an existing or new roof which can store up to 60% of incident rainwater helping to reduce local flood risk. Further benefits are: improved home insulation, storm water management, sound reduction, air quality improvement and microclimate effects. Therefore they are particularly useful to control runoff in areas where urban floods are likely to happen.

To conclude, many techniques and technologies have been developed, tested and implemented by a range of public and commercial actors to control water usage and therefore enhance the conservation of water resources. All these instruments and technologies have to be implemented as a first step toward sustainable water use. However, the water scarcity and floods problems faced are still present and will expand in the near future. Therefore, new urban water management approaches have to be adopted in order to enhance and reduce the impact caused by traditional approaches to urban water management. Decentralised treatment and reuse approaches seem to be a promising option to address the problems faced. This study will focus on identifying possible drawbacks to the widespread implementation of greywater recycling and rainwater harvesting technologies within new urban areas. Indeed, both systems are fairly new technologies within this context and have not yet been widely implemented. Therefore, further research needs to be carried out to identify if their implementation at catchment scale will support the ambitious of urban water management.

1.2.1 Greywater recycling technology introduction

Greywater recycling refers to the reuse of low-polluted wastewater from baths, showers and hand washing basins which following treatment can be used for non-drinking purposes such as flushing the toilet, landscape irrigation or washing cars (Friedler, 2004). Water recycling is considered as one of the main options to remedy water shortage caused by the increase in water demand due to climate change and population growth (Burkhard *et al.*, 2000).

In urban areas, greywater is most commonly reused for toilet flushing (Jefferson *et al.*, 1999; Niemczynowicz, 1999). The balance between the amount of greywater produced and demand for toilet flushing has been found to be almost equal. Therefore, if greywater systems are reliable, there is the possibility of replacing a high proportion of the toilet flushing demand and reduce up to 30 per cent of mains water usage (Diaper *et al.,* 2001). As a result, the implementation of greywater recycling involves a reduction of the volume of wastewater discharged (Tjandraarmadja *et al.*, 2005). This reduction in wastewater volume increases the potential for septicity, odours, contaminant impacts, and corrosion aspects (Tjandraarmadja *et al.*, 2005). However, a broad range of technologies are available to treat greywater such as reed beds, sand filters and Membrane Bioreactors (MBRs). A complete review of the treatment options and applications is provided by Pidou *et al.* (2008).

On-site greywater recycling prototypes at single house scale and in hotels have shown to result in water savings of up to 23 to 36 % (Birks *et al.*, 2004; March *et al.*, 2004; Ghisi and Mengotti de Oliveira, 2007). Hydraulic modelling assessments of greywater system have been conducted using modelling tools to identify the impacts of such technologies on the water cycle. Specified models such as the Urban Volume and Quality model (UVQ) were developed to estimate the water flows and contaminant loads within the total urban water cycle (Mitchell and Diaper, 2005). A decrease in water demand of 14% was modelled when greywater was used for toilet flushing.

Control of sewer flooding is also an important ambition of recycling water. By reducing the quantity of wastewater produced, the capacity of the sewer network to cope with heavy rainfall can be increased. Mitchell *et al.* (2003) and Rueedi *et al.* (2005) used the UVQ model to highlight that the use of greywater would lead to a decrease in sewerage volumes of 6 to 10%.

Despite the proven potential of greywater recycling technologies to decrease freshwater demand, there are a number of challenges involved in their implementation and operation. First, many studies carried out on sites recorded system failure due to design flaws, installation problems, and also maintenance issues (Birks *et al.*, 2004, Fittschen and Niemczynowick, 1997). Therefore, robust systems need to be implemented to obtain reliable results in terms of water saving. Second, whilst research carried out during the past 10 years demonstrates the high water quality that can be achieved using grey water recycling technologies, it also illustrates their variability in performance (Pidou, 2008). Techniques which achieve very good water quality tend to be fairly expensive (Jefferson *et al.*, 1999), therefore the payback period is long (Nodle, 2005; Ghisi and Mengotti de Oliveira, 2007), rendering water recycling rather uneconomic.

To conclude, greywater re-use has been shown to be an efficient way to reduce the demand on source water supply, when the technologies were running efficiently. The water quality achieved is sufficient for purposes such as toilet flushing. However, their high payback periods, maintenance and robustness issues have limited their implementation.

1.2.2 Rainwater harvesting

Rainwater harvesting has been practiced over thousands of years and refers to the collection and use of rainwater. Water can be collected from roofs and other hard surfaces around buildings. The aim of collecting and re-using rainwater is to reduce the use of mains water and limit stormwater problems by controlling urban runoff. For an in-depth overview of rainwater harvesting technologies and their practical application throughout the UK refer to Kellagher and Maneiro Franco (2005).

Quality analysis of rainwater harvesting has reported high levels of heavy metals and suspended solids (Burkland *et al.,* 2000). Moreover, microbiological quality analysis conducted by Albrechtsen (2002) detected pathogens in the collected rainwater. Efficient treatment techniques, such as membrane technologies or even simple filtration processes can remove contaminants and raise the water quality to a level where it can be used for toilet flushing (Kim *et al.*, 2005).

Using sophisticated technologies in rainwater harvesting increases the installation and running costs. Therefore the payback period of the system will increase; in general the cost of installation and running can be assumed to be very high (Niemczynowicz, 1999). However, studies evaluating payback periods vary greatly in their conclusions: Mustow *et al.* (1997) estimate a period of 6 to 210 years for costs to be amortised whereas Burkhard *et al.* (2000) calculated a time span of 50 years.

As the main domestic use of collected rainwater is to save drinking water, previous studies (Fewkes, 1999); Mitchell, 2007; Herrmann and Schmida, 1999; Kellagher and Maneiro, 2005; Rueddi *et al.*, 2005; Villareal and Dixon, 2005; mainly focused on the efficiency of water saving through rainwater harvesting by modelling the volume of drinking water saved. All these researches concluded that rainwater harvesting is an efficient way to save drinking water. Kellagher and Maneiro (2005) have shown that in the driest regions of the UK, where rainwater is collected from a roof area of $20m^2$/ person, the daily water demand could be reduced by 25l/c/d whereas Rueddi *et al.*'s study (2005) shows that the use of harvested water would decrease potable water use by about 6%. Villareal and Dixon's (2005) prediction for a large scale rainwater project to be built in Sweden is more optimistic: almost 40% of potable water demand was forecast to be reduced when low flush toilets were combined with a rainwater harvesting system. Villareal and Dixon (2005) also mentioned the potential for rainwater systems to be connected to large roof areas, which would improve stormwater management and wastewater treatment.

The use of rainwater tanks to supplement the existing water supply can also reduce localised urban flooding, improve stormwater quality and minimise the influx of stormwater into the sewer system (Coombes and Kuczera, 2002). Studies have highlighted dramatic benefits in reducing the volume of runoff with reductions of between 75% to 95% of the annual runoff being achievable (Kellagher and Maneiro, 2005). However, results also illustrate the potential limitations of reducing runoff through rainwater harvesting as the runoff decrease obtained for a 100mm rainfall event was 40% compared to only 20% for a 180mm rainfall event. Against this background, urban drainage systems are still needed to control runoff.

The decrease in stormwater and potable water use could be further enhanced by expanding the size of rainwater tanks and connected roof areas. Herrmann and Schmida (1999) concluded that the control of urban drainage is better at multi storey building scale and in densely populated districts. However, the hydraulic impacts at watershed level of up-scaling rainwater harvesting system innovations are still unknown and require further research. For example, the cumulative effect of harvesting rainwater may have an impact on downstream water availability at a river basin scale (Ngigi, 2003). The expected shifts in water flows in the water balance could affect both environmental and economic sectors depending on direct water withdrawals (Rockstrom *et al.*, 2001). Therefore, further study has to be carried out downstream to identify the possible effects on water availability for health and environmental impacts, prior to the introduction of the technology.

All the information presented in this section has been obtained from publications which report the application of small scale models with one system and one sub-catchment. No modelling studies have been reported in scientific papers which consider the impact of greywater and rainwater systems at whole catchment scale. Therefore there is a lack of knowledge about the possible impact of rainwater harvesting on runoff, downstream flows and on river basin dynamics. As a result there is a need to investigate the impacts of implementation of recycling and re-use technologies at catchment scale using hydrological modelling. The assessment of decentralising the water network to support the extension of cities and the climate-proof cities will generate a better understanding of and generate some guidance to set up the best systems to support urban surface water and wastewater management (e.g. best location / best size / best technologies) depending on catchment characteristics. The study will therefore be of benefit to planners and water managers designing future new developments.

1.3 Aim and objectives

Supplying sufficient water to consumers without damaging the environment is an emerging problem for many cities around the world. With increasing urbanisation and population, meeting this challenge will be even more demanding in the near future. Although the implementation of greywater recycling and rainwater harvesting has the potential to contribute to a reduction in demand for potable water and improve stormwater runoff management, the catchment scale impacts on hydraulic and hydrological flows are poorly understood. The research aim of the study presented in this thesis is to identify the hydraulic and hydrologic impacts of increasingly intense greywater recycling and rainwater harvesting activities at catchment scale.

The results obtained from the study will be used to highlight the benefits of implementing technologies in new urban areas to obtain efficient use of water resources and to reduce the frequency and intensity of floods from rivers and sewer overflows. Findings will enable planners and water managers to design appropriate sustainable water supply systems for new developments at catchment scale. Specific research questions to be addressed are:

RQ1: How does the scale up and configuration of greywater recycling systems influence flooding within the sewer network?

RQ2: How does the scale up and configuration of rainwater harvesting systems influence flooding within the sewer network?

RQ3: How does the scale up and configuration of greywater recycling systems influence river flows and flooding?

RQ4: How does the scale up and configuration of rainwater harvesting systems influence river flows and flooding?

RQ5: To what extent does the scale up and configuration of greywater recycling and rainwater harvesting systems reduce the stress on drinking water supply to a growing population?

RQ6: How are the responses to RQ1-5 influenced by climate change?

RQ7: What combination of technologies and configurations provide robust performance over different climate scenarios?

For this particular study, a computer simulation model was used to evaluate how increasing urbanisation, climate change and the implementation of greywater recycling technology and rainwater harvesting may alter the hydrological balance of a representative catchment located in the Dublin area (Ireland). The study evaluated how river flows, sewer flows, surface runoff and flooding events may be influenced within the catchment under a range of different scenarios. The results obtained from the study were used to highlight the benefits of implementing technologies in new urban areas to obtain efficient use of water resources and to reduce the frequency and intensity of floods from rivers and sewers overflows. The performance of combined systems was assessed by identifying an index of robustness for each scenario.

1.4 Thesis structure

This thesis is divided into eight chapters. A literature review was carried out (Chapter 2) which highlights the importance of using hydrological modelling as a support tool to provide solutions to improve water management as a whole. Chapter 3 describes the methodology employed to build the model networks and scenarios, the data used and the case study background. An uncertainty analysis of the model also forms part of this Chapter. Chapters 4 to 6 detail the results obtained when greywater recycling (Chapter 4), rainwater harvesting (Chapter 5) and combined technologies (Chapter 6) are implemented in new housing developments. A sensitivity analysis of the model outputs is reported in Chapter 7. Finally, Chapter 8 discusses and concludes the results presented in the previous chapters and introduces the index of robustness of each scenario and the radar charts. The Chapter outlines recommendations aimed at improving urban water management.

Chapter 2 Literature review

This chapter will cover all the essential information required to understand this study. Section 2.1 provides an overview of current water management practices. The subsequent sections introduce and discuss how modelling tools can support water management processes, highlighting both their potential as well as limitations.

2.1 Introduction

Today, water management interventions are primarily planned and applied at catchment scale, taking into consideration the complex interactions between the natural environment and human activities. In recent years, prompted by an increased awareness of the scarcity of water resources, new approaches to water resources management, such as Integrated Water Resource Management (IWRM) have become widely used. The Global Water Partnership (GWP) defines IWRM as “a process which promotes the co-ordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP TAC, 2000).

According to the IWRM framework, environmentally and economically sustainable development must be based on three fundamental elements. The ecological element, underlining the importance to be attached to the environment; the institutional element, calling for the participation of all actors in water management, and also, the instrument element which stresses the concept of water scarcity and calls for a more appropriate use of economic incentives to allocate resources and enhance water management capacities (GWP TAC, 2000).

Within the GWP’s IWRM model the integration of water resource management is considered within two categories: i) the natural system integration which concerns the critical importance for resources and quality, and ii) the human system integration which determine the resource use, the waste produced and the pollution of the resource. Therefore the key features of an IWRM framework in terms of the natural system are freshwater management, land and water management, surface water and groundwater management, the quantity and quality in water resources management as well as, the upstream and downstream water related interests. Features of the human component include the mainstreaming of water resources, cross-sectoral integration in national policy development, the macro-economic effects of water developments, basic principles for integrated policy-making, the influence of economic sector decisions, inclusion of all stakeholders in the planning and decision process and the integration of water and wastewater management.

The catchment or drainage basin can be defined as a unit hydrograph, which receives quantifiable inputs of precipitation which are transformed into flows and storages and into outputs of evaporation and runoff (Ward and Robinson, 2000). Therefore catchment management needs to consider a wide range of components present within the catchment particularly in the context of urban water cycle (Figure 2.1).

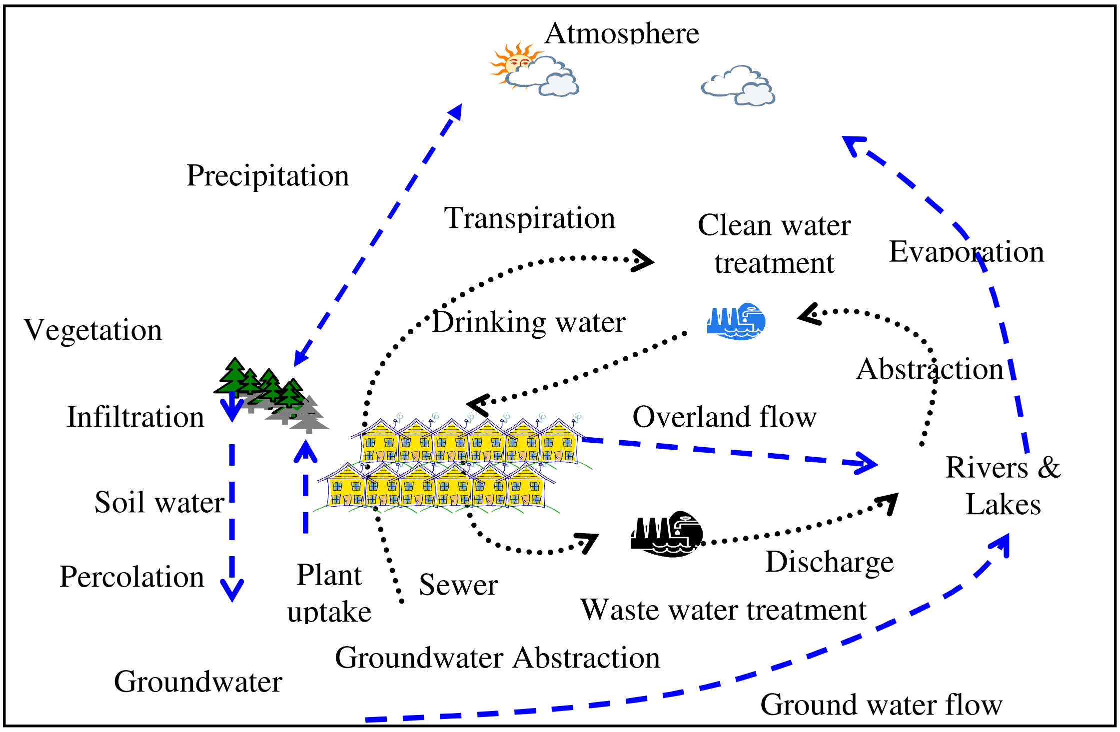


Figure 2.1. Urban water cycle.

This thesis will explicitly addressed the IWRM agenda by exploring the link between water efficiency interventions and other dimensions of the urban water cycle such as flooding and climate change. Finally, the last section Chapter 8 will resume the outputs of the modelling activities and proposed IWRM plans.

2.1.1 Water Framework Directive (WFD)

This sub-section describes the Water Framework Directive (WFD), at present the most important European Directive in the water sector providing a coherent approach to integrated water resources management across Europe. The Water Framework Directive is a piece of European legislation whose main purpose is to achieve good chemical and ecological status of all water bodies by 2015. The directive also aims to reduce and eliminate pollution especially from priority hazardous substances and to promote sustainable water use, by contributing to the mitigation of floods and droughts. It introduces the concept of Integrated River Basin Management (IRBM). The main tasks and deadlines of the WFD are shown in Figure 2.2.

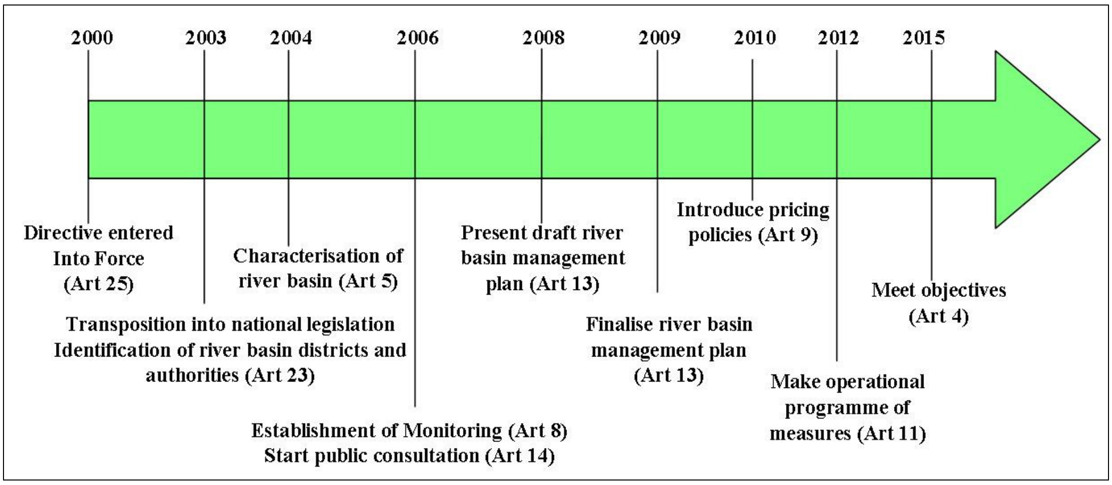


Figure 2.2. Tasks and deadlines to be met for the implementation of the WFD.

River basin management plans are to be developed for each river basin district in order to achieve WFD objectives and will also contribute to mitigate the effects of floods. The river basin management plans will set out in general terms how the water environment will be managed and provides a framework to help identify appropriate interventions. Each plan will include information on the characteristics of the River Basin District. The management of flood risks will be determined by the Member States and should be based on local and regional circumstances due to the variation of flood damages across countries and regions. Flood hazard maps and flood risk maps will be used to show the potential adverse consequences associated. Member states will then identify those activities that have the effect of increasing flood risks. Flood risk management plans will then be produced and focus on prevention and protection. Member states will then base their assessments, maps and plans on appropriate 'best practice' and available 'best technologies'. Figure 2.3 reviews the tasks and time lines of the Flood Directive (2007/60/EC).

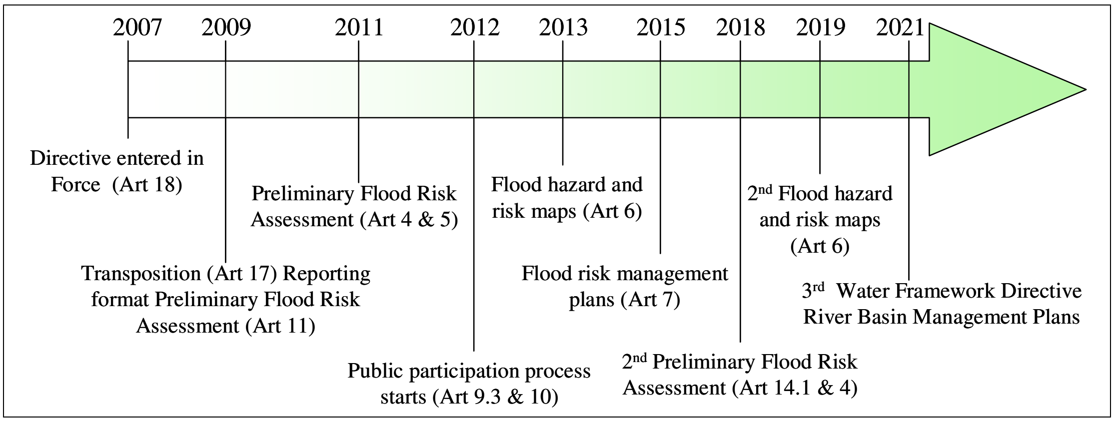


Figure 2.3. Flood Directive timetable to be implemented of the EU WFD.

Modelling tools are currently used to support water management integrations; the following sections will introduce hydrological modelling techniques.

2.2 Types of models available

Within the last 30 to 40 years, mathematical models have been developed and used to simulate and analyse a variety of hydrological processes such as rainfall, runoff and stormwater flows. Models can be broadly classified in three categories: physically-based, empirical and conceptual models. In practice, however, models representing a mixture of these categories are commonly used. Physically-based models derive from physical principles; they use fundamental equations with model parameters (Beven, 2001). Empirical models refer to the description of relations between inputs and outputs without reference to the physical or biological processes involved. Conceptual models are developed on the basis of knowledge of the system and often serve as the basis for a mathematical model (Van Waveren *et al.*, 1999). The catchment hydrological processes are described mathematically using parameters that may not have a direct physical meaning. Models can also be subdivided depending on the nature of the equations employed. The models as either deterministic or stochastic. When a deterministic approach is adopted, quantitative results are obtained. However for stochastic approach, outputs will vary for each run. Models can be further divided into lumped or distributed models. Lumped models simulate a spatially heterogeneous area or structure as a single value, while distributed models break the area or structure into discrete units. Temporal scales present a further criterion for classification. Static models are time independent while dynamic models include a time variation. And finally, models can be one-, two, or three-dimensional.

2.2.1 Hydrological modelling to support water management

Nowadays models are widely used in the water sector. Figure 2.4 illustrates the main steps in the evolution of water modelling from empirical to physical models, based on reviews carried out by Beven (2001) and Todini (2007).

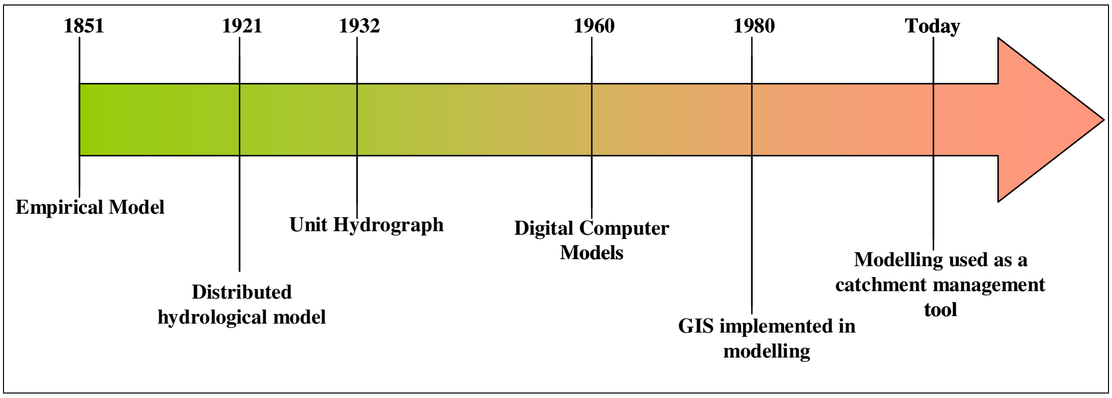


Figure 2.4. Review of hydrological modelling evolution (adapted from data collected from Beven, 2001 and Todini, 2007).

Water modelling started with the rational method processed by Mulvany in 1851 where an empirical model was used for the design of sewers. The model could estimate maximum runoff and peak flow (Todini, 2007). Later in 1921, for the first time the concept of distributed hydrological model was introduced by Ross, catchments were then divided in zones and a travel time parameter was introduced to compute runoff (Beven, 2001). However the model was linear and therefore the routing time determined was the same of each catchment zone. In 1932, Sherman introduced the unit hydrograph (UH) concept. The UH represents a discrete transfer function for effective rainfall to reach the basin outlet, it is easy to understand and is still one of the most common hydrograph modelling techniques used. The next step was to relate the unit hydrograph more directly to the physical structure of the catchment and in particular to the channel network. The hydrological response unit (HRU) was then introduced which allowed an overlay of spatial databases of soil, vegetation and topography data. It the early 60s the rainfall-runoff model was introduced within the first watershed model. The model was a complex conceptual model, with sufficient parameters and flexibility to be able to produce a reasonable fit to the rainfall-runoff data (Beven, 2001). In the 1970s, models able to simulate storm water quality and quantity appeared (Zoppou, 2001). In the 1980s, GIS started to be used to implement topography, vegetation and land use cover over catchment modelled. Nowadays, many types of models can be chosen to simulate flows and transport of pollutants. They are able to produce results representing the behaviour of the catchment responses as a function of time at several locations in the catchment (Zoppou, 2001). Such models can be combined to cover the entire water cycle in order to support integrated water management, as illustrated in Figure 2.5.

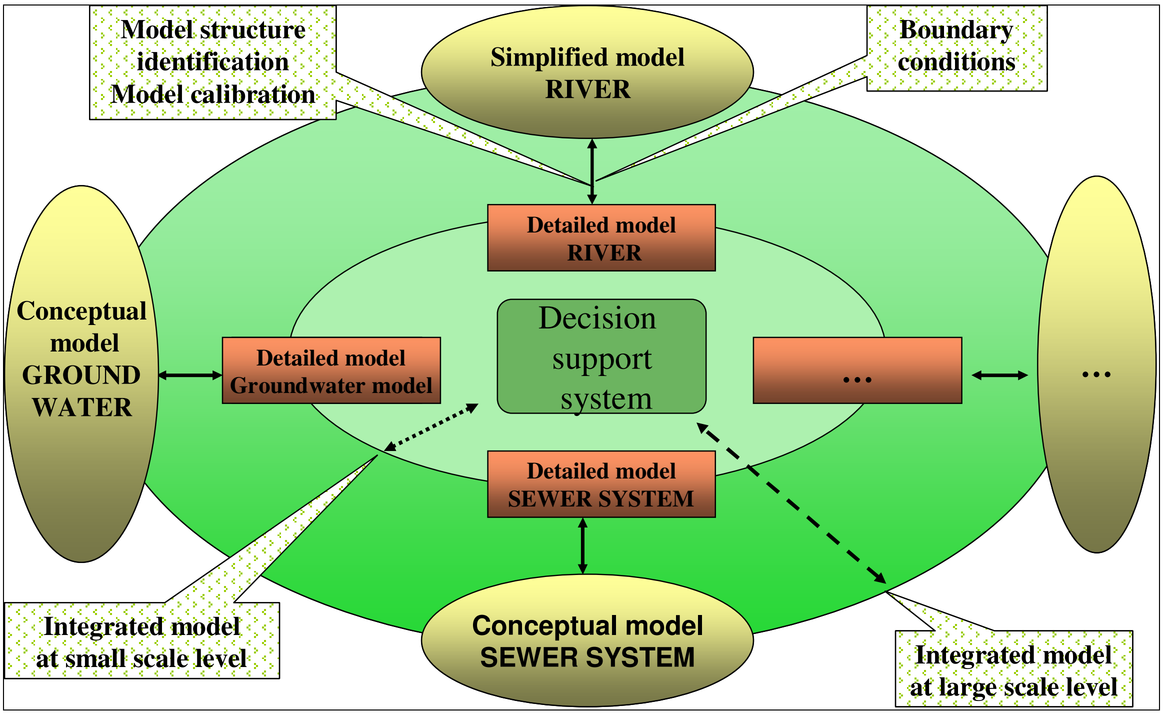


Figure 2.5. Integrated modelling: detailed models at small scale and conceptual model at large scale (adapted from Willems, 2003).

Many hydrological and hydraulic models have been designed and can be used for such purposes. However, the three most competitive software are MIKE (DHI), InfoWorks (HR Wallingford) and SWMM (Table 2.1. The software are widely used to undertake drainage and sewerage master planning or studies, assess the impact of climate change on urban drainage system, effectively implement sustainable urban drainage systems (SUDS), undertake hydraulic analysis of wastewater treatment works, flooding and pollution prediction etc. However, such software are complicated to use and understand. Therefore only experts can used them for planning purposes.

Table 2.1. Components of analysis in representative models (adapted from Zoppou, 2001).

Program name	Model component representation					References
	Pipes	Open channel	Retention ponds	Natural streams	Rainfall runoff	
MIKE-SWMM	✓	✓		✓	✓	Jia *et al.*, 2007
SWMM	✓	✓			✓	Park *et al.*, 2008; Jang *et al.*, 2007
InfoWorks CS	✓	✓	✓		✓	Butler *et al.*, 2007 ; Artina *et al.*, 2007 and Mark *et al.*, 2004

To provide user-friendly guidance and support multi-disciplinary modelling, decision support tools have been designed and implemented to process data obtained by various hydraulic and hydrological models. For example, the Modelling and Decision Support Framework (MDSF) applied by the Environment Agency, provides a structured framework, for instance to support the Catchment Flood Management Plans (CFMPs) process. The MDSF uses modelling results generated externally to provide an assessment of flood extent and depth, calculations of economic damages and social impacts due to flooding, estimation of uncertainty and comparison of flood damages and social impacts as an aid to policy evaluation (MDSF handnote, 2004). Other decision support tools have been designed to support the implementation of the WFD as part of the Integrated Catchment Water Modelling (CatchMod) project (Arnold et al., 2005). The objective of the CatchMod project is the development of common harmonised modelling tools and methodologies for the integrated management of water at river basin or sub-basin scales, including coastal zones. A similar tool, the MULINO-DSS was developed to improve the quality of decision making and to achieve a truly integrated approach to river basin management within the context of the WFD (Guipponi, 2007).

2.2.2 Modelling approach

The quality of models and their outputs is very important as they directly influence decision-making processes. First and foremost, hydrological models and their outputs need to be as accurate as possible. Against this background, there is a real need to establish guidelines and frameworks to improve the quality of modelling (Refsgaard and Henriksen, 2004). Refsgaard *et al.* (2007) for instance present a modelling framework inspired by their earlier work (Refsgaard *et al.*, 2005; Pascual *et al.,* 2003). The framework is presented in Figure 2.6 as it highlights the connection between the water management processes and modelling processes.

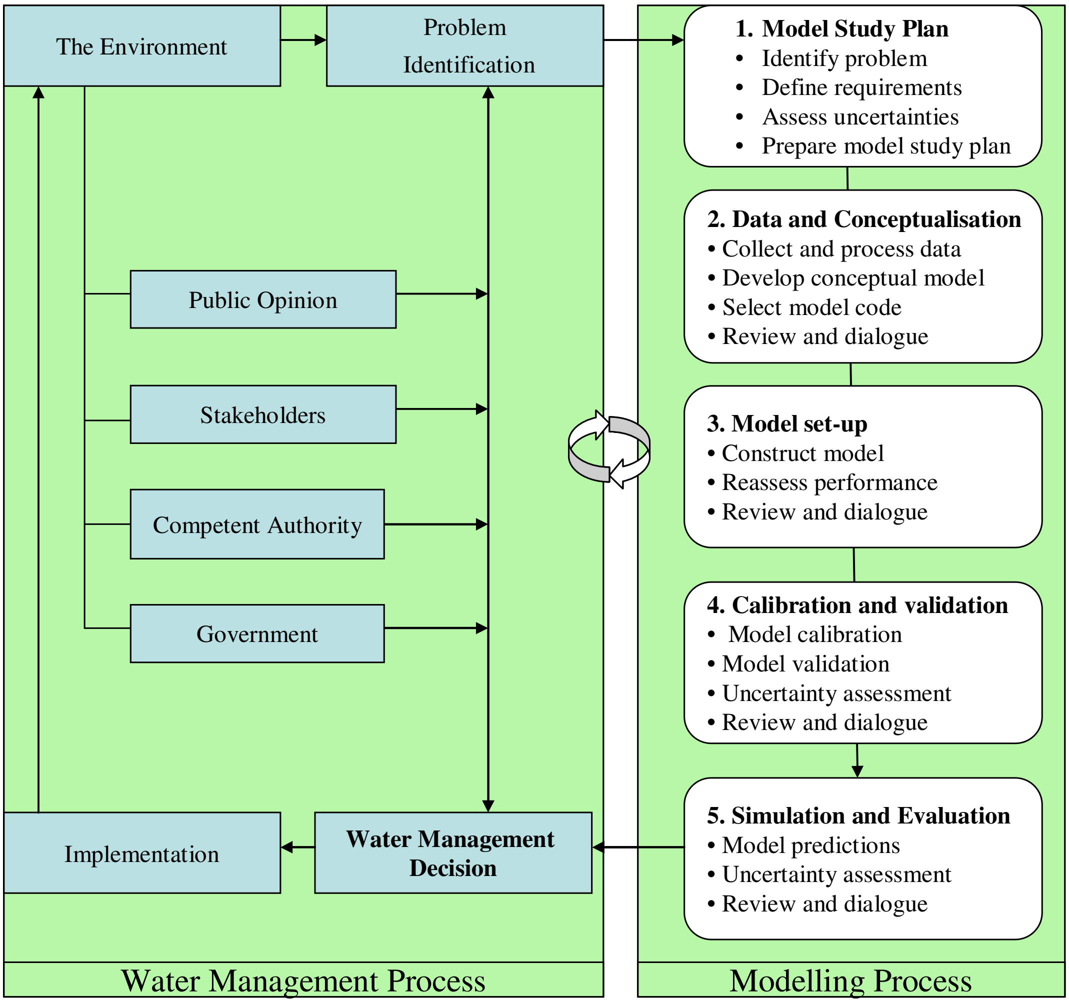


Figure 2.6. Interactions between the five steps of the modelling process and the water management process (Refsgaards *et al.*, 2007).

The water management process integrates all the key actors involved from the government to the stakeholders. The modelling process is divided into five steps. The first step aims to agree on a model study. At this stage the modelling process and water management process are strongly linked. A level of accuracy must be agreed by assessing the key sources of uncertainties between modeller and manager. In the second step, data and knowledge about the selected case study are reviewed in order to conceptualise how the system should be modelled in sufficient detail to meet the requirements specified during the first step. During the third step the model is designed. The fourth step is focused on model calibration and validation. And finally, the simulations are run and results evaluated during step number five. The assessment of uncertainty during steps 1, 4 and 5 emphasises the importance of ensuring the accuracy of modelling results in order to obtain robust decisions.

2.2.3 Review of modelling methodologies and comparison with the reference modelling process framework

The following section reviews the methodologies historically adopted by hydrological and hydraulic modellers and compares them to the framework introduced in Figure 2.6 (Section 2.2.2). The review is based on survey of the relevant literature and concludes by stating how knowledge from the review has been adopted for use in this study.

Coherent with the framework, all the studies reported below start by presenting the problem to be addressed and the model plan. Often, the objectives of the WFD or other water policies are listed as project aims. In other words, the majority of projects are designed to respond to governmental objectives. The framework emphasises the importance of involving different actors in the decision-making process. However, none of the papers makes reference to the participation of a wider range of actors. Possibly, this is due to the fact that the reviewed studies clearly focus on the modelling aspect of the water management process, thus failing to report the relation between the actors and the modelling process as well as final decisions.

Procedures and methods for data collection and catchment selection were reported in each study. Catchments were described in detail. Data sources and resolutions for land use and topographical data are frequently cited. A comparison of the reviewed papers identified variation between data available and catchment characteristics.

Table 2.2 lists the modelling platforms in the reviewed studies. The authors usually explain how models are selected, often running different models, and then selecting the most adequate model based on an uncertainty analysis (Gotzinger *et al.* 2006, Booij 2005).

All the studies reported model calibration. The length of data used for calibration varies from 6 months to 17 years depending on data availability. Models were mainly calibrated manually, with the exception of Zhang *et al.* (2006) and Booij (2005) who conducted automatic calibration using bespoke software. Where reported; studies assessed the accuracy of obtained results using the Nash-Sutcliffe efficiency technique (when a technique was mentions).

In the majority of the reported studies, validation procedures to verify modelling outputs were carried out, mostly using a different set of data than for the model calibration (see Table 2.2). Similar to the situation with calibration, data used during the validation process covered different time spans, varying from 6 months to 12 years. Finally, the term verification was used instead of validation in two studies (Table 2.2). Similarly, uncertainty and sensitivity assessment to evaluate the accuracy of model outputs were not applied consistently (Table 2.2). Of the reviewed studies only three reported the carrying out of uncertainty assessments. Two studies reported using a Bayesian approach to assess uncertainty, one study failed to detail which method was applied.

The duration of final simulation varied between studies with Andersen *et al.* (2006) simulating river flows over 30 years whereas Zhang *et al.* (2006) and Young (2006) only simulated river discharge over the period of one year.

Table 2.2. Review of methodologies used to carry out hydrological modelling at catchment scale.

References	Study purpose	Data	Software	Calibration	Validation	Uncertainty	Sensitivity	Comments
Zhang *et al.*, 2006	Runoff modelling in a catchment	2 years rainfall available	REWASH for hydrological modelling and GLOBE for sensitivity and automatic calibration	✓	✓		✓	Manual and automatic calibration Verification term was again used instead of validation 2 years data used for calibration
Young, 2006	Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model		Conceptual model for runoff simulation and Bayesian for uncertainty	✓		✓		
Gotzinger, *et al.* 2006	Integration of water balance models in RIVERTWIN		3 modes used to compare (HBV, LARSIM, MODFLOW)	✓				Compare efficiency of different type models to carry out water balance model (groundwater modelling)
Fleichbein *et al.*, 2006	Runoff response in the Mulde catchment		J2000 Physical based simulation	✓	✓			Calibration 1 year data Validation 3 years data used

References	Study purpose	Data	Software	Calibration	Validation	Uncertainty	Sensitivity	Comments
Liu, 2005	Flood forecasting	Few data available	TOPKAPI and Bayesian	✓	✓	✓	✓	Terminology verification used instead of validation Calibration based on uncertainty
Booij, 2005	Climate change	Catchment data review and uncertainties introduce	Two software version compare, conceptual model (HBV)	✓	✓	✓	✓	Parameter sensitivity carried out during calibration Calibration and uncertainty results reported but no details of methodology carried out
Andersen *et al.*, 2006	Climate change	Catchment runoff and precipitation details	Mike-11	✓	✓			Auto calibration routine The word validation was mentioned in the paper but no further information No sensitivity and uncertainty assessment reported
Menzel, 2006	Climate change	35 years data available	HBV	✓	✓			35 years data used for calibration and validation Sources of uncertainty reviewed

The review carried out above assessed modelling practices using Refsgaards' framework as a guide. It can be concluded that the modelling process adopted by Booij (2005) closest resembles the Refsgaards framework. All the studies carried out calibration and validation; however uncertainty and sensitivity analysis are not always undertaken. Finally, the importance of interaction between water management process and the modelling processes is not mentioned in any of the papers presented in Table 2.1. The carried out analysis identified the importance of following the detailed framework. Therefore for the purposes of the study, all the steps detailed within the water management process and the modelling process will be followed.

2.3 Previous work on catchment level modelling

This section identifies how computer modelling at catchment scale has been used to enhance catchment management. It reviews previous research which identifies the impacts of urbanisation and climate change on watershed and sewer network at catchment scale.

Floods in urban areas can be very complex to predict. The use of models allows the simulation of flooding events and the interaction between river flow volume and drainage (Siang *et al.*, 2007). The studies of Thorndahl and Willems, (2008), Stransky *et al.*, (2007) and Siang *et al.*, (2007) all focused on how storm duration affects catchment hydrology. Liu (2005), for example, used distributed models whereas Mark *et al.*, (2004) identified the limits of using a 1D model over 2D using a deterministic approach. Catchment flood model studies are also carried out along river catchments which are not specifically located in urban areas. For example, Leister *et al.* (2007) used a catchment flood model to determine the impact of localised changes in land use or management on the entire river catchment. A similar study was carried out in Australia to model floodplain inundation for environmental flows (Powell *et al.*, 2007). Estimations of river flood discharges were undertaken in Austria by Merz *et al.* (2008). Results were used to produce clear and easily understandable flood maps. Land use and climate change are both parameters influencing the catchment hydrology. Therefore, the following section will focus on reviewing previous work on the impacts of climate change and land use on catchment hydrology.

2.4 Impact of urbanisation and climate change on hydrologic and hydraulic flows

The possibility to simulate the interplay between a variety of parameters, such as precipitation, temperature and evaporation, enables modellers to assess the impact of climate change on water resources, both in terms of quality and quantity, as well as flood risks, as illustrated by Booij, 2005; Menzel *et al.*, 2006; Legesse *et al.*, 2003; Middelkoop *et al.*, 2001 and Semadeni-Davies *et al.*, 2008. Booij (2005) assesses the impact of climate change on flooding in the river Meuse on a daily basis using spatially and temporally changed climate patterns. The results showed that climate change provokes a small decrease in the average discharge and a small increase of discharge variability and extreme discharges due to storm events. Menzel *et al.*, (2006) study the impact of global climate change on regional hydrological dynamics with special emphasis on discharge conditions and floods. Runoff is simulated under present conditions over the German Rhine catchment. The study finds a potential increase in precipitation, mean runoff and flood discharge.

Studies by Legesse *et al.,* 2003 and Sullivan *et al.,* 2004 focus on the hydrological response of a catchment to climate and land use change in agricultural areas. Legesse *et al.*'s study was based in tropical Africa whilst that of Sullivan *et al.* (2004) was based in Cornwall (UK). Legesse *et al.* (2003) developed a physical process model to evaluate runoff volume under a wide range of hydrological conditions. The study highlighted the influence of climate change on the catchment hydrology, runoff, peak flow and annual river flow and discharge. A decrease of 10% in the amount of daily rainfall during the model simulation period resulted in an average annual decrease in runoff at the outlet of about 30%. The study also forecasts air temperature influences on river discharge. Indeed, a 1.5°C decrease of temperature results in a 20% increase in river discharges whilst a 1.5°C increase would result in a 15% decrease in the mean annual runoff. The influence of land use was also identified with a 50% land use change from grass land to woodland causing an increase of 2.5% in evaporation and a decrease in the mean annual river flow of 8%. Sullivan *et al.* (2004) found that long-term changes in the response of the catchment appear to emanate from the cumulative impact of climate change, combined with farming activities and urban expansion. However, no radical change in flood frequency was observed in their study.

Forecasting the hydrological influence of land use and climate change is a major challenge and an essential component of integrated management of water resources. Therefore Middelkoop *et al.*, (2001), Semadeni-Davies *et al.*, (2008), and Mignot *et al.* (2006a) focused their studies on how the hydrological cycle is influence by land use and climate change. Middelkoop *et al.*, and Semadeni-Davies *et al.*, assessed the impact of climate change and urbanisation on drainage and river flows. The study area selected by Semadeni-Davies *et al.* was in Sweden whereas Middelkoop *et al.*, assessed the average low and peak flow discharges for the entire river Rhine. For both studies catchment development and climate change were found to provoke an increase in the frequency and height of storm peak flows. A change in river flow patterns is observed for both case studies. Middelkoop *et al.* show the occurrence of low flows to be more frequent and to last longer during summer periods. As a consequence, water availability for domestic use, industry, navigation and agriculture will be affected and as a result water quality and ecology of the river will decrease. The study by Semadeni-Davies *et al.* study identified a systematic shift towards higher baseflows and a sharp rise in stormflows with climate change. Urbanisation promotes increases in storm peak flows but has limited impact on baseflow. Greater peak flows and heightened flood risk result from both urban development and climate change. Both Sullivan *et al.* and Semadeni-Davies *et al.* found that urbanisation has a minor effect on increasing flooding with climate change being the major driver of such events.

Sewer modelling studies have also been carried out to identify the risks of sewer flooding in big cities. Aradas *et al.* (2004) for example report how the model which was developed for the sewer network of the city of Buenos Aires, provided a useful understanding of the drainage system of the city. Mignot *et al.* (2006a) illustrate how a similar project contributed to an urban development plan for the city of Nîmes. Semadeni-Davies *et al.*, (2008) assessed the impact of climate change and urbanisation on a combined sewer system in Helsingborg (Sweden) reporting a 318% increase in total overflow volume when future conditions are compared to today. Urbanisation and climate change could results in a 450% sewer volume increase therefore Butler et al. (2007) studied the performance of sewer storage tanks under several climate change scenarios. The study was based on the London sewer network and indicates a 35% increase in the number of storm events that cause filling of the tank and a 57% increase in the average volume of storage required. Therefore larger storage tank volumes will be required to maintain the level of flood protection.

Downscaling techniques were used by most of the studies reviewed above (Menzel *et al.*, 2006, Semadeni-Davies *et al.*, 2008, Prudhomme and Davies (2008), Dibike and Coulibaly, 2007). The common downscaling technique used is called the Global Circulation Model (GCM) and report to mathematical models which are used to simulate the present climate and project future climate with forcing by greenhouse gases and aerosols (Dibike and Coulibaly, 2007). However, GCMs are generally not designed for local climate change impact studies and do not permit a good estimation of hydrological responses to climate change at local or regional scale (Dibike and Coulibaly, 2007). The study in Canada also used GCMs to model climate change. The output of the study identifies that the two hydrological models analysed performed less well and responded differently when precipitation and temperature data downscaled from GCM were used as inputs. The two models mostly underestimate the mean river discharges in the watershed when provided with downscaled meteorological inputs. The authors conclude that before starting any such climate change impact study, the appropriateness of both the downscaled meteorological variables and the hydrological simulation models have to be validated based on their performance in simulating the historical flows in the watershed corresponding to the baseline climate condition. Butler *et al.* (2007) also mentioned the huge climate change uncertainties due to the use of synthetically generated rainfall for present and future. Moreover, Booij (2005) estimated the uncertainty in river flooding with climate scenarios to be 40% and less than 10% for current conditions. Prudhomme and Davies (2008) assessed the uncertainties of climate change impact analyses on the river regimes in the UK. The study identifies that climate change uncertainties are higher than downscaling and hydrological uncertainties. The study shows that the larger source of uncertainties of downscaling modelling is to reproduce the baseline climate. For all the catchments studied, it has been found that for at least one month the simulated ranges were 90% outside the natural variability range. Therefore source of uncertainties are significant and should not be ignored. The authors also conclude that GCMs remain the best tools for forecasting future climate change scenarios, assessing and allowing for their limitations when undertaking a climate change study.

Finally, from the outputs of their studies Sullivan *et al.* (2004) and Middelkoop et al. (2001) propose that water management and policy considerations be carried out to mitigate the social, economical and environmental impacts of land use and climate changes. Sullivan *et al.* (2004) highlight the need for a holistic approach to the management of floods, involving a greater understanding of spatially and temporally variable hydrological processes operating across a range of scales. Moreover, due to the potential increases in flood risk related to climate change, it is imperative that the impacts of field-scale land use changes on peak flows at catchment-scale are fully recognised. From the output of their modelling study, Middelkoop *et al.* (2001) conclude that long term integrated river basin management should be considered due to the large hydrological changes forecasted from the modelling activities. Policy fields such as planning, environment and agriculture must be included in the management plans. However, due to the high uncertainties in the rate and magnitude of the changes, long terms plans and designs must be flexible. Finally, the authors conclude that efforts to improve model results for the Rhine basin should focus on reducing the climate change scenarios uncertainties by improving spatial resolution and reliable estimates of changes in precipitation amounts and intensity.

2.4.1 Options for reducing modelling uncertainties

Boughton (2006) highlighted that the quality of the results obtained for a modelling activity is more dependent on the specific data used to construct the model than the rainfall-runoff model itself in general. Authors such as Ettrich *et al.* (2005), Mark *et al.* (2004) and Stransky *et al.* (2007) stress the importance of the quantity and quality of data introduced to the model especially rainfall data and topography to predict accurate runoff values.

Rainfall-runoff modelling depends heavily on the resolution of rainfall records. A time step of one hour will provide better prediction than daily river gauge results (Beven, 2001). Stransky *et al.* (2007) studied the effect of rainfall measurement uncertainties on rainfall-runoff processes modelling. The study quantifies the rainfall uncertainties to underestimate the runoff volume by up to 15%. Measured rainfall volumes may be subject to error such as windy conditions, rainfall intensities and evaporation. An estimation of reduction of up to 20% for rainfall gauges only 30cm above ground level has been suggested (Rodda and Smith, 1986). Nowadays, radar rainfall measurements are available and offer a much greater appreciation of the temporal and spatial variability of rainfall intensities (Beven, 2001). However, radar rainfall data present important limitations. For example, radar does not measure rainfall at ground level but above and therefore there are potential spatial uncertainties of data monitored due to wind (Beven, 2001). Segond *et al.* (2007) studied the significance of spatial rainfall representation for flood runoff estimation. The study compared the runoff volume predicted when rain gauge and radar data are used. Their findings showed no difference in flow responses modelled with both rainfall data sets. Moreover, the study also concludes that, with urbanisation increasing and because of the sensitivity of urban area to spatial and temporal rainfall data, sub-hourly data and a high spatial resolution (few kilometres) are required and therefore there is a need for radar data.

Furthermore, the importance of using accurate topographical data as a prerequisite for generating precise estimates of flood volumes on the surface areas is frequently stressed (Ettrich *et al.,* 2005, Mark *et al.,* 2004, Mignot *et al.*, 2006a, Haile and Rientjes, 2005, Mitchell *et al.*, 2001 and Gutierrez Andres *et al.*, 2008). Mark *et al.,* 2004 and Haile and Rientjes, 2005 conclude that the resolution of a digital elevation model (DEM) significantly effect simulation results. Siang *et al.*, 2007 recommend using DEM and remote sensing to improve the accuracy of topographical data and therefore flood forecasting in urban catchments.

1D models show some limitations when representing and simulating floods due to the simplification of the formula between pipe network and a surface channel network which is only a rough approximation of reality. However, Mark *et al.* (2004) conclude that urban flooding is a very complex phenomenon. The inability to include all details in modelling should not discourage attempts to use a 1D modelling approach. Studies by Mignot *et al.* (2006b) and Schmitt *et al.* (2004) used a 2D model to simulate floods. Based on these results the authors recommend using of a code solving 2D shallow water equations to assess flood risk.

2.5 Summary

The literature review highlighted the evolution and availability of modelling software along the years. The role played by hydrological models to integrate and support water management has also been identified. In the context of urban water management, they are particularly useful to help to understand urban hydrology and therefore forecast to the potential effects of and interlinks ages between new developments. The Refsgaards framework has been introduced and research carried out to identify how the presented framework has been followed by modellers to carry out their projects. The study identified that the framework was well followed; calibration and validation of the models were systematically carried out. However, uncertainty and sensitivity analyses have not always been carried out. Therefore, for the purpose of our study, the framework designed by Refsgaards will be adopted; Figure 2.7 resumed how the various steps of the framework were divided into the chapters of the thesis.

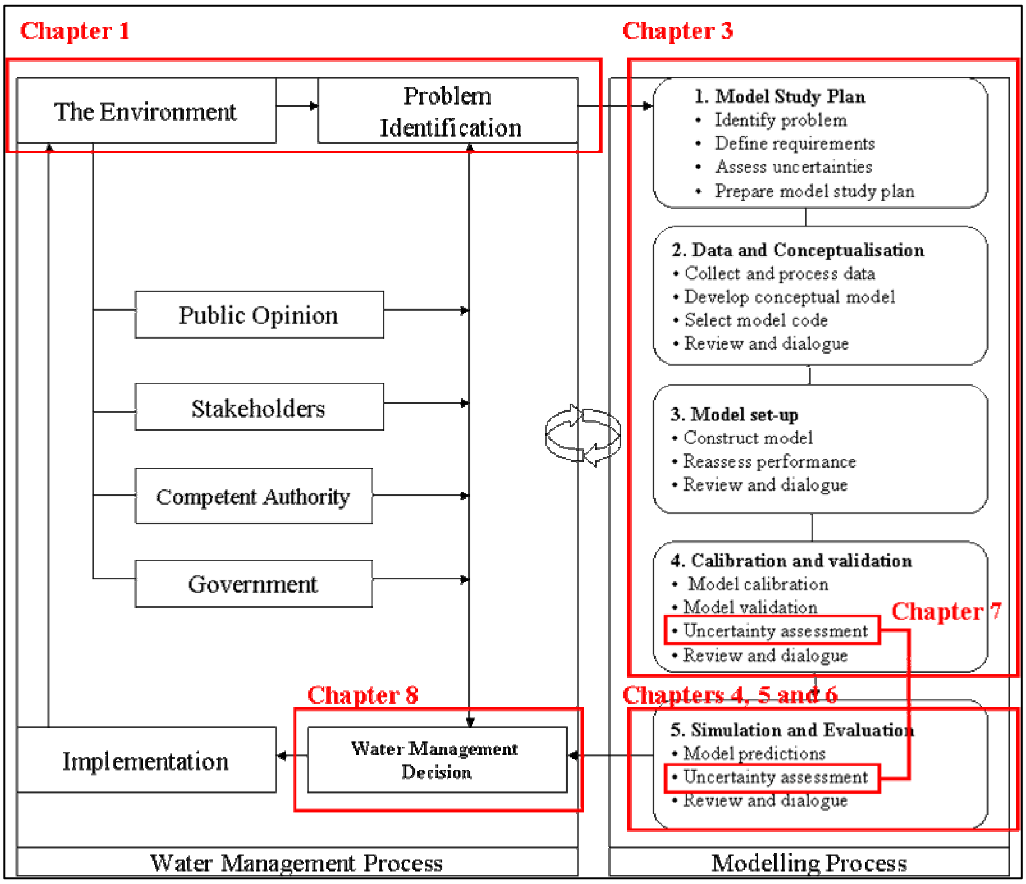


Figure 2.7. How the Refsgaards framework will be used for the thesis

This chapter reviews studies focusing on identifying the impacts of urban development and climate change at catchment scale. The findings introduced in Section 2.4 will be used in Chapter 8 in order to contrast the results obtained within our study.

The literature review also highlighted that the quantity of data available to carry out the studies varied considerably. Data used in the model needs to be as accurate as possible to obtain robust results and to avoid errors in forecasting runoff or flood events, as these outputs will eventually influence the decision-making process.

To conclude, modelling is a very powerful tool which can be used to forecast and support decisions in order to enhance water management. Nowadays, many software platforms and are available to carry out a wide range of studies from simple water demand forecasts, to climate change effects and flood risk assessments. The quality of the results is dependent on the amount and also the quality of data available. Model construction also requires accurate topographic data and knowledge of the catchment. Moreover, calibration, validation and sensitivity analysis requires a critical minimum amount of data to be carried out.

Chapter 3 Methodology

This chapter will introduce the methodology followed to conduct the study. The framework proposed by Refsgaard et al. (2007) and introduced in Chapter 2 was assessed to be a good guideline for carrying out the modelling study. It will therefore be used to structure the methodology chapter. Refsgaard decomposed the modelling process into five steps: i) model study plan, ii) data needed and available, iii) model set-up, iv) calibration and validation and v) simulation and evaluation. Therefore the following structure will be used in this chapter; the first part defines the study requirement and assesses the model uncertainties. The second part reviews the data and computer model selected. The third part is focused on reviewing how the model was built. The fourth part reviews the model calibration and uncertainty assessment carried out. And finally, the fifth and final part reports how simulation and evaluation were carried out in the study.

3.1 Model Study Plan

Chapter 1 already identified the importance and necessity of carrying out this study. As a consequence, this section details the study requirements and selection of the study area.

To be able to respond to the aims and objectives of the study (see Chapter 1), the study area must be subject to new development plans. However, the hydrology and geology of the catchment are the most important factors influencing the selection of a suitable catchment for this type of hydrological modelling. A small catchment with an impervious river system is required, as it is easier to assess the hydrological changes within a fairly small catchment as the flows and water levels will be more sensitive to rainfall events and changes in hydraulic stresses than within a bigger catchment. The criteria required to select the appropriate catchment for the study are listed bellow:

- Catchment size:

  A small catchment with a long river system will be ideal for the project as small catchments are easier to calibrate than large ones.

- Hydrology:

River system flowing along the catchment.

- Geology:

Impervious geology to avoid phenomenon such as groundwater recharge observed in chalk rivers for example.

- Gauges present on the catchment:

The catchment should have at least one rain gauge and one river monitoring gauge.

- Rainfall and flow data:

Rainfall and flow data should be available.

3.2 Conceptualisation

The conceptualisation section introduces the catchment selected and all the data collected to populate the model and scenarios. The applied modelling software is presented and the available functions of the tool are described.

3.2.1 Catchment selected introduction

The Carrickmines catchment was selected due to its small area, its non-impervious and long river system. Moreover, several flood events occurred in the Carrickmines catchment in recent years. The following two sections review the Carrickmines catchment geography, land use patterns, urban development phases, hydrology, climatic conditions and the results of previous hydrological studies.

3.2.1.1 Catchment geography, land use and urban development

The Carrickmines catchment is located in Ireland, south of Dublin in Dun Laoghaire County, (Figure 3.1). The catchment stretches approximately 9km from west to east and 6km from north to south. It covers an area of approximately 3,200ha with around 2,000 inhabitants in 2002, the majority of which live in the two towns of Carrickmines and Shanghanagh.

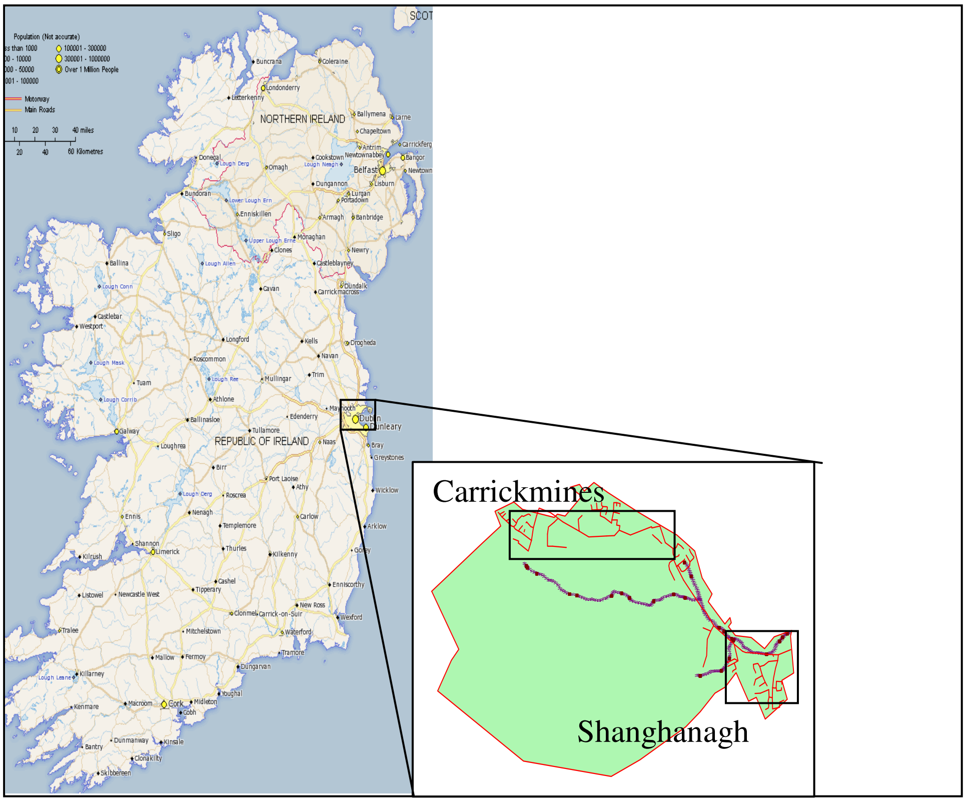


Figure 3.1. Geographical location of the Carrickmines Catchment (Source Tele Atlas, 2007).

The Carrickmines catchment is best described as semi-rural with urban areas accounting for only about 20% of the total land area (Figure 3.2). These urbanised, largely residential areas are mainly located in the north of the catchment. Detailed land use data was not accessible but a site visit showed that the southern parts of the catchment are mainly used for farming.

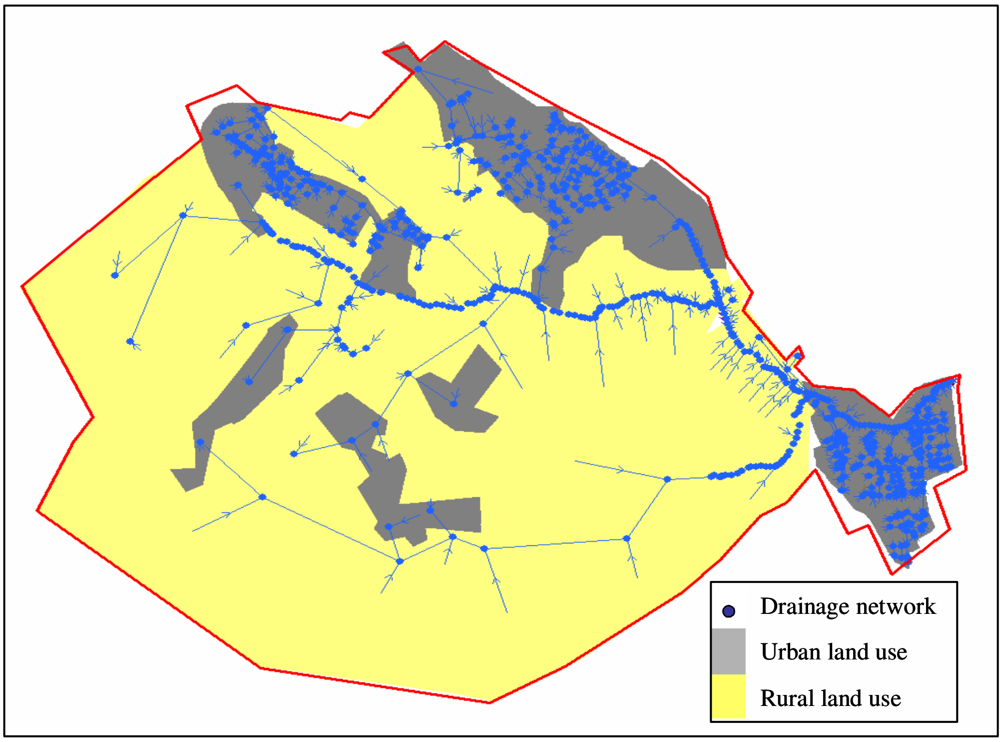


Figure 3.2. Carrickmines land use in 2002.

In 2007, Irish economic growth was expected to reach 6%, which represents double the EU average (Beary, 2007). Due to a healthy economy in Ireland and demand for new habitation, new residential developments are planned for the future. Figure 3.3 illustrates housing types to be built within the catchment in the coming years, the photograph on the left shows actual habitation which are fully detached houses whereas the picture present on the right shows future intensive type habitation to be built in the catchment.

Figure 3.3. Example of existing housing types in the Carrickmines catchment.

3.2.1.2 Carrickmines catchment hydrology, climatic conditions and past studies

The catchment's river system is composed of several water courses, primarily flowing from west to east, Figure 3.5 illustrates the river network. The two largest rivers are the Shanganagh River in the south and the Carrickmines River in the north, (Figure

3.4). The topography of the Carrickmines catchment varies from approximately 150m in the north around the main residential developments to almost 0m at the costal area.

Figure 3.4. Pictures of the catchment water bodies, a) from the Carrickmines river gauge; b) by at the junction of the Carrickmines and Shanganagh rivers, and c) from the Common's road from river gauge.

The major floods recorded at the river gauges are shown in Table 3.1 (HR Wallingford, 2001).

Table 3.1. Flows observed at the two river gauges during extreme rainfall events.

	Peak flow monitored at the river gauges	
Date of flood occurrence	**Carrickmines bridge**	**Common's road**
6th November 1982	5.4m^3/s	13.5m^3/s
26th August 1986	5.1m^3/s	11.5m^3/s
26th May 1993	6.9m^3/s	14.3m^3/s

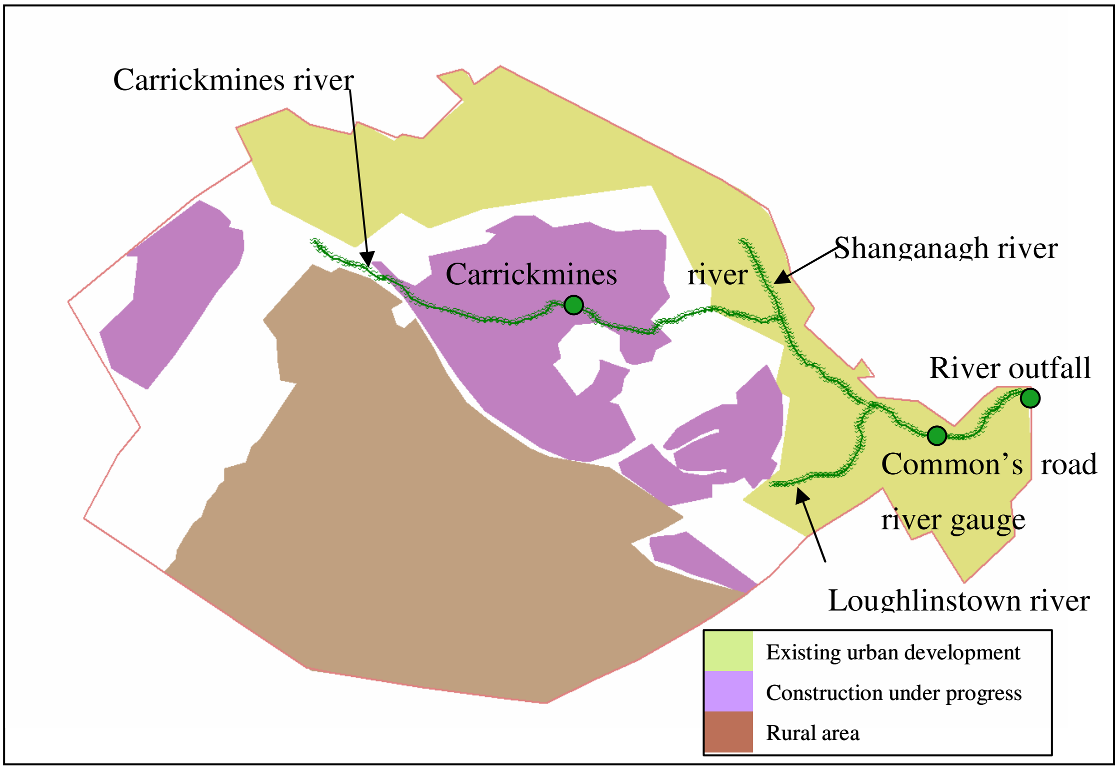


Figure 3.5 River system network within the Carrickmines catchment.

The annual average precipitation measured over the last 40 years in the Carrickmines catchment is 726.9mm. Figure 3.6 compares the annual rainfall events observed in the Carrickmines catchment with the annual rainfall events observed in England and Wales from 1960 to 1999. For all the observed years, the average rainfall for England and Wales has been higher than incident rainfall in the Carrickmines catchment.

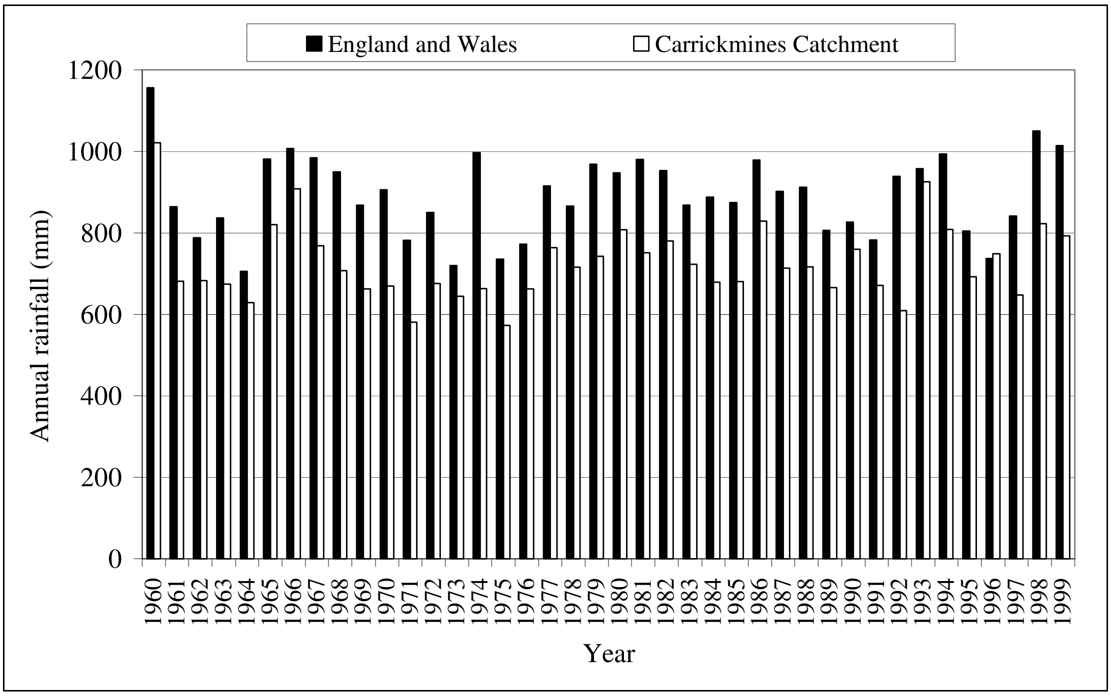


Figure 3.6. Comparison of annual rainfall in England/Wales and the Carrickmines Catchment from 1960 to 1999 (Adapted from data provided by HR Wallingford and Met office data assessed in 07/08).

The majority of sewer networks in Ireland are non-combined systems which provide separate channels for sanitary sewer and stormwater runoff, meaning that only a very small amount of rainwater enters the sewer networks. However, a small area of the Carrickmines catchment is contributing to the sewer network. This area has been estimated to be 5% of the roof area. Concerning the treatment work facilities available for the Carrickmines catchment, sewage is treated at the Shanghanagh Wastewater Treatment Work (WwTW). Due to the close proximity to the sea, the effluent from the Shangahbagh WwTW is discharged to the sea near Killiney Beach. In 2000, approximately 65,700 households were connected to the Shanganagh WwTW (GDSDS, 2005).

Three studies have been carried out by HR Wallingford on the hydrology and hydraulics of the catchment. In 2001 an assessment of the impacts of urban development on the hydrological and hydraulic conditions using InfoWorks^{TM}CS and ISIS was carried out (HR Wallingford, 2001). The second and third studies, (DDC, 2006a) carried out in 2005 assessed the impacts of urban development and climate change on the catchment hydrology and hydraulic networks (DDC, 2006b). Summary findings of the three reports are:

- 35 properties are likely to be flooded for a 50 year return period rainfall event.
- 29 sewer nodes at 14 locations have a flood in excess of $25m^3$ for 5 year return period events.
- The construction of the motorway and the impact of climate change will significantly influence runoff within the Carrickmines catchment.

3.3 Data available for the Carrickmines Catchment

Data were collected from January to June 2006. During a visit to the Carrickmines catchment (April 2006) and members of the Dun Laoghaire County Council were consulted to obtain a clearer understanding of the catchment. They provided the majority of the data used to populate the model, along with the Irish Environment Protection Agency (EPA) and HR Wallingford. Table 3.2 provides an overview of the data used to design and run the model for this study.

Table 3.2. Review of the data obtained to support modelling of the catchment

Data needed	Data obtained	Provided by
Hydrological data	River flows (10 years for Carrickmines river gauges and 16 years for Common data available) Hourly daily flows at the two river gauges, for the Carrickmines river gauges data from 82 to 92 are available and for the Common's Road gauges data from 81 to 97 are available. River Floods Peak flows observed in the two river gauges during flood events are available.	EPA/ HR Wallingford
Hydraulic data	Sewer flow (1month data available) Daily Average, Minimum, Maximum and total flow available from the 1st of June 2006 to the 31st of June 2006. Daily rainfall data at the two locations for this period are also available.	DLCC
Climatic data	Rainfall (39 years data available) Hourly rainfall data in mm from the Casement Aerodrome at Baldonnel from 1980 to 1997 Dublin Daily rain from 1960 to 1999, 12 rain gauges included Casement Aerodrome Evapotranspiration Monthly data January to December	HR Wallingford
New urban development	Urbanisation plan (number, size of houses, population) The development plan contains: 1) overview strategy, future resident developments and review of new development per area (number of houses/ density/ area) 2) 14 maps of the future development 2004-2010 of the Dun Laoghaire catchment	DLCC
Technology	Information such as: volume of water use per day per inhabitant, required to implement technology within the hydraulic model were searched within literature available in order to design the most appropriate and realistic recycling systems.	Literature detail in Sections 3.4.2 and 3.4.3.
Catchment data	South Eastern Motorway River Catchment Study (Report 1) Carrickmines Catchment, Phase 2 Model Preparation, Verification and System Performance (Report 2) Carrickmines Catchment, Phase 3 – Needs, Options and Strategy (Report 3)	DLCC DDC DDC

3.3.1.1 Irish Water Management context and policies

Ireland is among the European countries with the highest availability of freshwater, with a relatively high rainfall and low population density. This water represents a key economic resource as a supply for domestic, industrial and agricultural uses. It is also important in terms of ecosystem, tourism and leisure uses. Ireland is the only country in Europe where water is not taxed. Therefore, there are no meters to help for householders limit their water consumption. As a result, Irish daily water consumption is very high; it has been estimated by Waterwise to reach 190 litres per person per day (Defra, 2008). On top of that, in 2000 47% of water has been estimated to be lost nationally through leakage (WWF, 2003). So far, Ireland has not suffered from water scarcity due to the huge volumes of freshwater available. Nevertheless, surface waters suffer from eutrophication caused primarily by agricultural activity; this problem causes economic and environmental impacts. Moreover, with WFD objectives focused on promoting good ecological status all over Europe by 2015, Ireland will have to control and solve point source and diffuse pollution problems. Floods from rivers and stormwater pipe networks in response to extreme rainfall events often also occur due to urbanisation (GDSDS, 2005). In 2000, the Office of Public Works (OPW) identified up to three hundred areas of the country at serious risk of periodic flooding (WWF, 2003).

In December 2003, the WFD was transposed into Irish law. It designates the Irish Environmental Agency (EPA) and local government authorities as 'Competent Authorities'. It also states the duties of each Competent Authority and provides a framework for coordination between these bodies under each article of the WFD. The EPA tasks are to identify and map River Basin Districts (RBD), map and categorize water bodies for the purposes of Article 5 and draw up a programme of water quality monitoring. The EPA is also in charge of facilitating and promoting the coordination of activities for Articles 4, 5, 7, 10, 11 and 13 of the WFD (see 2.1.1, Figure 2.2). The 26 local government authorities have been designated to establish the environmental objectives, the monitoring programmes and the setting up of river basin management plans. These bodies have overall statutory responsibility for water management. They also have responsibility for public water supply and wastewater treatment. The formulation of policies and legislation on water quality, water supply and wastewater related services are implemented by the department of Environment, Heritage and local Government (DoEHLG). Other government departments have various functions with regard to water quality and water management. For example, the Office of Public Works (OPW) carries out land drainage and flood protection works.

In Ireland there are four river basin districts (RBDs) wholly within the State: the Eastern, South Eastern, Western and South Western. In 2004 a characterisation and analysis of all RBDs in Ireland was undertaken as required by Article 5 of the WFD. In this characterisation study the impacts of a range of pressures were assessed including diffuse and point sources pollution, water abstraction and morphology (EPA, 2008). The WFD provides the option of supplementing the strategic RBD Management Plans with sub-basin plans. Sub-basin planning deals with particular aspects of water management either at a smaller geographical scale or in respect of a particular issue, and could play a key role is securing participation at a local level.

To support the Eastern RBD the Great Dublin Strategic Drainage Study (GDSDS) is focused on improving urban drainage in the Dublin Local Authorities area and has been implemented. The two projects aim at protecting water quality through the implementation of measures to control runoff quality and point and diffuse source pollutions.

3.3.2 Modelling platform selection

Concerning the computer tool to be used for the study, the modelling tool needed to be suitable to carry out both hydraulic and hydrological flow and flood analyses such as rainfall to runoff formation, overland flow and flow in the sewer system. Moreover, the model needed to allow for greywater recycling and rainwater harvesting systems to be represented within the tool.

In this research InfoWorks^{TM} Collection System (CS) version 6.5 developed by Wallingford Software is used as the modelling platform. The main application of the software is the combination of modelling hydraulic and hydrological models to predict floods and to support the integrated management of the water cycle which is required for the purposes of the project. InfoWorks^{TM} CS is widely used by water utilities such as Thames Water, as well as by environmental consultancies and Local

Authorities in England and Ireland and has proven to be a robust model in similar studies. Moreover, previous studies of the Carrickmines catchment have been carried out within InfoWorks^{TM} CS and a version of the model was provided by HR Wallingford for the purpose of this study.

InfoWorks^{TM} CS combines two models: a hydrological model simulates runoff rainfall and a hydraulic model represents flows in pipes (Figure 3.7). The two models are separated when simulations are running. The software first computes the surface runoff from rainfall, from which a surface hydrograph is determined for each sub-catchment. Then, the runoff hydrographs previously computed from each sub-catchment are used as input for the hydrodynamic model, simulating the flows in pipes and street systems.

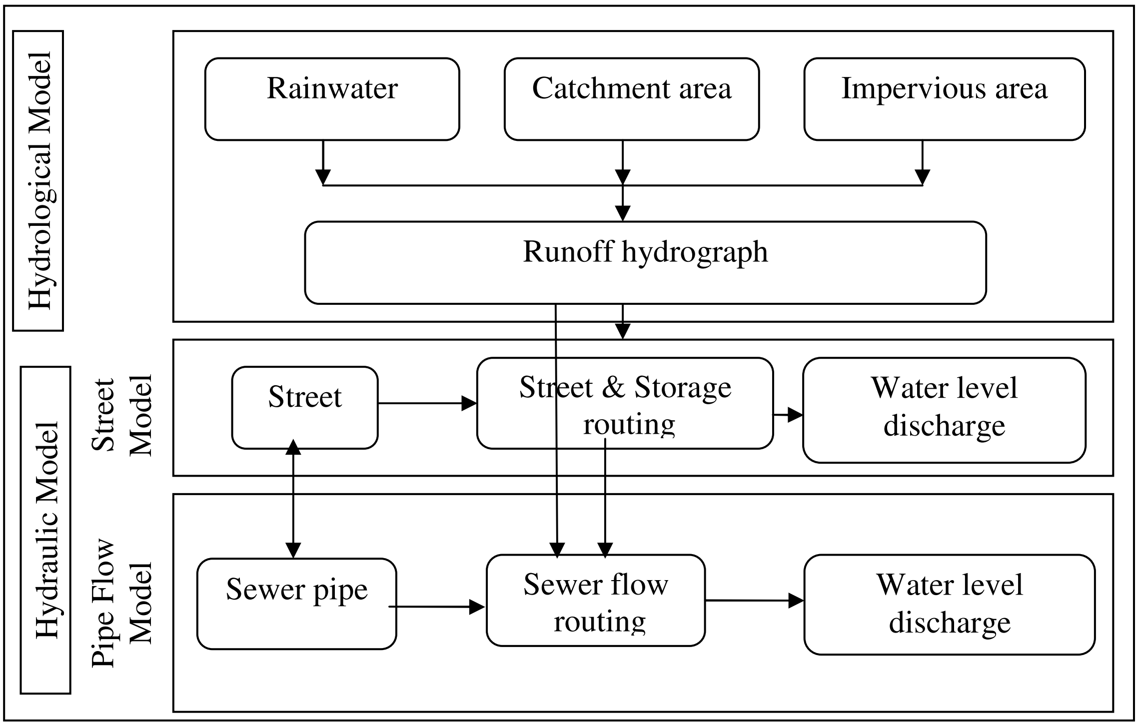


Figure 3.7. Interactions between hydraulic and hydrological platforms in an integrated urban water modelling approach. (adapted from Mark *et al.*, 2004).

3.3.2.1 The hydrological models

In the context of this work, the hydrological models integrate the urban catchment and the rainfall events to compute the surface runoff for individual sub-catchments. Two main types of rainfall data are used in InfoWorks^{TM} CS: observed and synthetic. Observed rainfall data represents actual rainfall events whereas synthetic rainfall represents a statistical event of known length and return period, derived from the analysis of rainfall records. Rainfall events are distributed uniformly over one sub-catchment, but variation can be applied over the whole catchment from one sub-catchment to another. Evaporation is generally considered to be of lower importance for the within-event representation of rainfall losses. As the amount of evapotranspiration (Et) is dependent on the weather conditions, it largely varies according to the time of the year. The amount of evapotranspiration is higher during summer time than winter. To estimate Et, InfoWorks^{TM} CS uses a simple equation to represent actual evapotranspiration in the UK and Ireland (Equation 3.1), where Et is the potential evapotranspiration rate (mm/day) and j is the day number since start of the year.

$$Et = 1.5\ (1+\sin\ (2\ \pi\ j\ /\ 365 - \pi\ /\ 2)) \qquad \textbf{Equation 3.1}$$

The percentage of runoff (PR) is generated as a function of the characteristics of the ground surfaces in the catchment, and the rainfall-runoff model which is used for each surface type. This defines how much of the rainfall occurring in a catchment runs off and how quickly it enters the drainage systems. The runoff equation was designed to be applied to typical UK urban catchments and is able to represent the transformation of rainfall into runoff for urban catchment areas contributing to piped and channelled drainage systems. Equation 3.2, also called the PR Equation, shows how InfoWorks^{TM} CS calculates PR based on the percentage of impermeability (PIMP) calculated for the respective catchment (see below), the Urban Catchment Wetness Index (UCWI) and the index of the water holding capacity of the soil (SOIL).

$$PR = 0.892\ PIMP + 25\ SOIL + 0.078\ UCWI - 20.7 \qquad \textbf{Equation 3.2}$$

The percentage of impermeability is an important factor in determining the percentage of runoff in individual sub-catchments. Therefore for each sub-catchment, the percentage of impervious and pervious surfaces has to be identified in order to compute PR. The percentage of impervious and pervious surfaces is introduced in InfoWorks^{TM} CS under the following appellations: R1, R2 and R3. Where R1 represents the roof area connected to the sewer network, R2 the road surface area and

R3 the pervious area. For each sub-catchment, R1, R2 and R3 have to be calculated and entered in order to compute the percentage of runoff for each sub-catchment.

InfoWorks^{TM} CS includes a simplistic representation of river cross sections. The river cross section is divided into a series of panels, in each panel the flow is one dimensional and is calculated independently. Therefore flow can spill from one panel to another one. Each section of the channel is considered to be trapezoidal for the purposes of calculating width, area, and wetted perimeter. The conveyance in the channel is the sum of the conveyances in each panel.

3.3.2.2 The hydraulic model and sewer transport

The hydraulic model is divided into two virtual platforms, the street model and the pipe flow model. The street model represents the drainage from the roof and roads whereas the pipe flow model computes the wastewater flow in the catchment. For both models, InfoWorks^{TM} CS computes the wastewater flow or stormwater flow.

In the street model and the pipe flow model, hydraulic flows are generated in conduits, also called links. The conduits' lengths are defined by the distance between the two respective nodes of each pipe. The gradient of each pipe is defined by the invert level at the each end of the link. A variety of pre-defined cross-sectional shapes may be selected for both closed pipes and open channels. Generally, circular cross-sections are selected to represent pipes within the pipe flow model and open channels for street drainage within the street model.

Pump systems can be applied within the hydraulic model in InfoWorks^{TM} CS. The user defines the pumping flow rate and the pump is controlled by the switch-on and switch-off levels for the water level in the upstream node. A Real Time Control (RTC) function is also available to set up to control the operation time of the pumps. In this way, pumping flows can be controlled throughout the system according to the time and water level in the node.

3.3.3 Modelling flooding

Within InfoWorks^{TM} CS, the flood volume is expressed as a function between the depth of flooding and the volume of flood. The model indicates the volume of flooding at different flood depths in two conical volumes as shown in Figure 3.8. Therefore, high resolution data on catchment topography are required to compute water flood volume. Moreover, it has to be noted that floods are simplified. Indeed, InfoWorks^{TM} CS stores flood water in a virtual reservoir and the stored volumes flow go back into to the system once capacity becomes available.

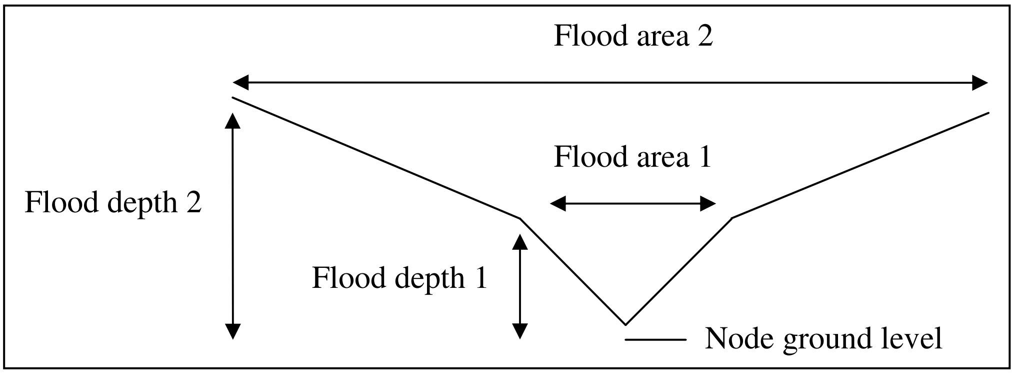


Figure 3.8. Flood level representation in InfoWorks^{TM} CS

The way floods are simplified within the stored flood option influences the overland flow paths that might be happening on the surface. Therefore, newer versions of InfoWorks^{TM} CS (from version 8.5) incorporate a 2D surface model in order to account for the complex interactions between surface flows, flow paths and the network flood events. However, the modelling has been carried out with the version 6.5 as version 8.5 is only available since 2008.

3.4 Model set-up

In order to achieve the aim and objectives of this research, both new urban development and greywater recycling and rainwater harvesting technologies have to be implemented within a modelled representation of the Carrickmines catchment. Section 3.4.1 reports the design of the urban development scenarios, followed by the specification of the greywater recycling and rainwater harvesting systems in Sections 3.4.2 and 3.4.3 respectively.

3.4.1 Design of the new urban development

Maps provided by the Dun Laoghaire County Council were used to identify the location of new housing and commercial developments to be built by 2010 (Figure 3.9). Dwelling and business developments are expected to be very dense with 50 to 80 units per hectare (Gough and Cremins, 2004). For the situation in 2050, no information was available and therefore the remaining urban area south of the catchment was assumed to be fully developed at the same level of density within the next 40 years. Table 3.4 details the designed scenario for urban development in the catchment.

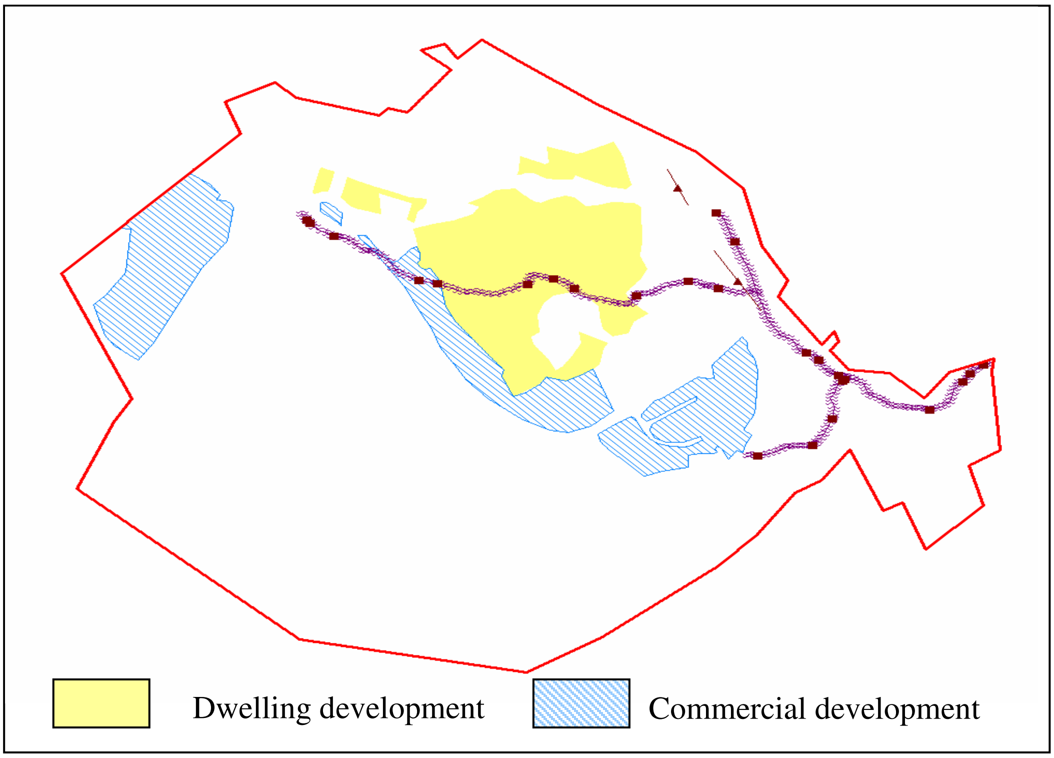


Figure 3.9. 2010 development locations (Information obtained from the Dun Laoghaire development plan)

Table 3.3. Urban development scenarios extrapolated from development plan

	2010 new development area	**2050 new development area**
Total area of new development	325ha resident development and 350ha office development	1,284ha resident development
Total Inhabitants	20,000 residents and 10,000 workers	83,600 residents
Inhabitants per building	72 per domestic and 150 commercial	76 resident development
Number of node[1] added to the model	278 residents nodes and 66 office nodes	1100 residents nodes

[1] for development 2010 and 2050, one node in the Carrickmines catchment represents one building.

3.4.1.1 Urban development implementation in the model

Using the information detailed in Table 3.4, two development scenarios were designed. To implement urban development within the model, the existing hydrological and hydraulic components had to be augmented. First of all, sewer networks using a pipe flow model were designed, then the runoff hydrograph and impervious area parameters were updated and finally a street model was specified. The following paragraph details the methodology used for each of these steps.

To design the sewer network, new nodes representing the new buildings were specified. Three sewer networks were designed, the first one to represent the baseline 2002 sewer network and the other two to represent sewer networks for 2010 and 2050. Existing maps of the catchment were used to identify the location of existing habitations to insert the nodes for the 2002 scenario, 1,225 houses were identified. For the 2010 scenario, the location of new housing developments was derived from urban planning maps provided by the Dun Laoghaire County Council (Figure 3.9). However, the development plan only provides very rough indications of the areas which will be developed and fails to detail the exact location of new buildings. Therefore houses and nodes were located randomly within the development areas outlined by the urban development plan. Due to a lack of plans outlining strategies for urban development in the catchment beyond 2010, polygons were drawn in the remaining rural area of the Carrickmines catchment and nodes were then added randomly to provide a scenario for 2050.

Ground elevation of the implemented existing nodes was identified. However, due to the unavailability of a full elevation map of the Carrickmines catchment (data not available) within InfoWorks^{TM} CS, the Network Inference function had to be used to calculate the ground-level of all newly specified nodes according to the ground-level of already present nodes. In cases, where the software failed to calculate the ground level due to too long distances between nodes, the respective nodes were removed and the scenarios re-arranged.

New urban development areas within the model were divided into sub-catchments (one sub-catchment per node). The division of the urban area into sub-catchments is necessary to be able to estimate the contribution of each area to the sewer network flows. The runoff coefficient (R1) represents the area of roof connected to the sewer which is calculated using Equation 3.3, with the impervious area = 70% of the new development, the total roof area = 40% of the impervious area and roof area contribution to sewer = 5% of the roof area.

R1= sub-catchment area * Impervious area * total roof area * roof area contributing to sewer **Equation 3.3**

The R1 determined through Equation 3.3 is different for each sub-catchment as the calculation is dependent on the sub-catchment surface area. However the type of buildings located in the sub-catchments was assumed to be the same in all future scenarios. The roof area values obtained varied from 0.18ha to 0.0004ha with an average connected roof area of 0.04ha. To conclude, the method used to calculate roof area connected to the sewer network overestimates the roof surface area connected to the sewer network for some sub-catchments. Therefore during heavy rainfall, the volume entering the sewer will be also overestimated which may promote sewer flooding.

The wastewater network is designed to move sewerage from the North-West of the catchment to South-East of the catchment. Due to the hilly topography in the centre of the catchment, it was impossible to connect all new housing developments and design one fully gravity fed system for the entire catchment. Pumps could have been added to connect the sewer networks. The addition of pumps, an option which was considered to connect the sewer networks, was foregone due to their potential instability. Thus, it was decided to design individual sewer networks. Once all the pipes were implemented in the model, the upper and invert levels were calculated using the Network Inference function available in InfoWorks^{TM} CS. The size of the sewer pipes was determined based on the literature since data was not available. According to Reed (1995), sewer pipes should be as small as possible and the minimum pipe size generally ranges from 75 and 100mm for houses to 100 to 150mm for the upper reaches of public networks. Eventually, circular pipes were selected with a diameter of 150mm for all the pipes of the new urban developments within the catchment. Finally, pipe size had to be increased for some sections due to the flooding observed during dry events (when no rainfall occurs). Pipe sizes were upgraded from 150mm to an adequate diameter until no floods happened during a period of 24hours when no rainfall occurred (Table 3.4).

Table 3.4. Review of the diameters of pipes.

	Number of pipes with the following diameter size (mm)									
	150	**175**	**200**	**250**	**375**	**300**	**400**	**425**	**475**	**675**
2010 development	353	0	17	1	0	1	2	0	0	0
2050 development	353	251	18	1	55	1	2	17	2	1

Urban drainage systems were introduced to the model to drain storm water to the river. Urban drainage networks were only designed for 2010 and 2050 scenarios as the 2002 scenario already had a drainage system implemented. The same methodology used to design the sewer network was followed. The nodes were added first, followed by the division of the catchment into sub-catchments, calculation of the new runoff coefficients, pipe implementation and finally connection to the river section. To add nodes, sewer nodes were duplicated and their ground-levels were elevated from 20mAD. Then the polygon was divided into as many sub-catchments as nodes added per new urban polygon. The runoff coefficient for each sub-catchment was then calculated to estimate the area of roof and road that are connected to the street network. Equation 3.4 represents how the runoff coefficient was calculated.

New R1= Roof and Road area not connected to sewer **Equation 3.4**

The street network is a copy of the sewer network; coordinates of the conduits are similar. The shape and size of the conduits are rectangular with a width of 1500mm and a height of 1000mm. The street network drains directly to the river at six locations and to the already existing street network at three locations. The three street networks are illustrated in Figure 3.10.

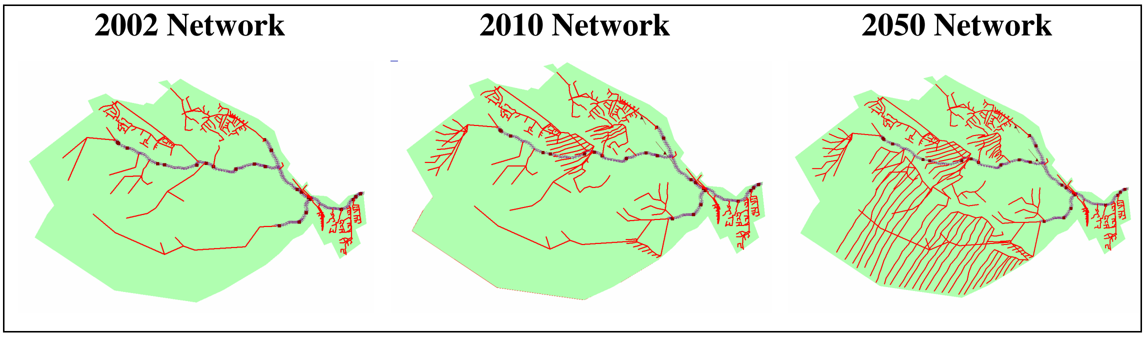


Figure 3.10. The three street network design

As noted above, Waterwise (Defra, 2008) data estimate the Irish average water use at about 190 litres per person per day. The Waterwise data highlights Ireland as the third biggest water consumer of water in Europe after Spain. For example, in the United Kingdom consumption is estimated to be 150 litres per person per day and in Germany 127l. Therefore, 150 litres was selected to be the wastewater volume produced per person for the purposes of the study. Moreover the water usage patterns have to be taken into consideration within the model in order to have a realistic wastewater volume and peak flow in the sewer. Therefore to represent the daily wastewater production per inhabitant the profile in Figure 3.11 was used.

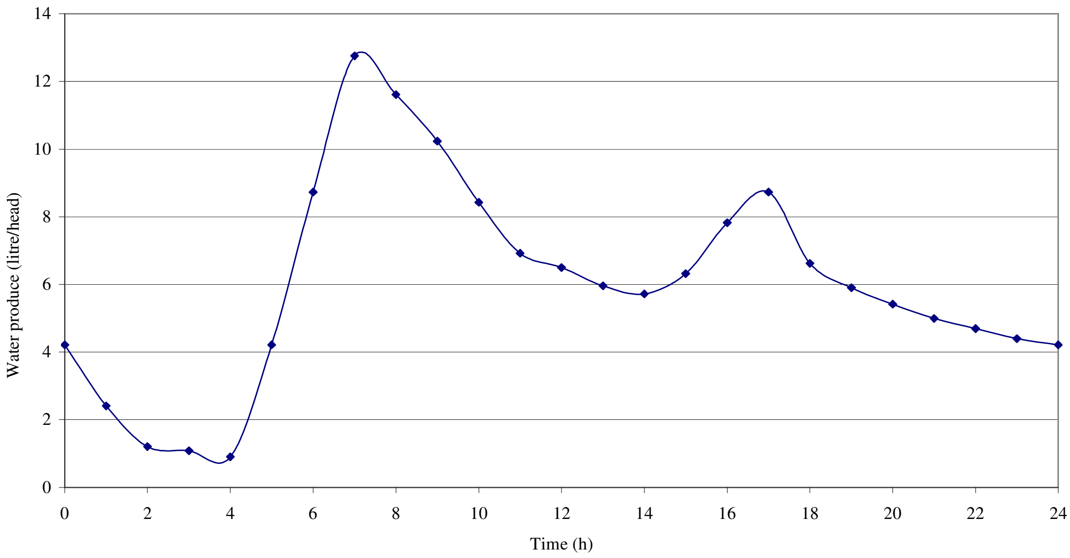


Figure 3.11. Typical wastewater profile. (from HR Wallingford, 2005)

Finally, a base model design of the Carrickmines catchment implemented by HR Wallingford has been updated in order to represent the land use changes involved in the new development. This included updating the percentage of impermeable area and the runoff hydrographs, Equation 3.5, Equation 3.6 and Equation 3.7 were used to calculate the new coefficients.

New R1= Initial R1 + total area *impervious area **Equation 3.5**

New R2= Initial R2 **Equation 3.6**

New R3= Initial R3 - total area *impervious area of new development **Equation 3.7**

Figure 3.12 shows the size and location of the urbanised areas in the three development scenarios which are detailed in Table 3.5.

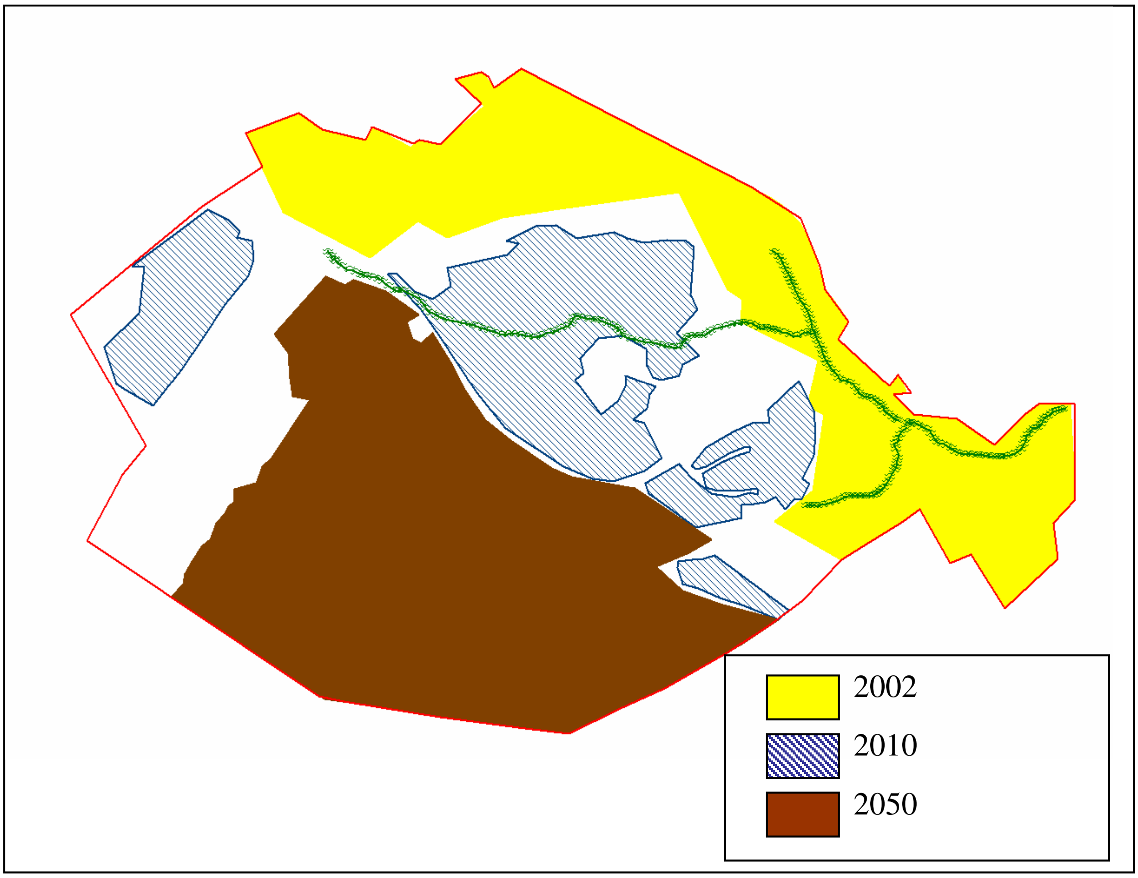


Figure 3.12. Final urban development implementation in the Carrickmines catchment.

Table 3.5. Urban development scenarios extrapolated from development plan

	2010 new development area	**2050 new development area**
Total area of new development	560ha residential development	1,422ha residential development
Total Inhabitant	30,876 residents	82,944 residents
Inhabitants per node	108 and 150 per house block	256 resident development
Number of nodes added	261 residents nodes	324 residents nodes

Using the three urban developments designed, three basecase networks have been built in InfoWorks CS called: basecase 2002, 2010 and 2050 respectively. The three networks do not include representations of greywater recycling and rainwater harvesting systems. They will be used as reference conditions blank to identify the influence of implementing technologies on the catchment hydraulics and hydrology.

3.4.2 Representation of greywater recycling system

The following sections outline the implementation of greywater recycling technologies in the base model. Systems are introduced at three different scales, namely at block scale (one greywater recycling per building), neighbourhood scale (five buildings connected to one system) and municipal scale (one system for the whole catchment) in order to investigate the influence of scaling up greywater recycling systems on the hydraulic and hydrologic performance of the Carrickmines catchment. Tank sizes, greywater generation profiles and pumping rates are linearly and proportionally scaled up according to the size of the system.

The initial approach to model greywater recycling was to represent a greywater recycling system within InfoWorks^{TM} CS. A tank, a pump and an overflow back to the sewer were implemented. Tank sizes were derived from the relevant literature. (Sundendran & Wheatley, 1998; Brewer *et al.*, 2000; Gerba *et al.*, 1995; Santala *et al.*, 1998 ; Friedler *et al.*, 2004 ; Mars, 2004). Table 3.6 shows the size selected for each development scenario and scale.

Table 3.6. Storage tank size selected for the greywater modelling activity.

	Size of the greywater technology tank (m^3)		
	Block	**Neighbourhood**	**Municipal**
2010 development	5.4	27	281
2050 development	12.8	64	832

Greywater system operation was based on 50l of greywater being generated per day per person and greywater being pumped back to the house twice a day between 07.00 to 08.30 and 20.30 to 22.00. Within InfoWorks^{TM} CS, each node and its respective catchment is linked to a wastewater profile which generates the wastewater quantity produced for each particular scenario. A tank was added with a pump and a weir to represent each greywater system (Figure 3.13). The greywater production profile determined by Sundendran and Wheatley, (1998) during their study was used to create wastewater profiles to be used. Figure 3.14 reviews the two wastewater profiles applied to the hydraulic model to represent greywater recycling systems with WP1 representing the wastewater produced minus the greywater produced per hour and per head and WP2 representing the quantity of greywater produced per hour and per head.

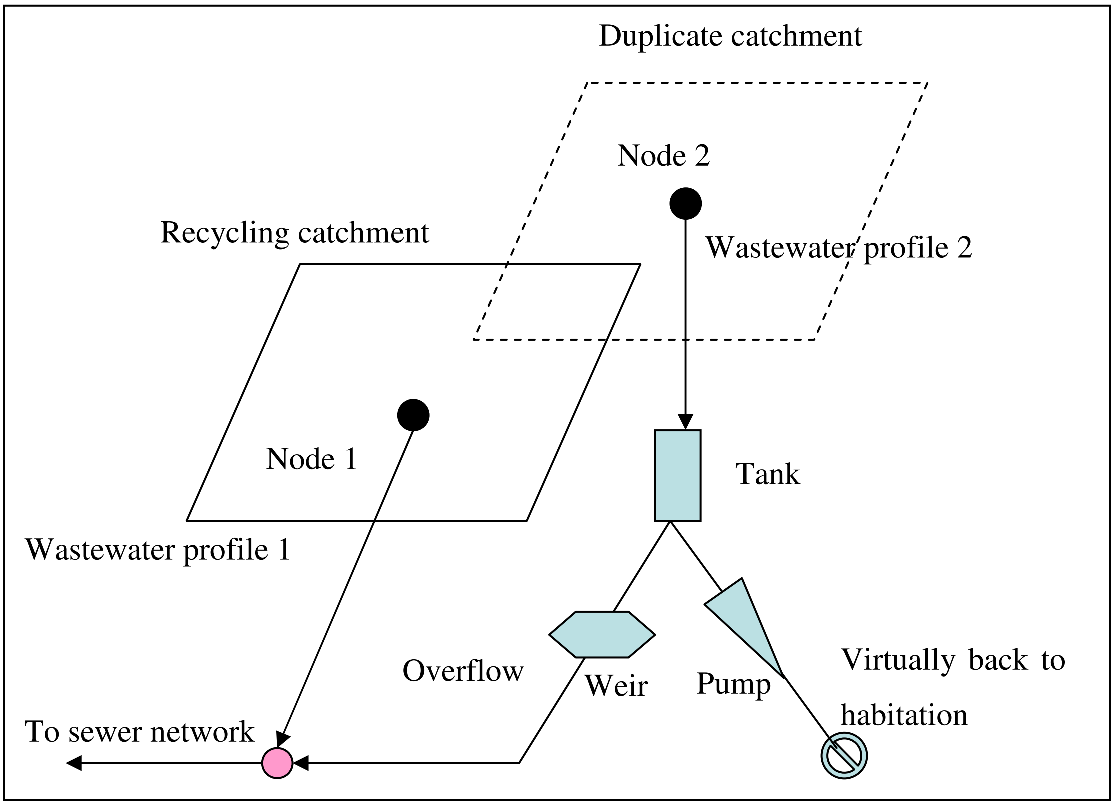


Figure 3.13. Representation of Greywater re-use system.

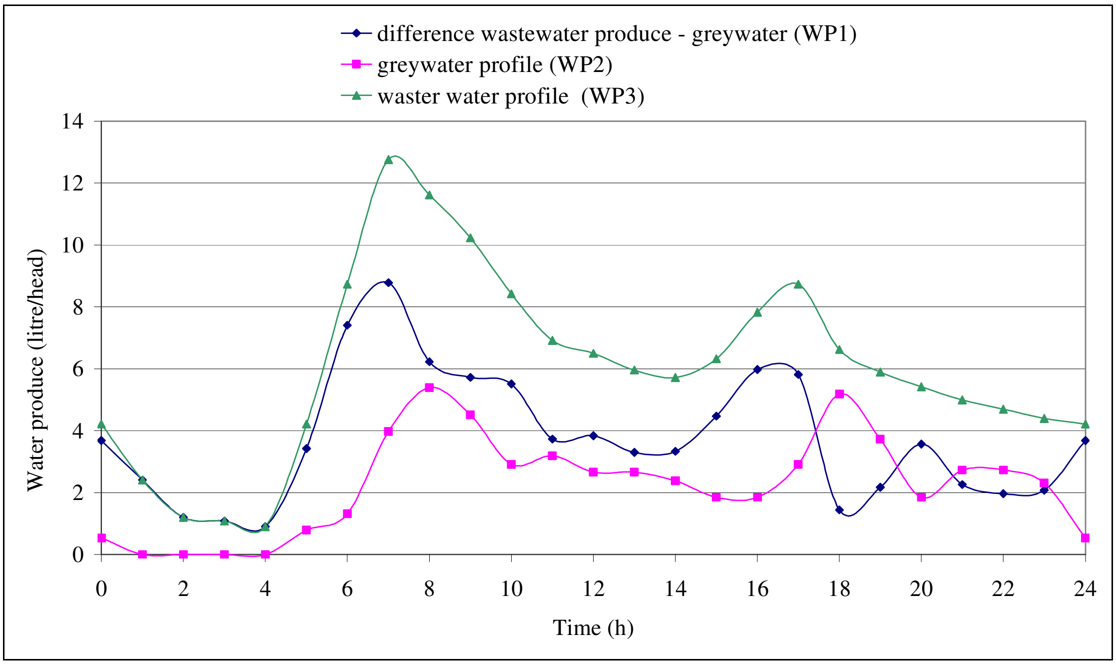


Figure 3.14. Wastewater profiles implemented to represent greywater production (adapted from Sundendran & Wheatley, 1998).

Figure 3.15 shows the volumetric variation within the three different scales of greywater system modelled. The way pumps were set up (twice a day between 07.00 to 08.30 and 20.30 and 22.00) influence the level of greywater present in the tank in such a way that the result of the tank level does not match reality. In order to obtain, a more suitable tank level, an hourly pumping ratio corresponding to the volume of greywater usage throughout the day should be implemented. However, due to the complexity to set up pumps in InfoWorks™ CS it has been decided not to work with hourly pumping and fixed pumps have therefore been preferred for this study.

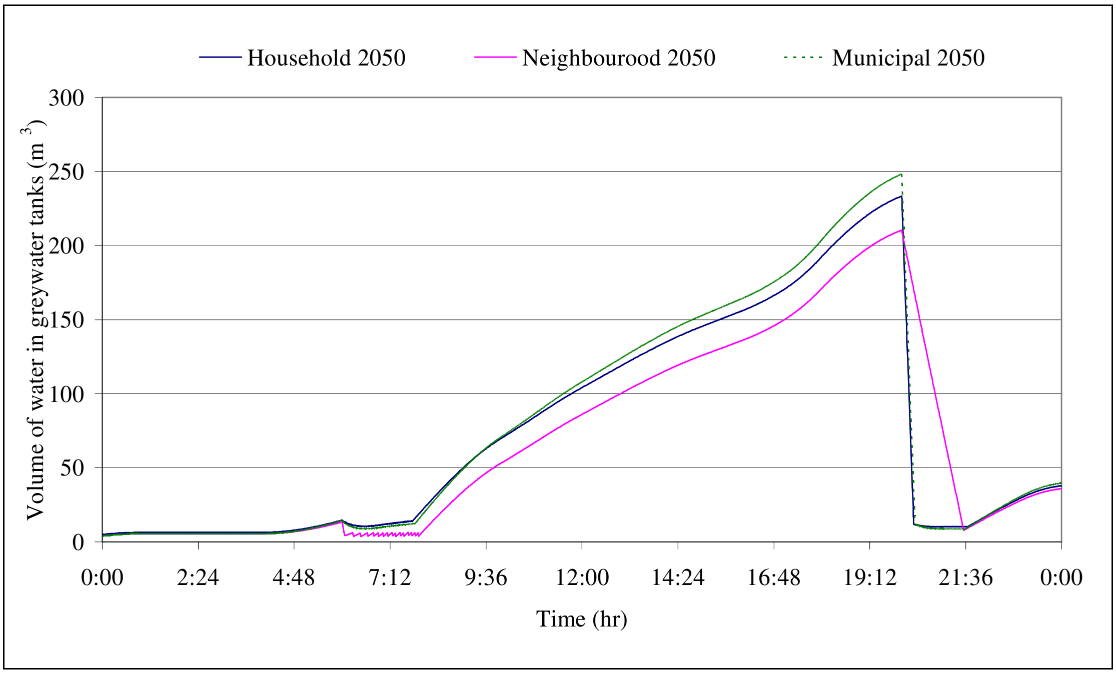


Figure 3.15. Variation of volume in greywater tank over 24 hours.

Because of the difficulty faced to obtain realistic greywater level in the recycling systems, the tank, pumps and weir were not implemented to represent greywater within their respective network as they were not needed. Wastewater profiles were changed from WP3 to WP1 where appropriate (Figure 3.14). However, using this method the representation of some scales (e.g. neighbourhood and municipal) can not be achieved. Therefore only block scale applications (referencing to single block with 108 person connected) were explored. Concerning the hydrological model, no change was required. The sub-catchments and runoff coefficients remain the same as for their respective basecase networks.

Table 3.7 and Table 3.8 provide a detailed overview of the greywater recycling systems specifications implemented under each urban development scenario. The locations of the greywater recycling systems are shown in Figure 3.16 and Figure

3.17. Habitations in orange do not recycle whilst those in yellow are connected to a greywater system.

Table 3.7. Design of greywater systems within each scenario

Development	Scheme scale	% of buildings connected	Number of systems	Number of total inhabitants connected	Number of inhabitants per system	Tank Size in m^3
Existing development		0	0	0	0	0
Basecase 2010	No recycling	0	0	0	0	0
Extended	Block	20%	52	5616	108	5.4
		50%	129	13932	108	5.4
		80%	206	22248	108	5.4
Basecase 2050	No recycling	0	0	0	0	0
Extended		20%	65	16640	256	12.8
		50%	164	41984	256	12.8
		80%	260	66560	256	12.8

Table 3.8. Simulation label matrix

	2010			**2050**		
% Buildings connected	20%	50%	80%	20%	50%	80%
Simulation label	1B2010	2B2010	3B2010	1B2050	2B2050	3B2050

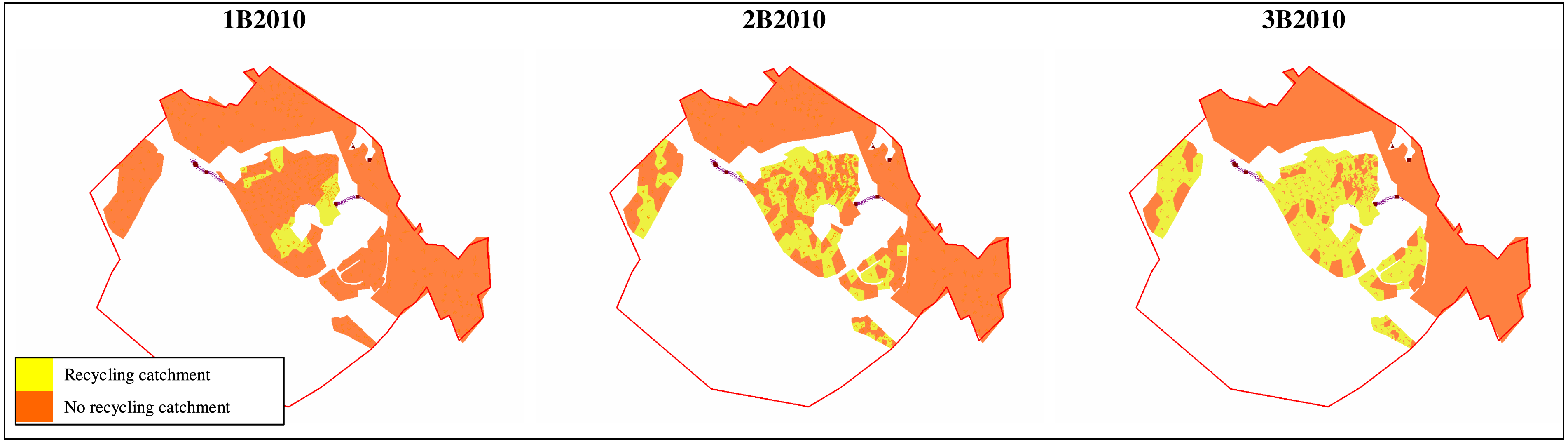


Figure 3.16. Location of sub-catchment connected to a greywater recycling technologies in the respective scenarios within development 2010.

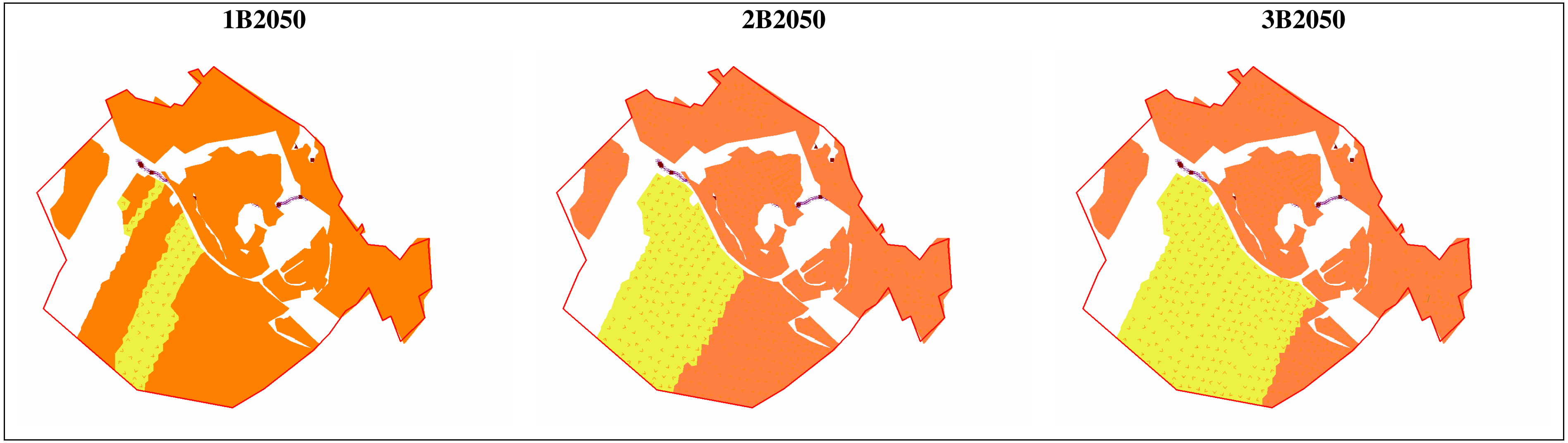


Figure 3.17. Location of sub-catchment connected to a greywater recycling technologies in the respective scenarios within development 2050.

3.4.3 Representation of rainwater harvesting systems

Having presented the different greywater recycling schemes and their integration into the hydrological and hydraulic model in InfoWorks^{TM} CS, this section reports how rainwater harvesting systems were represented in the model.

For each rainwater harvesting system represented within the model, a tank, a pump and an overflow back to the river system were defined. The most suitable tank size for rainwater harvesting was determined to be 0.75m^3 per habitant connected to the system, as recommended by Kellagher and Maneiro Franco (2005) (Table 3.9).

Table 3.9. Storage tank size selected for the rainwater modelling activity.

	Size of the rainwater harvesting technology (m^3)		
	Household	**Neighbourhood**	**Municipal**
2010 development	81	405	4212
2050 development	192	960	12480

Roof area sub-catchments to which the rainwater harvesting systems could be connected were generated. The runoff coefficients applied to the re-using sub-catchments were calculated from Equation 3.8 (CIRIA, 2001). This runoff coefficient indicates how much rainwater is entering the rainwater harvesting tanks. It is dependent on the roof area, the filter coefficient and roof coefficient. The filter coefficient was assumed to be equal to 0.9 and the roof coefficient equal to 0.85 (CIRIA, 2001).

Recycling catchment R1= Roof area * Filter Coefficient * Roof Coefficient **Equation 3.8**

Figure 3.18 resumes the approached followed to represent rainwater harvesting systems within InfoWorks CS.

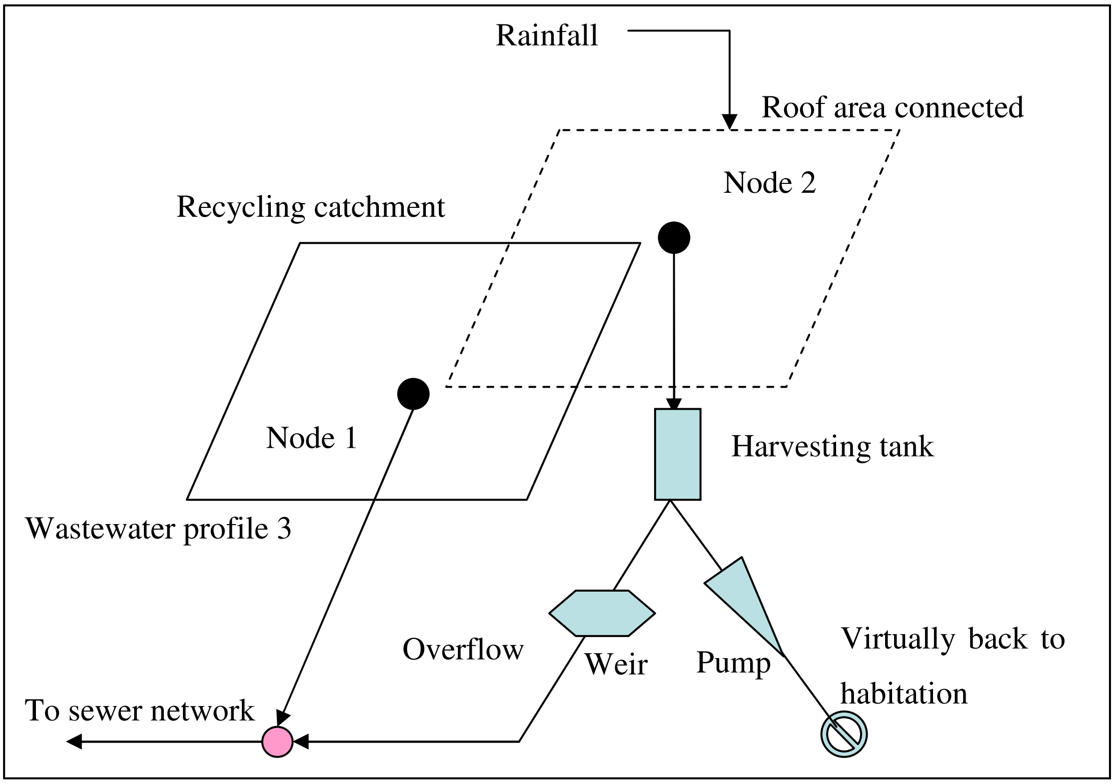


Figure 3.18. Representation of Rainwater harvesting system as implemented in InfoWorks CS.

The rainwater recycled for household use was assumed to be pumped and recycled twice a day between 07.00 to 08.30 and 20.30 to 22.00 at the rate of 50l per day per in habitant. For each scenario an adequate Real Time Control (RTC) file was set-up in order to pump the right amount of water. An overflow system was applied to each tank in the shape of a weir which was connected to the nearest street network and river network.

As the implementation of rainwater harvesting systems does not influence domestic water consumption, the wastewater profile applied to the sewer network (see Figure 3.11) remains unchanged. However, the runoff coefficients of all the sewer sub-catchments connected to rainwater harvesting systems are set to 0 as their roofs are no longer connected to the sewer network.

In the hydrological model, the street network had to be updated for each appropriate sub-catchment. The runoff coefficients of streets in sub-catchments connected to rainwater harvesting systems are set to 0 as their roofs and roads are no longer connected to the street network. It also should be noted that the tank overflow weirs were connected to the hydrological drainage conduits, and therefore were draining directly to the river.

Table 3.10 and Table 3.11 provide an overview of the specifications of the rainwater harvesting systems integrated into the networks. The location of rainwater systems are shown in Figure 3.19 and Figure 3.20, in orange habitation which does not recycle can be seen whilst those in yellow are connected to a rainwater harvesting system. However, the rainwater harvesting scaling-up at block and neighbourhood scales under development 2050 could not be built and implemented within model due to software limitations on the number of allowed nodes. Indeed, the InfoWorks™ CS 6.5 version available to run the simulation is limited to a total of 2,000 nodes. Therefore under the 2050 urban development, only the rainwater harvesting at municipal scale has been assessed.

Table 3.10. Design of rainwater harvesting systems within each scenario

Development	**Scheme scale**	**% of buildings connected**	**Number of systems**	**Number of total inhabitants connected**	**Number of inhabitants per system**	**Tank Size in m^3**
Existing development	No recycling	0	0	0	0	0
Basecase 2010	No recycling	0	0	0	0	0
Extended Urban development 2010	Block	20%	52	5616	108	81
		50%	129	13932	108	81
		80%	206	22248	108	81
	Neighbour	20%	10	5400	540	405
		50%	26	14040	540	405
		80%	40	21600	540	405
	Municipal	20%	1	5616	5616	4212
		50%	1	13932	13932	10449
		80%	1	22248	22248	16686
Basecase 2050	No recycling	0	0	0	0	0
Extended Urban development	Municipal	20%	1	16640	16640	12480
		50%	1	41984	41984	31488
		80%	1	66560	66560	49920

Table 3.11. Simulation matrix

		2010			**2050**	
% Buildings connected	**20%**	**50%**	**80%**	**20%**	**50%**	**80%**
Block	1B2010	2B2010	3B2010			
Neighbourhood	1N2010	2N2010	3N2010			
Municipal	1M2010	2M2010	3M2010	1M2050	2M2050	3M2050

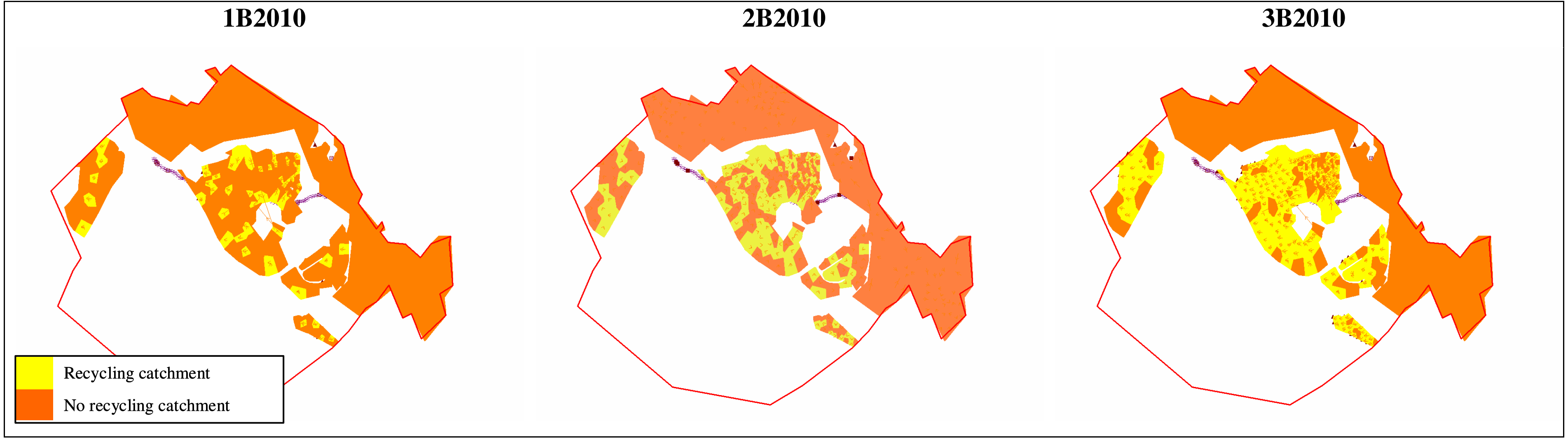


Figure 3.19. Location of sub-catchment connected to a rainwater harvesting technologies in the respective scenarios within development 2010.

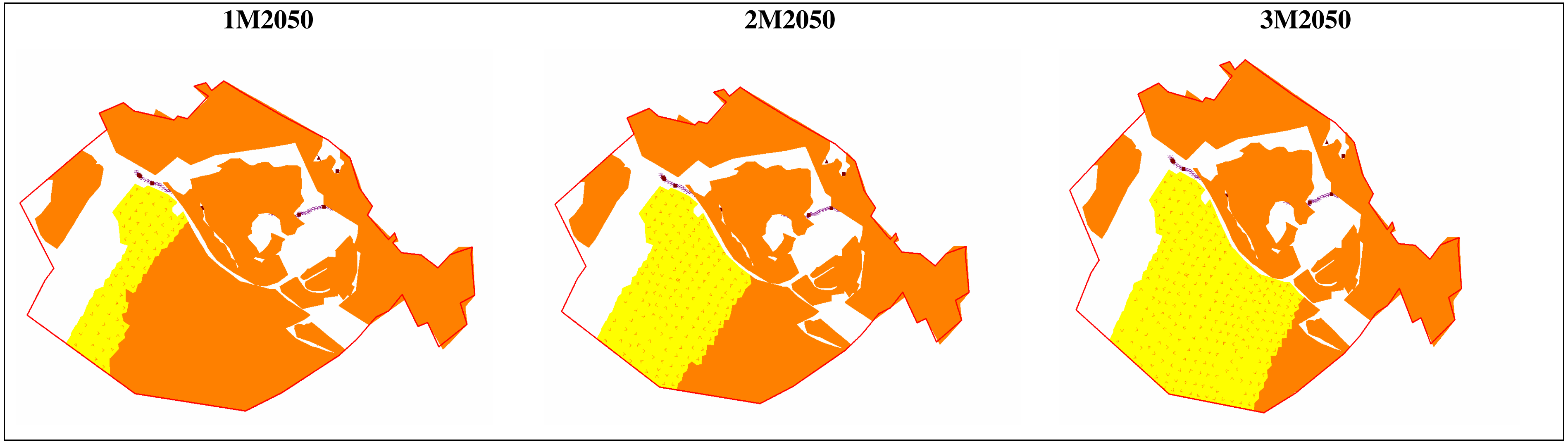


Figure 3.20. Location of sub-catchment connected to a rainwater harvesting technologies in the respective scenarios within development 2050.

3.5 Calibration and validation

The terminology associated with modelling processes and tools has been the cause of much confusion as reported by Refsgaard and Henriksen (2004): there are no coherent, widely accepted definitions for some of the key terms and they are often applied inconsistently. The terms ‘validation’ and ‘verification’ are often confused. For example, Zhang *et al.* used the two terms in two papers published in 2005 and 2006 to refer to the same modelling approaches. In the following paragraphs, key terms used throughout this thesis will be defined.

The goal of model calibration is to ensure that parameter values results in outputs that match the ‘real-world’ as closely as possible (Van Waveren *et al.*, 1999). To do so, real-world data are compared with the results obtained by the model, and then parameters are modified where needed. They can be modified manual or automatically using computer software. Calibration is an essential part of the modelling process in order to predict accurate results.

Validation is defined as establishing the usefulness and relevance of a model for a predefined purpose (Van Waveren *et al.*, 1999). In the case of predictive models, model validation mainly seeks to assess the prediction accuracy. Therefore, the modelling outputs are compared to real-world data. It should be noted that the data sets used for model calibration and validation should differ, this is due to the fact that the model parameters were modified in order that output results obtained with calibration data match the observed data. Therefore using a different set of data will able to assess if the model is 'good' to reproduce.

An uncertainty analysis determines the degree of uncertainty each component of the model contributes to its outputs. Uncertainties may arise from natural and inherent uncertainty, model uncertainty, and parameter uncertainty. McIntyre *et al.* (2002) defined uncertainty analysis as “The means of calculating and representing the certainty with which the model results represent reality”. The difference between modelled results and observed data can result from: i) model parameter errors (e_1), ii) model structure errors (e_2), iii) numerical errors in the model implementation (e_3), iv) boundary conditions (e_4). Field data are only an approximation of reality and data error can arise from: i) sampling errors (e_5), ii) measurement errors (e_6) and iii) human reliability (e_7). The model uncertainty can be represented as Equation 3.9.

$$\text{Model} - e_1 - e_2 - e_3 - e_4 = \text{Observation} - e_5 - e_6 - e_7 \qquad \textbf{Equation 3.9}$$

Sensitivity analysis evaluates how sensitive model outputs are to changes of model inputs (Smith, 2007). Most of the variation of outputs is generally caused by a small number of inputs. Sensitivity analysis is executed as part of the calibration process. Sensitivity analysis can help the modeller to measure model adequacy, and relevance, to detect interactions between factors, to establish priorities for research and to simplify the model structure. In general, sensitivity analysis is performed by modifying the values of model parameters by various quantities, re-running the model, and computing the changes in model output relative to its output with initial parameters values. The most common method is ‘one-at-a-time’ sensitive analysis. In this method, one input parameter at a time is varied with all the other inputs kept at nominal values.

3.5.1 Model calibration

As described above the calibration process aims to adjust the parameter set of a model in order to reduce the difference between model predictions and monitored data of the real system to a minimum. Once the model is built, test simulations are compared to observed data and eventually, parameters are adjusted using manual or more sophisticated calibration procedures. For this study, manual calibration methods were applied involving the running of multiple simulations based on which parameter settings were corrected.

The base hydrological model of the Carrickmines catchment had already been calibrated by HR Wallingford prior to the outset of this study. However, a sensitivity analysis was carried out to estimate how well the model matched the real context as reported below in Chapter 7.

The hydraulic network design for the existing development (2002 scenario) was calibrated using the data collected by the Shanghanagh WwTW. Data on wastewater flows through the wastewater treatment plant were available for the period starting the 9th of January 2006 and ending the 31st of January 2006. The objective of the calibration process was to set up the sewer outfall mass balance and the shape of the peaks as close as possible to the results provided by the Shanghanagh WwTW. The sewer calibration was carried out in two steps. The hydraulic model calibration was first performed during dry weather flow (DWF) conditions in order to obtain a mass balance that would fit observed conditions. Total daily flow data recorded from the 9th of January to the 31st of January 2006 were used to calculate the mean total daily flow discharge into the sewer during a dry period. Once the mass balance was set up, peak flow intensity was calibrated. It has to be mentioned that the rainfall data available only specified the amount of rainfall per day. Rainfall event intensity was estimated in order to match the peaks flows of the monitored data. Figure 3.21 compares the modelled and surveyed total daily wastewater volume obtained for the calibrated period. It can be observed that the model is over estimating sewer flows for small rainfall events and under estimating flows for bigger storm events. The correlation gap is most likely a function of the lack of suitable data with which to design the sewer network.

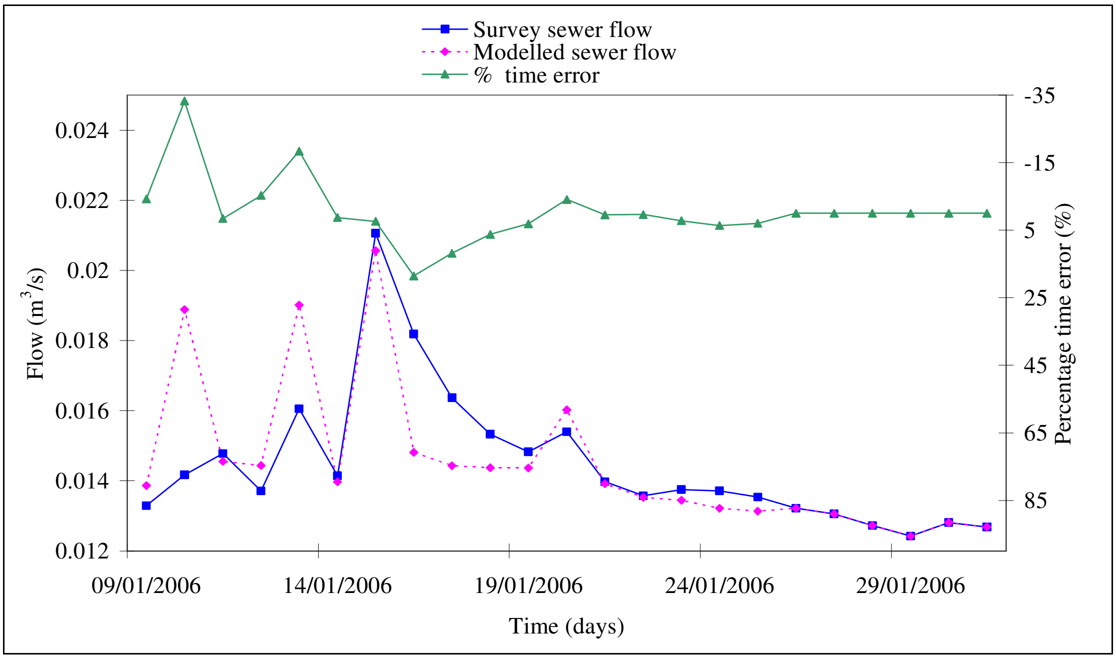


Figure 3.21. Calibration hydrograph of the sewer network.

3.5.2 Validation

Model validation is crucial if we want to ensure that models and their outputs resemble the real world context as accurately as possible. Due to the lack of wastewater flow data available, validation of the designed sewer network could not be carried out. However, river flow data collected at the two river gauges and rainfall events data available were used to validate the river system.

First, short validation simulations were carried out. The validation was conducted for the three heavy rainfall events which occurred on the 13th of December 1984, 25th of August 1986 and 11th of June 1993. For those three events, hourly rainfall data were available from HR Wallingford. The 26th of August 1986 rainfall event was reported one of the biggest floods in the history of the Carrickmines catchment. During the rainfall event on 13th of December a total amount of 58mm of rainfall has been recorded, on the 11th of June 1993 June 125mm of rainfall spread over seven days and to 101mm on the 26th of August 1986. Using different rainfall events to validate the model will help determine how accurate the predictions are.

In order to evaluate the goodness of fit between measured and simulated data, the Nash-Sutcliffe simulation efficiency index (E_{NS}) has been chosen for hydraulic simulations. The Nash-Sutcliffe simulation efficiency index (E_{NS}) is calculated using Equation 3.10.

$$E_{NS} = 1 - \left(\frac{\sum_{i=1}^{n} (measured_i - simulated_i)^2}{\sum_{i=1}^{n} (simulated_i - simulated_{average})^2} \right) \qquad \textbf{Equation 3.10}$$

The coefficient evaluates the performance of hydrological models by measuring how well the simulated results predict the measured data relative to simply predicting the quantity of interest by using the average of the measured data over the period of comparison. The values of E_{NS} vary from negative infinity for a poor model to 1.0 for a perfect model. A value of 0.0 means the model is better predictor of the measured data than the measured data average. A major disadvantage of Nash-Sutcliffe is the fact that the difference between the measured and simulated values are calculated as squared values and thereby places emphasis on peak flows. As a result the impact of larger values in a time series is strongly overestimated whereas lower values are neglected. Values should be above zero to indicate minimally acceptable performance.

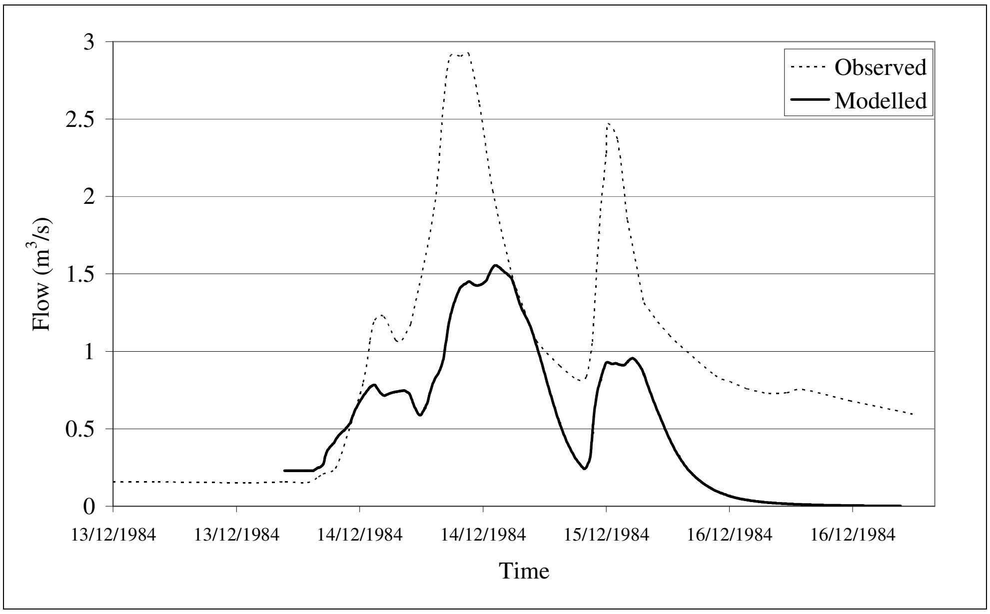


Figure 3.22. River validation 13th of December 1984 event at the Carrickmines river gauge.

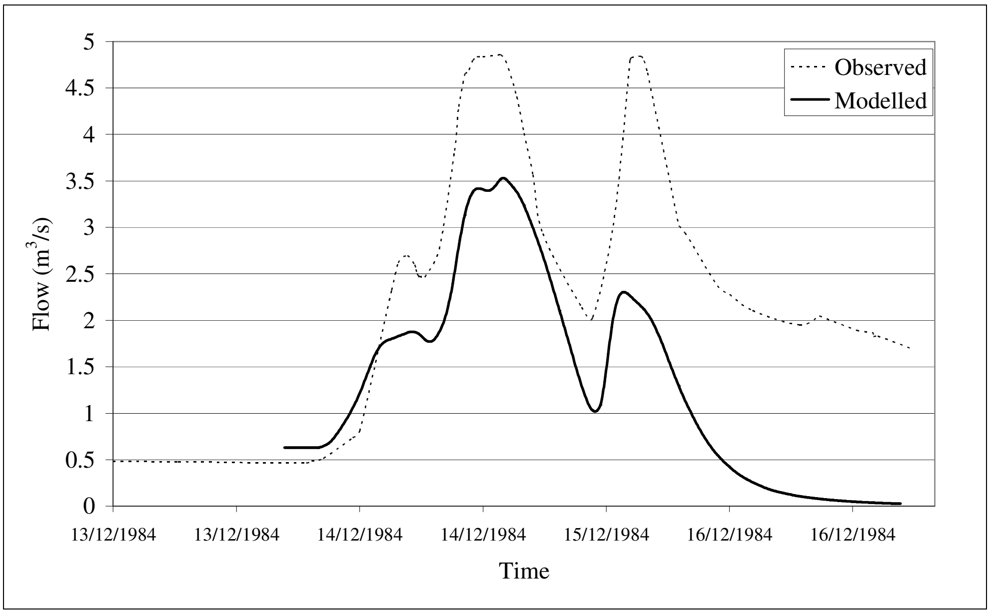


Figure 3.23. River validation 13th of December 1984 event at the Common's road river gauge.

Figure 3.22 and Figure 3.23 shows an underestimation of the river flow during the rainfall event, therefore the Nash-Sutcliffe coefficient estimated is really small with a value of 0.57 for Carrickmines river gauge and 0.04 at Common's road.

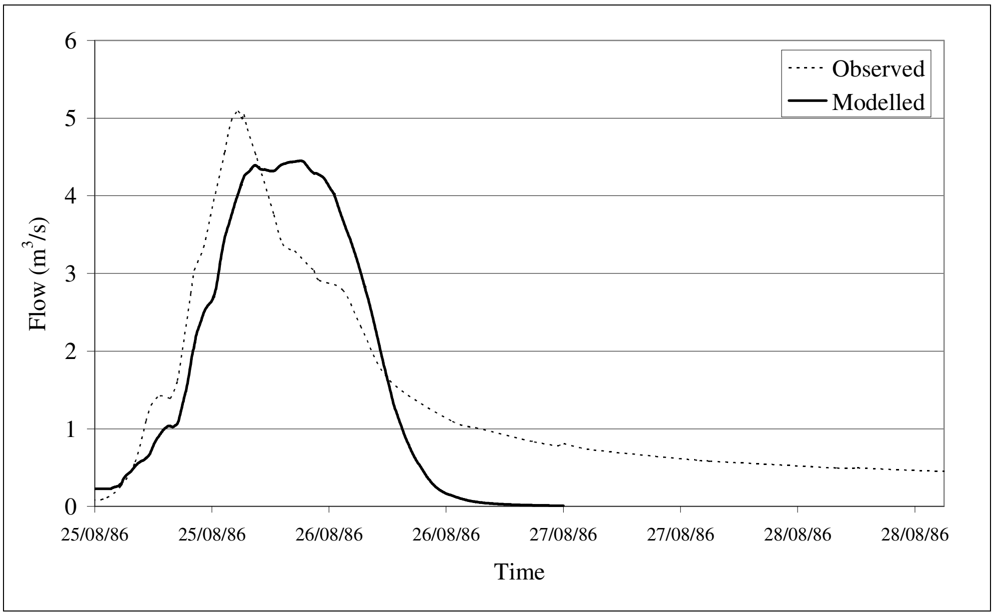


Figure 3.24. River validation 25th of August 1986 event at the Carrickmines river gauge.

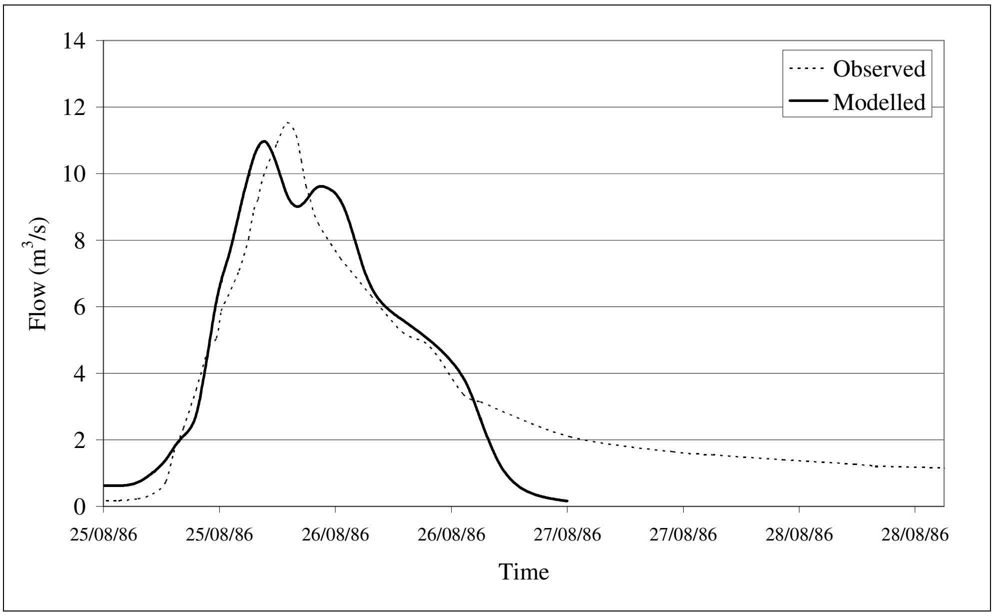


Figure 3.25. River validation 25th of August 1986 event at the Common's road river gauge.

Figure 3.24 and Figure 3.25 show a good fit of the peak flow at the two river gauges. The Nash-Sutcliffe coefficient estimated is higher with a value of 0.79 for Carrickmines river gauge and 0.82 at Common's road. The river base flow model is lower than the monitored values. The model fails to identify floods at the two river gauges for the August 26th 1986 event, when, in reality, major floods were observed. However, simulation outputs forecasted floods not far from the two river gauges stations. Therefore, it can be concluded that the model is comparatively more accurate in predicting river peak flows during storm events than during small rainfall events.

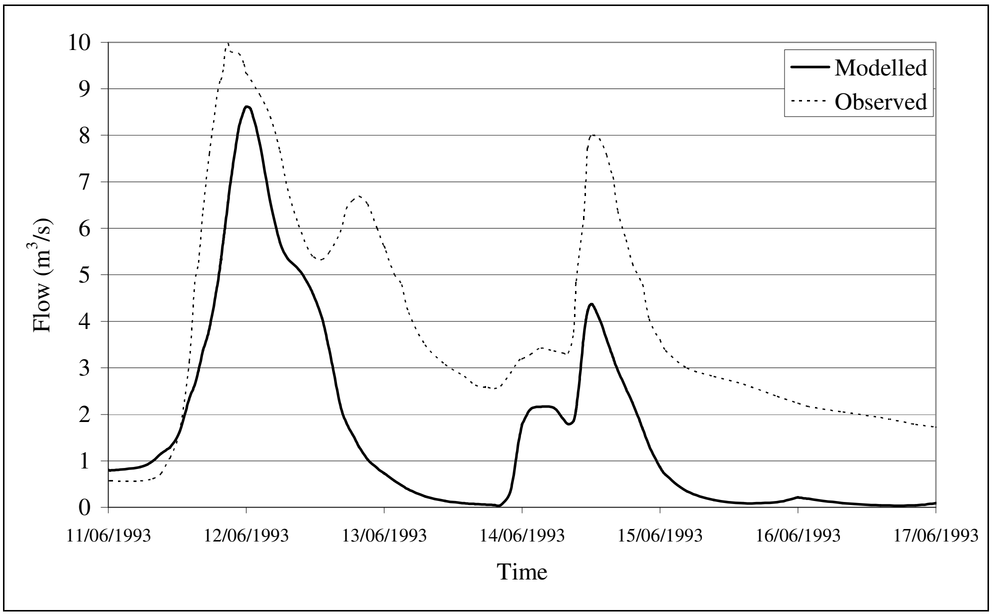


Figure 3.26. River validation 11th of June 1993 event at Carrickmines river gauge.

Figure 3.26 emphases the results obtained from the two previous simulations with the river base flow model always lying below the monitored base flow. This explains why the modelled peak flows tend to be lower as well. Further one year duration simulations were carried out to validate the model. However, the lack of detailed rainfall data did not permit conducting useful long term simulations. To conclude, river peak flows are predicted fairly accurate by the model. The peak flows are slightly underestimated due to a lower base flow in the model.

3.6 Simulation and Evaluation

Rainfall event scenarios were generated using two sets of storm events. First of all, a series of storm events were simulated to undertake the hydraulic assessment of the Carrickmines catchment. A total of 42 storms were run. Storm events were generated in InfoWorks^{TM} CS using the UK rain event generator, on the following basis:

- Return Period (years) 1yr, 5yr, 10yr, 20yr, 50yr and 100
- Durations (minutes) 30, 60, 90, 120, 180, 240, 480

Secondly, in order to determine the hydrological response of the catchment during frequent and intensive rainfall events, the top 100 events from each of the 5-year and 100-year stochastic series were selected. The rainfall time series were designed by HR Wallingford using the Time Series Rainfall Simulations (TSRsim) tool. Where TSRsim is a continuous or discontinuous record of individual rainfall events generated artificially or selected real historical events, which are representative of the rainfall in the area. The present day series was calibrated against hourly data from the Met Office Greenwich rain gauge. The future series was developed based on six hourly outputs from the Hadley Centre Climate Change Model (HadRCM2) for the medium high scenario for the United Kingdom Climate Impacts Programme 98 (UKCIP98) analysis. HadCM2 refers to a mathematical model used to design climate change scenarios. Also, two set of 5 year continuous rainfall data were available, one from 1981 to 1985 which represent present rainfall conditions and the second set from 2075 to 2079 also named future conditions to run long simulations.

Table 3.12 provides an overview of the simulations run for rainwater harvesting, greywater recycling and combined technologies scenarios. In this table, the terms ‘frequent’ and ‘extreme’ refer to 5 year return period events and 100 year period events.

Table 3.12. Simulation and results table

		Rainfall events simulated									
		Real rainfall event used					Design storm event				
	Technology	Top 100 Frequent present	Top 100 Extreme present	Top 100 Frequent future	Top 100 Extreme future	5 years rainfall event present and future	1yr	5yr	10yr	50yr	100yr
Greenfield 2002	N/A	✓	✓	✓	✓		✓	✓	✓	✓	✓
Basecase 2010	N/A	✓	✓	✓	✓		✓	✓	✓	✓	✓
Basecase 2050	N/A	✓	✓	✓	✓		✓	✓	✓	✓	✓
1B2010	Greywater	✓	✓	✓	✓		✓	✓	✓	✓	✓
2B2010	Greywater	✓	✓	✓	✓		✓	✓	✓	✓	✓
3B2010	Greywater	✓	✓	✓	✓		✓	✓	✓	✓	✓
1B2050	Greywater	✓	✓	✓	✓		✓	✓	✓	✓	✓
2B2050	Greywater	✓	✓	✓	✓		✓	✓	✓	✓	✓
3B2050	Greywater	✓	✓	✓	✓		✓	✓	✓	✓	✓
1B/N/M2010	Rainwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2B/N/M2010	Rainwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3B/N/M2010	Rainwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1M2050	Rainwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2M2050	Rainwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3M2050	Rainwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Scenario 1	Combined	✓	✓	✓	✓		✓	✓	✓	✓	✓
Scenario 2	Combined	✓	✓	✓	✓		✓	✓	✓	✓	✓
Scenario 3	Combined	✓	✓	✓	✓		✓	✓	✓	✓	✓
Scenario 4	Combined	✓	✓	✓	✓		✓	✓	✓	✓	✓

3.6.1 Results

For each simulation run, the following standard results were abstracted:

- total wastewater volume produced,
- total wastewater flood, volume, depth and location,
- total river flow,
- river flow at the two river gauges,
- river flood volume, depth and location, and
- volume of water re-used.

Individual results were first compared with the basecase results to identify the hydrological and hydraulic influences of each technology scenario. The reductions of wastewater volume, river volume, floods and of water supply were calculated. Data was extracted from the storm events simulation runs, particularly on peak flows, total wastewater volumes and river water volumes. Furthermore, return periods were analysed to determine the performance of each individual pipe in the sewer network. In order to carry out an adequate comparison of the obtained results and determine which technology combination will have a better influence on the catchment hydrology, indexes were determined using four sets of Top 100 events results. The calculations are presented in more detail in the following Section 3.6.2.

3.6.2 Comparison analyses

The following Section introduces and details the methodology used and designed to conduct the comparison analyses. The method has been designed by Udale-Clarke and Kellagher (2007) to assess the sustainability of urban drainage by comparing all the results obtained per scenario. The methodology designed by HR Wallingford has been adapted for the purpose of our study. For the purpose of the analyses, the performance observed for each scenario has been quantified in a way that takes account of all the results. In other words, the results obtained for the four set of Top 100 events (under extreme, frequent, past and present events) (See Section 3.6 and Table 3.13 for more details) were compared with the 2002 basecase to generate a set of "comparison coefficients".

Four sets of coefficients were designed to compare the final results:

i) the peak flow coefficient, which identify the influence of each scenario to control river flow and therefore flooding.

ii) the runoff volume coefficient, which provide understanding of the influence of each scenario to control running water within the catchment.

iii) the sewer volume coefficient, which assess the ability to control the volume of water within the sewer network and therefore sewer flooding.

iv) finally the volume of re-used water coefficient, the results highlight the performance to save drinking water.

The four coefficients were calculated as follows:

The peak flow (PFC) coefficient was calculated using Equation 3.11.

$$PFC = \frac{\sum_{i=1}^{N} |Di - Gi| / A}{N}$$

Equation 3.11

Where D_i is peak flow rate of event i (m^3/s); G_i basecase 2002 peak flow rate of event i (m^3/s); A is the site area (ha); and N the total number of events.

The runoff volume coefficient was calculated using Equation 3.12.

$$RVC = \frac{\sum_{i=1}^{N} |Di - Gi| / A}{N}$$

Equation 3.12

Where D_i is runoff rate of event i (m^3/s); G_i basecase 2002 runoff rate of event i (m^3/s); A is the site area (ha); and N the total number of events.

The sewer volume coefficient (SVC) was calculated using Equation 3.13

$$SVC = \frac{\sum_{i=1}^{N} |Di - Gi| / A}{N}$$

Equation 3.13

Where D_i is total wastewater volume rate of event i (m^3/s); G_i basecase 2002 total wastewater volume rate of event i (m^3/s); A is the site area (ha); and N the total number of events.

The volume of re-used water coefficient (VRC) was calculated using Equation 3.14.

$$VRC = \frac{\sum_{i=1}^{N} |Di| / A}{N}$$ **Equation 3.14**

Where D_i is total volume of water re-used of event i (m^3/s); A is the site area (ha); and N the total number of events.

The comparison indices are summarised in Table 3.13. The obtained coefficients were grouped to represent a value in a range of 1 to 7, which will be referred as the comparison index. The radar charts have been divided in 7 indices in order to obtain a clear representation and highlight difference between scenarios.

Table 3.13. Comparison indices tables

Comparison index	PFC	SVC	VRC	RVC
1	0 to 0.5	0 to1	>1	<10
2	0.5 to 1	1 to 2	0.8 to 1	10 to 20
3	1 to 1.5	2 to 3	0.6 to 0.8	20 to 30
4	1.5 to 2	3 to 4	0.4 to 0.6	30 to 40
5	2 to 2.5	4 to 5	0.2 to 0.4	40 to 50
6	2.5 to 3	5 to 6	0 to 0.2	50 to 60
7	3 to 4	6 to 7	0	>60

Once the indices are calculated the robustness of each scenario will be presented as a radar chart (Figure 3.27). And where index equals at 1 represent an important reduction of the initial volumes. The radar charts integrate all the results obtained and compared the influence of each scenario to control the problems faced by centralised wastewater system, introduced in Chapter 1 (such as river and sewer flooding and water scarcity). Therefore, the comparison analysis presented in this section will help ranking the tested scenarios carried out all along the project. As a result, the most appropriate approaches (technologies combination, size and number) to enhance water management will be determined.

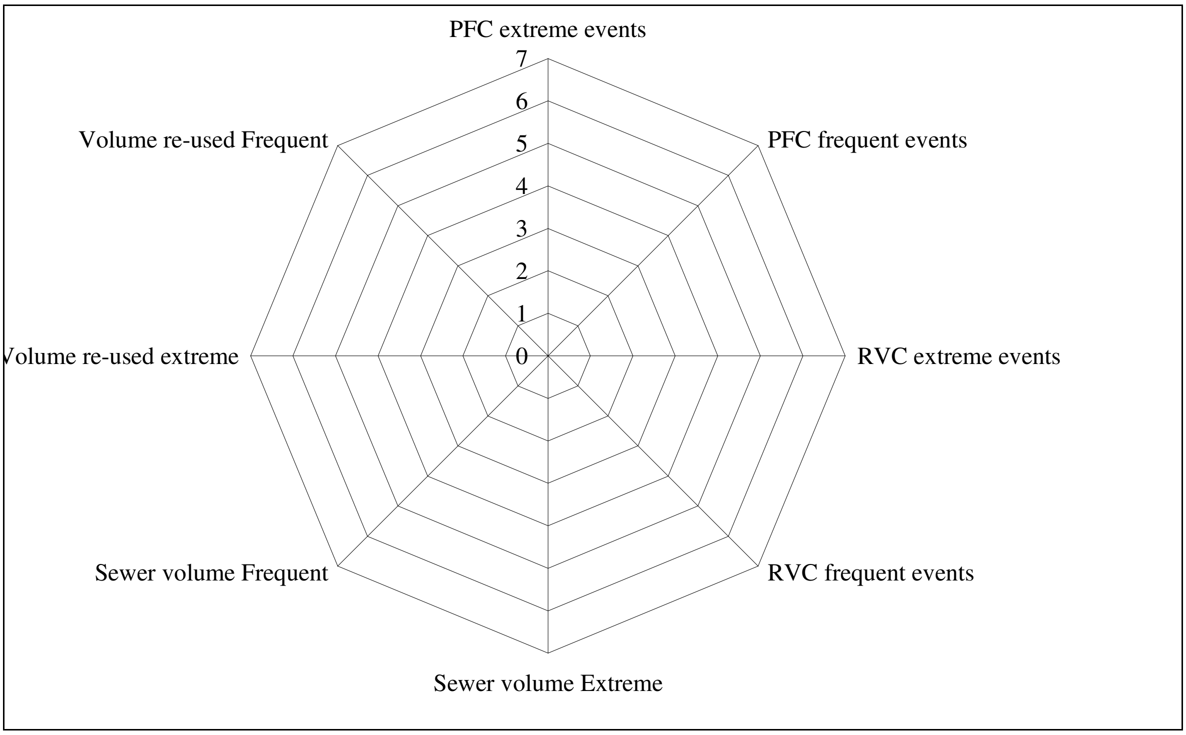


Figure 3.27. Example of comparison radar chart.

3.7 Methodology summary

This Chapter has reviewed the methodology used to carry out the study. Figure 3.28 resumes the steps followed to design and built the 25 networks used designed for the study.

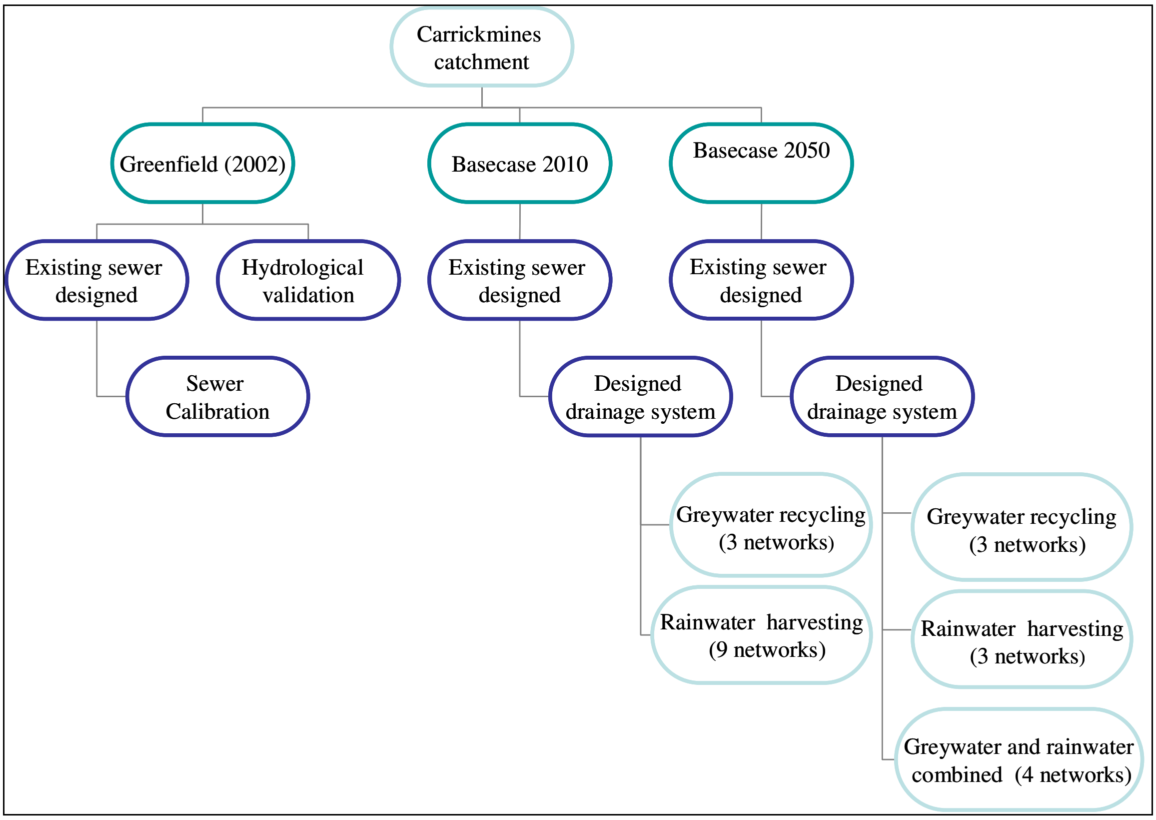


Figure 3.28. Summary of the steps followed to design and build the model.

A total of 10,290 simulations have been carried out, 10,260 were fast simulation (24 hours simulated) which took approximately ten minutes for InfoWorks^{TM} CS to execute each simulation. Concerning the 30 others simulations, continuous five years simulations have been conducted and therefore are considered as long simulations. Running long simulations within InfoWorks^{TM} CS can be extremely long in term of time needed to simulate, and will also generate some extremely large files (over 100Gb have been obtained). Moreover time needed to extract data from InfoWorks^{TM} CS was extremely long (more than 3 hours to extract some river flow data).

The data obtained were stored within two external memory disks, one of 250Gb capacity and the other one of 550Gb. Several times, the maximum capacity of storage has been reached. Therefore, stored simulations had to be deleted once results were extracted. The shortage of memory caused failures and stopped the software several times when simulations were running.

The problems of memory and time faced to carry out long simulations have obliged to simplify the network and scenarios used. Finally, the 30 long simulations were focused on the surface management of the Carrickmines catchment rather than on the hydraulic part of it. Nevertheless, each simulation took over one day to be completed and the size of the simulation exceeded (52,000Kb).

Once simulated, data needed to carry out the analyses (river peak flow, runoff, wastewater flows, etc) were extracted or exported directly within Excel database using the statistical functions or tools provided by InfoWorks^{TM} CS. As mentioned above, for long simulations, the time needed for the computer to calculate data and extract them was extremely long; therefore the extractions for long simulations have been done overnight. The extracted results were passed to Excel or directly extracted under excel format file (CSV Excel file).

Chapter 4 Greywater results

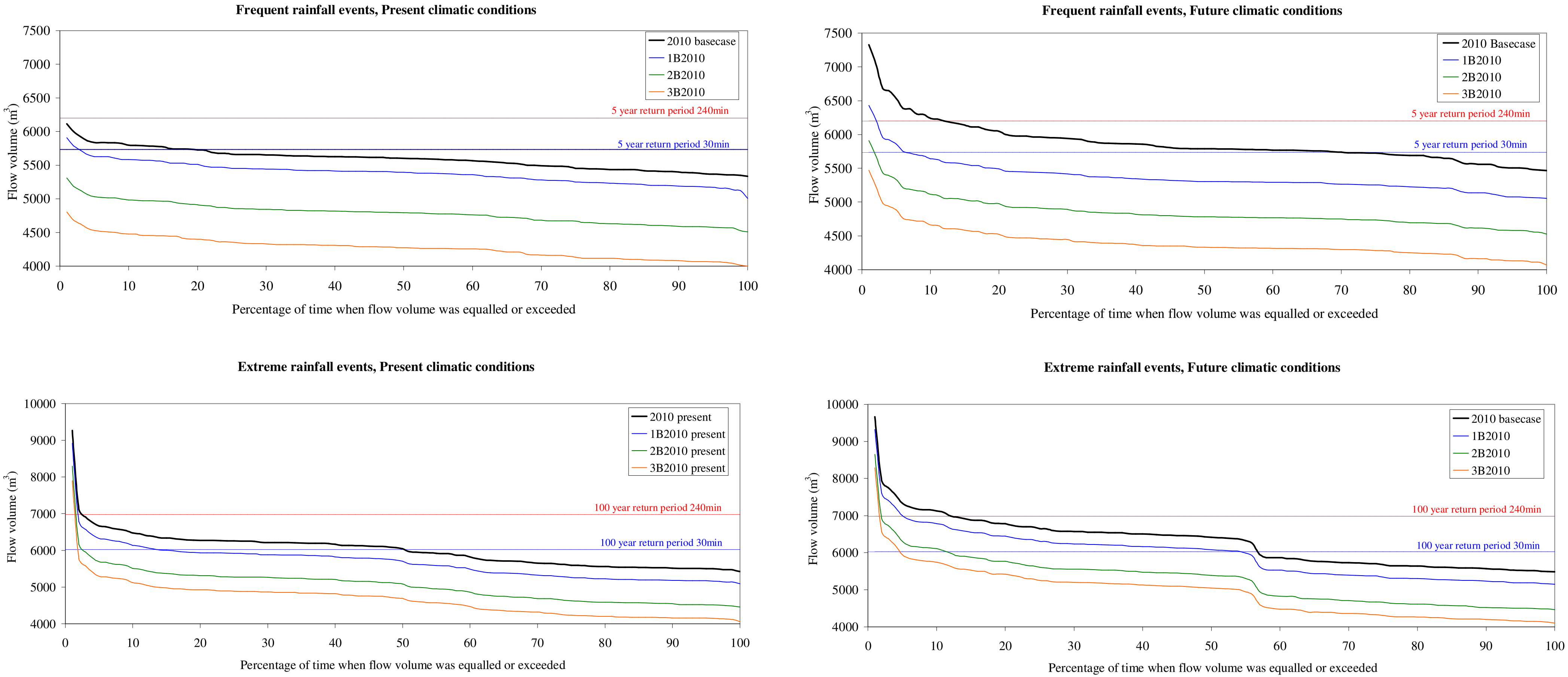
This chapter presents the results obtained for the greywater recycling scenarios. The Chapter is divided into four sections. Section 4.1 presents the influence of greywater recycling systems on the wastewater network. The variations in wastewater volumes produced are compared with their respective basecase scenario values and the influence of greywater recycling on flood control is assessed. The influence of greywater recycling systems on the catchment hydrology is then presented in Section 4.2. River peak flow at the two river gauges, level of flood along the river and the variation in total volumetric flow in the river were compared with the basecase scenarios. Section 4.3 then quantifies the amount of drinking water saved when greywater recycling systems are implemented. This chapter concludes with a comparison of sewer volume, river peak flow, runoff volume and drinking water volume saving obtained under the four top 100 scenarios (see Section 3.6.1). Finally, the results of the comparison analysis are introduced.

4.1 Influence of greywater recycling on the wastewater sewer network

This Section will illustrate how the implementation of greywater recycling at different scales affects the wastewater sewer network. First the total wastewater flows are presented, and then the reduction and the ratio rainfall/wastewater are introduced. Finally the influence of greywater recycling on sewer floods will be presented.

4.1.1 Variation of total sewer volume

In order, to assess to what extent greywater reuse reduces the wastewater volume within the study area, the scenarios presented in Chapter 3 were simulated with i) the designed storm events and ii) the top 100 frequent and extreme events under present and future conditions. All the simulations were executed over a 24 hour time period. The total wastewater volume at the outfall of the sewer network was extracted for each simulation to provide a comparative analysis of the wastewater volume for rainfall events under the different urban development scenarios. Figure 4.1 and Figure 4.2 combined the results obtained for both sets of rainfall data (designed and existing) and express the percentage excess of total wastewater flow obtained for each simulation. In both figures, 1B refers to 20% of the houses connected to greywater recycling systems, 2B to 50% and finally 3B to 80% (See Table 3.12 in Section 3.4.3). For each figure, four set of rainfall simulations results are presented for: i) Frequent event rainfall under present conditions, ii) Frequent event rainfall under future conditions, iii) Extreme event rainfall under present conditions iv) Extreme event rainfall under future conditions. Where frequent rainfall events refer to a five year rainfall return period event (M5) and extreme event to a 100 year return event (M100). Under existing condition refers to real rainfall event data monitored between 1981 and 1985 whereas under future condition rainfall data introduced climate change conditions to the modelling activities and refer to five years computed rainfall data (starting in 2075) (See Table 3.13 in Section 3.6 which resumes simulation carried out).

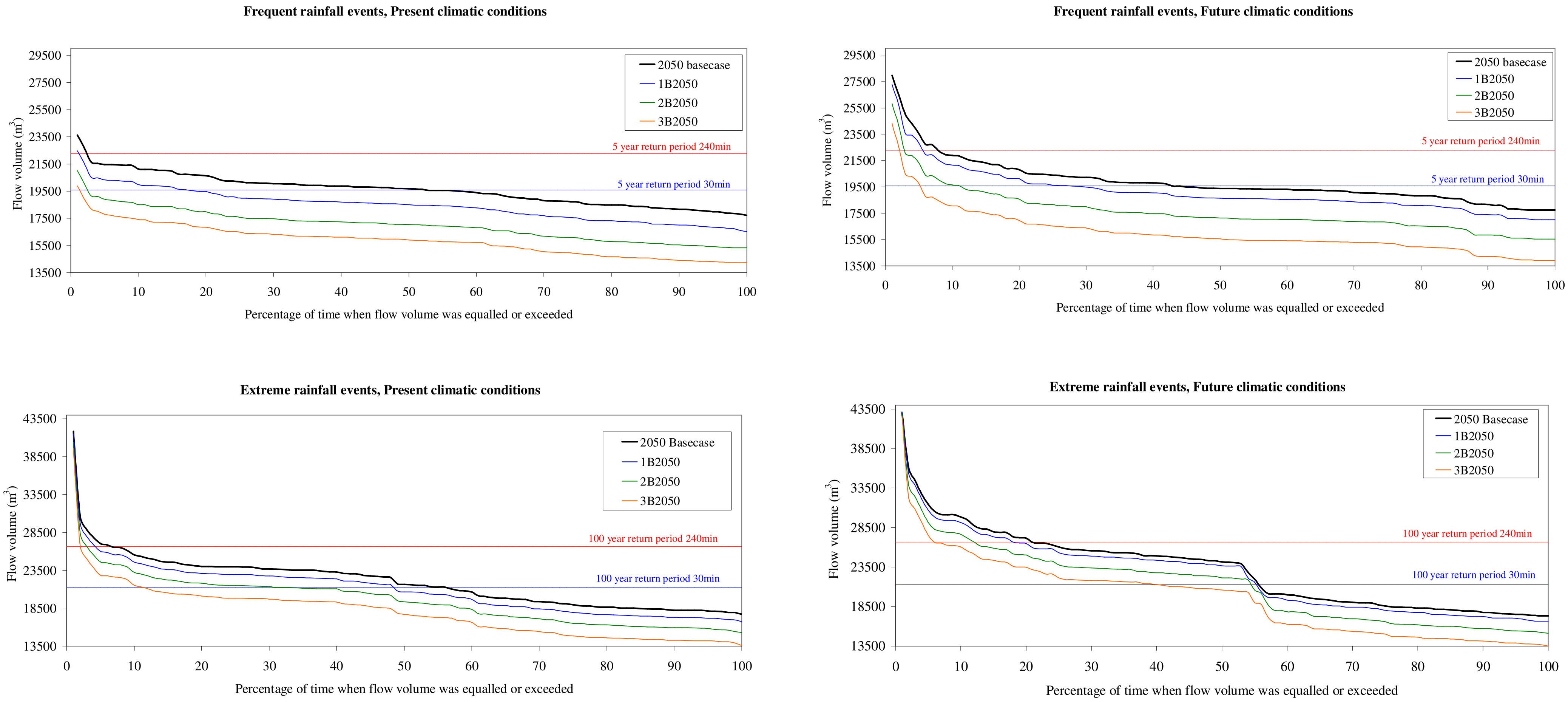

Frequent rainfall events, Present climatic conditions

Frequent rainfall events, Future climatic conditions

Extreme rainfall events, Present climatic conditions

Extreme rainfall events, Future climatic conditions

Figure 4.1. Sewer volume variation obtained for the 2010 development when greywater recycling systems are implemented



Frequent rainfall events, Present climatic conditions

Frequent rainfall events, Future climatic conditions

Extreme rainfall events, Present climatic conditions

Extreme rainfall events, Future climatic conditions

Figure 4.2. Total Sewer volume variation obtained for the 2050 development when greywater recycling systems are implemented.

Figure 4.1 and Figure 4.2 identify a systematic reduction of the wastewater volume discharged in the sewer network for all the scenarios when compared to the respective basecase scenario. We can observe that the reduction of wastewater is linked to the number of technologies implemented, in other words the more houses are connected to greywater recycling system the less wastewater will be discharged.

Figure 4.1 and Figure 4.2 also highlight the fact that the designed rainfall events are more intense than the four sets of top 100 events. For example, the wastewater volume obtained with the rainfall data designed by HR Wallingford under frequent events under present conditions never exceeds the total volume of wastewater obtained with the rainfall event designed by InfoWorks^{TM} CS, 5 year return period 240 min (also called M5-240) duration events. The results highlight an important influence of rainfall on the volume present in the sewer network. When results obtained for the top 100 events under frequent and extreme conditions (both under present conditions): were compared, a maximum increase of 34% of total wastewater volume was observed between frequent and extreme events; however the observed average increase was only 6.6%. Similar analysis was carried out between present and future rainfall condition and a maximum difference of 20% was calculated and the average difference observed was 4.5%.

Table 4.1 summarises the volume of and reduction in wastewater flows obtained. Furthermore, results show that the wastewater volume reduction is not linked to rainfall events; the reduction when the total volume is compared to basecase scenarios is constant for the rainfall events simulated.

Table 4.1. Summary of reductions in wastewater volumes discharged to the sewer network.

	2010 development		**2050 development**	
	Daily reduction in wastewater produced (m^3)	Reduction of wastewater discharged to sewer	Daily reduction in wastewater produced (m^3)	Reduction of wastewater discharge in sewer
1B2010/2050	333	7%	932	5%
2B2010/2050	896	17%	2495	7%
3B2010/2050	1362	24%	3900	15%

4.1.2 Total wastewater reduction

Figure 4.1 and Figure 4.2 also highlight that the decrease of the wastewater volume is proportional to the number of greywater technologies set up in the network. Therefore, analysis to identify the relationship between the percentages of habitation connected to a greywater recycling system and the total volume of wastewater produced under each scenario (2010 and 2050 urban development scenarios) on a rainless day has been identified and is presented within Figure 4.3. The understanding and establishing of such relationship is useful in order to quantify the volume of daily wastewater flows expected to be produced by the new blocks for each development stage.

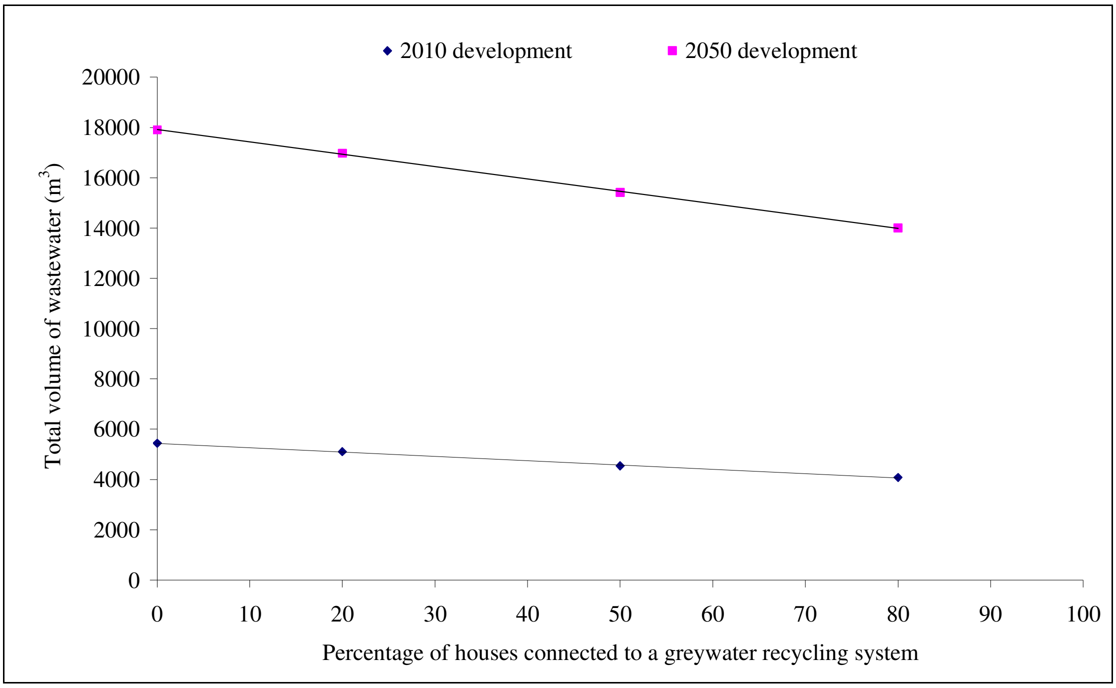


Figure 4.3. Relationship between the total volume of wastewater and the number of greywater recycling system connected over one day simulation.

For the 2010 development, Equation 4.1 describes the proportional reduction in wastewater volume as a function of the number of houses connected to greywater recycling schemes.

Total volume of wastewater = -4915 percentage of houses connected + 17916 **Equation 4.1**
with $R^2 = 0.9995$

For the 2050 development, Equation 4.2 determines the proportional reduction in wastewater volume as a function of the number of houses connected to greywater recycling schemes.

Total volume of wastewater = -1721 percentage of houses connected + 5439 **Equation 4.2**
With $R^2 = 0.9985$

The constant reduction of wastewater volume discharged to the sewer network and the constant intrusion of rainwater will alter the content of the sewer network. Therefore, the next sub-section identifies the variation of the ratio rainwater / wastewater in the sewer network.

4.1.3 Ratio rainwater / wastewater

The constant reduction in wastewater volume due to the use of greywater recycling systems causes a change in the rainwater/wastewater ratio in the sewer network. Figure 4.4 illustrates the variation in this ratio for the four sets of rainfall events and compares two extra cases, the 2050 basecase scenario with the 3B2050 scenario. Under frequent conditions, the ratio does not exceed 0.45 during present conditions and 0.75 under future conditions. However, in the case of heavy rainfall events, the ratio exceeds 1.8 under present conditions and 2.0 under future conditions. As a result, the wastewater will be highly diluted. Therefore the amount of rainfall entering the sewer network will considerably increase the volume of wastewater to be treated. Furthermore, given that the amount of rainwater entering the system in extreme weather events considerably increases the total volume of water in the sewer network, floods are more likely to occur. This problematic will be investigated in more detail in the following sub-section.

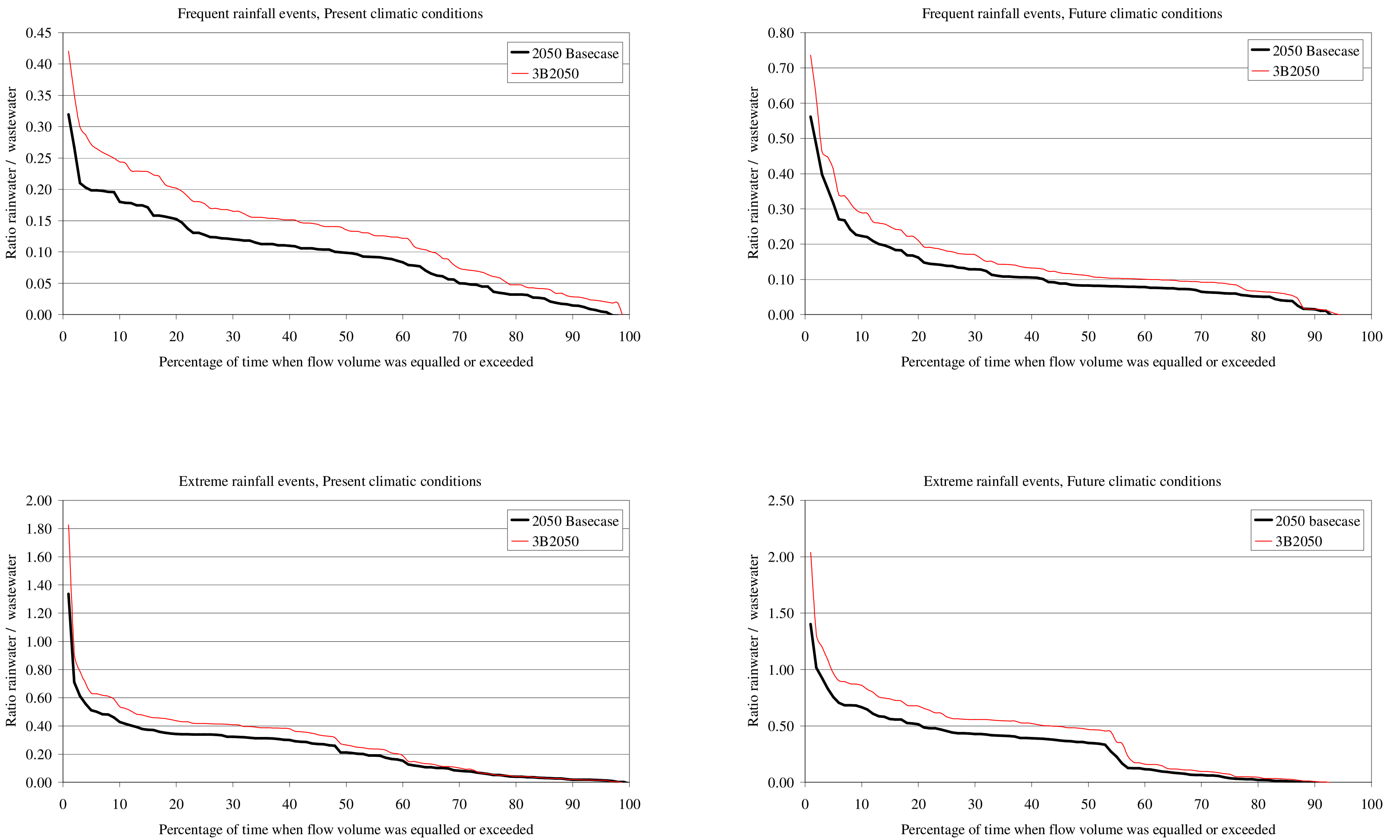


Figure 4.4. Ratio rainwater / wastewater into sewer system obtained when greywater systems are present within 2050 development.

4.1.4 Variation of total sewer flood volume

To be able to quantify the total volume of flood, the volume of flood occurring at each node was identified and summed to determine the total volume of flood per scenario. The results obtained for each scenario were then plotted and compared with data obtained for the basecase scenario. The results, presented in Figure 4.5 and Figure 4.6, show that greywater recycling schemes contribute to a reduction in sewer flooding for a given simulated rainfall event. A reduction of 11 % was observed for 1B2010, of 17 % for 2B2010 and of 23 % for 3B2010 for M1-240 events compared to a reduction of 2 % for 1B2010, 5 % for 2B2010 and of 7% for 3B2010 for M100-240 rainfall event. Results show a bigger reduction in flooding for short and small events than for intense and long rainfall events. Figure 4.5 also illustrates the important increase in sewer flooding between the M100-30 and M100-60 rainfall events where a 65% increase in flood volumes was observed.

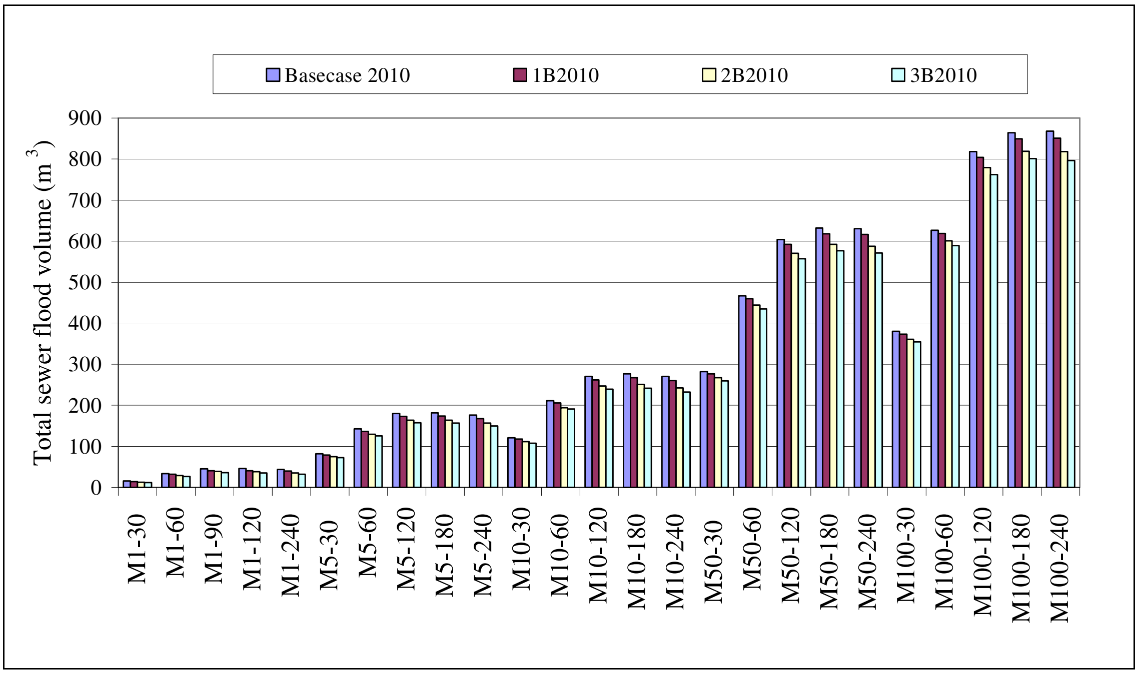


Figure 4.5. Wastewater volume flood occur during sewer flooding when greywater recycling systems are within 2010 development.

Figure 4.6 shows that, under the 2050 scenario, flooding occurs for one year return period events of 90 minutes duration. A reduction in flood volume is observed for scenarios 1B2050, 2B2050 and 3B2050 when compared to the basecase scenarios for all of the designed flood events. The results show that the flood volume reduces as a result of implementing greywater recycling systems. However, the results also indicate that floods still occur under each scenario with the exception of scenario 3B2050 for one year return period events. For five year return events of 30 minutes duration, a reduction of 35% for the 1B2050 scenario, of 48% for the 2B2050 scenario and of 65% for the 3B2050 scenario was observed. The reduction observed is quite consistent; however for heavier rainfall events such as the 100 year return event with a duration of 240 min, a reduction of 4% for the 1B2050 scenario was observed, 6% for the 2B2050 and 11% for the 3B2050 scenario. To conclude, greywater recycling can reduce sewer floods. However, the reduction is far too small to be highly significant during heavy storm events.

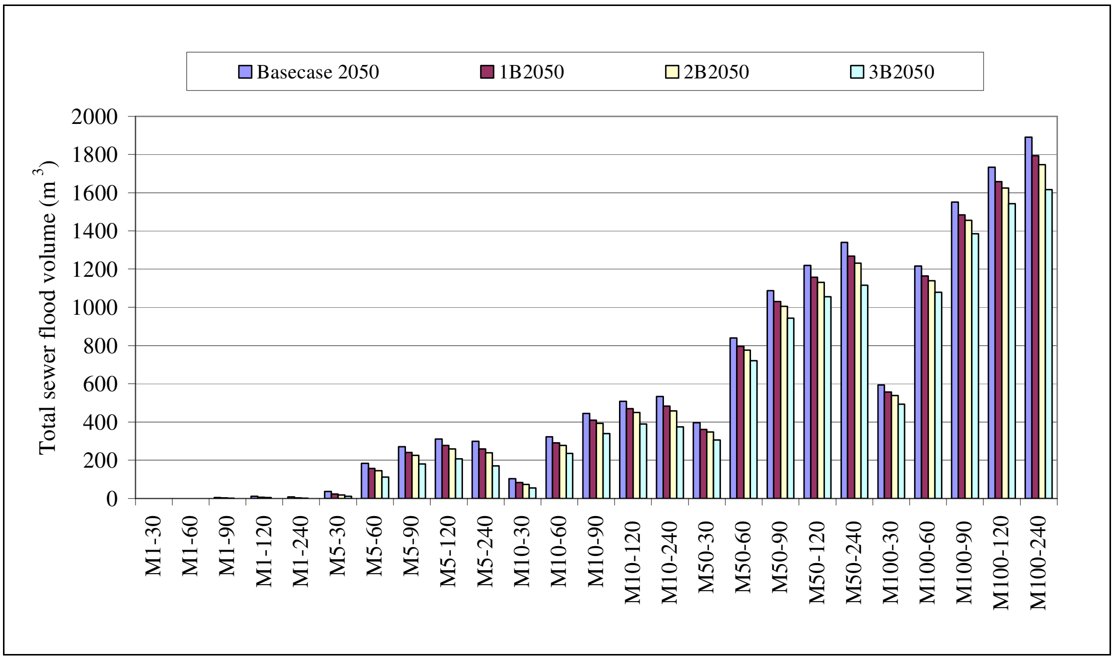


Figure 4.6. Wastewater volume flood occur during sewer flooding when greywater recycling systems are present within 2050 development.

A general comment can be made on the sewer floods occurrence, sewer flood starts to occur under one year return period event of 30 minutes duration. Existing sewer network are designed to cope under 30 year return period events (Reed, 1995).

In order to better understand the ability of greywater recycling systems to mitigate flooding, flood occurrences in each individual node were analysed. Return Period Analysis (RPA analysis) was carried out for 5 year return events and 100 year return events with durations of 30 to 240 minutes (See Section 3.6). Table 4.2 shows the number of nodes affected by floods above and below, 25m^3 and the number of surcharges in each scenario. Surcharges refer to a condition where nodes reach their maximum capacity.

Table 4.2 Number of nodes where floods occur under 5 and 100 year return periods

	One in 5 year event			
	Basecase	1B2010/2050	2B2010/2050	3B2010/2050
Number of nodes above 25m^3	14 (11)*	14 (11)	13 (10)	9 (6)
Number nodes less than 25m^3	54 (39)	54 (34)	55 (29)	59 (33)
Surcharges	222 (124)	226 (125)	233 (127)	223 (127)
	One in 100 year event			
	Basecase	1B2010/2050	2B2010/2050	3B2010/2050
Number of nodes above 25m^3	42 (29)	41 (27)	38 (27)	33 (22)
Number nodes less than 25m^3	183 (147)	185 (149)	185 (147)	188 (147)
Surcharges	232 (87)	231 (86)	233 (88)	237 (92)

* results obtained for 2050 scenarios only.

Following this initial analysis, all the nodes whose flood level was above 25m^3 were identified within the Carrickmines catchment. All of them are junction nodes connecting two or three conduits (see Figure 4.7). The highest flood level for the 5 year return period storm event was recorded at 92m^3 and 312m^3 for the 100 year return period respectively in the 2050 basecase scenario simulations. Figure 4.8 shows the locations of the nodes where floods occurred under 100 years return period events. Nodes where floods were found to be below 25m^3 tend to be situated in the centre of a sewer row. At the beginning of each row were non flooding nodes were identified. Furthermore, Figure 4.8 also illustrates that in the 2050 scenario, 85% of the nodes are subjects to floods.

Results show that flood volumes reduce when greywater recycling systems are implemented. Detailed data for each node analysed through the RPA are presented in the Annex 1 (Table A1.1 and Table A1.2). Some nodes were identified as not flooding anymore, 100% reduction was achieved. For the 5 year return period event, a total of 4 nodes were identified with 100% reduction for scenario 1B2050, 10 nodes for 2B2050 and also 10 nodes for scenario 3B2050. A similar observation could be made for the 100 year return period storm event. Here, flooding was reduced by 100% in 2 for the 2B2050 scenario and 8 nodes for the 3B2050 scenario. Figure 4.8 illustrates the locations of flooding habitations depending on the number of greywater recycling systems present.

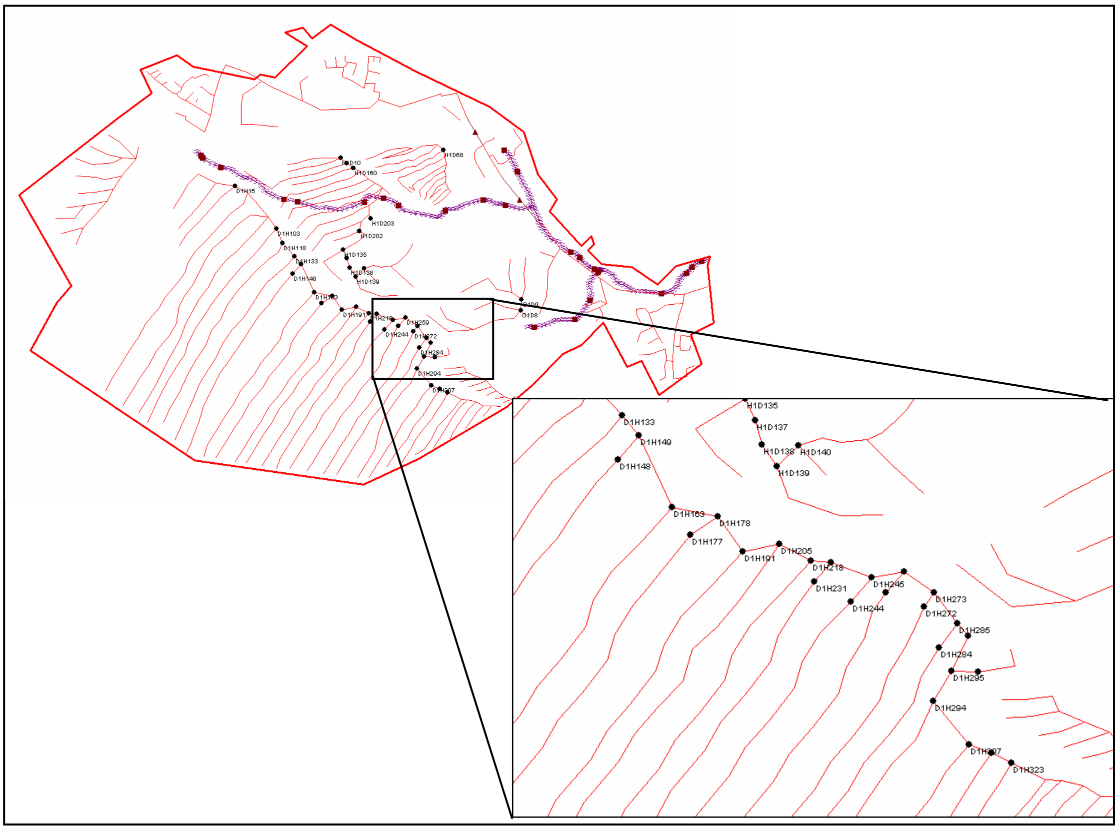


Figure 4.7. Location of nodes where floods above 25m^3 occurred.

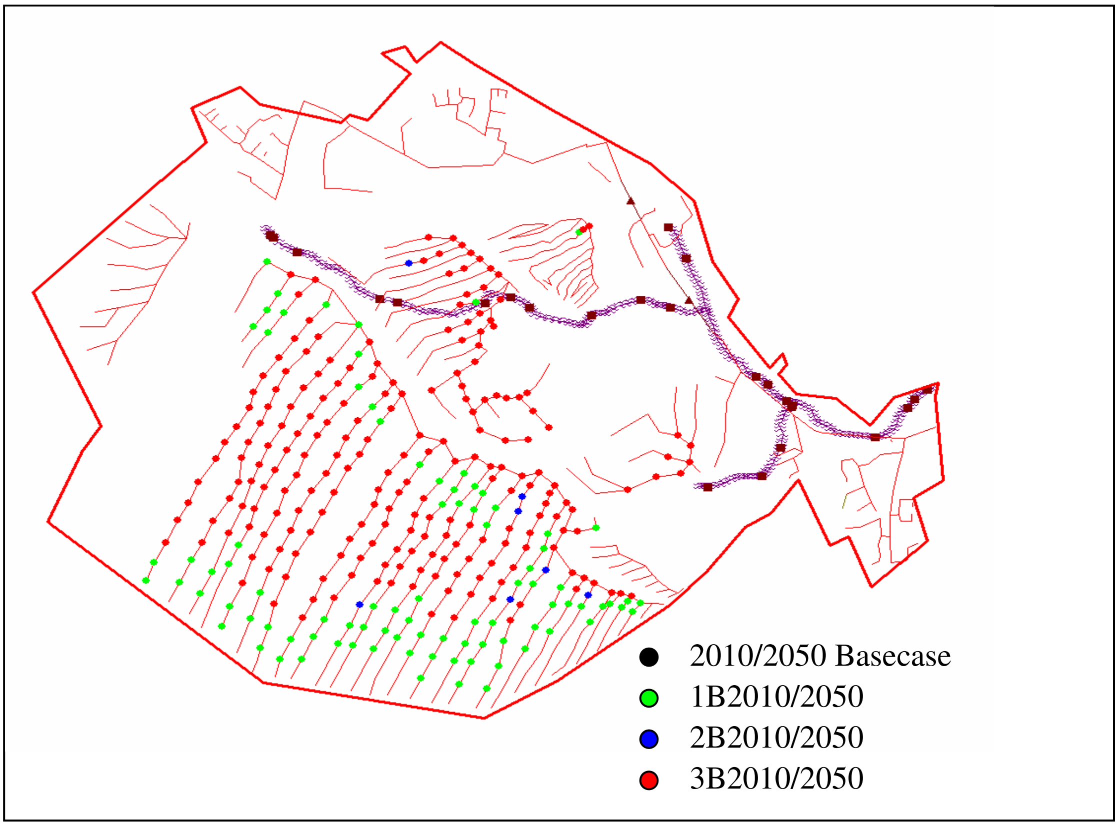


Figure 4.8. Location of nodes where floods occurred for all the scenarios during 100 year return period events.

4.2 Influence of greywater recycling system on the Carrickmines catchment hydrology

The following section assessed the influence of greywater recycling systems on the hydrological network of the Carrickmines catchment. The study also carried out a hydrological analysis of the new development on the hydrology of the catchment. The total river volume, the peak flows at the two river gauges and the total river flood volume were quantified to identify the influence of i) the new development and ii) the rainfall events on the catchment hydrology.

Figure 4.9 and Figure 4.10 show the variation of total river flow within the river system of the catchment for the three basecase scenarios (2002, 2010 and 2050) for the four set of top 100 events. The results indicate a net increase in total river volume due to the planned catchment urbanisation and the different profile of rainfall events predicted by the climate change scenarios.

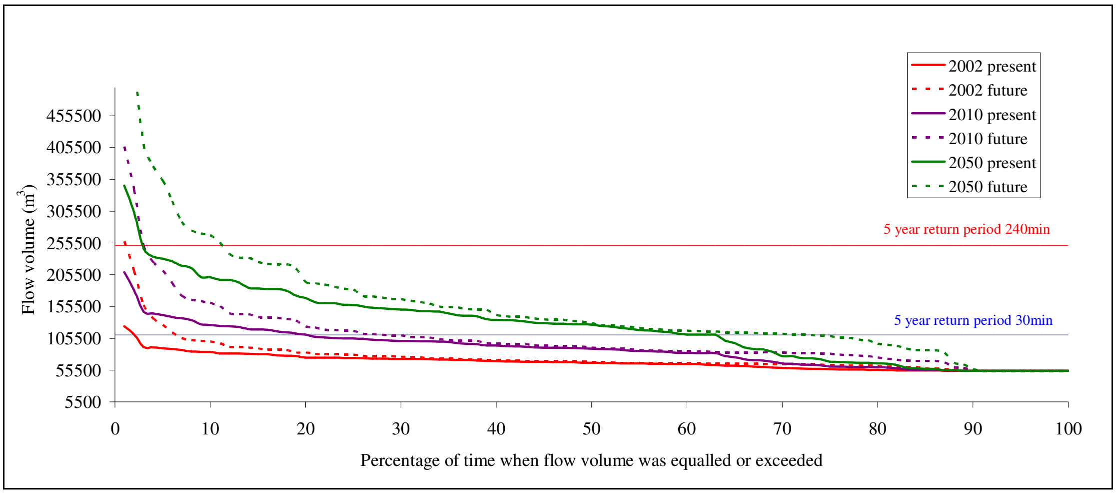


Figure 4.9. Comparison of the total river volume variation during frequent rainfall events for the three urban developments.

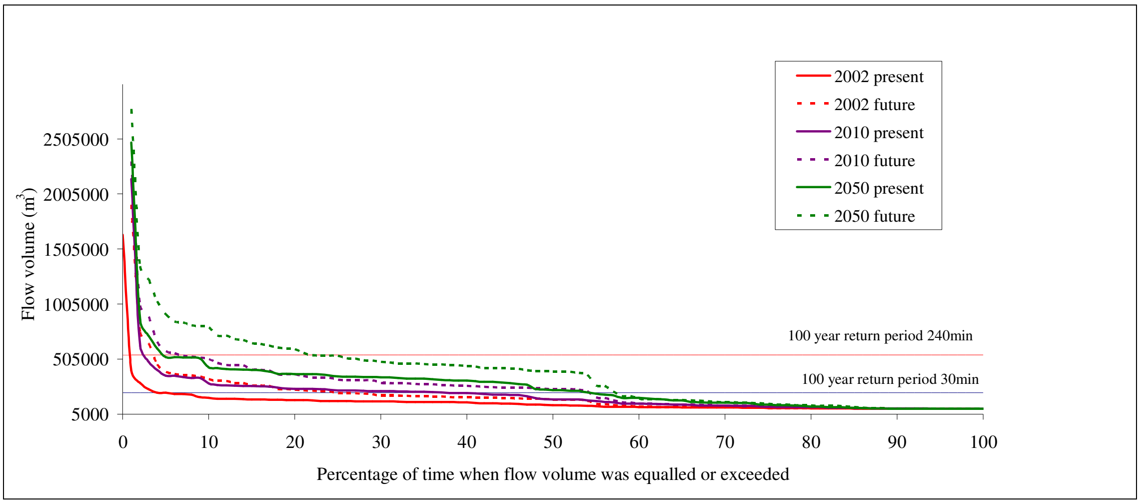


Figure 4.10. Comparison of the total river volume variation during extreme rainfall events for the three urban developments scenarios.

Figure 4.11 and Figure 4.12 illustrate how expanding urban developments and different rainfall events influence the peak flow at both river gauges. The peak flows modelled for each rainfall event are compared with the maximum river gauge readings observed on the 26th of May 1993, where 14.3m^3/s flow was observed at Common's Road and 6.9m^3/s flow at Carrickmines respectively. The results show a constant increase between basecase 2002, 2010 and 2050 as a result of the growing urbanised areas. Peak flows increase considerably, as can be seen. For example, under present conditions, the peak flow exceeds 6.9m^3/s for 40% of the time but 67% of the time under future conditions, i.e. larger urban development and more rainfall events, in 2050. Moreover, under future conditions and in the case of extreme events the peak flow is shown to reach 60m^3/s. Increases in peak flows at Common's road bridge, are shown to be less dramatic (Figure 4.12). This might be explained by the fact that both the 2010 and 2050 urban developments are draining stormwater to an area close to the Carrickmines Bridges river gauge.

The model did not predict flooding at the two river gauges for any of the simulations. However, floods are observed in the river very close the two river gauge nodes, Figure 4.14 identifies the location of floods in the river.

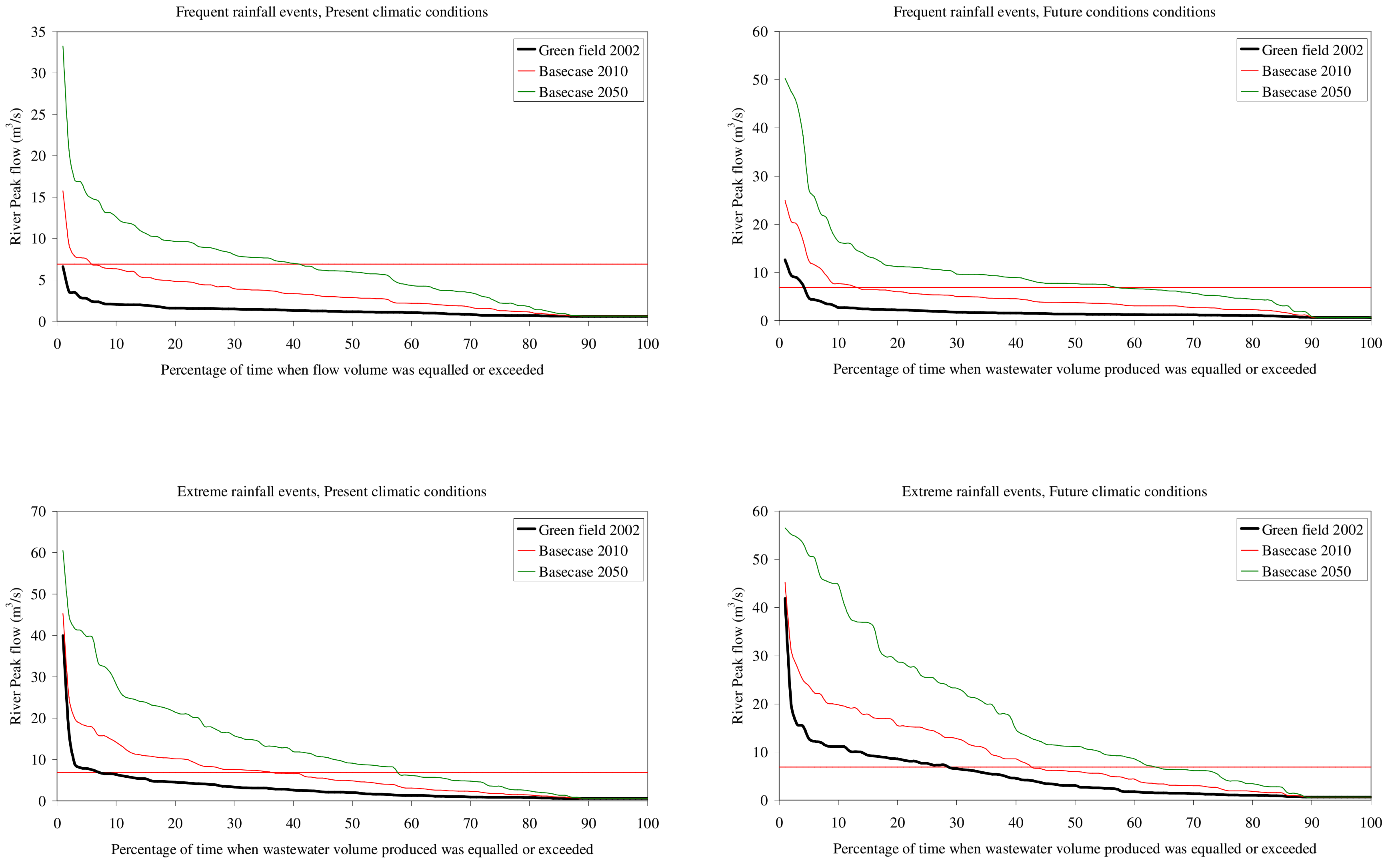
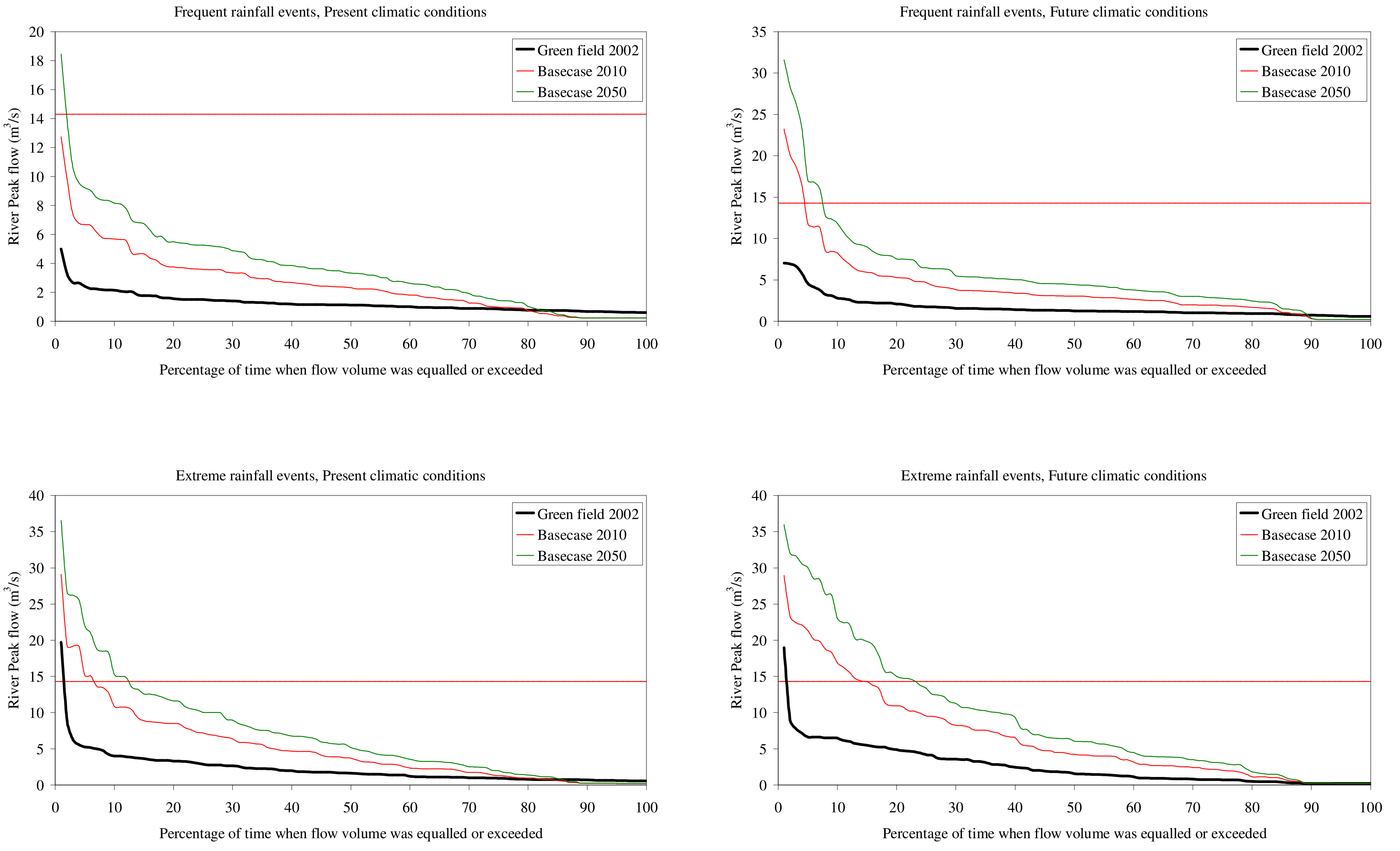


Figure 4.11. Peak flow variation at Carrickmines Bridge river gauge when greywater recycling systems are present.


Frequent rainfall events, Present climatic conditions

Frequent rainfall events, Future climatic conditions

Extreme rainfall events, Present climatic conditions

Extreme rainfall events, Future climatic conditions

Figure 4.12. Peak flow variation at Common's road river gauge when greywater recycling systems are present.

Results suggest that the total river flood volume is highly influenced by urban development and rainfall events (see Figure 4.13). Indeed, under the 2002 urban development scenario, river flooding sets in with a 50 year return period event whereas for the 2010 and 2050 urban development scenarios, floods are observed for the one year return period event.

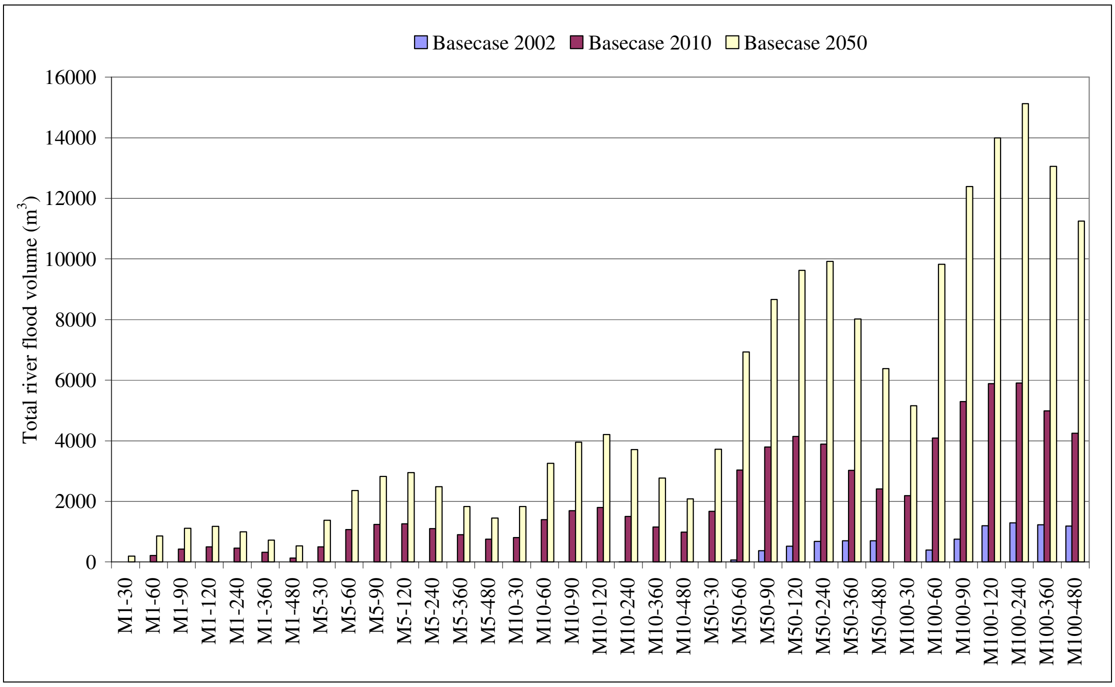


Figure 4.13. Total volume of river floods for 2010 and 2050 urban development.

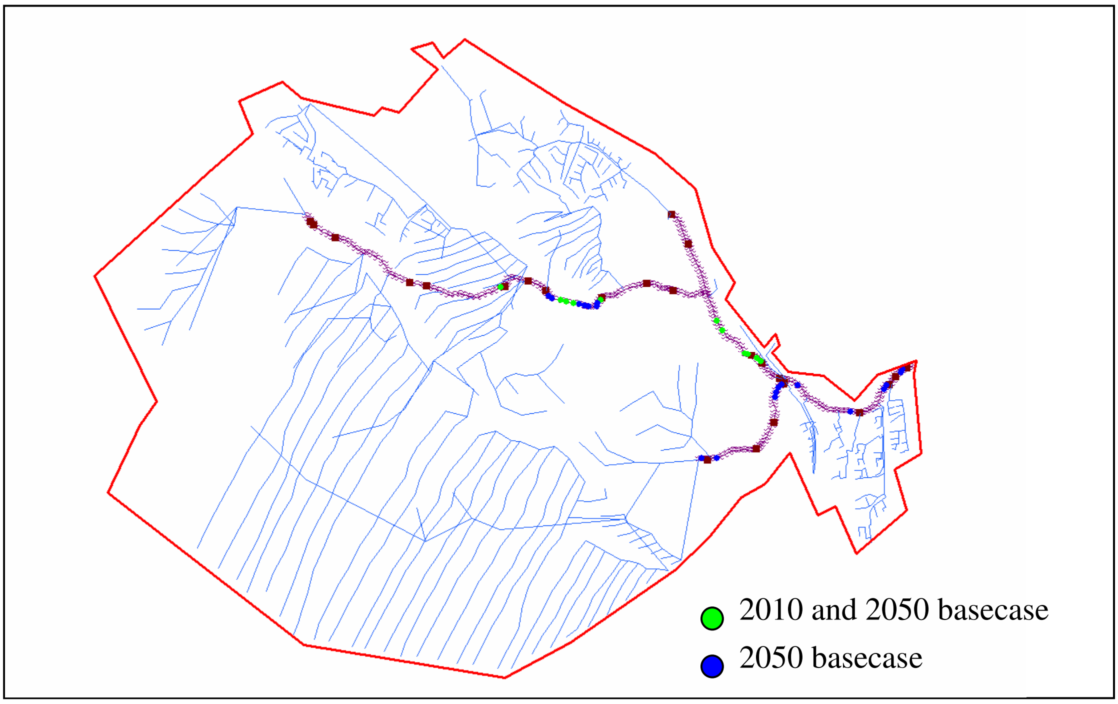


Figure 4.14. Location of nodes where floods occurred in the river during 100 year return period events.

4.3 Influence of greywater systems on saving drinking water quantity

The volume of drinking water saved was assessed by comparing the total volume of wastewater produced for each scenario (1B2010, 2B2010, 3B2010 and 1B2050, 2B2050, 3B2050) with the respective basecase scenarios for a rainless day. Therefore, the volume of drinking water saved is equal to the volume of wastewater reduction. However, to enable this analysis, the following assumptions had to be made: each housing block in the catchment was assumed to display the same household habits by producing and using the same amount of greywater daily. Table 2 summarises the amount of drinking water saved per year for each development scenario.

Table 4.3. Summary of drinking water saved.

	2010 development		**2050 development**	
	Volume of drinking water saved per year	Average reduction of wastewater produced	Volume of drinking water saved per year	Average reduction of wastewater produced
1B2010/2050	123 Ml	6%	340 Ml	5%
2B2010/2050	327 Ml	16%	858 Ml	12%
3B2010/2050	497 Ml	24%	1371 Ml	19%

The results show that for the 2010 development scenario a maximum 24% of drinking water and for the 2050 scenario up to 19% of drinking water can be saved respectively.

4.4 Comparative analysis

The comparative analysis method detailed in Section 3.6.2 has been followed to compare the results obtained for greywater recycling systems for the two urban development scenarios in order to determine the relative performance of greywater recycling technologies for each scenario with respect to reducing drinking water demand, wastewater volume, and runoff volume and river peak flow.

4.4.1 Comparison of the hydraulic performance of the 2010 urban development

The radar charts present in Figure 4.15 and Figure 4.16 compare and integrate the results obtained when greywater recycling systems are implemented at catchment scales for the scenarios tested. Figure 4.15 reviews the results obtained under present conditions whereas Figure 4.16 is focused on future rainfall events. Section 3.6.2 reviews in detailed the methodology carried out to produce the two charts.

First of all, the radar charts highlight a constant and important decrease of the index of volume of water re-used (VRC) as more technologies are implemented in the Carrickmines catchment, from index 7 to 4 for the scenario 3B2010. The same observations and results are obtained under present and future climatic conditions (Figure 4.15 and Figure 4.16). Therefore, the volume of re-used water is not dependent of climatic conditions.

The comparison analysis also identifies a reduction in sewer flow volume coefficient (SVC) for 2010 under present conditions, from index 3 to 2. However, the obtained reduction is the same for scenarios 1B2010, 2B2010 and 3B2010 (index 2). Moreover, under extreme future conditions, the sewer volume coefficient is not influenced by the implementation of greywater harvesting systems for scenario 1B2010. As a result, the obtained reduction of sewer volume is therefore not important; as a result sewer flooding may remain an issue.

The comparative analysis on volumetric performance for runoff volumes coefficient (RVC), and peak flow coefficient (PFC) under frequent and extreme events shows that the implementation of greywater recycling systems does not support and enhance hydrological parameters within the Carrickmines catchment under all the tested rainfall events.

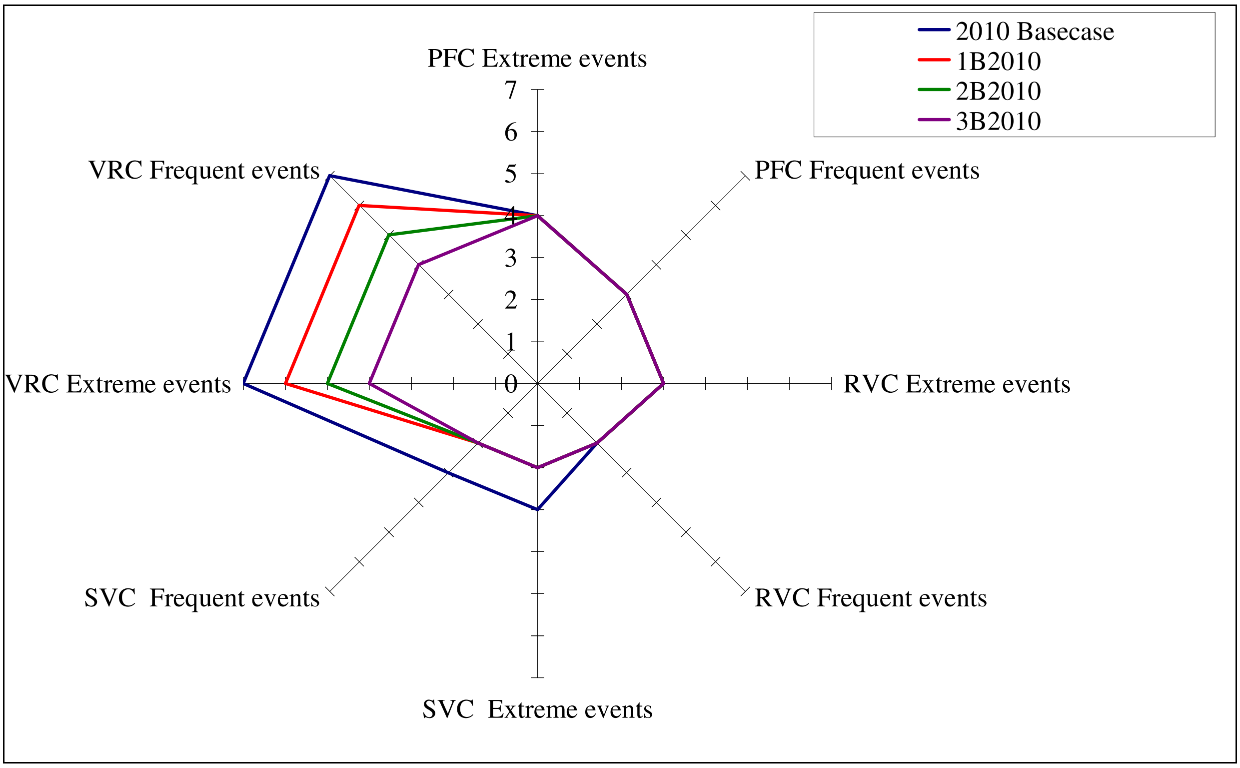


Figure 4.15. Comparison of the hydraulic performance indices for urban development in 2010 under present climate conditions.

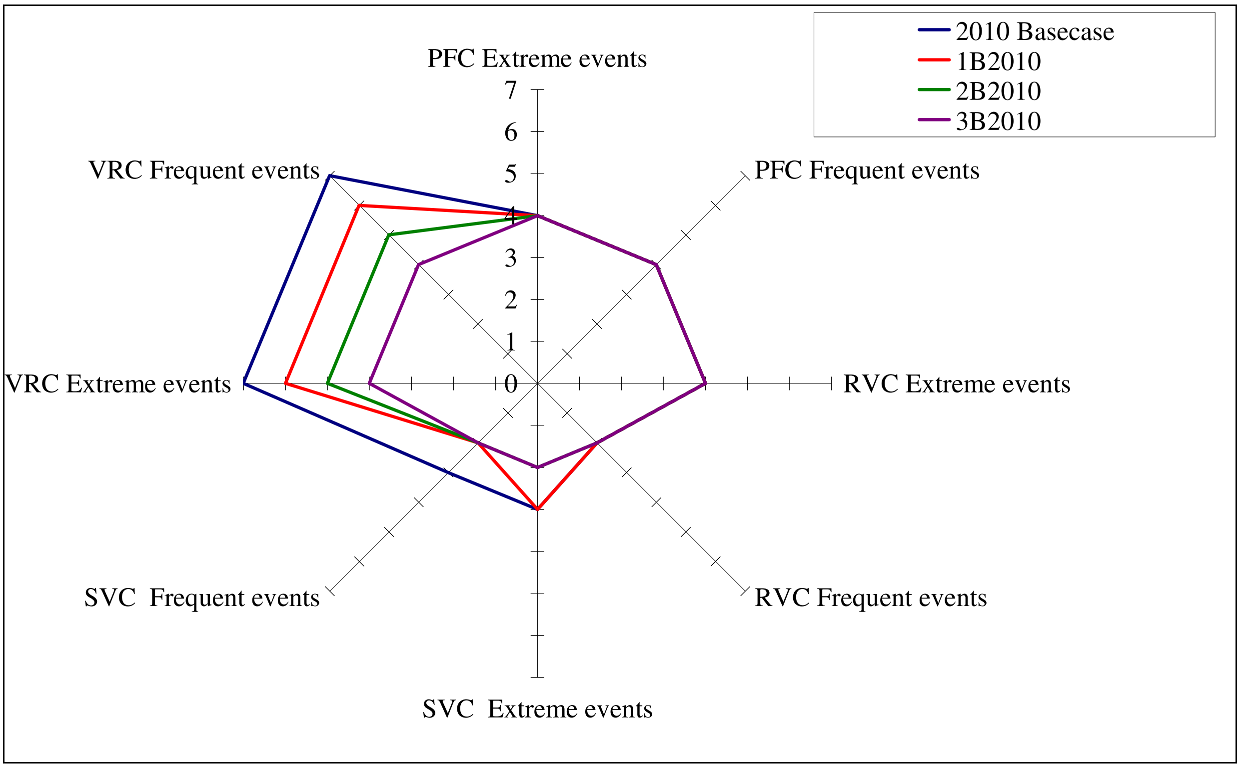


Figure 4.16. Comparison of the hydraulic performance indices for the urban development 2010 under future climate conditions.

4.4.2 Comparison of the hydraulic performance of the 2050 urban development

Similar results can be reported for the 2050 scenario, where a larger urbanised area and higher population numbers were assumed.

No influence on the river peak flow and runoff volume was observed as a result of the implementation of greywater technologies. Scenarios 2B2050 and 3B2050 show a constant reduction of sewer flow volume even during extreme events under future conditions. In contrast, under scenario 1B2050 the indices only indicate a reduction of wastewater volume present in the Carrickmines sewer network under extreme present conditions (Figure 4.17 and Figure 4.18).

The comparison analyses identify the high ability of greywater recycling system to reduce the volume of drinking water. Indeed, the consumption of drinking water constantly decreases under scenarios 1B2050, 2B2050 and 3B2050, both under present and future conditions.

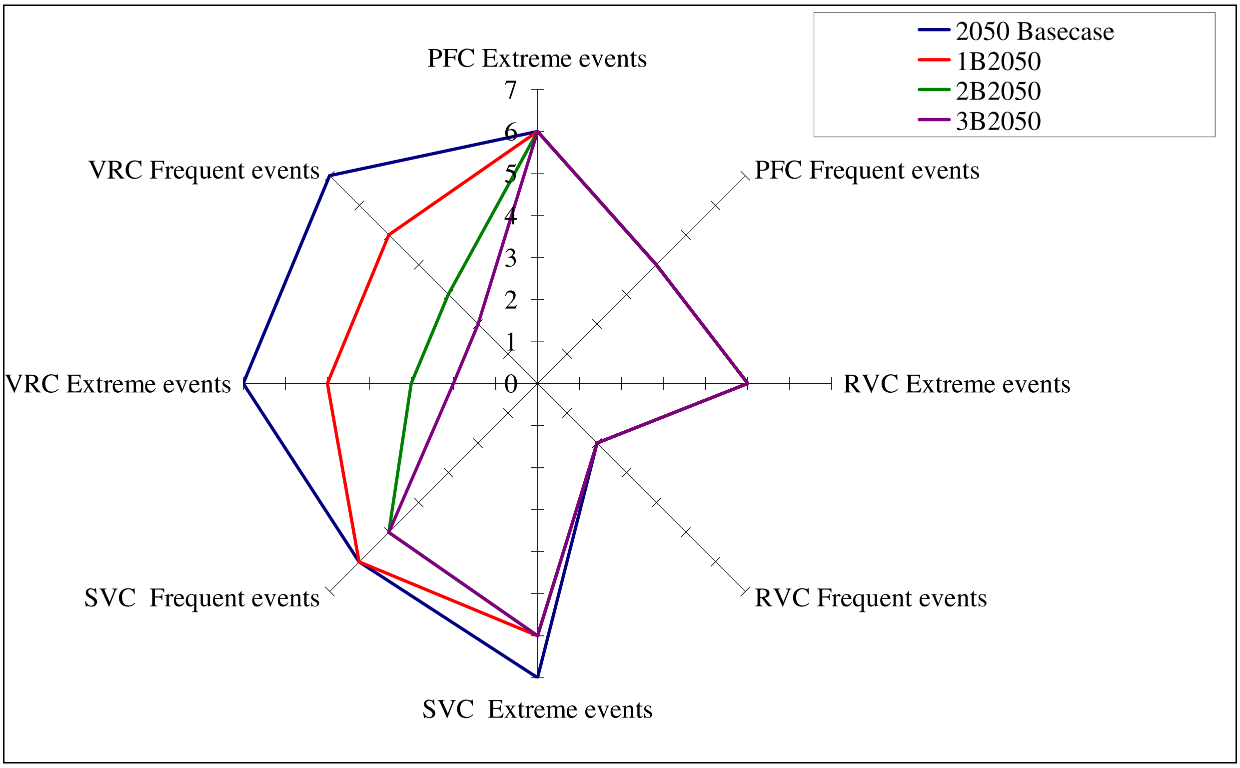


Figure 4.17. Comparison of the hydraulic performance indices for the urban development 2050 under present conditions.

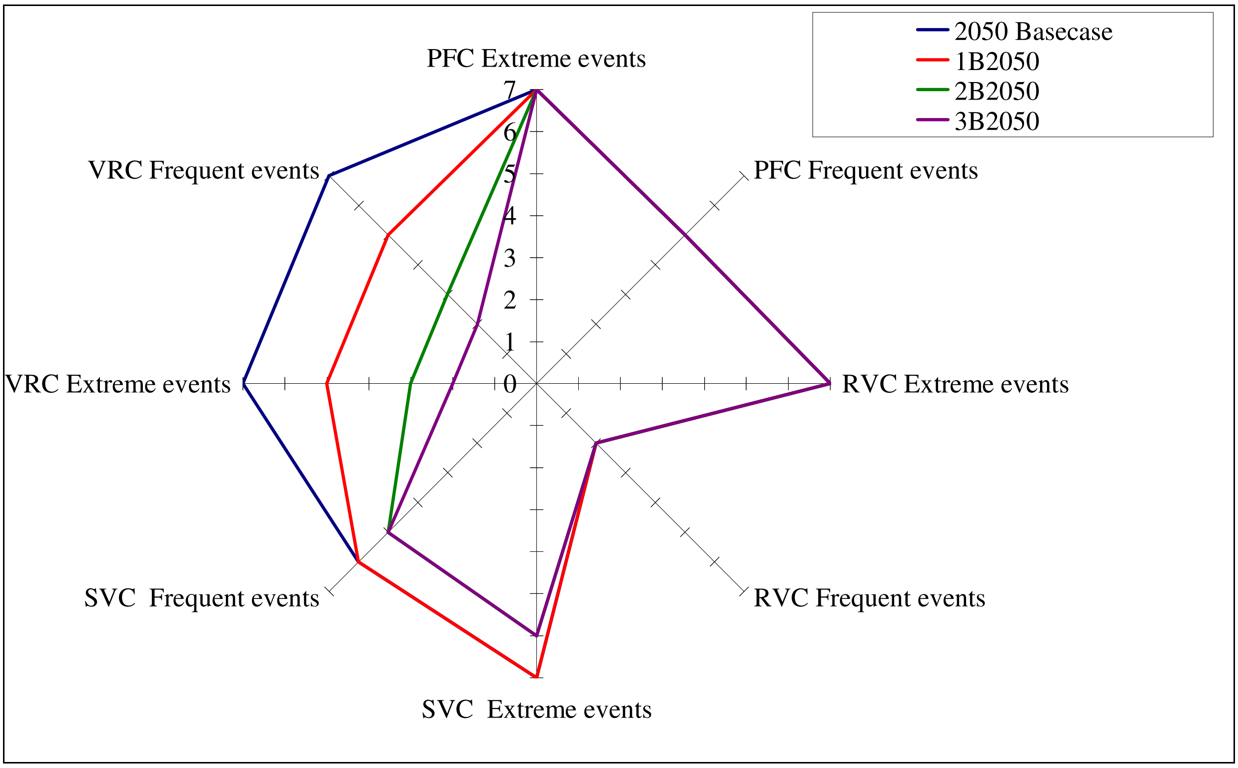


Figure 4.18. Comparison of the hydraulic performance indices for the urban development 2050 under future conditions.

To conclude, the radar charts show that implementing greywater recycling systems is a very efficient technology to control the volume of drinking water. However regarding the three other tested parameters (sewer volume, runoff and peak flow) the analyses identified the technology to be inefficient under any rainfall events tested.

4.4.3 Conclusions

This Chapter has identified and quantified wastewater volume reductions and drinking water savings that can be achieved by implementing greywater recycling technologies at catchment scale. However, the representation of the three different scales (household, neighbourhood and municipal) within the sewer network could not be represented within InfoWorks^{TM} CS. Therefore, the modelling activities carried out can not unambiguously inform conclusion about the hydraulic impacts of greywater recycling systems implementation.

The comparison analysis identified a net reduction in drinking water volume. However, the sewer volume coefficients obtained show that greywater recycling implementation is not sufficient to reduce sewer volume significantly. As a result, sewer flooding may still be an issue. This observation has been confirmed by results presented in Section 4.1.4. Indeed, results show that sewer flood volumes can be significantly reduced, namely by up to 90%. However, the frequency of floods and node surcharges has been shown to decrease only slightly. Therefore, although floods will still be experienced, the implementation of greywater technologies might help to reduce the severity of floods and the damage they cause.

Finally, difficulties to represent the scaling-up effects on the sewer network for greywater recycling technologies have been faced during the modelling activities. Therefore it is now difficult to analyse and conclude the impact caused by municipal scale greywater recycling at urban catchment scale.

Chapter 5 Rainwater harvesting results

This Chapter presents the results obtained for the rainwater harvesting scenarios. Following the reporting structure adopted in Chapter 4, the first section reviews the influence of rainwater harvesting systems on the wastewater network. Then, the influence of rainwater harvesting systems on the catchment hydrology is illustrated through reference to the river peak flow at the two river gauges, levels of flooding along the river and the variation of total volume flow in the river compared with basecase scenarios. The third section quantifies the amount of drinking water saved when rainwater harvesting systems are implemented. Finally, the last section provides a comparative analysis of the runoff, peak flow, drinking water and total wastewater reduction achieved under present and future conditions for both the 2010 and 2050 urban development scenarios.

5.1 Influence of rainwater harvesting systems on the wastewater sewer network

The influence of rainwater harvesting on the wastewater sewer network was assessed by quantifying the wastewater volume obtained under each simulation, represented as the rainfall/wastewater ratio. The extent to which rainwater harvesting technologies reduce sewer flooding was assessed by quantifying the volume of sewer floods for each simulation and by identifying the location of flooding.

5.1.1 Variation of total sewer volume

In order to assess the extent to which rainwater harvesting systems contribute to a reduction in the waste water volume, the total volume of wastewater obtained for each scenario was compared with the respective basecase scenario. Table 5.1 shows the wastewater reduction both in volume and percentage terms under 5 year and 100 year return events of 60 minutes duration. The percentage reduction was determined by comparing the volume of wastewater reduction to the total wastewater produced during a dry day. The analysis shows that significant reductions in the wastewater volume can be achieved though the implementation of rainwater harvesting systems. The results indicate that the reduction increases proportionally with the number of technologies implemented as well as the intensity of the rainfall events. For instance, the highest reduction rates were observed for 3B2010 (26%) and 3B2050 (18%) during M100-240 events (Annex 2, FigureA2.1). Findings therefore suggest that rainwater harvesting technologies can contribute to controlling rainwater intrusion into sewer networks.

Table 5.1. Reduction in wastewater volumes observed for 5 year and 100 year return period event of 60 minutes duration.

One in 5 year 60 minute event				
	Volume of wastewater reduction (m^3)	% wastewater volume reduction	Volume of wastewater reduction (m^3)	% wastewater volume reduction
	2010 development		2050 development	
1B2010/2050	168	3%	420	2%
2B2010/2050	433	7%	1086	5%
3B2010/2050	632	10%	1586	7%
One in 100 year 60 minute event				
	Volume of wastewater reduction (m^3)	% wastewater volume reduction	Volume of wastewater reduction (m^3)	% wastewater volume reduction
	2010 development		2050 development	
1B2010/2050	292	5%	710	3%
2B2010/2050	751	12%	1835	8%
3B2010/2050	1093	18%	2675	12%

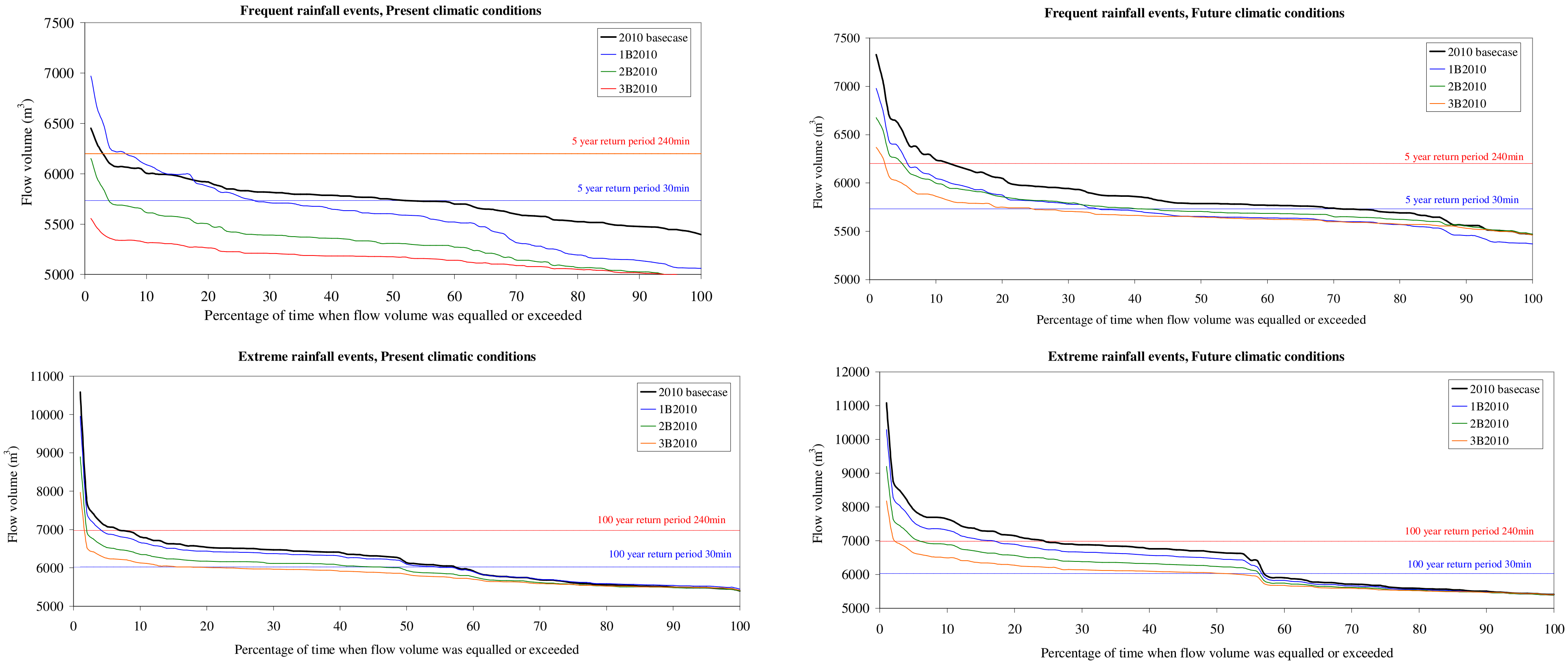


Figure 5.1. Variation in sewer flows obtained when rainwater harvesting are present within development 2010.

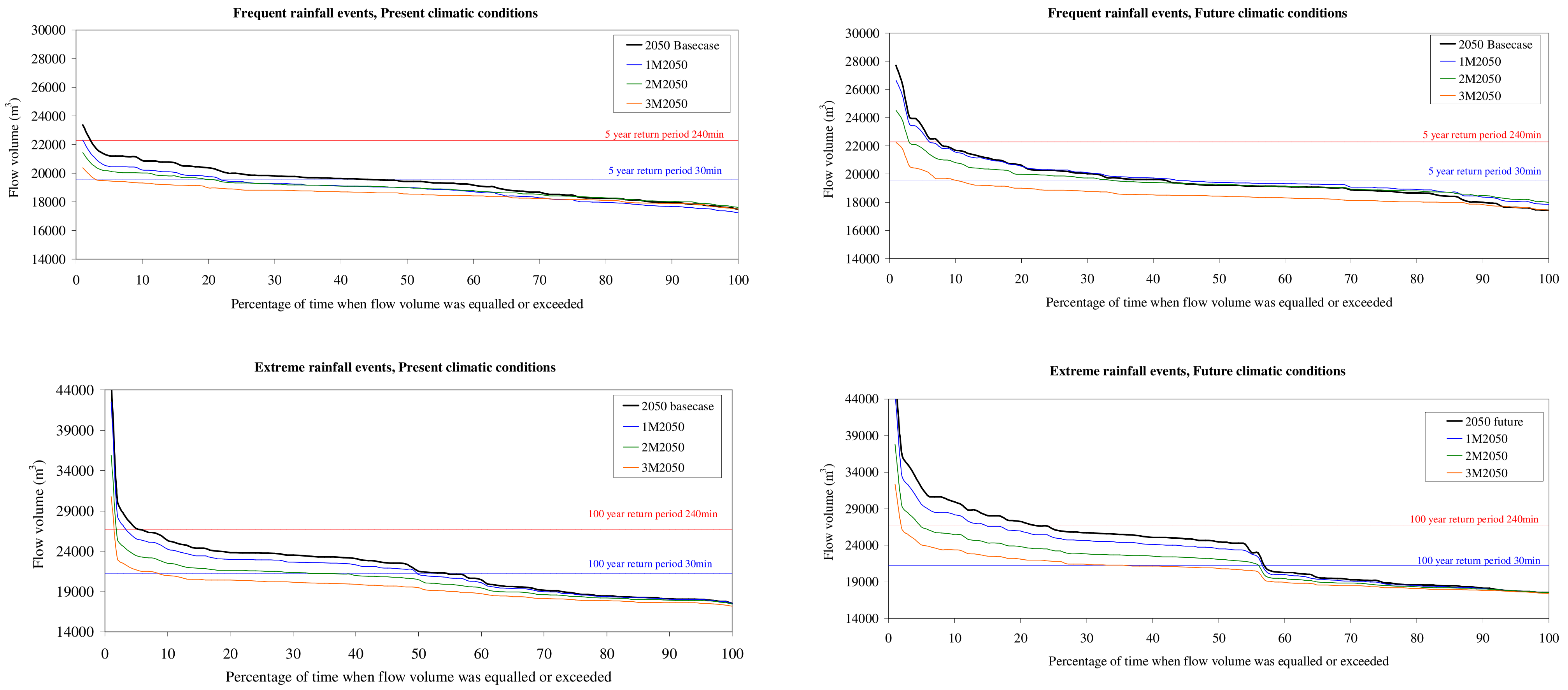


Figure 5.2. Variation in sewer volume flows obtained when rainwater harvesting are present within development 2050.

To quantify the extent to which wastewater volumes were reduced, 24-hour periods were simulated. It was attempted to run longer simulations covering a time-span of five years. However, the time needed to complete such long simulations and the physical size of the file created exceeded the capacities of the available computer facilities. As a result and due to the numerous factors influencing the reduction of wastewater volume the quantification and forecasting of wastewater volume is therefore complicated. However, the next section will review and make conclusions on the influence of rainwater harvesting systems different rainfall events in wastewater flows.

5.1.2 Total wastewater reduction

Figure 5.3 shows the total wastewater volume produced during the designed storm events. It highlights how the wastewater volume decreases proportionally to the number of houses connected to rainwater harvesting systems. Regression coefficients (R^2) were calculated for each simulated rainfall event and all are above 0.99 (Table 5.2), thereby confirming a positive relationship between wastewater reduction and number of rainwater harvesting technologies implemented.

Secondly, it can be noted that during M1-240 events more water enters the network than during a M5-30 event surprisingly the volume of water entering the network is smaller for an M100-30 event than for an M5-240 event (see Figure 5.3).

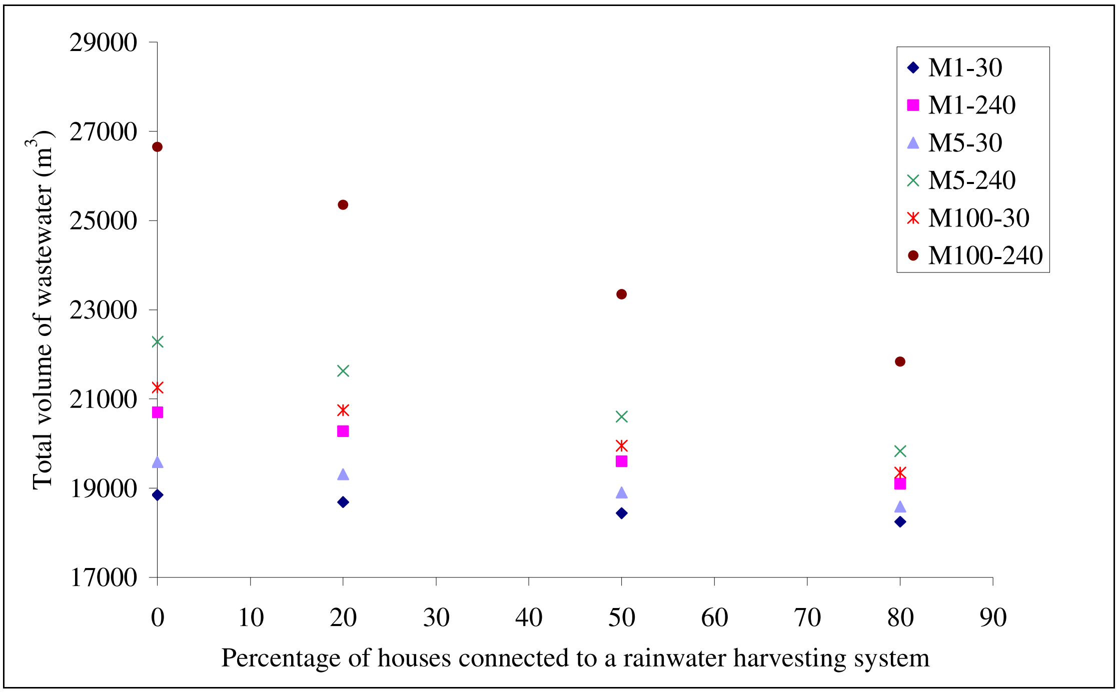


Figure 5.3. Variation in total wastewater volume (m^3) as a function of percentage of houses connected to rainwater harvesting systems under different rainfall events development 2050.

Table 5.2. Wastewater volume relationships

Rainfall events	Equations	R^2
M100-240	$y = -60.714x + 26570$	0.9958
M100-30	$y = -24.083x + 21226$	0.9963
M5-240	$y = -30.955x + 22244$	0.9961
M5-30	$y = -12.591x + 19567$	0.9958
M1-240	$y = -12.591x + 19567$	0.9959
M1-30	$y = -7.5966x + 18838$	0.9960

To conclude, the wastewater volume analysis has shown that rainwater harvesting is a good technique to control rainwater intrusion within the sewer network. Moreover, the wastewater volume reduces consistently with a 26% reduction for the 2010 urban development scenario and 18% for the 2050 scenario. Therefore this important reduction must have a consequence on the ratio of rainwater to wastewater and on sewer flooding. The two subsequent sections will evaluate the influence of rainwater harvesting systems on the ratio of rainwater to wastewater and sewer flood occurrences.

5.1.3 Rainwater / wastewater ratio

The forecast wastewater volume reduction caused by the implementation of rainwater harvesting technologies is likely to change the rainwater/wastewater ratio in the sewer network. Figure 5.4 illustrates the variation of the ratio for the four sets of rainfall events and compares the 2050 basecase scenario with the 3B2050 (extreme case) scenario. For each set of rainfall events, results show that the ratio decreases in the extreme case scenario when contrasted with the basecase scenario. Under the extreme conditions, ratio rainfall/wastewater decreases from 1.5 to 0.7 when rainwater harvesting are present under 3B2050 scenario. These findings suggest that less water is entering the sewer network, and, as a consequence, the waste water will be less diluted. Furthermore, sewer floods can be expected to occur less frequently.

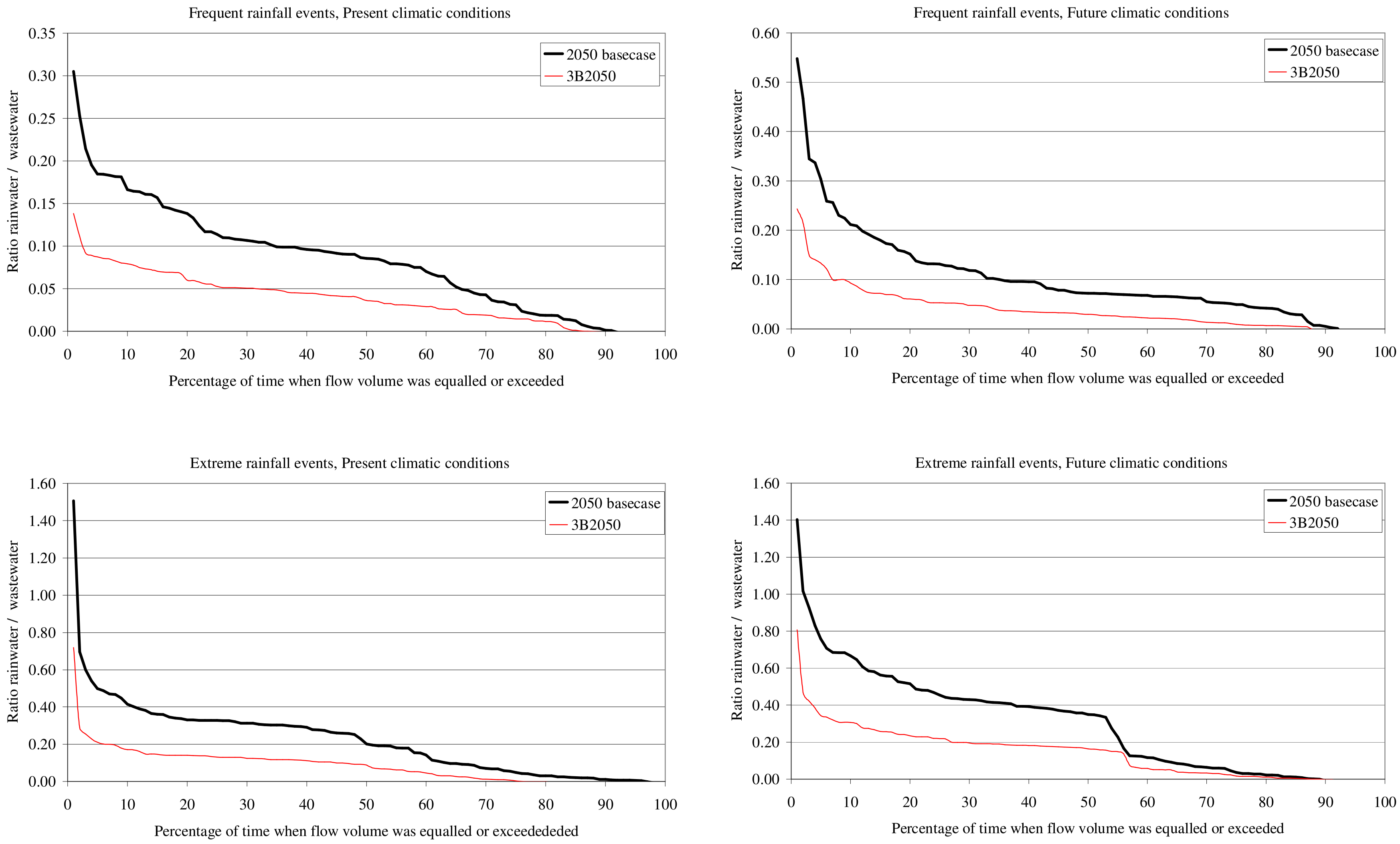


Figure 5.4. Ratio rainwater / wastewater into sewer system obtained when rainwater harvesting systems are present within 2050 development.

5.1.4 Variation of total sewer flood volume

In order to assess the influence of rainwater harvesting systems on sewer flooding, the total flood volume at each node was extracted from the results obtained with designed rainfall events. The total flood volume was then identified per simulation and compared (Figure 5.5 and Figure 5.6). The location and number of nodes where flood and surcharge occurred were identified, the results are presented in Table 5.3 and a map was produced and introduced as Figure 5.7.

A net reduction in sewer flooding is observed for the 2010 development scenario (Figure 5.5). For the 1B2010 scenario, the same sewer flood frequency was observed. Sewer flooding occurs from rainfall event M5-30. The volume of floods has considerably decreased compared with flood volume occurring for the basecase 2010 scenario. A maximum decrease of 67% was observed for the M10-90 event and a minimum of 40% for M100-60 events. Therefore, a constant decrease of sewer floods was identified for scenario 1B2010. Moreover, the quantity of floods observed within the 2010 urban development scenario can be considered as minor floods. Indeed, as Table 5.1 shows, under frequent events, none of the floods exceeds $25m^3$ under the 1B2010 scenarios. However under extreme events three nodes are subject to floods exceeding $25m^3$ compared to 13 for the respective basecase scenario. For the 2B2010 scenario, floods begin occurring following M50-30 rainfall events but never exceed $9m^3$. Therefore for scenario 2B2010, the reduction in sewer flooding is constant with none of the floods occurring during very extreme rainfall events reaching or exceeding the critical volume of $25m^3$. Finally, under the 3B2010 scenario, no floods occurred during any of the simulated rainfall events.

Under the 2050 development, the reduction of rainwater within the sewer network coincides with a reduction in sewer flooding, the same phenomenon has been observed for urban development 2010 (Figure 5.6). However, due to the more expansive development in 2050, the flood volumes observed are considerably higher; a total sewer volume of $1890m^3$ was observed for the basecase scenario under an extreme event of M100-120. For the 1M2050 scenario, floods begin occurring from the 5 year return event with a duration of 30 min (M5-30). For the 2B2050 scenario flooding sets in with 50 year return period events lasting one hour (M50-60) with flood volume reduced by 91%. As observed for M2050 a net reduction of flood volume is observed. For the M5 to M20 storm events, flood volumes reduced by more than 50%, regardless of the duration of these storms. For the M20 to M100 events slightly lower reductions were observed at 40%. Under the 3B2010 and 3M2050 scenarios, the sewer network remained completely free of floods. These results suggest that if 80% of the new urban developments are connected to rainwater harvesting systems, it can be reasonably expected that none of the new development areas will experience any floods. The flood reduction observed is significant suggesting that sewer flood problems could be solved by capturing rainfall and limiting its intrusion in to sewer networks.

For both developments, it needs to be pointed out that flood volumes increased for storm events of 30min to 90min duration for development 2010 and for events from 30min to 240min duration for development 2050. However when the storm event duration exceeded 90 and 240min flood levels decreased compared to volume. This observation highlights the limit of the InfoWorks™ CS to model and forecast extreme flood volume and events. The simplification of flood modelling involved in InfoWorks™ CS version 6.5 has been described and explained in Section 3.3.3.

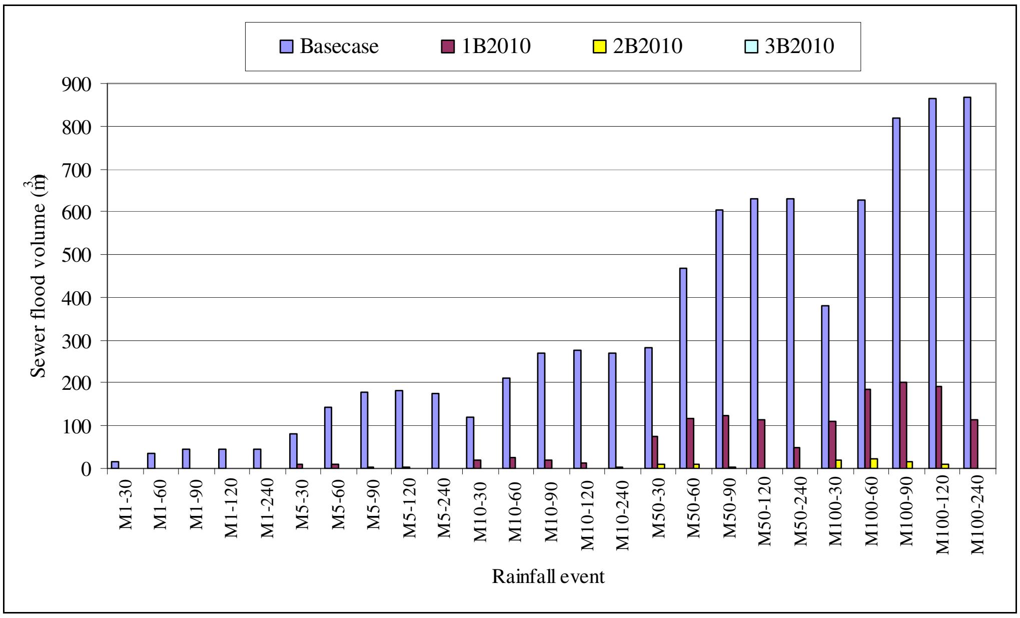


Figure 5.5. Variation of sewer flood volumes under 2010 development during designed rainfall events.

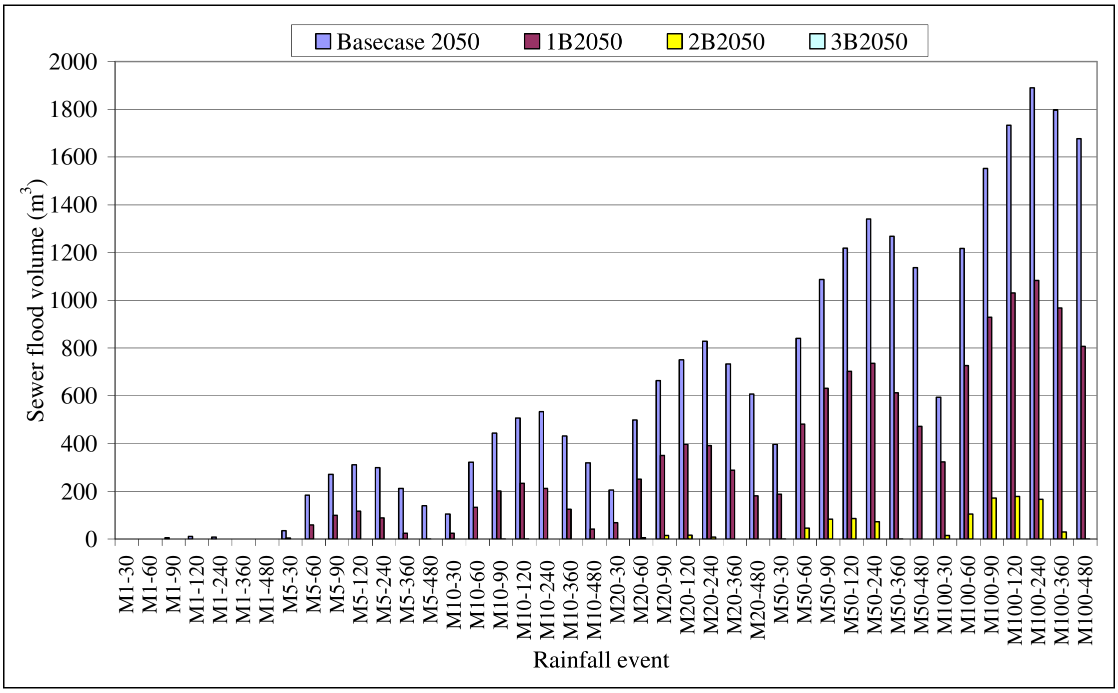


Figure 5.6. Variation of sewer flood volumes under 2050 development during designed rainfall events.

Table 5.3 reviewed the number of nodes where floods occur for developments 2010 and 2050 under frequent and extreme events. First of all, the results show that under frequent events, none of the nodes experiences extreme floods as after the implementation of rainwater harvesting systems. However, in the case of extreme rainfall events, extreme floods occur under scenarios 1B2010/2050 and 2M2050. However the number of flooded nodes is reduced considerably.

Table 5.3 Number of nodes that flood under 5 and 100 year return period.

		One in 5 year event		
	Basecase	1B2010/2050	2B2010/2050	3B2010/2050
Number of nodes above 25m^3	14 (11)*	0(0)	0(0)	0(0)
Number nodes less than 25m^3	54 (39)	24(22)	0(0)	0(0)
Surcharge nodes	222 (124)	155(107)	42(19)	5(0)
		One in 100 year event		
	Basecase	1B2010/2050	2B2010/2050	3B2010/2050
Number of nodes above 25m^3	42 (29)	18(15)	3(3)	0(0)
Number nodes less than 25m^3	183 (147)	73(60)	19(17)	0(0)
Surcharge nodes	232 (87)	188(102)	130(71)	46(16)

* results obtained for 2050 scenarios only.

Figure 5.7 illustrates the location of all floods identified under all the scenarios. Under the 2010 and 2050 scenarios floods with a volume exceeding 25m^3 are present at the main junction of conduits. Prior to the implementation of rainwater harvesting systems, floods occur all across the catchment under the basecase scenario 2050 (black nodes). Under the 1M2050 scenario, the nodes where flood still occur are located in the "middle part" of the catchment (green nodes) and under the 2M2050 scenario at the right of the catchment (blue nodes). These results raise the question of whether the location of rainwater harvesting systems implemented under development 2050 influences where floods occur. The next section will address this query by exploring whether the location of rainwater harvesting systems influence the flood location and the flood intensity.

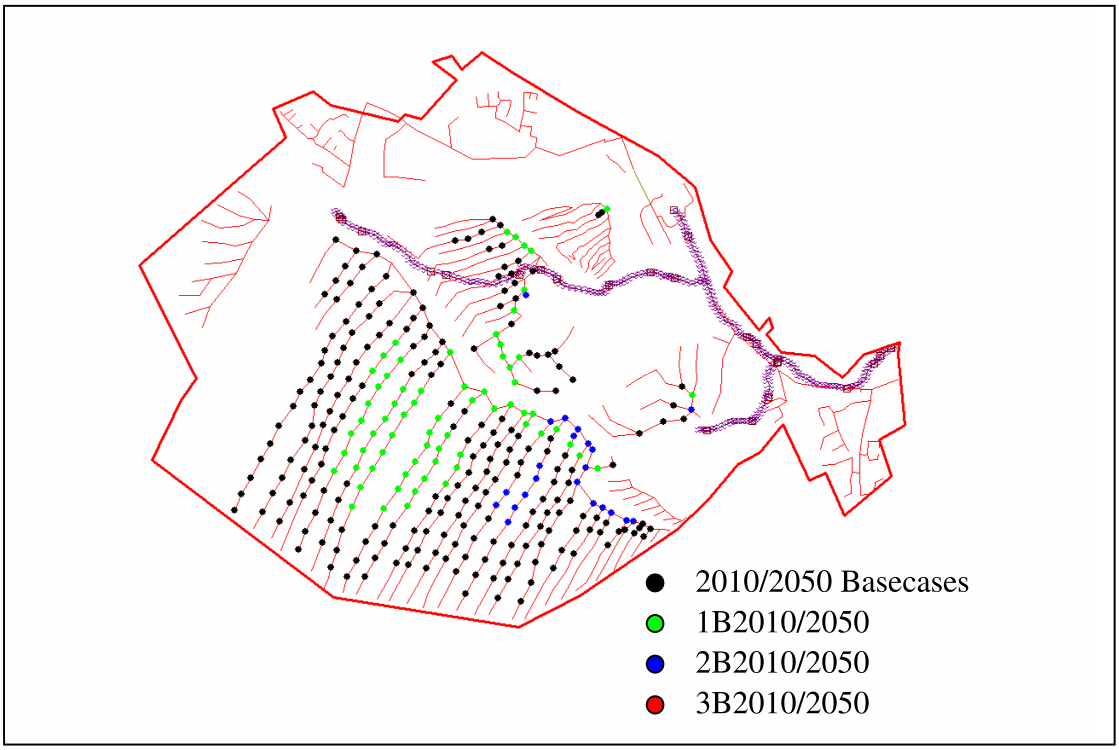


Figure 5.7. Location of nodes where floods occurred during extreme event scenarios (M100 rainfall events).

5.1.4.1 Influence of rainwater harvesting system location on sewer flood intensity and occurrence.

In order, to identify if the location of rainwater harvesting across the urban development in 2050 has an impact on the sewer flood occurrences, six different networks were designed, the location of the rainwater harvesting systems have been randomly chosen (using the random option available within Excel), three different scenarios of 1M2050 (20% of houses connected) and three 2M2050 (50% connected) have been built within InfoWorks^{TM} CS. Figure 5.8 represents the three maps representing the six designed networks, in yellow the three new 1M2050 scenarios can be observed and in blue the 2M2050 scenarios. The designed networks were simulated under extreme designed rainfall events (M100-30 to M100-480).

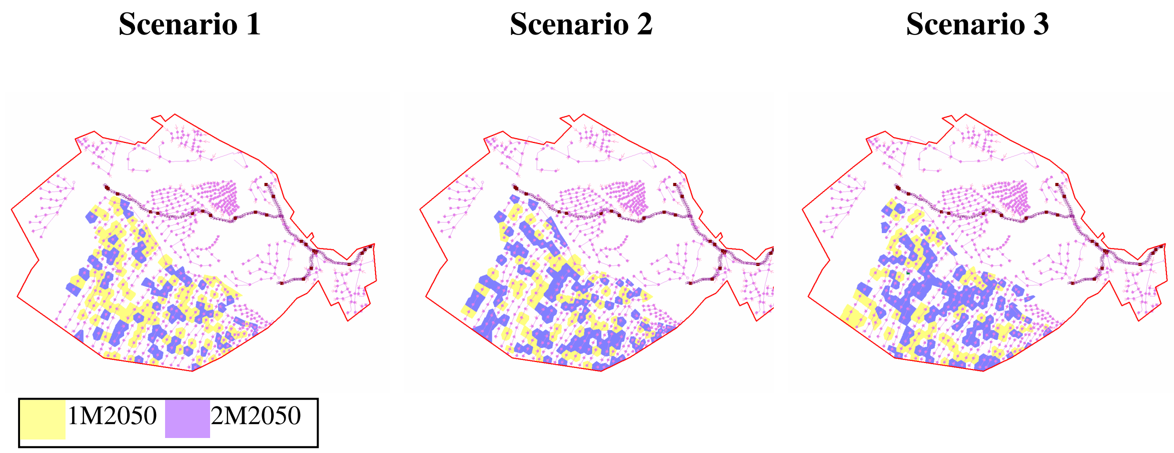


Figure 5.8. The three scenarios of rainwater harvesting system locations

The results show that when rainwater harvesting systems are widely spread across the Carrickmines catchment, the number of nodes where extreme flood events occur only varies marginally. The results vary between 15 and 14 nodes under scenario 1M2050 and between 2 and 3 under scenario 2M2050 (Table 5.4). However the number of nodes where flood volumes remain below 25m^3 shows that the location of rainwater harvesting systems is linked to the flood occurrences within the network. Indeed, for Scenario 3, only 44 nodes flooded compared to 60 in the initial scenario (1M2050) (Table 5.4). The total volume of sewer floods varies between 199m^3 to 182m^3 for the 50% connected scenarios (2M2050) and between 1158m^3 and 1140m^3 for 20% connected scenarios. These results suggest that the location of the technologies is relatively unimportant with respect to total flood volumes. However, flood volumes vary at the level of individual nodes. Under the ‘20% blocks connected’ scenario, the maximum volume observed varies between 51m^3 to 3m^3 and for the ‘50% blocks connected’ scenario, the volume varies between 205m^3 and 113m^3 (Figure 5.5). Therefore the location of rainwater harvesting has an influence on the total volume of wastewater flooding at household scale (for each nodes present within the catchment).

Table 5.4. Number of nodes that flood under 100 year return period

20% blocks connected				
	1M2050	Scenario 1	Scenario 2	Scenario 3
Number of nodes above 25m^3	15	14	14	15
Number nodes less than 25m^3	60	52	49	44
Surcharge nodes	102	134	138	137
50% blocks connected				
	2B2050	Scenario 1	Scenario 2	Scenario 3
Number of nodes above 25m^3	2	3	3	2
Number nodes less than 25m^3	17	13	14	12
Surcharge nodes	71	102	104	98

Table 5.5. Influence of the location of rainwater harvesting technologies on flood intensity

20% blocks connected				
	1M2050	Scenario 1	Scenario 2	Scenario 3
Total flood volume (m^3)	1158	1146	1043	1140
Maximum flood volume observed (m^3)	113	205	121	197
50% blocks connected				
	2B2050	Scenario 1	Scenario 2	Scenario 3
Total flood volume (m^3)	187	182	199	188
Maximum flood volume observed (m^3)	32	40	35	51

Figure 5.9, Figure 5.10 and Figure 5.11 represent the flooding maps obtained for the three extra designed scenarios, the green nodes represent flood volume <25m^3 and red nodes represent flood volume >25m^3. The flood maps highlight that the majority of the floods occur in the centre of the catchment. However the lower part of the Carrickmines catchment does not face flood problems for Scenarios 1, 2 and 3. It can therefore be concluded that when rainwater harvesting systems are spread more widely across the Carrickmines catchment, the area where floods occur will be reduced. However, the maximum flood volumes observed in individual nodes differed between the three scenarios and the initial one.

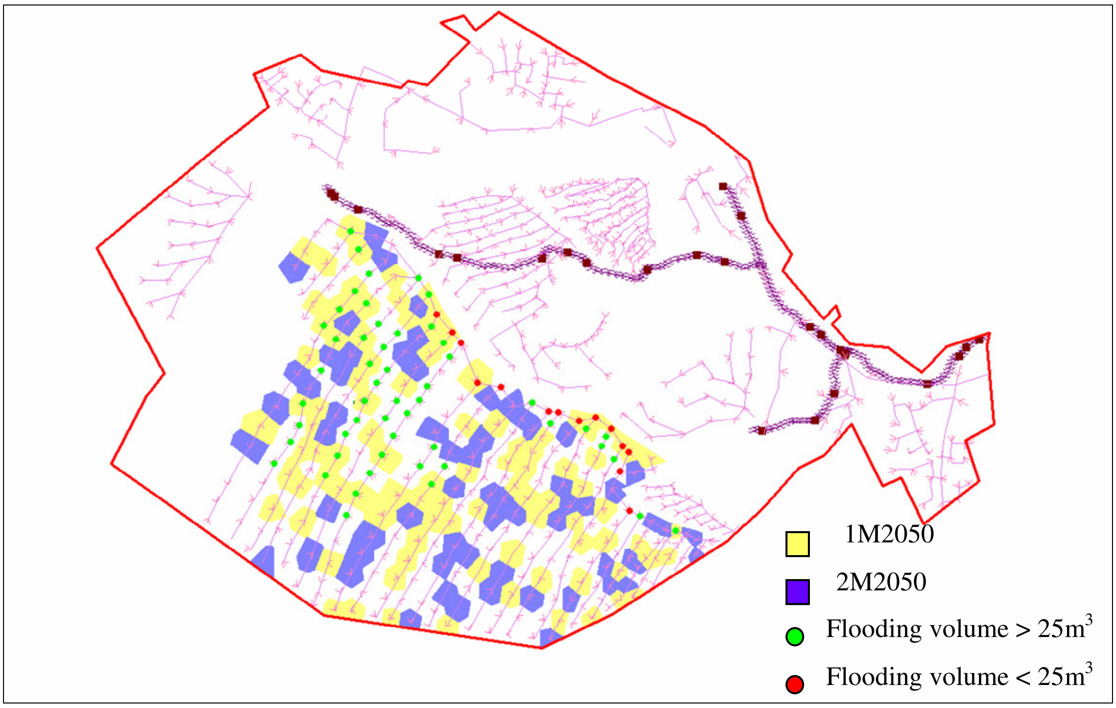


Figure 5.9. Flood location for Scenario 1.

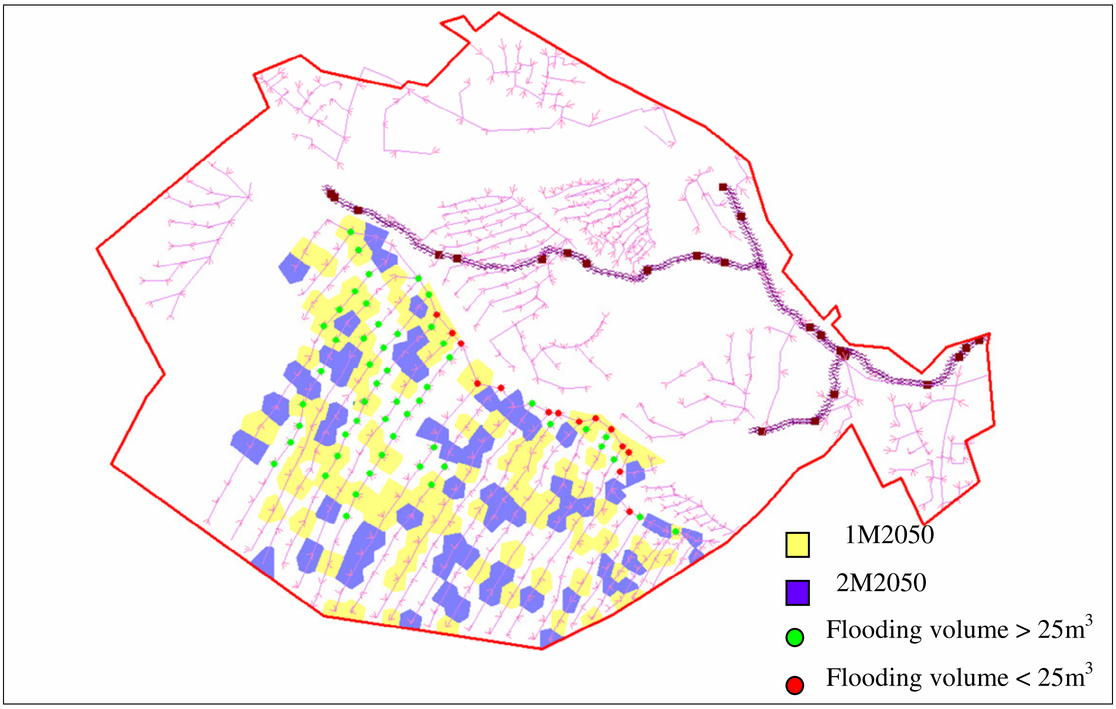


Figure 5.10. Flood location for Scenario 2.

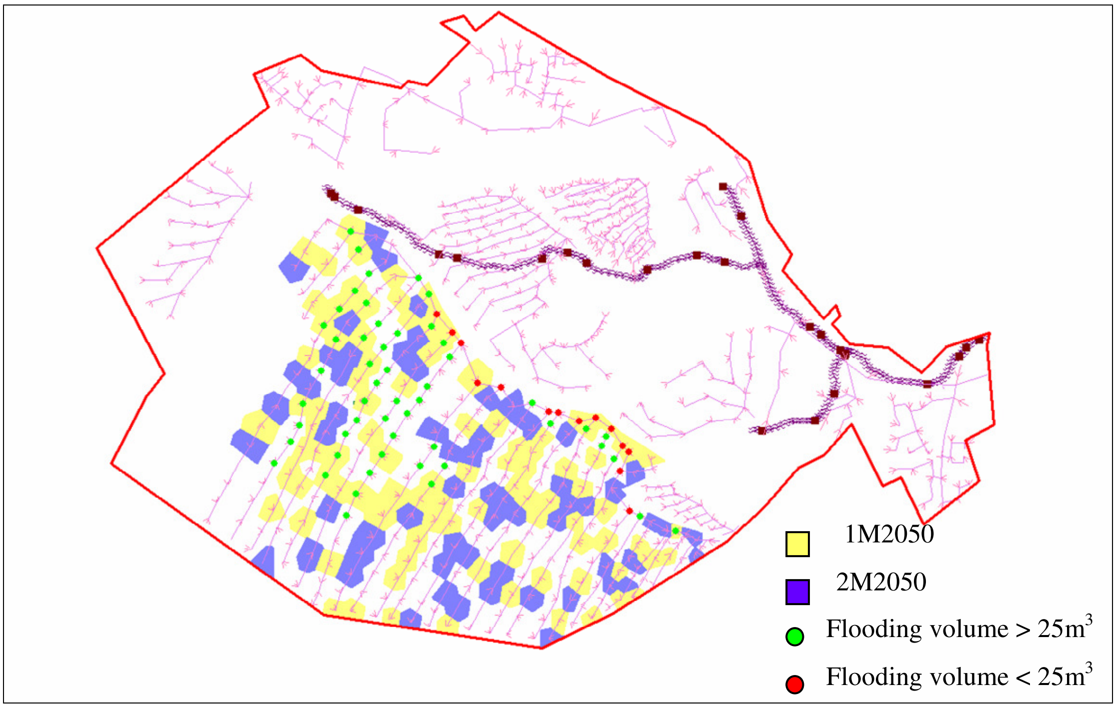


Figure 5.11. Flood location for Scenario 3.

To conclude, these findings suggest that rainwater harvesting systems contribute to a reduction in sewer network floods. Moreover, the results show that the location of these schemes may influence the flood volume intensity and the number of nodes affected by floods. Modelling results indicate that more widely-distributed technologies more efficiently control the number of flood occurrences. At the same time, however, flood volumes seem to increase locally.

5.2 Influence of rainwater harvesting systems on the Carrickmines catchment hydrology

In order to identify the influence of installing rainwater harvesting systems on the Carrickmines catchment hydrology, the total river flow volume as well as the peak flow at the two river gauges were analysed. A river flood volume and low flow analysis were also conducted to obtain a clear picture of the impacts of rainwater harvesting systems on the Carrickmines catchment hydrology.

5.2.1 Influence of rainwater harvesting of the urban runoff volume

Runoff refers to the water from precipitation that flows off a surface to reach a drain, sewer or receiving water. The influence of rainwater harvesting on the runoff volume was assessed within the two urban developments and the scenarios run. For scenarios 1B2010, 2B2010 and 3B2010, the total runoff is forecast to decrease by 2, 4 and 11% respectively. Decreases of 6, 20 and 30% respectively are estimated for scenarios 1M2050, 2M2050 and 3M2050. Furthermore, total river flow volumes are expected to reduce by 1, 8 and 12% respectively in scenarios 1M2050, 2M2050 and 3M2050 (see Annex 2, Figure A2.9).

For the purpose of assessing the links between implementation scale and runoff volume, the total runoff volume obtained for the three tested scales (household, neighbourhood and municipal) were compared (Annex 2, Figure A2.5, Figure A2.6, Figure A2.7). Results show that the percentage by which the runoff volume is reduced varies depending on the scale at which the rainwater harvesting technologies are implemented. For example, for scenario 1B2010 (household scale) a 3.14% reduction was obtained, for 1N2010 a 4.77% (neighbourhood scale) and for 1M2010 (municipal scale) a 5% reduction. To assess the extent to which runoff volumes differed depending on implementation scale, the mean, standard deviation and difference in percent were calculated and showed that the differences were small. This difference observed between the total runoff volumes obtained is caused by the way the scenarios were designed determine. The scenarios were designed based on the number of blocks connected to re-use systems rather than the surface area connected. Moreover, it was assumed that all residential units within the new urban developments were identical. However, due to the way the sub-catchments were designed, each node covers a different surface area. As a result, each scenario contains a different total surface contributing area (see Annex 2, Table A2.1). Therefore in order to continue the analysis, the percentage by which the total runoff was reduced was compared to the percentage by which the contributing area was reduced due to the implementation of rainwater harvesting systems. The correlation coefficient R^2 was calculated for the three scales all together in order to identify if there was a significant difference in the extent to which the three scales of technology reduce the total runoff volume. The analysis was carried out for four rainfall events (M5-30, M5-240, M-100-30 and M100-240) to further assess whether the rainfall intensity influences the results. None of the correlation coefficients is above 0.991 indicating that implementation scale and runoff volume are not associated (for the three series). The results show linearity between the three different scales under 2010 urban development scenarios. Therefore, it can be concluded that scaling rainwater harvesting systems is unlikely to contribute to a reduction of runoff volumes within the Carrickmines catchment for any rainfall events.

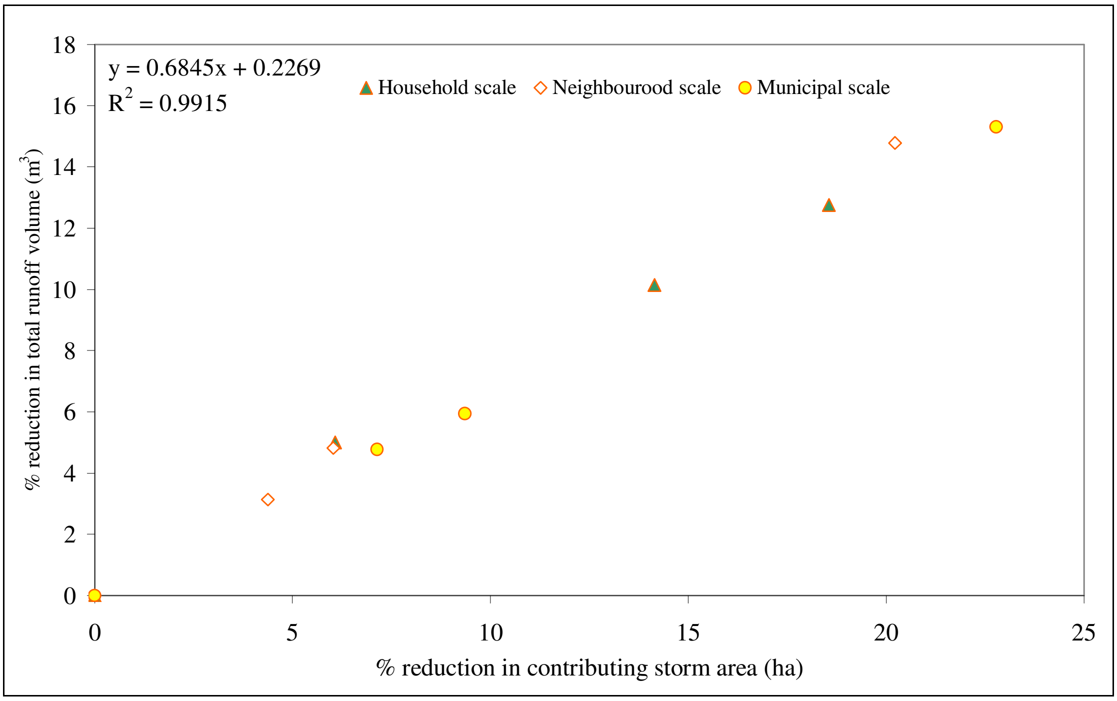


Figure 5.12. Impact of scaling up rainwater harvesting on runoff volume reduction for a M100-30 event.

The carried out analyses highlighted the fact that runoff volume reduction and control is proportional to the impervious surface area reduction. As a result, scaling up the implementation of rainwater harvesting systems will not increase the reduction of runoff. However, having many rainwater harvesting systems within a catchment will considerably control urban runoff.

Figure 5.13 shows that the runoff volume reduces proportion to the reduction of the storm contributing area. For rainfall events lasting 240min, the reduction of runoff volume is smaller. Indeed, the percentage of runoff reductions for M5-240 and M100-240 events is slightly below the ones obtained for M5-30 and M100-30. These findings indicate that rainfall intensity only marginally influences the runoff volume.

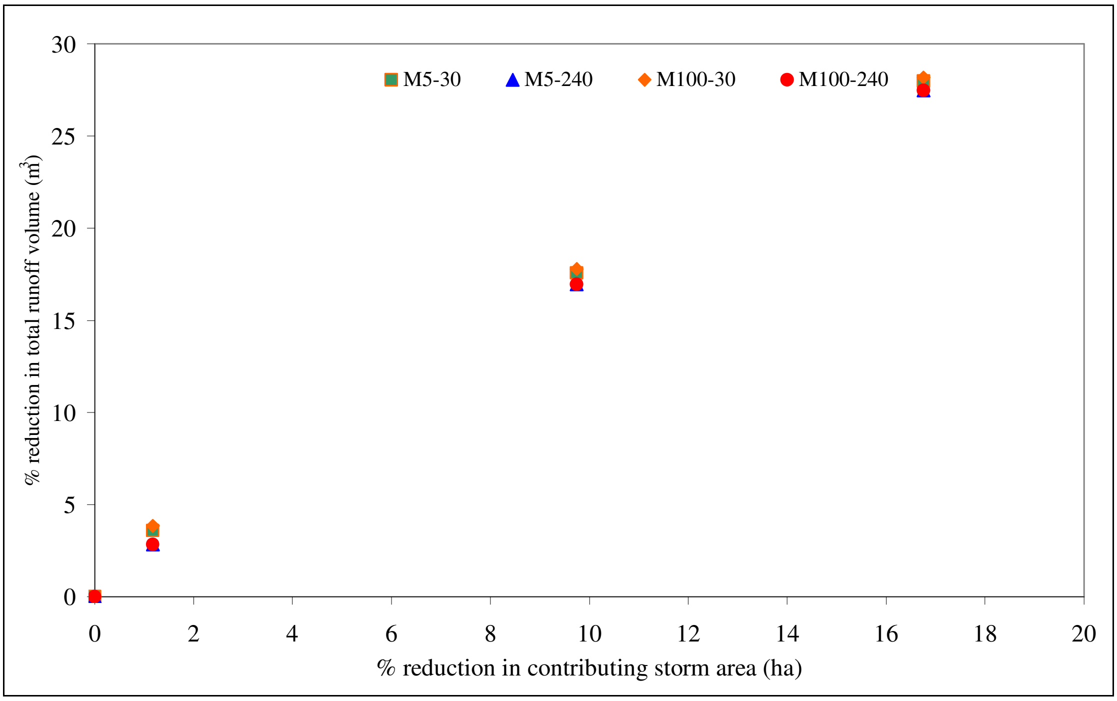


Figure 5.13. Comparison of scaling up rainwater harvesting on the total runoff volume reduction 2050 development.

Runoff volume is highly influenced by the impervious surface area of the catchment. Given that rainwater harvesting systems reduce the impervious surface area (roof and road), runoff volumes can be assumed to reduce considerably. This reduction is likely to directly influence the hydrology of rivers within the catchment, an issue, which will be addressed in more detail in the following section.

5.2.2 How rainwater harvesting systems influence river hydrology

In order to understand how the implementation of rainwater harvesting technologies in the Carrickmines catchment influence the river hydrology, both volumetric flows as well as peak flows were assessed. Figure 5.14 and Figure 5.15 compare the volume of the river flow in all four scenarios under four sets of rainfall (events under present and future conditions).

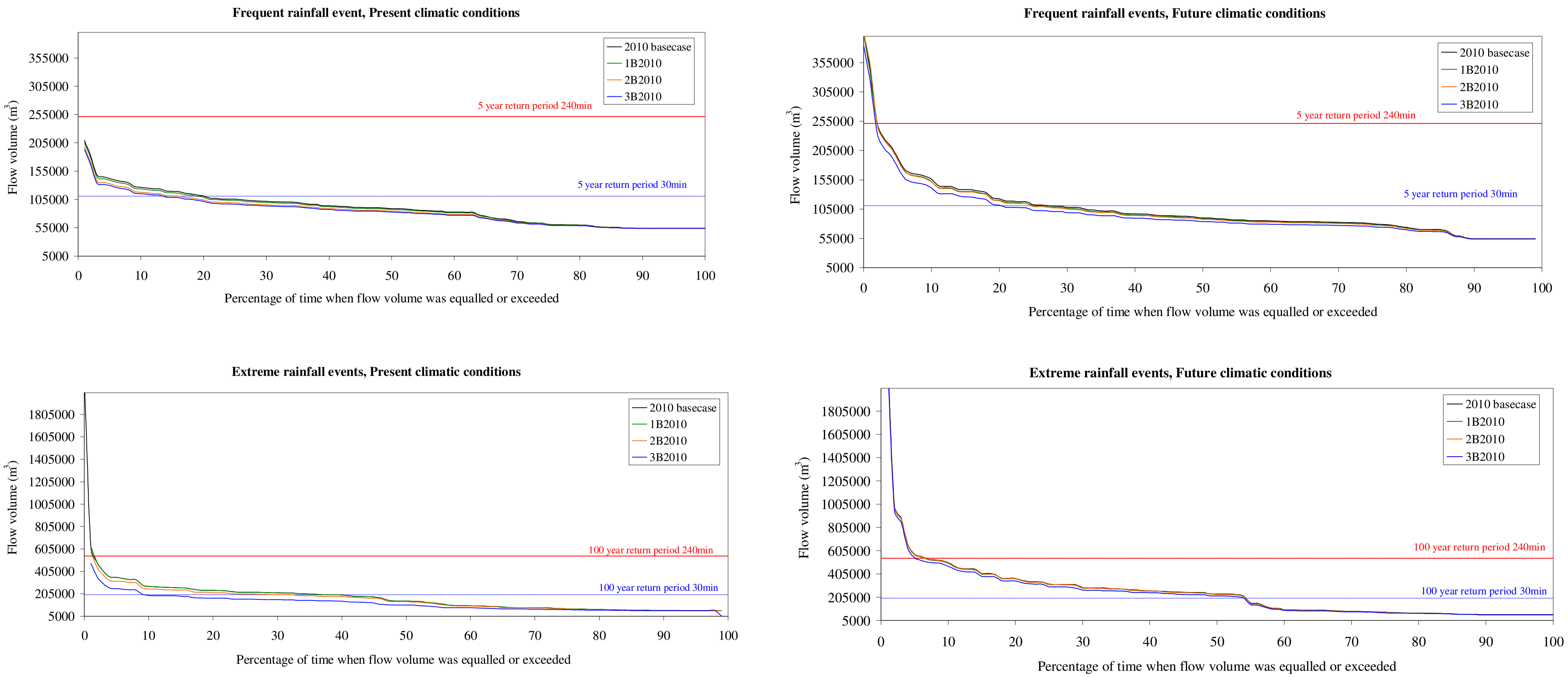


Figure 5.14. River flow variation when rainwater harvesting systems are present within development 2010.

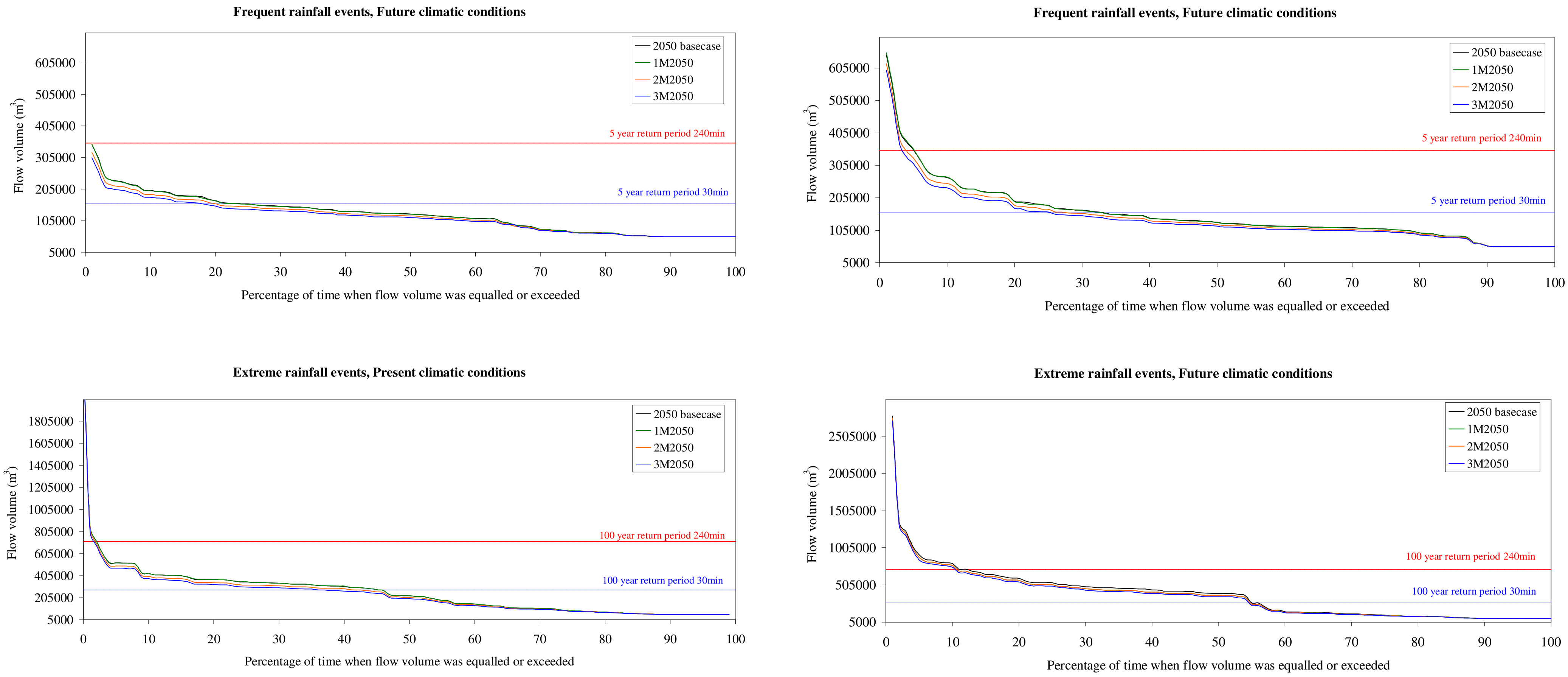


Figure 5.15. River flow variation when rainwater harvesting systems are present within development 2050.

Findings clearly illustrate how of the river flow volume is reduced when rainwater harvesting systems are implemented (see Annex 2 Figures A2.8 and A2.9 and Tables A2.9 to A2.14). The same correlation analysis carried out to assess and compare the runoff volumes for three different implementation scales (reported in the previous sub-section) was performed to assess how technology scale influences the total river flow volume. When the river volume results obtained for the three scales were compared a difference of volume was observed, between 3% and 11%. It was also observed that the difference between the river flow volumes is considerable increasing with the intensity of rainfalls. Talking about the correlation coefficient obtained, the value does not exceed 0.45 for M5-30 rainfall event. Moreover, the R^2 coefficient obtained decreases with the intensity of rainfall events. These results suggest that the extent to which river flow volumes are reduced mainly dependent on the intensity of the rainfall events. However, Figure 5.6 highlights the fact that the reduction of river is proportional to the reduction of contributing storm area up to 10% reduction in area (see red circle in Figure 5.16). According to the results, municipal scale show to be less effective to reduce river flow when it is applied to many habitations than neighbourhood and household scale. Therefore, further investigations are needed to understand the non-linearity of the river volume reductions, the river peak flow at the two river gauges was analysed.

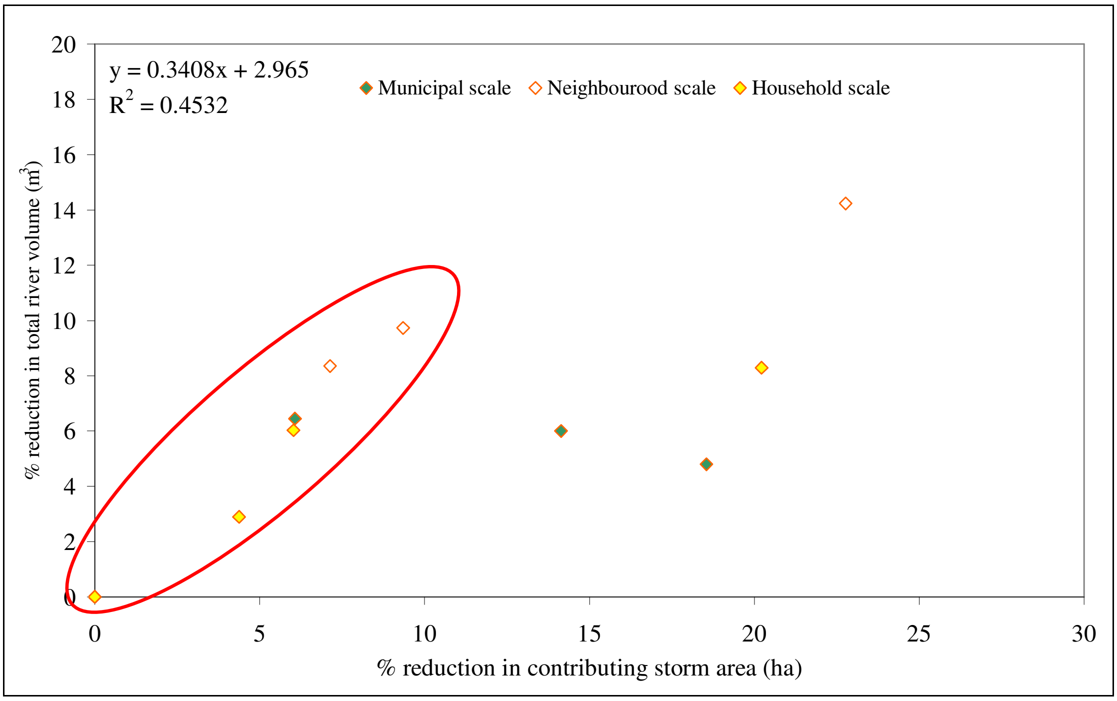


Figure 5.16. Comparison of scaling up of rainwater harvesting technologies on the total river flow volume reduction for a M5-30 event.

The river flows under the 2050 development reduces by 7% for the 1M2050 scenario, by 12% for the 2M2050 scenario and by 15% for the 3M2050 scenario (see Annex 2 Table A2.15). The relationship between the percentage reduction of the river volume and the contributing areas is represented in Figure 5.17. The results show that under M5-30 (frequent event) the relationship is linearly proportional. However, with a growing rainfall intensity the relationship becomes increasingly logarithmic. This observation suggests that the potential of rainwater harvesting technology to decrease the volume of river flows is limited.

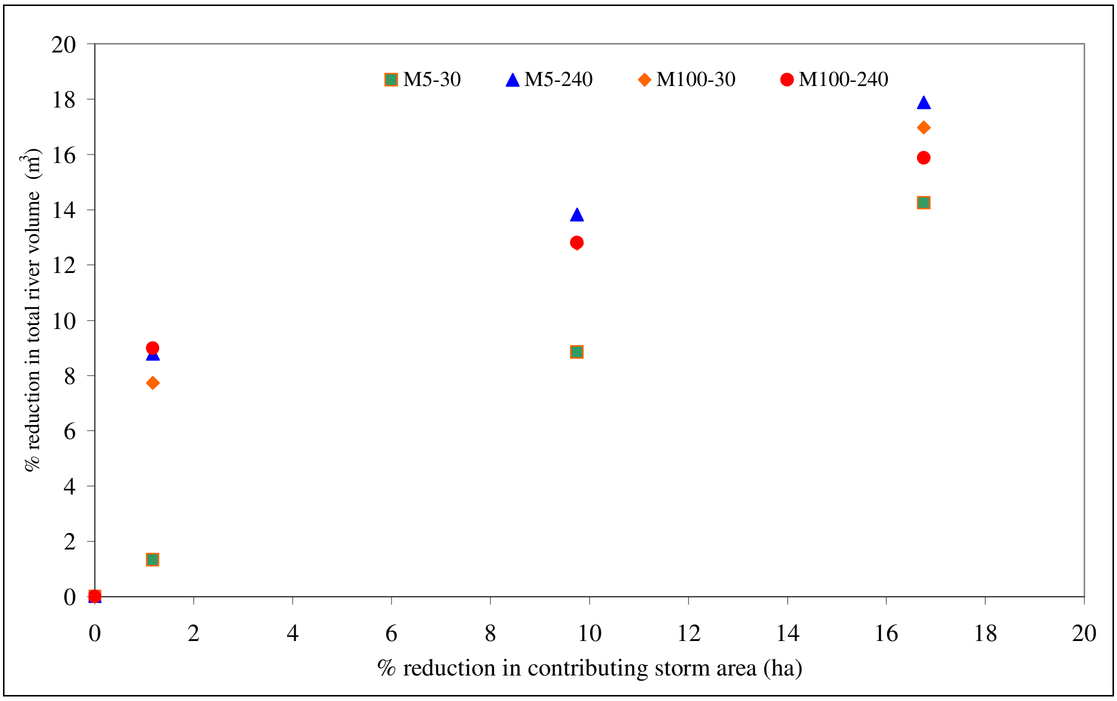


Figure 5.17. Comparison of total river flow volume reduction under development 2050 under 5 and 100 return period events of duration of 30 and 240 minutes.

In order to understand why the river volume reduction is lower during extreme rainfall events, the peak flows at the two river gauges were identified. Figure 5.18 and Figure 5.19 show the peak flow variation at the Carrickmines bridge river gauge for the four sets of top 100 events. Under urban development 2010, the peak flow is reduced for the four top 100 events at the Carrickmines bridge river gauge. However for urban development 2050, under future conditions and for frequent and extreme events, the peak flow intensity for the 1M2050 scenario, the 2M2050 scenario and the 3M2050 scenario exceeds the basecase peak flow. In other words, the implementation of rainwater harvesting systems at municipal scale may influence and cause river flooding under extreme rainfall events. Similar results were obtained when analysing the peak flow variations at the second gauge at Common's road. These can be found in Annex 2 (see Figures A2.13 and A2.14).

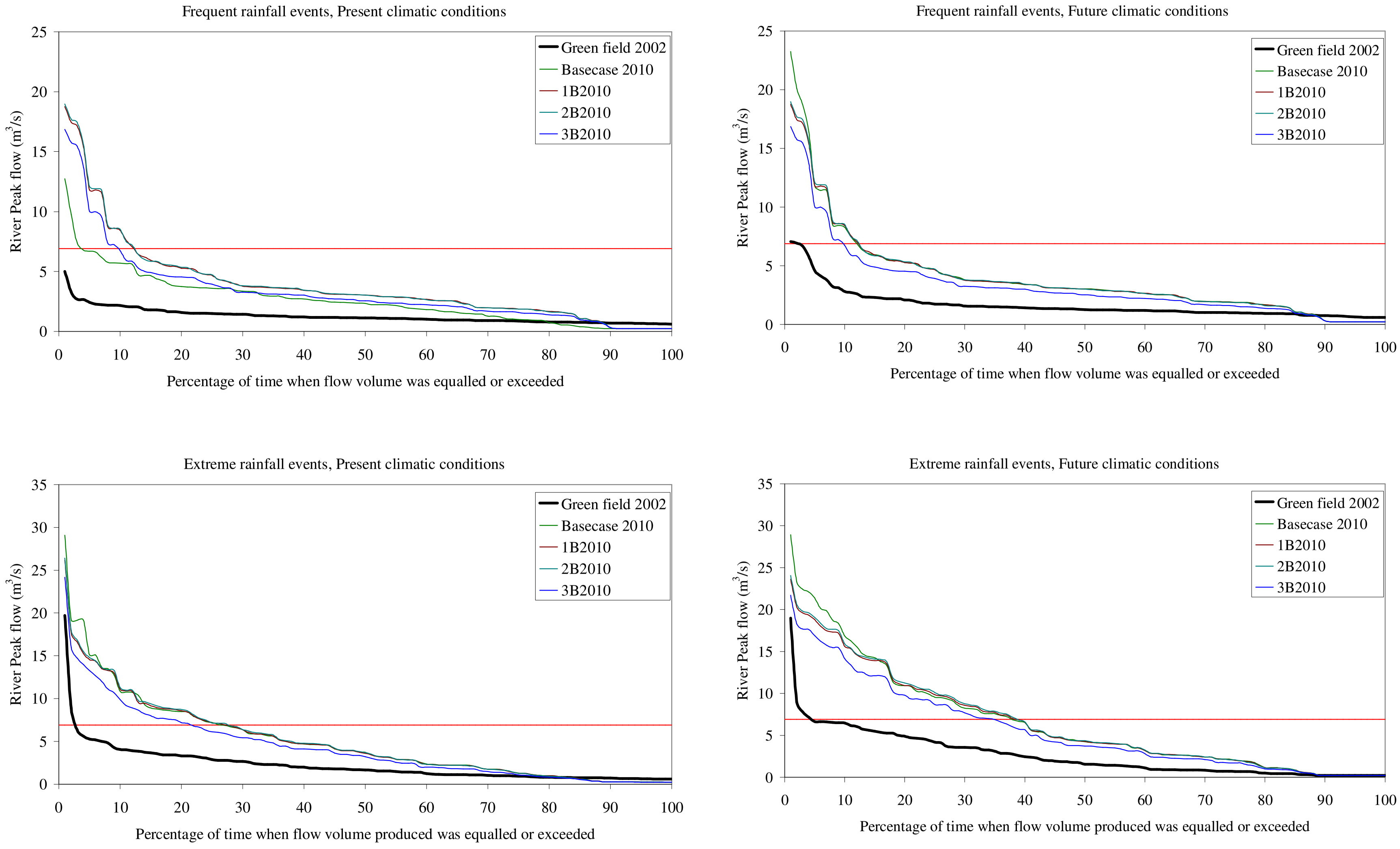


Figure 5.18. Peak flow variation at Carrickmines Bridge river gauges obtained when rainwater harvesting systems are present within development 2010.

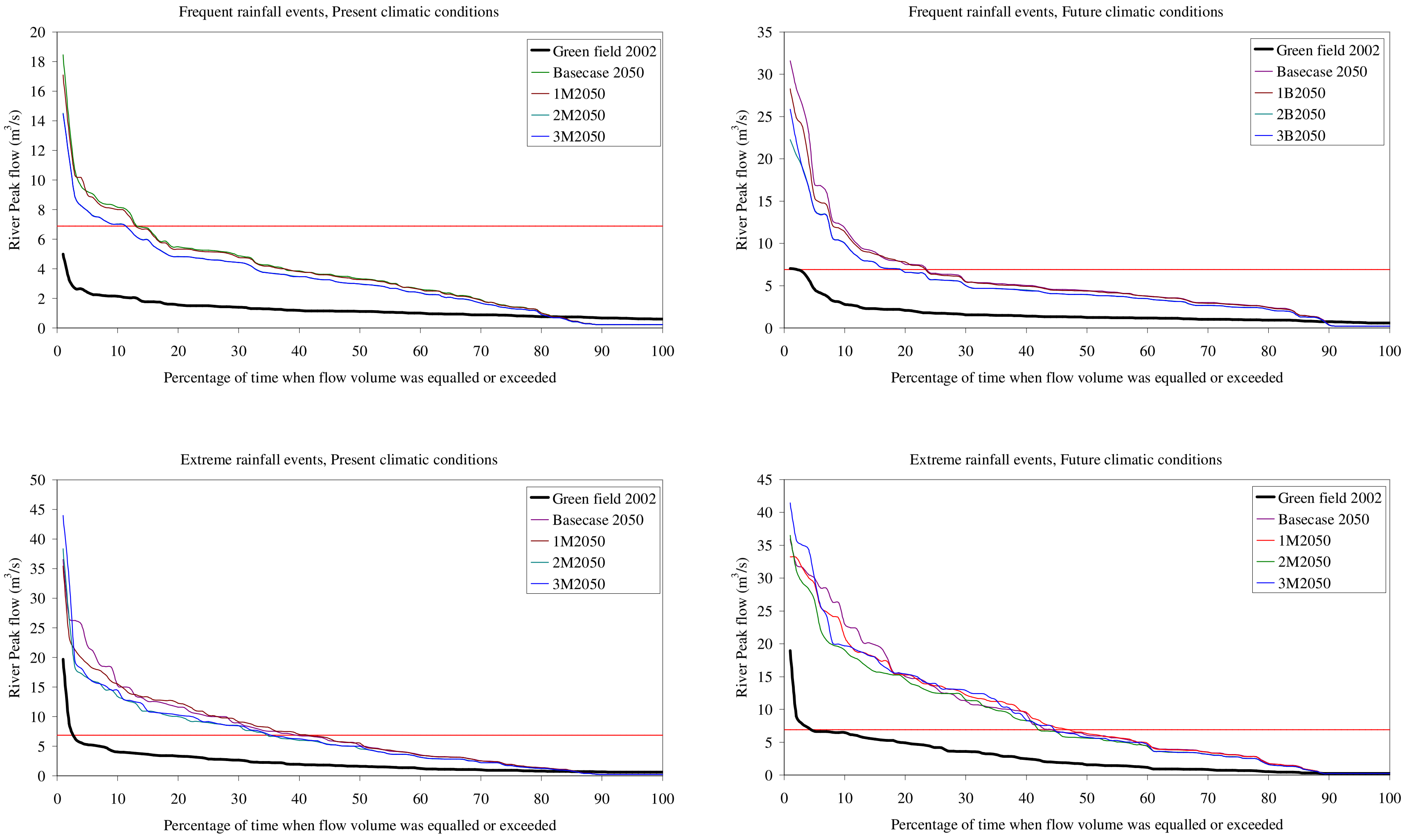


Figure 5.19. Peak flow variation at Carrickmines Bridge river gauges obtained when rainwater harvesting systems are present within development 2050.

For extreme events, the peak flow increases at the Carrickmines bridge river gauge for many scenarios at the three tested scales. The increase of river peak flow under extreme event conditions might be a result of overflowing rainwater tanks. Therefore the weir over flow volumes have been analysed for the scenarios (Annex 2, Table A2.35 to Table A2.38). Significant amount of water flooding from rainwater harvesting tanks are occurring during heavy rainfall events at all scales and for both urban development scenarios. The amount of water is proportional to the size of the rainwater harvesting systems. Moreover, for small rainwater technologies, the overflow volume is spread across the catchment whereas for the implementation at municipal scale, the overflow volume is centralised and influences drainage hydrology downstream from the discharge point. Figure 5.20 illustrates the influence of flow at a drainage node downstream from the municipal overflow weir within the 2050 development scenario. The hydrograph shows a reduction in the peak flow from $10m^3/s$ for the 2050 basecase scenario to 9 for the 1M2050 and 6 for scenarios 2M2050 and 3M2050. This decrease might be attributed to the runoff volume which is reduced by the rainwater harvesting technologies. However; the hydrograph highlights the appearance of another peak caused by over-flooding of the municipal rainwater harvesting system. The peak observed is delayed when compared to the initial peak observed for the 2050 basecase scenario but more intense for 3M2040 where a peak flow of $14m^3/s$ is indicated.

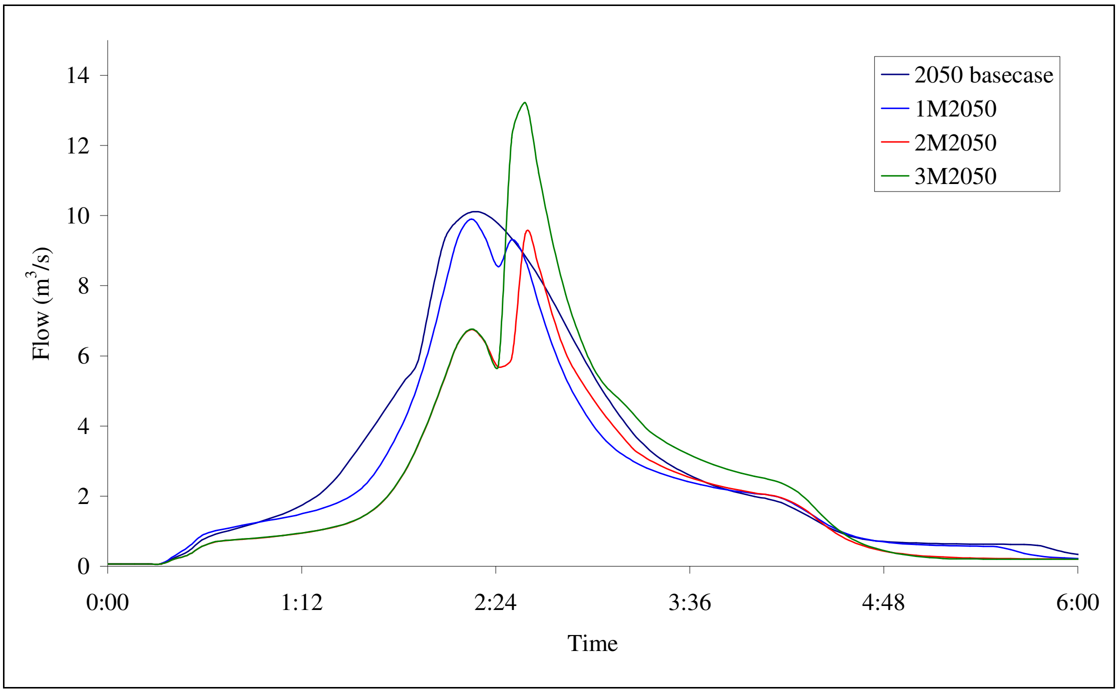


Figure 5.20. Influence of municipal scale tank overflow on urban drainage system for a 100 year return period event of 240min duration under the 2050 development.

Figure 5.21 and Figure 5.23 illustrate the extent to which the different implementation scales reduce the contributing surface storm area as well as the flood volume under the different scenarios. Within 2010 urban development scenario, during frequent storm events (M5-30), a maximum reduction of 90% of the river flood volume was observed if the contributing area is decreased by 15% under neighbourhood and municipal scales. In contrast, if technologies are implemented at the household scale, the river flood volume only reduces by a maximum of 60% at the maximum. One more time the correlation coefficient R^2 has been calculated in order to assess the difference between the three scales implemented at different number able to control the river flood volume. The correlation coefficient R^2 obtained for M5-30 events for the three scales is 0.749. The river flood volume analyses show that R^2 decreases with increasing rainfall intensity and river volume. Moreover, the three set of data show that larger the scale is bigger the flood river reduction is achieved; indeed municipal scale shows better results than neighbourhood and households scales.

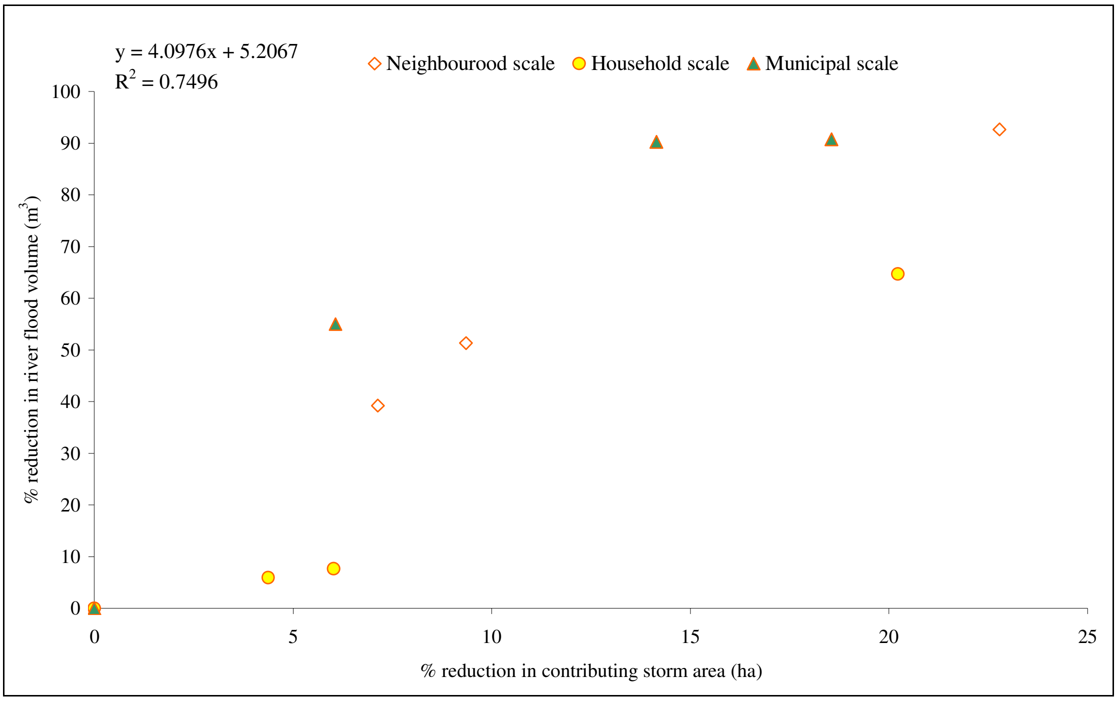


Figure 5.21. Comparison of scaling up rainwater harvesting on the total river flood volume reduction for a M5-30 event.

For the 2050 development, the analysis shows that rainwater harvesting systems reduce the river flood volume by up to 40%. Figure 5.22 and Figure 5.23 detail the variation of total river flood volume and the reduction in percent. As can be seen in Figure 5.22, river flood volumes increase within 1M2050 for M5-240 and for 3M2050 under M100-240. Figure 5.23 highlights that significant difference river flood volumes are not significantly different between scenarios 2M2050 and 3M2050 under frequent events. However under extreme events, we observe a significantly higher reduction in flood volumes for scenario 3M2050 than in the other scenarios, suggesting that the implemented rainwater harvesting scheme is more likely to mitigate river floods.

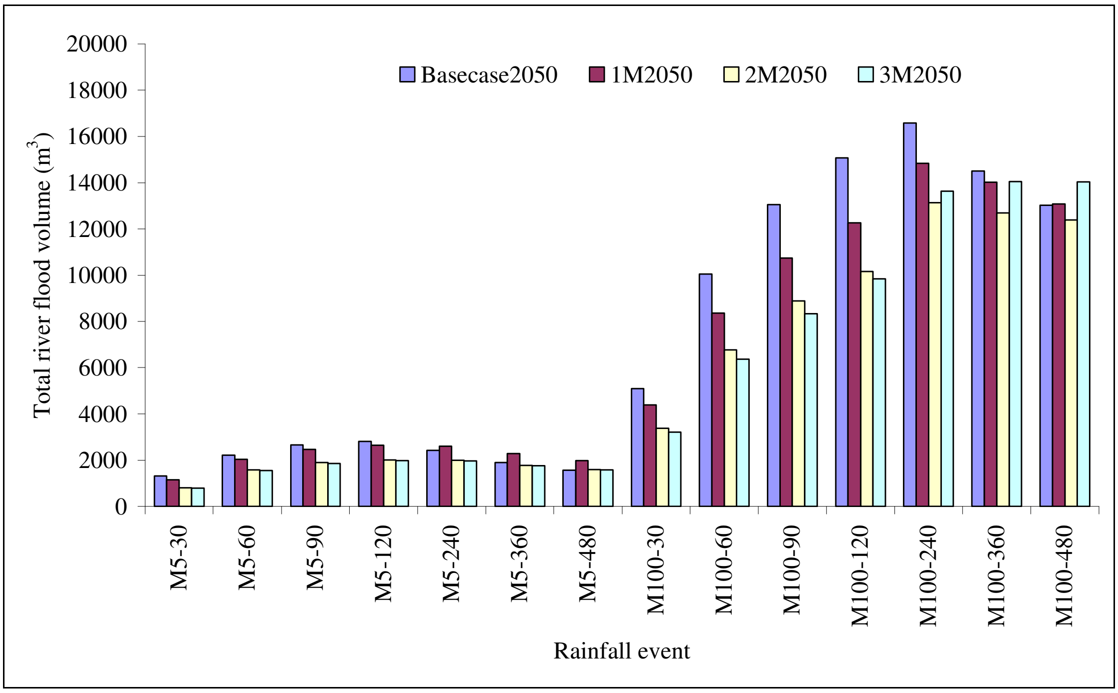


Figure 5.22. Total river flood volume when rainwater harvesting systems are present within development 2050 under 5 and 100 year return period events.

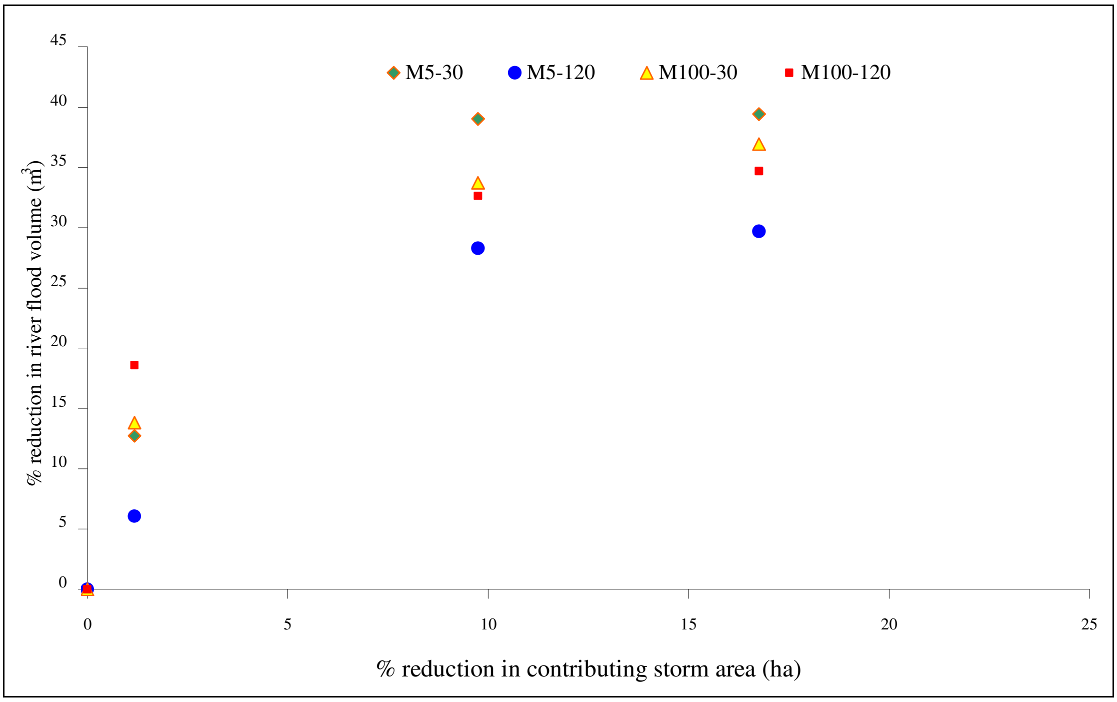


Figure 5.23. Comparison of total river flood volume reduction for extreme and frequent events when rainwater harvesting systems are present within urban development 2050.

5.2.3 Influence of rainwater harvesting on river low flows

Drought and river water abstraction are well known to be the cause of low river flow. Therefore, the impact of rainwater abstraction on the river flow in the Catchment was simulated for a period of five years. Given the considerable time and computational capacities required to perform such long-term simulations, wastewater flows were not modelled during this activity. Consequently, rainwater tanks were removed; the problem of overflowing tanks due to extreme rainfall events will therefore not be addressed in this analysis. For both urban developments, the basecase scenario flow was compared with the flows simulated for scenarios 3B2010 and 3M2050. As can be seen in Figure 5.24 and Figure 5.25, the river flow volume is reduced in both development scenarios.

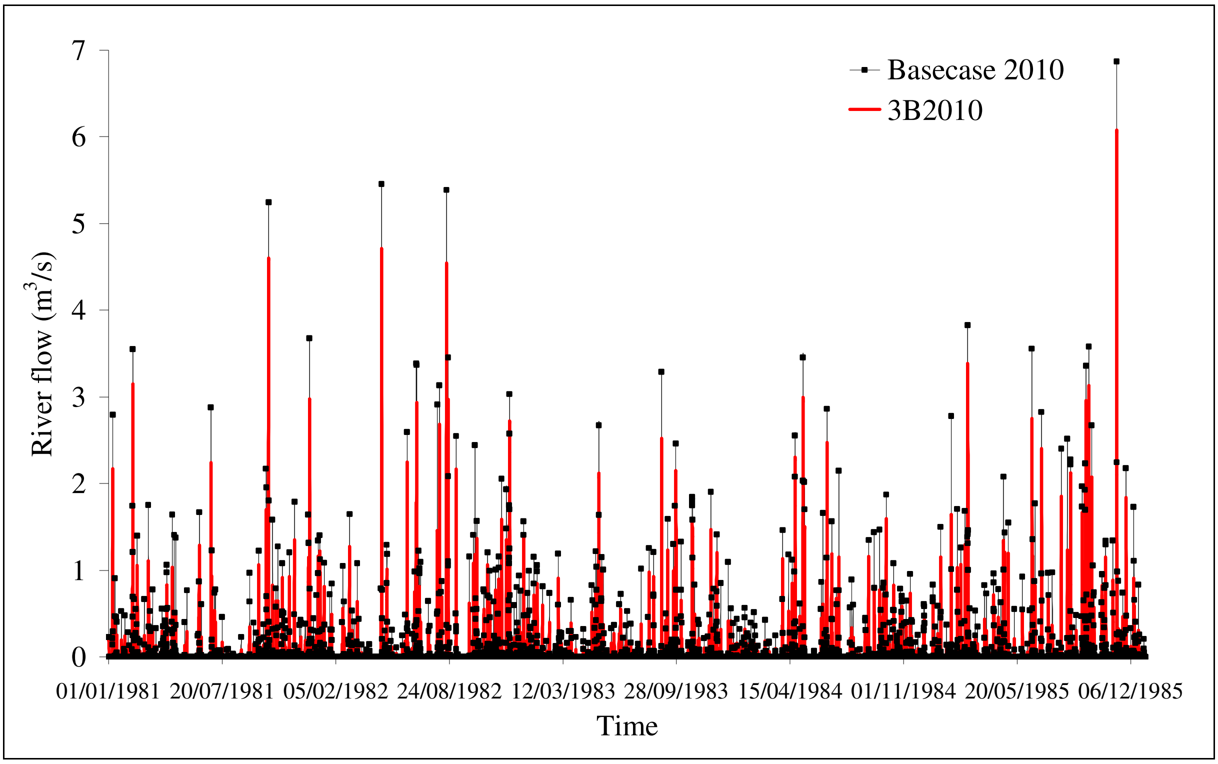


Figure 5.24. Variation of river flow at the Carrickmines Bridge river gauge between 2010 basecase and 3B2010 under present conditions.

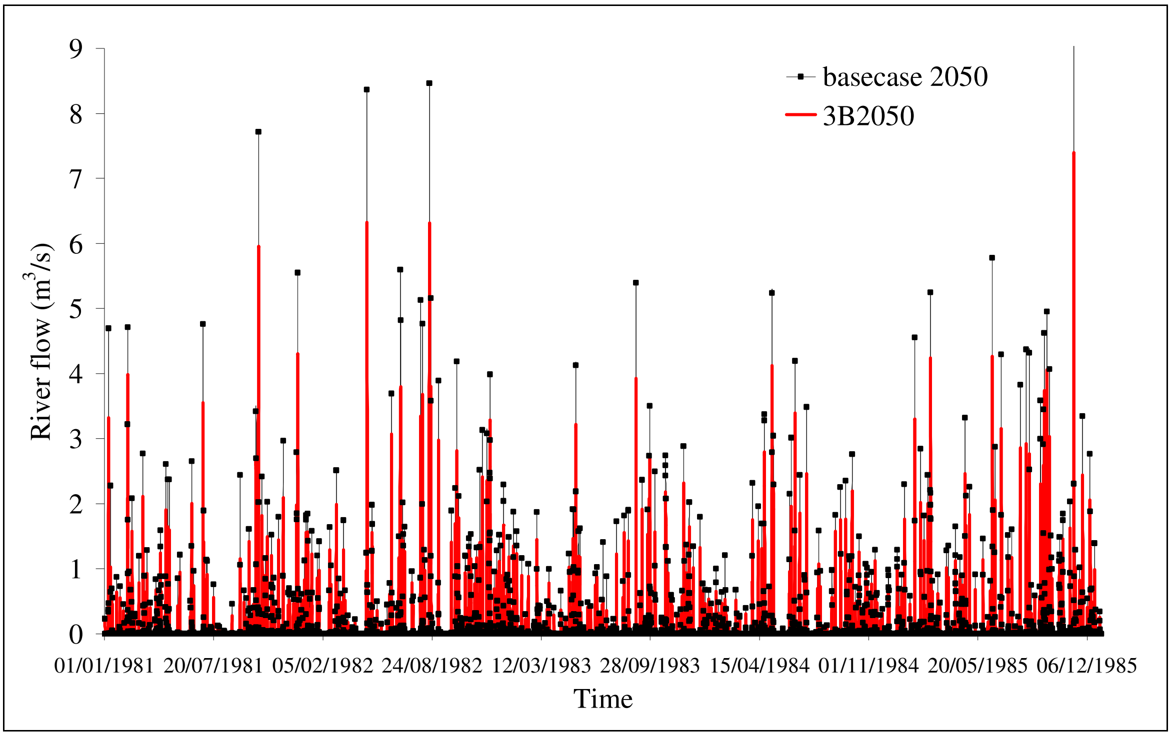


Figure 5.25. Variation of river flow at the Carrickmines Bridge river gauge between 2050 basecase and 3M2050 under present conditions.

In order to assess if low flows were occurring within the Carrickmines catchment, the peak flow observed at the Carrickmines bridge river gauge was compared with the river low flow data determined by the Irish EPA. According to the Irish EPA, low flow is occurs at the Carrickmines bridge road river gauge when the river flow does not exceed 0.025m^3/s. However, the results obtained for the four simulations carried out and presented in the Table 5.6 show that the river peak flow is 80% of the time lower than the low flow definition determined by the EPA.

Table 5.6. Review of the results obtained for the low flow analysis at the Carrickmines Bridge river gauge.

Scenarios	**% of the time when peak flow is equal to 0m^3/s**		**% of the time when peak flow does exceed 0.025m^3/s**	
	Present	**Future**	**Present**	**Future**
Basecase 2010	43	58	83	88
3B2010	46	58	85	88
Basecase 2050	43	78	84	88
3M2050	43	78	84	88

This observation provides evidence that the baseflow data used to carry out the study is under estimated. Therefore in order to re-assessed the low flow analysis of the

Carrickmines river, monitored baseflow data must be available and used to rerun the simulations. And therefore, the low analysis carried out for the Carrickmines bridge river gauges is not really representative of the river flow expected for long term simulations.

5.3 Influence of rainwater harvesting systems on drinking water

Finally, the ability of rainwater harvesting systems to conserve drinking water sources has been assessed. The first observation of Table 5.7, Table 5.8 and Figure 5.26 is the difference of volume collected between 1981 and 1985 (present conditions) and 2075 and 2079 (future conditions). Under future conditions, the total volume of water collected and re-used is smaller than the volume re-used under present conditions. For 1981 (year 1), 1982 (year 2) and 1984 (year 4), under present condition, the total amount of water re-used was 14, 28l. This figure is 36% higher than under future conditions. In contrast, 2077 (year 3) and 2078 (year 4) under future conditions, 10 and 11% more water was re-used when compared to present conditions. Overall, household use of collected rainwater (in volume) progresses linearly under present conditions. In other words, the amount of water collected and re-used per year does not vary too much across the five year period. For the years 1981, 1983 and 1984, the amount of water re-used represented 18% of the total volume of water re-used along the five years simulations. However for 1982 and 1985, the percentages were 22 and 24%. For future conditions, similar results were observed. For the years 2075 and 2076 the volume of rainwater re-used equals 18% of the total volume re-used during the five years. For 2079, 17% and for the years 2077 and 2078 23% for each year. To conclude, the volume of water re-used over the 10 year period simulated did not vary significantly from one year to another. The repartition of pumping period along the year and for each year is also an interesting point to check to see when the rainwater harvesting will be present to be re-used, Figure 5.27. As expected, the more technologies are implemented within the catchment, the more water can be saved. However, the reduction is directly linked to the quantity and frequency of rainfall in the catchment.

Table 5.7. Summary of drinking water saved in 2010. Average value obtained for the 5 year simulation.

	2010 present conditions		**2010 future conditions**	
	Volume of drinking water saved per year	Average reduction of wastewater produced	Volume of drinking water saved per year	Average reduction of wastewater produced
1B2010	63Ml	3%	55Ml	3%
2B2010	157Ml	8%	136Ml	7%
3B2010	251Ml	12%	217Ml	11%

Table 5.8. Summary of drinking water saved in 2050. Average value obtained for the 5 year simulation.

	2050 present conditions		**2050 future conditions**	
	Volume of drinking water saved per year	Average reduction of wastewater produced	Volume of drinking water saved per year	Average reduction of wastewater produced
1M2050	245Ml	4%	213Ml	3%
2B2050	618Ml	9%	587Ml	8%
3B2050	979Ml	14%	851Ml	13%

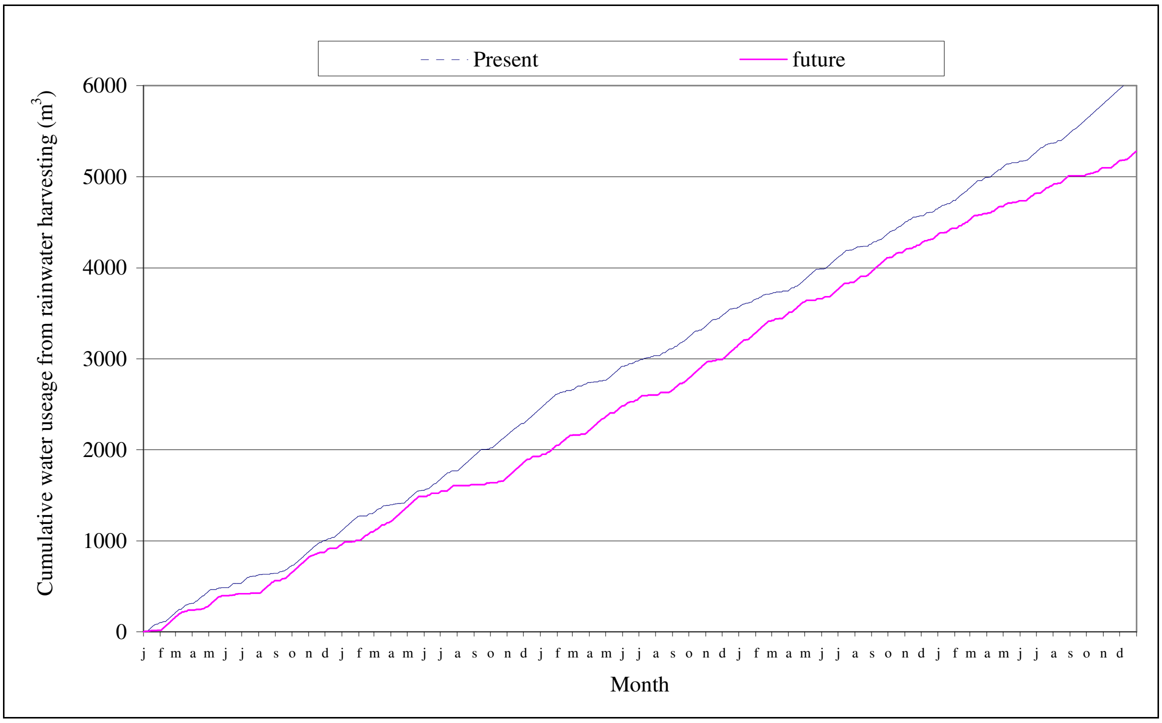


Figure 5.26. Cumulative rainwater re-use for household during present and future conditions for urban development 2050.

Table 5.9. Rainwater harvesting system performance over five years.

	Cumulative volume (m^3)		**Rainwater harvesting collected (m^3)**		**% of rainwater harvesting volume re-used per year**	
Years	Present	Future	Present	Future	Present	Future
Year 1	1117	964	1117	964	18	18
Year 2	2458	1935	1341	971	22	18
Year 3	3570	3160	1112	1225	18	23
Year 4	4565	4369	1085	1209	18	23
Year 5	6089	5280	1434	911	24	17

Figure 5.27 illustrates the percentage of pumping time over the five years simulated for present and future events. Figure 5.27 shows the availability of collected rainwater during winter/spring, summer and autumn/winter. During the summertime of year 1 under present conditions and year 2 under future condition rainwater was available for re-use less than 40% of the time (Figure 5.27). In contrast the same period in year 2 under present condition was rather wet and therefore rainwater was available for re-use 78% of the time. These findings illustrate that rainwater availability significantly varies from one season to another. In the best case, rainwater is available 95% of the time and in the worst only 35% of the time. Therefore, whilst rainwater harvesting is a good technique to control drinking water demand, its efficiency is highly dependent on rainfall frequency and intensity.

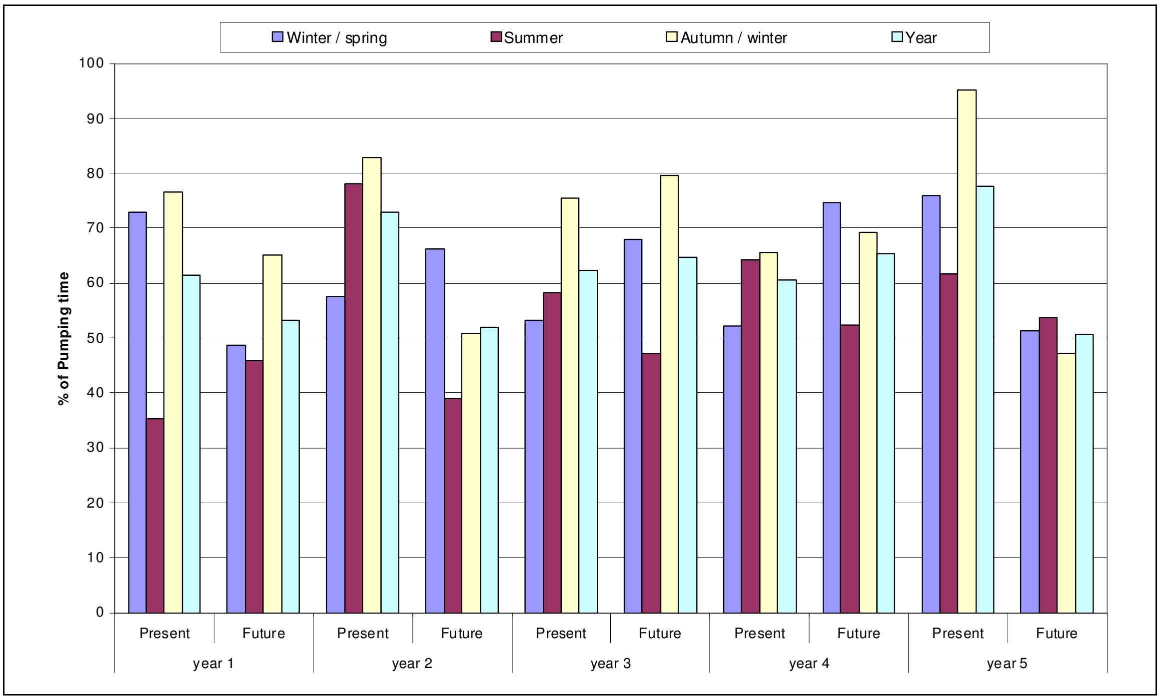


Figure 5.27. Pumping time comparison over the 5 year simulations for present and future conditions.

5.4 Comparative analysis

In order to determine the relative performance of rainwater harvesting technologies in terms of reducing drinking water demand, wastewater volume, runoff volume and river peak flows under each scenario, a comparative analysis was conducted (see Section 3.6.2).

5.4.1 Comparison of the hydraulic performance under the 2010 urban development

The radar charts present in Figure 5.28 and Figure 5.29 compare and integrate the results obtained when rainwater harvesting systems are implemented at catchment scales within 2010 urban development scenarios. The results highlight a reduction of index for the volume of re-used under all the tested rainfall events (4 top 100 events simulations). The volume of drinking water savings consistently increase with the number of technologies implemented in the Carrickmines catchment.

Concerning the sewer volume coefficient (SVC) no reduction of index has been observed under all the tested rainfall events.

Moreover, Figure 5.28 highlights an important decrease in the peak flow coefficient (PFC) under present and extreme rainfall conditions. Indeed for 2B2010 and 3B2010 scenarios index drop from 4 to 3 and 2 respectively under extreme events. As a result, rainwater harvesting systems have an impact on catchment hydrology and therefore river peak flow. Concerning the runoff volume coefficient (RVC), the analysis identifies a reduction of RVC for scenario 3B2010 under frequent event.

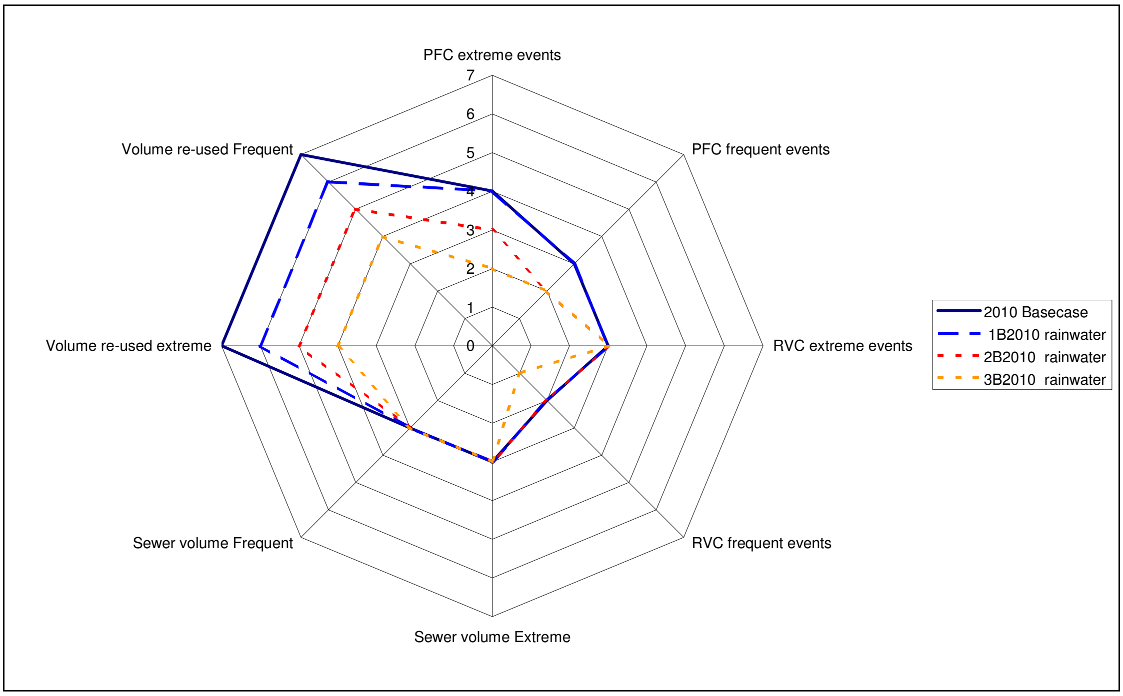


Figure 5.28. Comparison of the hydraulic performance indices for the 2010 urban development under present conditions.

Similar observations are made for Figure 5.29 under future rainfall events, concerning the hydraulic flows (VRC and SCV). However concerning the hydrological network, only for scenario 3B2010 (80% of the accommodations are connected to a rainwater harvesting system) a reduction of peak flow coefficient (PFC) and runoff flow coefficient (RFC). The radar charts results identify the rainwater harvesting capacity limit to control hydrological flow under extreme and future rainfall conditions.

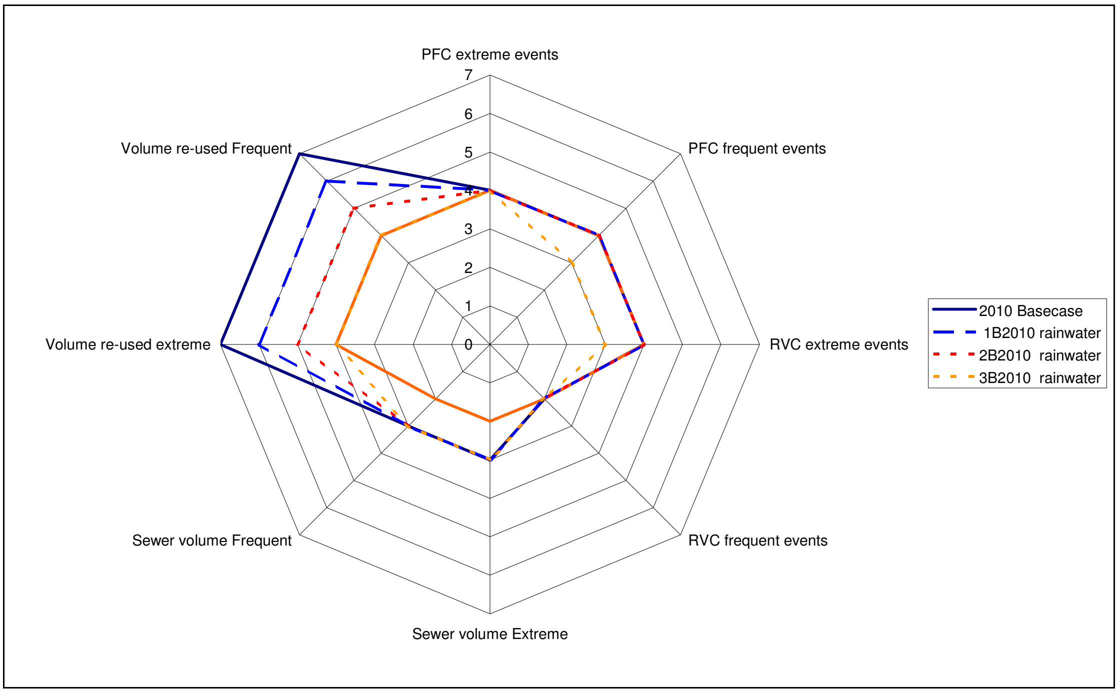


Figure 5.29. Comparison of the hydraulic performance indices for the 2010 urban development under future conditions.

5.4.2 Comparison of the hydraulic performance of the 2050 urban development

This section introduced to radar charts obtained for 2050 development using the comparison method designed in Section 3.6.2, (he Figure 5.30 and Figure 5.31). The implementation of rainwater harvesting systems contributes to reduction volume re-used coefficient (VRC) for all the rainwater harvesting scenarios for the 2050 development. The 2050 basecase index was 7 and for the scenario 3B3050 (when 80% of the accommodation are connected to a system), an index of 3 was obtained. Concerning the variation of sewer volume coefficient (SVC), a reduction is observed however it is minim as index drop from 7 to 6 under frequent event.

Concerning the hydrology influence of rainwater harvesting on the hydrology of the Carrickmines catchment, this time only peak flow coefficient (PFC) for scenario 3M2050 is influenced for the four testes set of rainfall events (frequent, extreme, present and future). Moreover, the coefficient value obtained is 6 (the basecase scenario 7). Therefore, comparing results obtained for both developments, the comparison analysis has highlighted a most import influence on hydrological parameters within development 2010 (with is 20% smaller than development 2050).

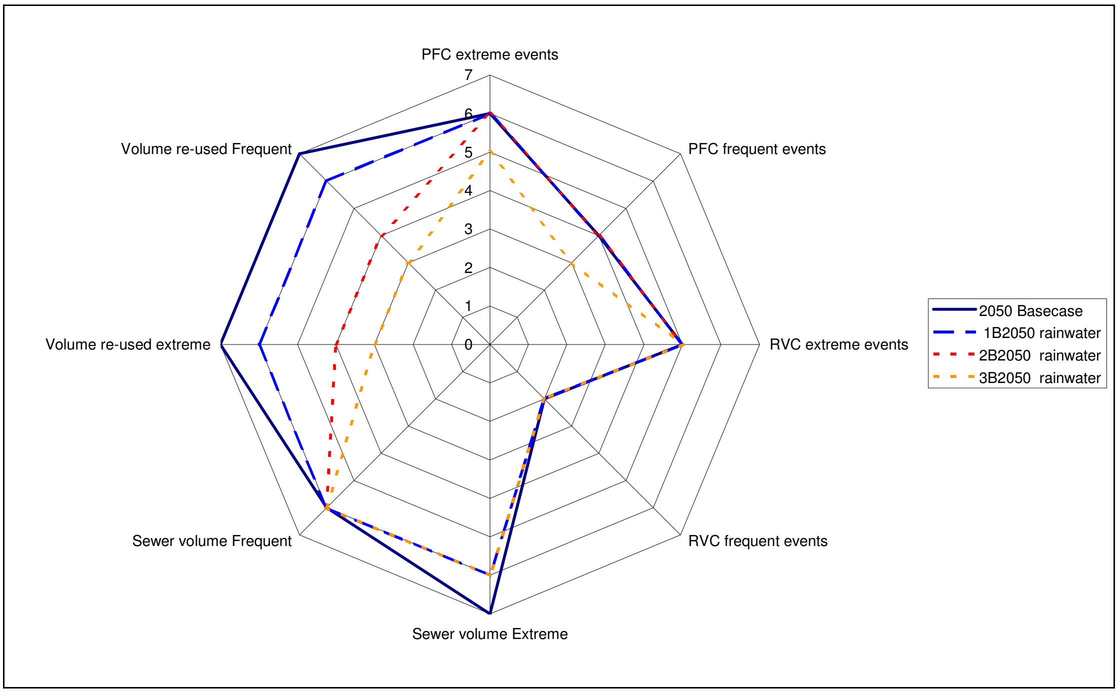


Figure 5.30. Comparison of the hydraulic performance indices for the urban development 2050 under present conditions.

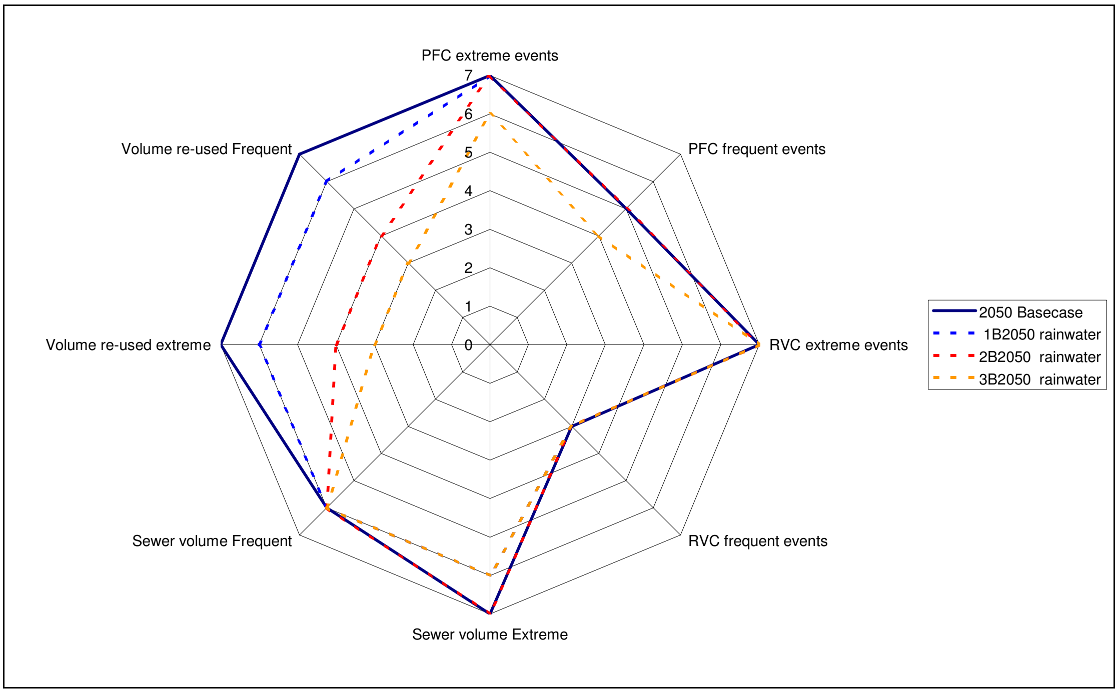


Figure 5.31. Comparison of the hydraulic performance indices for the urban development 2050 under future conditions.

The comparative analysis shows that the implementation of rainwater harvesting systems will considerable reduce water supply, and also reduce sewer flows, peak flow and runoff volume.

The modelling activities carried out on the Carrickmines catchment to identify the influence of implementing rainwater harvesting system at different scale and number have quantified the variation of wastewater volume discharge within the sewer network, the sewer flood volume, the river volume, the peak flow volume at both river gauges and the volume of drinking water saved.

The results show a net reduction of wastewater volume and flood when rainwater harvesting systems are implemented. Findings suggest that the implementation scale has little influence on the wastewater volume. When 80% of households are connected to harvesting technologies, sewers remain free of floods regardless of the severity of the rainfall events.

The results show a net reduction of river flow volume and flood when rainwater harvesting systems are implemented. The size of the technology influences the extent to which the volume as well as peak flow levels reduce. Results suggest that rainwater tank overflows influence the peak discharge of the river at the Carrickmines bridge river gauge. The influence has been found to be related to the scale of the technology. More specifically, when harvesting systems were implemented at the municipal scale under the 2050 urban development the river peak flow increases under heavy rainfall events (M100).

A significant increase of water available for domestic use can be achieved. The volume of water is directly linked to the rainfall pattern. Results indicate that the amount of water saved per year does not vary significantly from one year to another. However, under future rainfall conditions, the volume of rainwater available for re-use was significantly smaller than the volume available under current conditions. Therefore tank size may have to be upgraded in order to increase the volume of water for re-use. Moreover, the pumping time assessment shows a significant difference in the pumping times from month to month. As a result, water might not be made available when it might be needed most. Therefore, combining rainwater harvesting systems with a recycling technology which is independent of rainwater patterns could be a solution to save drinking water during dry periods.

5.5 Summary

The quantitative modelling activities carried out to identify the influence of implementing rainwater harvesting systems on the sewer hydraulic network show a consequent reduction of the total volume present in the Carrickmines sewer network. The analyses identified a complete reduction of sewer flood when most of the new habitations (80%) for both urban development stages (2010 and 2050) are connected to a rainwater harvesting system.

Moreover, a decrease of runoff volume across the entire catchment has also been identified. The modelling activities show that the scale of the rainwater harvesting systems does not affect the volume of runoff reduce. Indeed, the correlation coefficient analyses carried out show that for the three testes scales (household, neighbourhood and municipal) the coefficient was always exceeded 0.99.

Concerning the ability of rainwater harvesting systems to influence river volume and peak flow, this time the results are influence by the scale of the technologies implemented. Indeed, municipal scale technologies involve a river peak flow increase (when compared to the basecase peak flow obtained) under extreme condition due to a massive overflow of the harvesting tanks. However, under frequent event the implementation of rainwater harvesting at any scale and number is a useful technique to control river flow and floods.

Finally, reusing harvested rainfall to flush to toilet will induce a reduction in drinking water supplied for domestic purposes. This amount of water saved has been quantified for the 10 years tested (5 years present and 5 years future conditions). The results show that the volume reuse is directly link to the volume of rainfall; therefore the rainwater harvesting volume available may be different from one year to another. However, the volume of water re-used over the 10 year period simulated did not vary significantly from one year to another. More important, the volume of water reused under present condition is higher than under future conditions, as a result rainwater harvesting systems may have to be resized (harvesting tank bigger for example) in order to optimise the rainwater re-used. This tank optimisation will also be able to balance the difference in pumping time observed depending of the season of the year.

Chapter 6 Results for combined greywater and rainwater systems

This Chapter presents the results obtained when the rainwater harvesting and greywater technologies are combined within the Carrickmines catchment. The combined technology scenarios designed for the analyses are detailed in Table 6.1. The first section reviews the influence of the combined technologies on the wastewater network. Then the influence on the catchment hydrology is illustrated. The third section quantifies the amount of drinking water saved. Finally, the last section reviews the results and compares the runoff, the peak flow, the drinking water and total wastewater reduction achieved under present and future conditions for the four scenarios.

Table 6.1. Introduction of combine technologies scenarios designed.

	Percentage of blocks connected to rainwater harvesting systems	Percentage of blocks connected to greywater recycling systems
Scenario 1	20	20
Scenario 2	80	80
Scenario 3	20	80
Scenario 4	80	20

6.1 Influence of combined systems on the wastewater sewer network

The influence of combining rainwater harvesting and greywater technologies on the wastewater sewer network was assessed by quantifying the wastewater volume obtained for each simulation. The influence of reducing sewer flood was assessed by quantifying the volume of sewer flood volume for each simulation and by identifying the locations of floods.

6.1.1 Variation of total sewer volume

In order to assess the extent to which the combination of greywater and rainwater harvesting systems contribute to a reduction of the waste water volume, the total volume of wastewater obtained for each scenario was compared to their respective basecase scenario. The results obtained under the four top 100 simulations (Table 5.1) show that the wastewater volume discharged in the sewer network systematically reduces in all scenarios when both technologies are implemented. Substantial reductions are observed in Scenario 2 where 80% of households are connected to both rainwater harvesting and greywater recycling technologies. Table 6.2 shows that under 100 year return period events lasting 60minutes, wasterwater reductions can be achieved of up to 20% Findings suggest that the more technologies are implemented the bigger the reductions will be. Figure 6.1 provides a more detailed illustration of the wastewater reductions in each scenario under frequent events. As already stated, scenario 2 involves the highest reductions under frequent and extreme events at present and future rainfall conditions. Under heavy rainfall events, comparatively higher reductions can be observed in Scenarios 2 and 4. In contrast, Scenarios 3 and 2 achieve higher reductions under the driest rainfall events. Given these differences, we can conclude that rainwater harvesting systems seem to be more effective to control wastewater volumes during extremes rainfall events whereas greywater recycling systems tend to be more effective under dry events.

Table 6.2. The reduction of wastewater volume observed for 5 year and 100 year return period event of duration of 30 minutes.

	One in 5 year 60 minutes event		**One in 100 year 60 minutes event**	
	Volume of wastewater reduction (m^3)	% wastewater volume reduction	Volume of wastewater reduction (m^3)	% wastewater volume reduction
Scenario 1	977	5%	1018	5%
Scenario 2	4182	22%	5834	26%
Scenario 3	3802	20%	3840	19%
Scenario 4	1692	9%	2374	11%

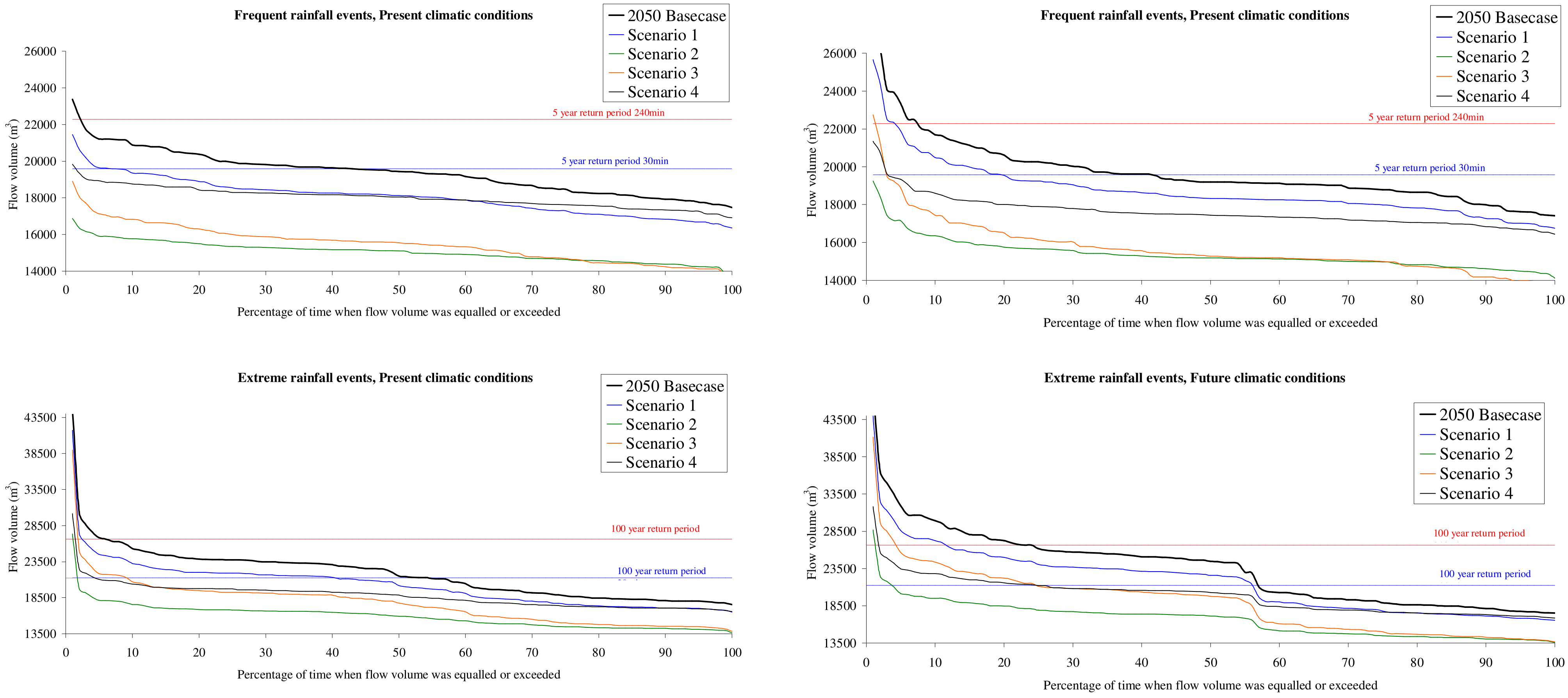


Figure 6.1. Total sewer volume variation obtained for the four greywater and rainwater technologies are combined within urban development 2050.

6.1.2 Ratio rainwater / wastewater

The forecast wastewater volume reduction caused by the implementation of rainwater harvesting and greywater recycling technologies is likely to change the rainwater/wastewater ratio in the sewer network. Figure 6.2 illustrates the variation of ratio for the four set of rainfall events and compares the 2050 basecase scenario with the four combined scenarios. Results show that the ratio observed in Scenario 3 is exceeding the basecase curve under extreme rainfall events and Scenario 2 under small rainfall events. Under frequent rainfall conditions, the ratio obtained does not exceed the value of 0.35 during present conditions and 0.6 under future condition. Therefore the amount of rainfall entering the sewer network is acceptable and the degree of dilution is not expected to affect the water treatment process significantly. A net increase of Scenario 3 is observed under extreme rainfall conditions with the ratio lower than 1.8 under present and 2 under future conditions. These findings show that under extreme conditions the implementation of the two technologies might result in the heavy intrusion of rainfall into the sewer network and eventually the dilution of wastewater and the increased occurrence of sewer floods. The latter problematic will be addressed in the subsequent sections.

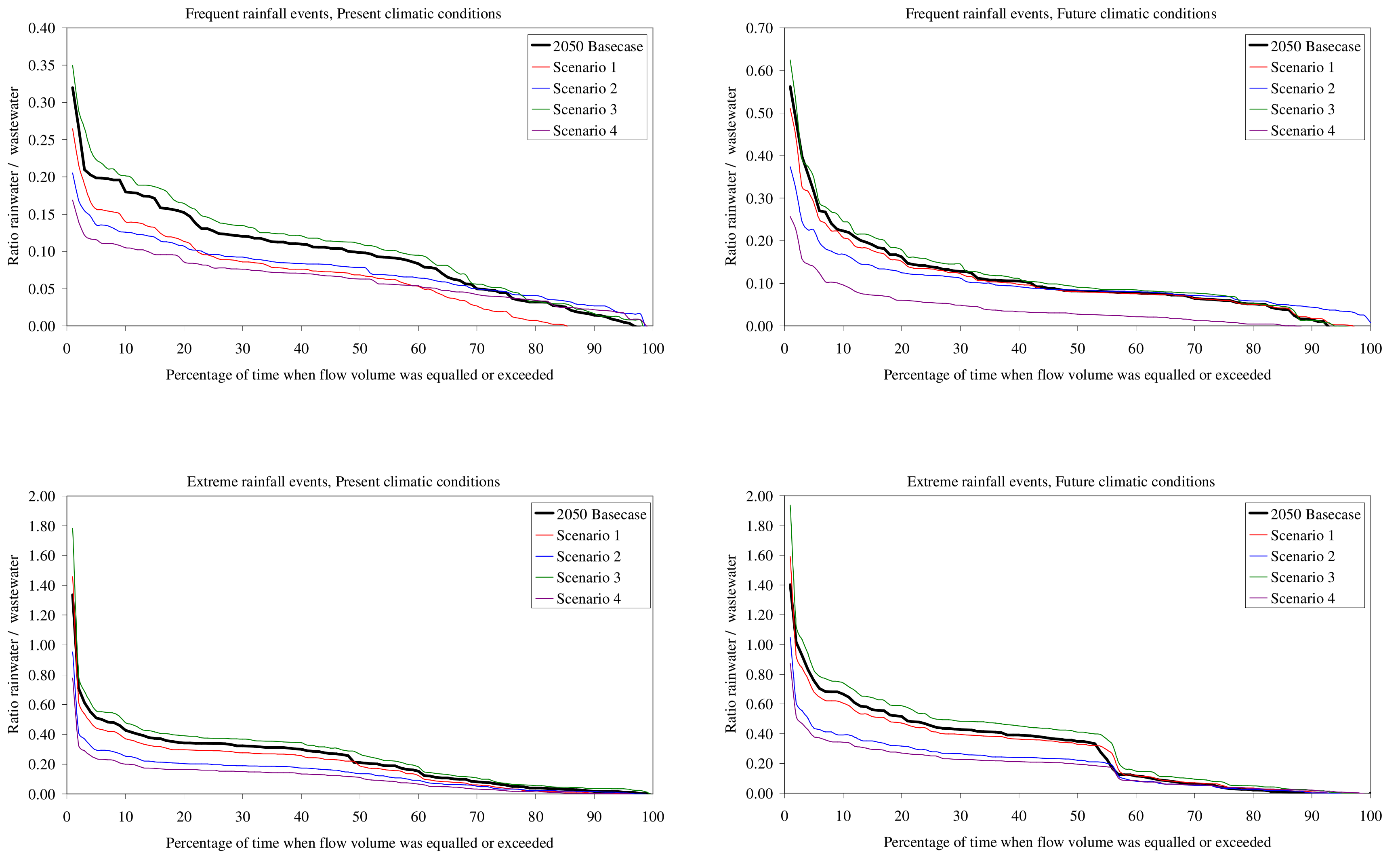


Figure 6.2. Ratio rainwater / wastewater into sewer system when greywater and rainwater technologies are present within urban development 2050.

6.1.3 Variation of total sewer flood volume

In order to understand how the concurrent implementation of rainwater harvesting and greywater recycling technologies affects sewer flood volume, the total flood volume was identified for each scenario and compared with the 2050 basecase scenario (Figure 6.3). First it should be noted that no floods occurred within the new 2050 urban development under Scenarios 2 and 4 when 80% of all the blocks are connected to rainwater harvesting systems. Figure 6.3 shows that for M50-480 rainfall event, the total flood volume is considerably reduced by at least 91%. Under Scenarios 1 and 3, sewer floods set in with five year return period events. The total flood volumes for both scenarios, however, are with 40 and 13m^3 lower than the 2,353m^3 recorded in the 2050 basecase scenario.

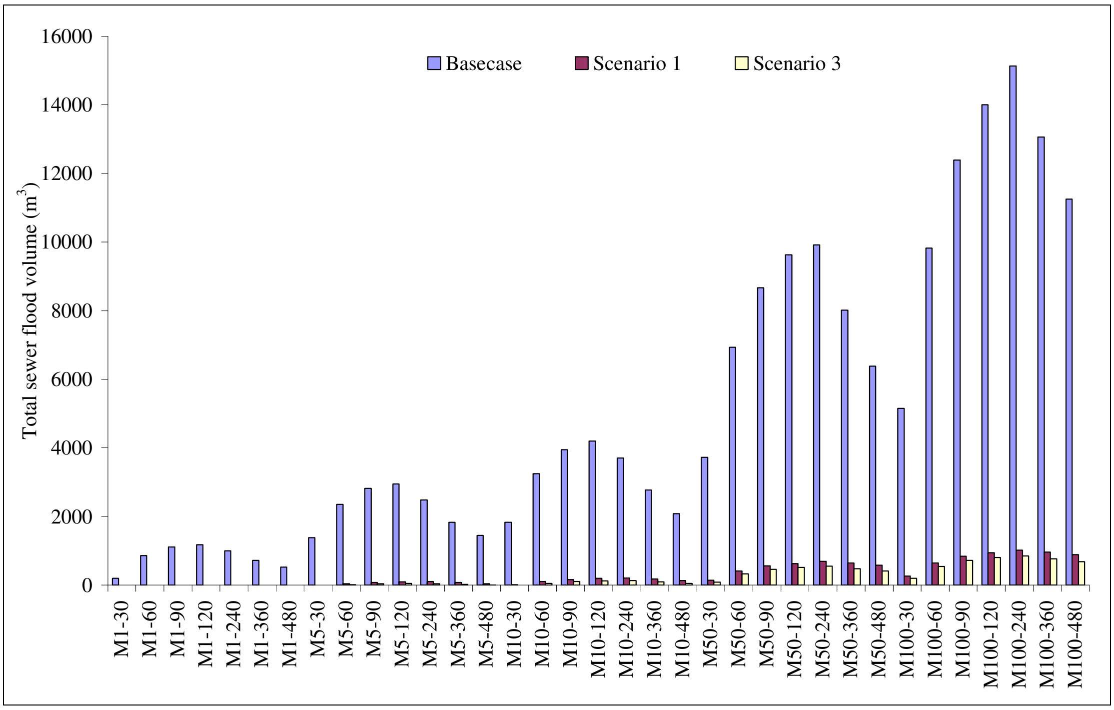


Figure 6.3. Total sewer volume within development 2050.

Following this analysis, the location and number of flooded nodes for 5 year events and 100 year events with a 30 to 240 minutes duration were identified The analysis distinguishes between nodes where floods volumes lie below 25m^3 and those where the volume exceeds 25m^3. Furthermore nodes where surcharge occur were counted, surcharge occurs when the conduit reaches its maximum volume capacity. Figure 6.3

shows that for the four scenarios and under five year return events, none of the nodes flooded at a level above 25m^3. Moreover the results obtained for Scenario 1 and 3 are really similar when the numbers of nodes are compared for 5 and 100 year events. Therefore, it can be concluded that when 80% of blocks are connected to rainwater harvesting systems, floods cease to occur within the sewer network for the 2050 development scenario. When 20% of blocks are connected to rainwater harvesting systems and 80% or 20% to greywater re-use technologies, the flood intensity is considerably reduced but the flood frequency remains the same when compared to the basecase scenario.

Table 6.3 Number of nodes than flood under 5 and 100 year return period

One in 5 year event					
	Basecase	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of nodes above 25m^3	11	0	0	0	0
Number nodes less than 25m^3	39	16	0	12	0
No flood but surcharge	124	41	0	37	0
One in 100 year event					
	Basecase	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of nodes above 25m^3	29	15	0	13	0
Number nodes less than 25m^3	147	59	0	58	0
No flood but surcharge	87	103	16	101	15

Figure 6.4 and Figure 6.5 indicate the position of the nodes where floods or surcharges occur under the 2050 development scenario. In Figure 6.4 green nodes represent nodes where nodes did not exceed 25m^3 and in brown nodes where surcharge occurred whereas in Figure 6.5 blue nodes identified flood bigger than 25m^3, green nodes represent flood locations smaller than 25m^3, and brown nodes highlight the location of surcharge occurrences.

As can be seen, the majority of floods occur in connection nodes where conducts join. It should also be noted that flood nodes are located in the south east of the sewer network. Figure 6.5 shows that under 100 year return period events, most of the 2050 urban development will be affected by sewer network flood, even though the volume of floods has been identified to be very small compared to the basecase scenario. Therefore, the technology combination tested in Scenario 1 (20% rainwater harvesting technologies and 20% greywater recycling technologies) might not be the best to solve sewer flood problems.

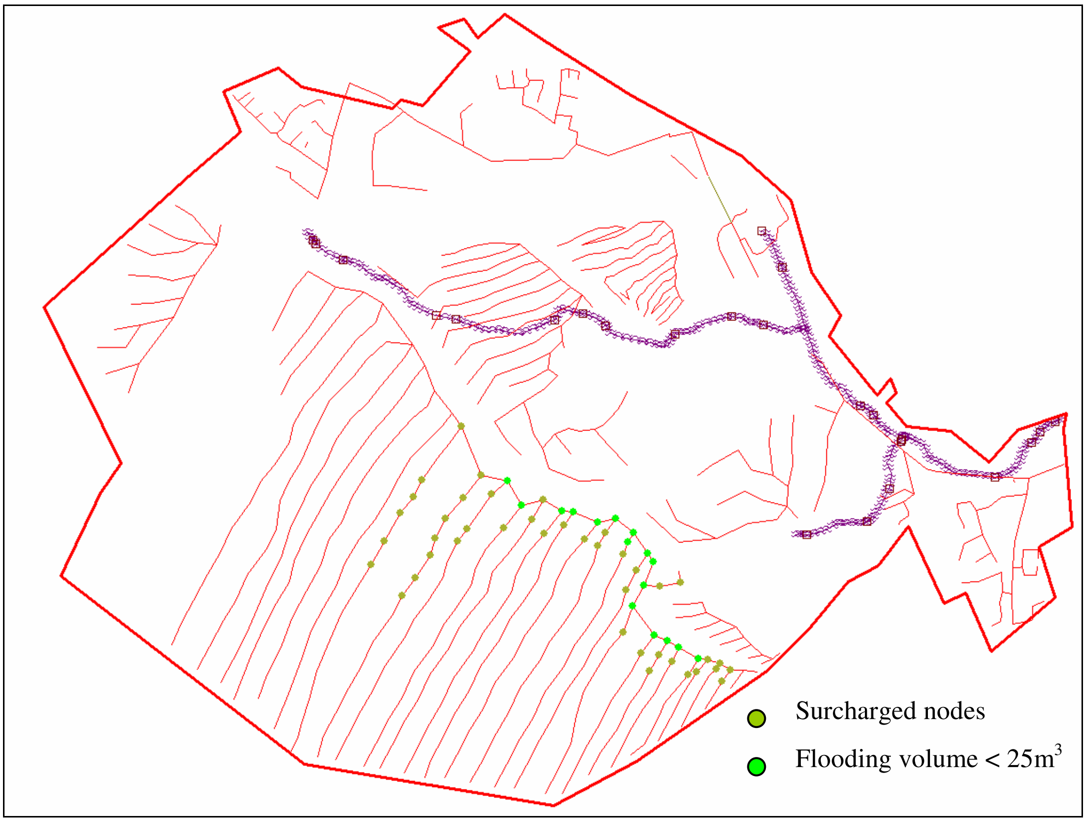


Figure 6.4. Flood identification for Scenario 1 under the 5 year return period event.

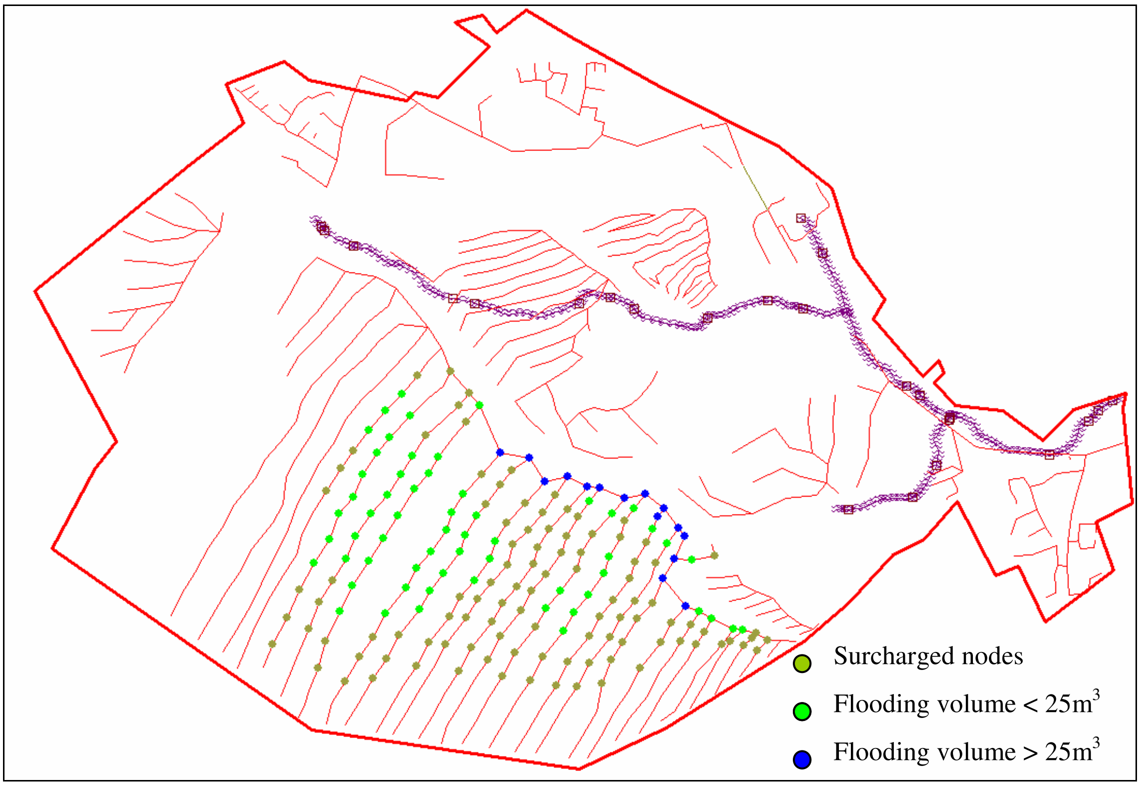


Figure 6.5. Flood identification for Scenario 1 under the 100 year return period event.

Figure 6.6 shows the nodes facing surcharge problems under the 100 year return period event for Scenarios 2 and 4 (brown nodes show surcharge). When 80% of the blocks are connected to rainwater harvesting systems, none of the nodes experiences sewer floods and only few nodes are facing surcharge problems under heavy rainfall. Moreover, there was little variation in the results when comparing the flood data, regardless of whether 20% or 80% greywater recycling systems were implemented in addition to the rainwater harvesting systems present in the catchment.

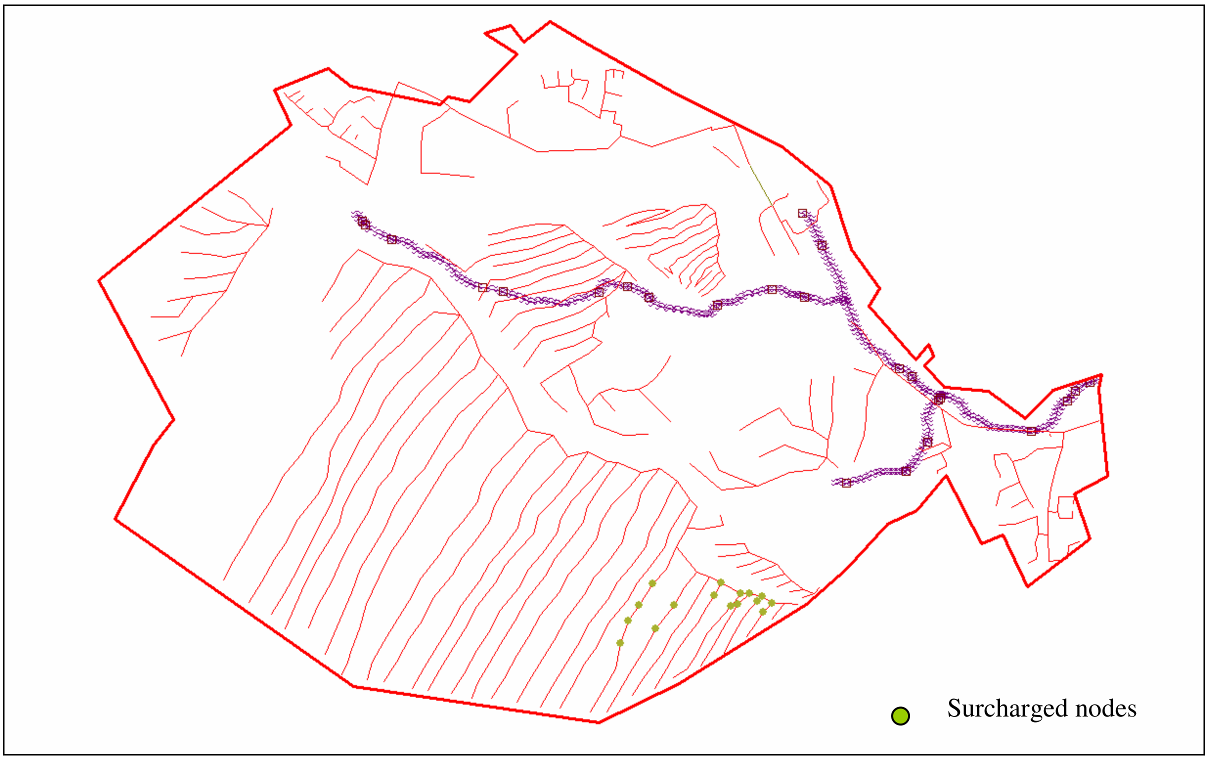


Figure 6.6. Surcharge nodes identification for Scenarios 2 and 3 under 100 year return period event.

Scenario 3 produced results very similar to Scenario 1 (Figure 6.7 and Figure 6.8). The lower part of the catchment suffers from the same sewer floods under 100 year return period event. When results are compared with Scenario 1, the results indicate that the higher number of greywater recycling systems reduces the intensity of flood volume occurrences. However, the location and frequency of floods are not affected; floods are still occurring all over the sewer network while many habitations are connected to technologies. Based on these findings, it can be concluded that the technology combination in Scenario 3 (20% rainwater harvesting and 80% greywater) is not the most suitable to effectively control sewer flooding.

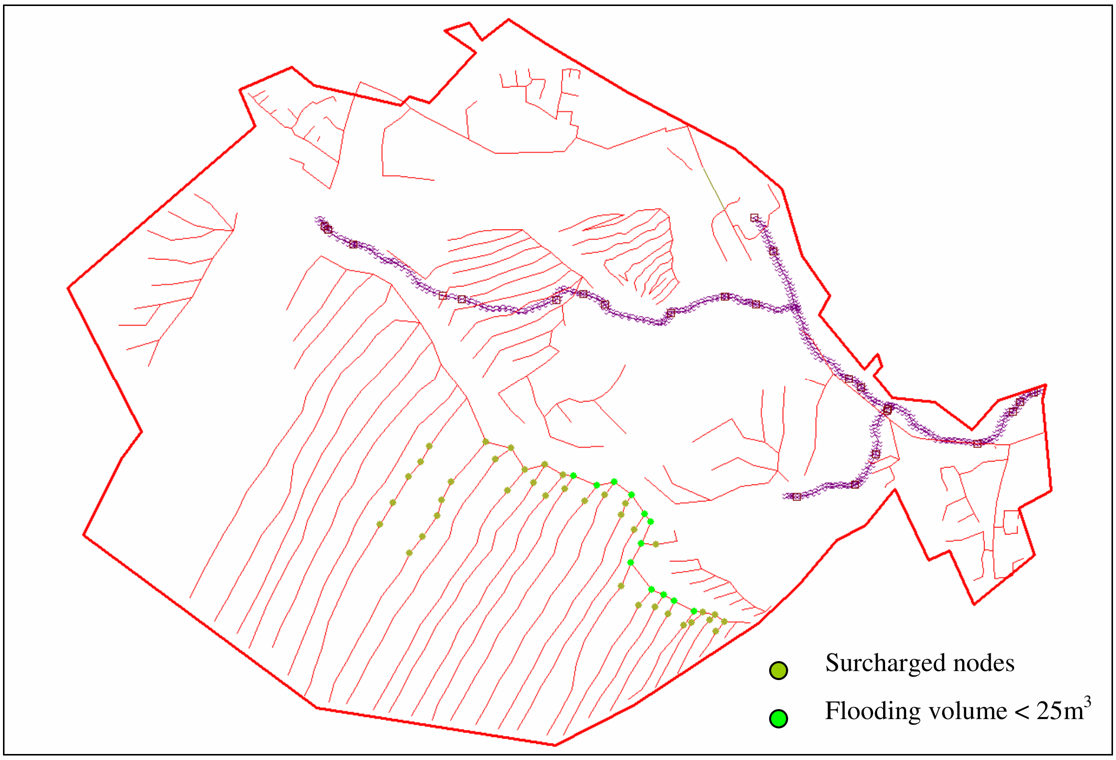


Figure 6.7. Floods identification for Scenario 3 under 5 year return period event.

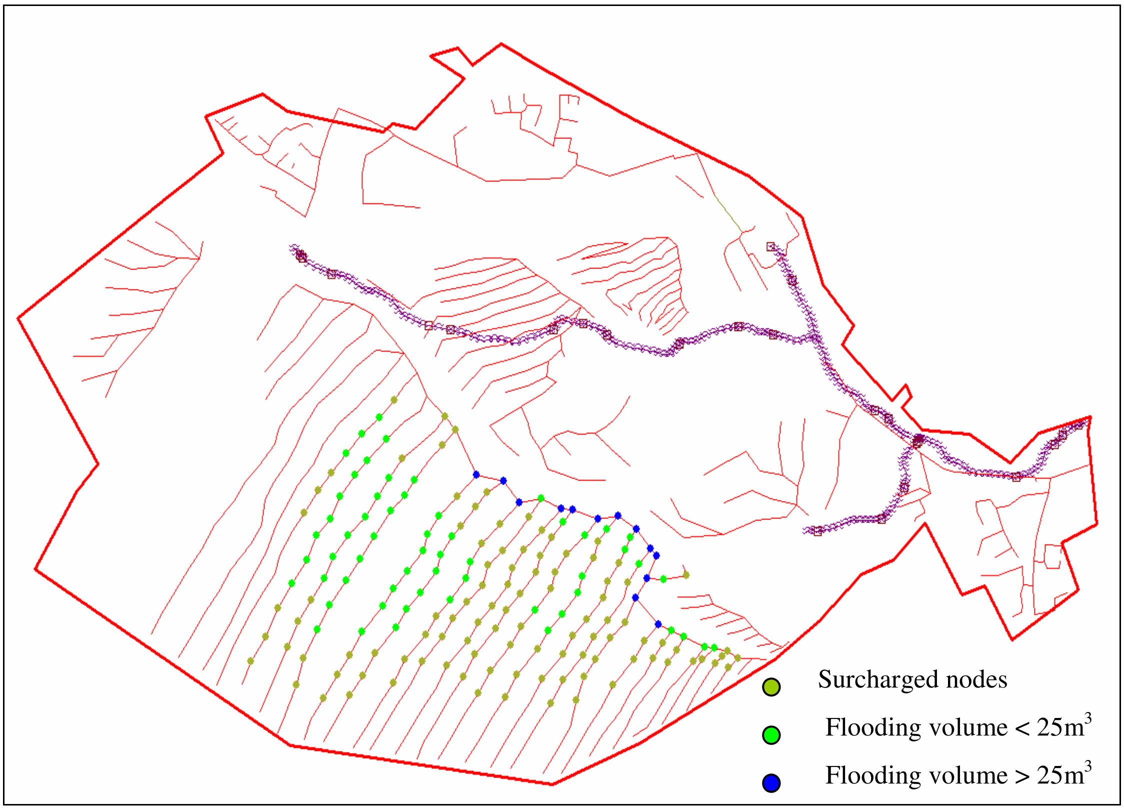


Figure 6.8. Floods identification for Scenario 3 under 100 year return period event.

6.2 Influence of combined systems on the Carrickmines catchment hydrology

The influence of installing combined technologies on the Carrickmines catchment hydrology was assessed. However, the analyses showed that Scenarios 1 and 3 hydrology network behave like scenario 1M2050 (Chapter 5) and Scenarios 2 and 4 is like 3M2050 (see Annex 3, Figure A3.1, Figure A3.2 and Figure A3.3). Therefore, a detailed description of results in this Chapter will be foregone and results will only briefly be summarised: the total volume of the river flow will reduce under frequent and extreme events in each of the four scenarios The peak flows at the two river gauges will reduction under any rainfall for Scenarios 1 and 3; however for scenarios 2 and 4 under extreme event and at Carrickmines bridge river gauge an increase of peak flow can be observed due to rainwater harvesting tanks overflowing into the river.

6.3 Influence of combined systems on drinking water

The volume of drinking water saved was assessed by adding the total volume of harvested rainwater and of greywater re-used. Table 6.4 summarises the total drinking water volume modelled to be saved under present and future conditions. A maximum of 36% of drinking water can be saved in Scenario 2 under present condition. Considering that Scenario 2 foresees the highest implementation rate for both technologies, the results where expected. A comparison between Scenario 3 and 4 shows that 25% of drinking water is saved in Scenario 3 as opposed to 20% in Scenario 4. This result indicates that that greywater recycling systems are comparatively more effective in terms of water saving than rainwater harvesting technologies.

Table 6.4. Average drinking water saved for the 5 year simulated under present and future conditions.

	2050 present conditions		**2050 future conditions**	
	Volume of drinking water saved per year	Average reduction in water supply	Volume of drinking water saved per year	Average reduction in water supply
Scenario 1	585Ml	9%	553Ml	8%
Scenario 2	2,350Ml	36%	2,222Ml	34%
Scenario 3	1,616Ml	25%	1,584Ml	24%
Scenario 4	1,319Ml	20%	1,191Ml	18%

6.4 Comparison analysis

In order to determine the relative performance of the technologies with respect to reducing drinking water demand, wastewater volume, runoff volume and river peak flow in each scenario, a comparative analysis was carried out (See Section 3.6.2). Figure 6.9 represents the results obtained under present conditions.

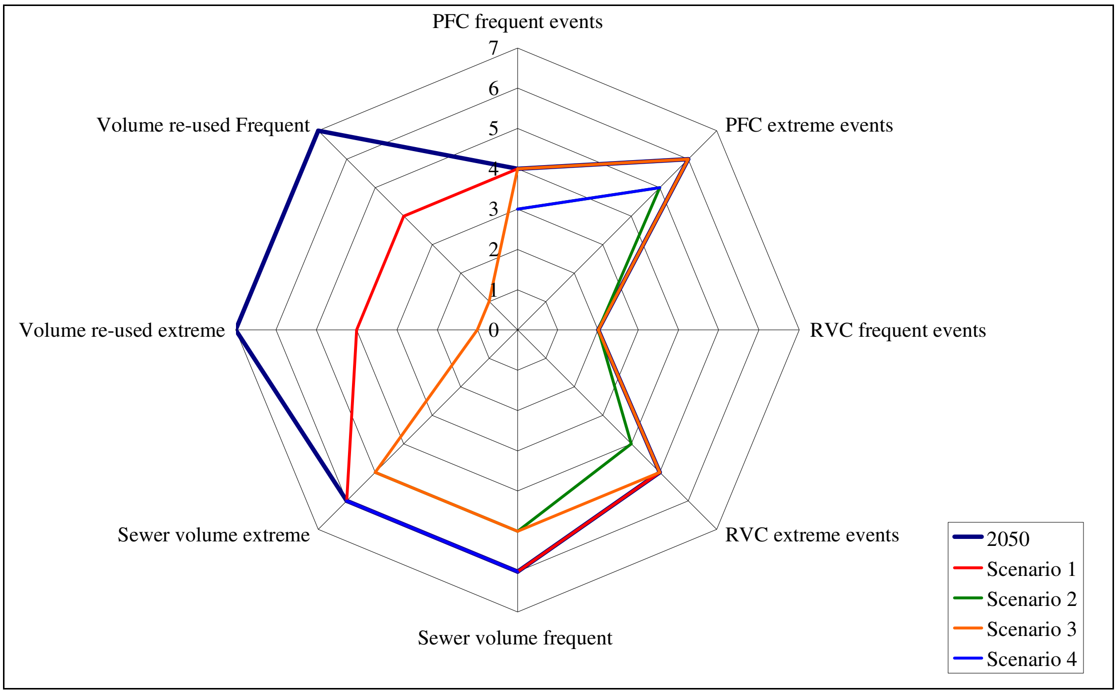


Figure 6.9. Radar chart obtained for combined technologies under present conditions

The Figure 6.9 represents the ability of each of the four scenarios to enhance the water cycle within the Carrickmines catchment. The results highlight the efficiency of combining the technologies to save drinking water when coefficients are compare to the one obtained for the basecase scenario. For example, Scenarios 2, 3 and 4 volume re-used indexes show better result than index obtained for Scenario 1. Concerning the sewer volume reduction, only Scenarios 2 and 3 (both have 80% greywater recycling technologies) show a reduction in the total sewer volume index.

Finally, concerning the change in the catchment hydrology (runoff and river peak flow) Scenarios 2 and 4 (both have 80% rainwater harvesting technologies) show a reduction for PFC and RVC under extreme events.

Figure 6.10 reviews the results compare for the future climate change simulated.

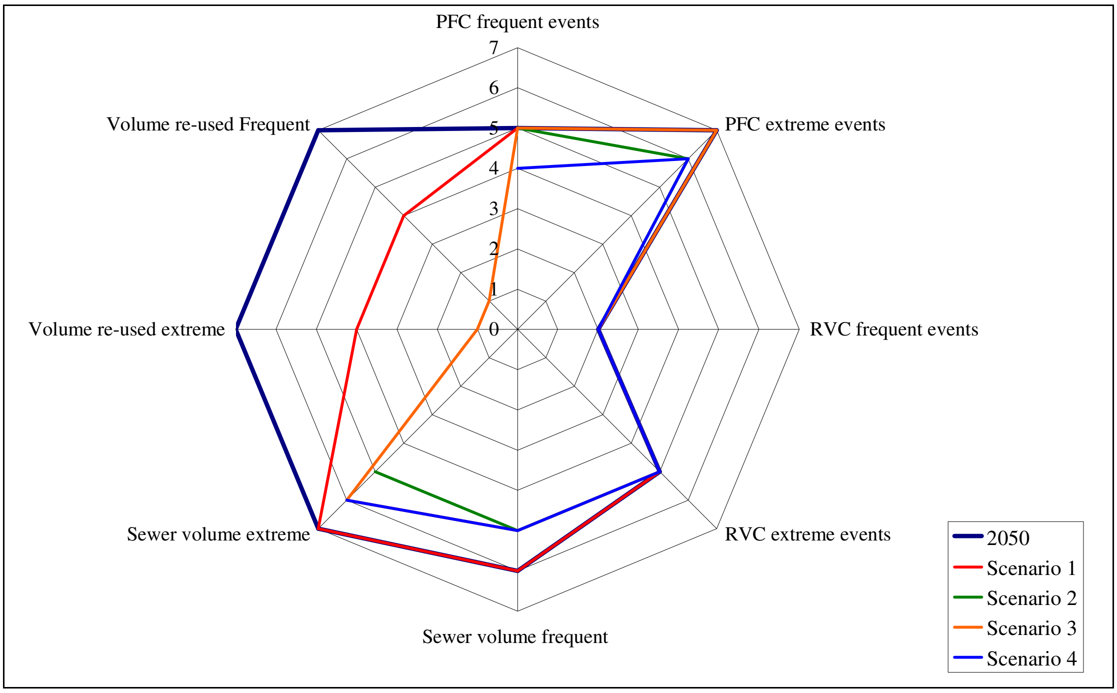


Figure 6.10. Radar chart obtained for combined technologies under future conditions

The results obtained under present conditions are confirmed under future conditions. Very good indexes are obtained for Scenarios 2 and 3 concerning the volume of re-use water. However, the comparison analyses show that the use of the combined technologies in order to control runoff and river peak flow is not limited and not sufficient. Indeed, when results are compared with the basecase runoff and peak flow indexes obtained no significant indexes reductions are obtained except for PFC extreme events for Scenarios 2 and 4.

To conclude, volume of drinking water re-used coefficient (SRC) is the parameters compared in the analysis the most influenced. Moreover, the combination of both technologies does not influence much the sewer volume coefficient (SVC) and the two hydrological parameters assessed (PFC and RVC). Therefore, the comparison analysis highlights a little benefit in combining of the two technologies (greywater and rainwater systems) in order to improve hydrological flows.

6.5 Summary

The modelling activities quantified the effect of combining greywater recycling and rainwater harvesting within the 2050 urban development of the Carrickmines catchment on: the total volume present in the sewer network, sewer floods, the river flow and flood as well as the cumulative amount of drinking water saved.

The results show a net reduction of wastewater volume and sewer flood when both technologies are implemented. Scenario 2 and 4 shows to be more efficient to reduce sewer floods, as no floods were observed under both scenarios. However, Scenario 1 (20% greywater and 20% rainwater harvesting) did not show to be the best combination to solve sewer flood issues under extreme rainfall events.

Concerning the influence of the combined technologies to reduce runoff volume and river peak flow, the results identified a reduction in runoff volume due to the presence of rainwater harvesting technologies. However, the ability of the harvesting technologies to control runoff under extreme events has been shown to be limited. Therefore, combining the technologies is not sufficient to control surcharge of the hydrological under extreme rainfall events and under the tested future climate change conditions. As a result, in order to enhance urban drainage and control river flood occurring other technologies such as SUDS should be implemented to support the urban hydrology.

The findings suggest that a combination of rainwater harvesting and greywater recycling systems can successfully control rainwater intrusion into the sewer network as well as reduce the production of daily wastewater.

Chapter 7 Sensitivity Analysis

This Chapter focuses on the sensitivity analysis executed to assess the variation of output of the design model to different sources of input. The parameters selected can influence the model output therefore sensitivity analysis has to be carried out to identify any variation due to the parameters used. This chapter will review the methodologies available to carry out sensitivity analysis. Then the two conducted analyses will be introduced, the first one assessed the parameters present within the runoff equation and the second analysis focused on the assumptions used to design the urban development scenarios.

7.1 Proposed approach for the sensitivity analysis

Sensitivity analysis is part of the calibration process and it is carried out to rank model parameters according to the degree to which they influence the model outputs. The analysis can be either qualitative or quantitative. Qualitative methods are aimed at screening or ranking active factors whereas quantitative techniques can be designed to give information on the amount of variance explained by each factor. Local approaches, also called ‘one-at-a-time’, identify the effect of variation of a single factor whereas global approaches estimate the effect on the output of a factor when all the others factors are varying, enabling the identification in interactions on non-linear models (Cariboni *et al.*, 2007; Francos *et al.*, 2003). Table 7.1 reviews the different methods available to carry out sensitivity analysis.

An approach similar to the one used by Artina *et al*. (2007) was adopted to carry out the sensitivity analysis in this study. The one-at-a-time method is used in the initial software (InfoWorks^{TM} CS) and a Nash-Sutcliffe coefficient estimation was carried out to test the behaviour and reliability of the model to parameters (see Section 3.5.2). This method was selected because it does not require the use of other modelling tools and is able to carry out both a qualitative and quantitative analysis of the model.

Table 7.1. Summary of methods used to carry out sensitivity analysis for modelling purposes

Methods	**Details**	**References**
Qualitative method		
Morris Method (One-at-a-time)	Model free method used to determine the non-influential factors (or the most influential factors) The method gives a ranking of all the factors in the model in order of importance When simulation time is very large, sensitivity analysis is problematic Method recommended for high number of parameters or model computationally expensive Perfect as preliminary analysis tool followed by quantitative sensitivity analysis such as Latin hypercube simulation or Fourier amplitude sensitivity test (Fast)	Cariboni *et al.* ,2007 Francos *et al*, 2003
Quantitative method		
Fast (Fourier amplitude sensitivity test)	FAST computes the main effect contribution of each input factors is exposed by a suitable defined search-curve Robust methods based on Monte Carlo regression and correlation analysis The Fast sensitivity index is then determine and represents how much the variance of the output will be reduce if the input parameter could be fixed with no uncertainty.	Saltelli *et al*., 1999 Francos *et al*, 2003
Generalised likelihood uncertainty estimation (GLUE)	Method successfully applied for complex hydrological models, The method used a regression based global sensitivity analysis using Monte-Carlo simulations and used previously identified sensitive parameters to validate the model. Generalised likelihood uncertainty estimation can be conduct with the identify sensitive parameters	Pohlert *et al*, 2007
Latin hypercube	The method used qualitative and quantitative way to carry out sensitivity analysis using Monte Carlos simulations, it is widely used in sensitivity analyses of environmental models It is a powerful tool for model analysis because it offers the flexibility of random sampling and required less computer power.	Sierber and Uhlembrook, 2005
Nash-Sutcliffe coefficient estimation	Method to test and perform the most relevant quality and quantity parameters using initial software in this case: InfoWorks^{TM} CS and Mouse Many simulations are carried out, in order to test their behaviour and reliability	Artina *et al*., 2007

The sensitivity analysis looked at two data sets. Runoff parameters were selected to identify the influence of PR equation present within InfoWorks CS on river flow prediction and the second set of data assessed the designed parameters used to build the two urban development scenarios.

The parameters selected for the test were the runoff parameters on which the runoff coefficient is calculated in the model: i) Runoff routing value (RRV) determines how quickly the rainfall enters the drainage system from the catchment, ii) Initial Loss values (LS) determines the quantity of rainfall required to just cause overland flow and iii) Fixed Runoff Coefficient (FRC) defines a fixed percentage of the net rainfall, which becomes runoff (Table 7.2). However, using fixed runoff coefficients for pervious areas is not recommended as the runoff from these areas varies with the antecedent wetness of the catchment. In these situations it may be necessary to vary the coefficient for different storm conditions.

Table 7.2. Hydrological default values typical for impervious area

Parameters	Default value	Value changed
Runoff Routing value (RRV)	1.0	0.2, 1.0, 2.0, 4.0, 6.0
Initial Loss (m)	7×10^{-5}	$5\ 10^{-4}$, $1\ 10^{-5}$, $1\ 10^{-6}$, $1\ 10^{-7}$
Fixed Runoff Coefficient	0.70	0.1, 0.5, 1.0.

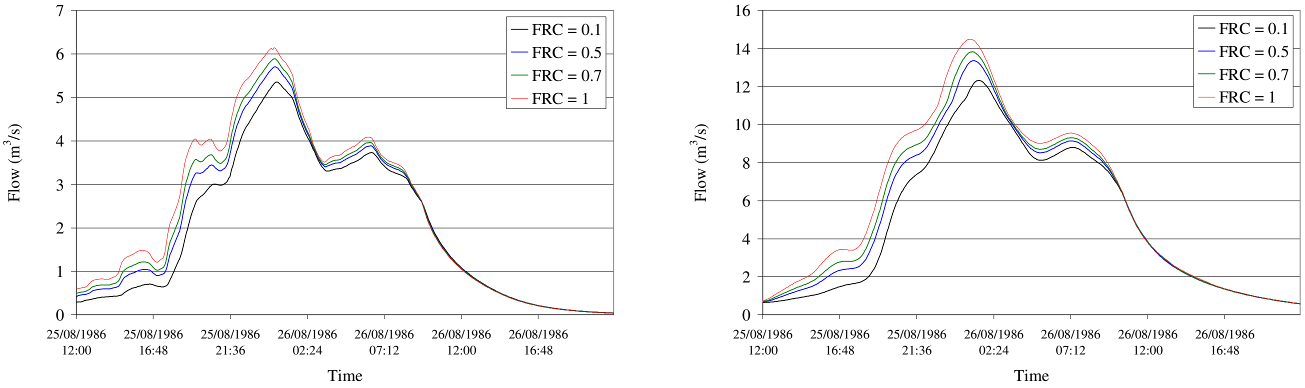
The parameters’ influence on the river flow at the two river gauges was assessed for the three basecase networks (basecase 2002, 2010 and 2050), as well as for three rainfall events: 25th August 1986, and 5 and 100 year return period events. A total of 252 simulations were run. The goodness of fit between measured and simulated data was then evaluated using the Nash-Sutcliffe coefficient (E_{NS}).

7.2 Influence of the runoff parameters on the hydrological network

The peak flow observed at the two river gauges for each run are reported for the three rainfall events for each of at the three urban developments scenarios. The section is divided into three sub-sections. Each sub-section covers the results of the three runoff parameters tested. It also has to be mentioned that due to the lack of measured data available, the Nash-Sutcliffe coefficient (E_{NS}) has been calculated comparing modelled data obtained using the initial or default parameters with results obtained with changed parameters.

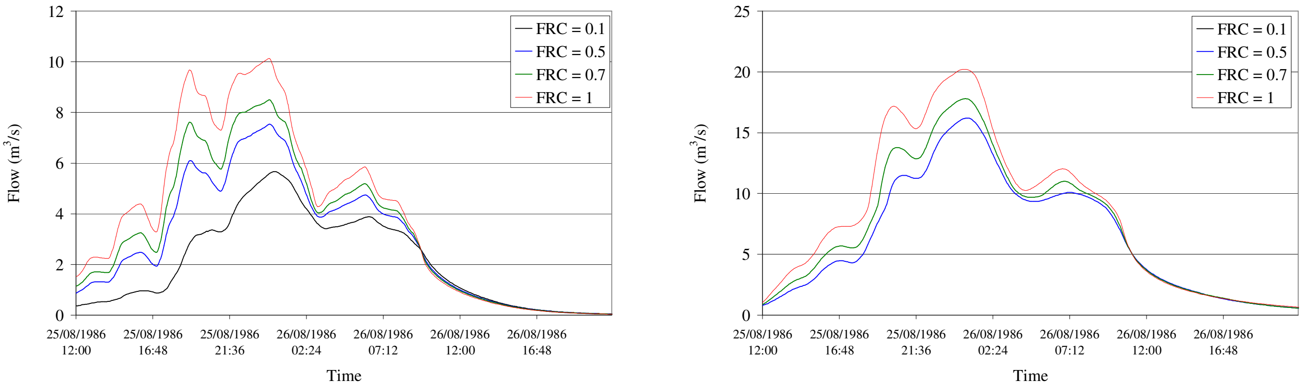
7.2.1 Influence of the Fixed Runoff Coefficient (FRC) on the hydrology

Figure 7.1, Figure 7.2 and Figure 7.3 review the hydrographs obtained for the three rainfall events under 25th of August 1986 rainfall event, the 100 year return period event and the 5 year return period event. The results show the river peak flow to be influenced by the FRC value. When the FRC value increases, the river peak flow observed at the two river gauges also increase, and when FRC decreases toward 0.1 the peak flow values also decrease.



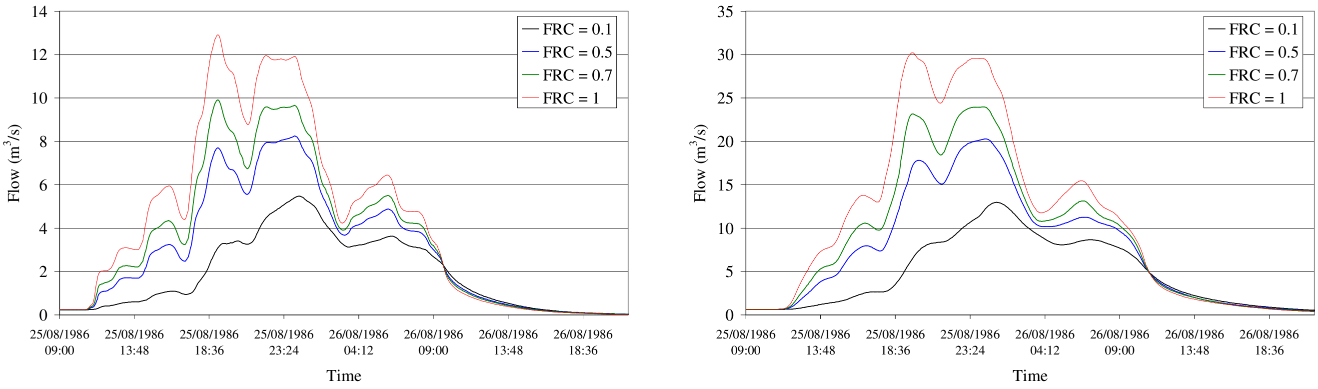
Carrickmines river gauge in 2002

Common's road river gauge in 2002



Carrickmines river gauge in 2010

Common's road river gauge in 2010

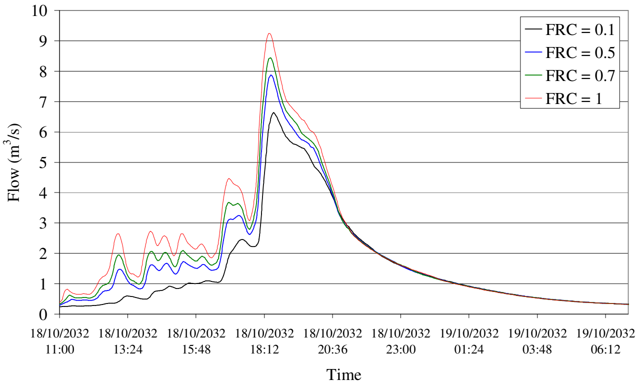


Carrickmines river gauge in 2050

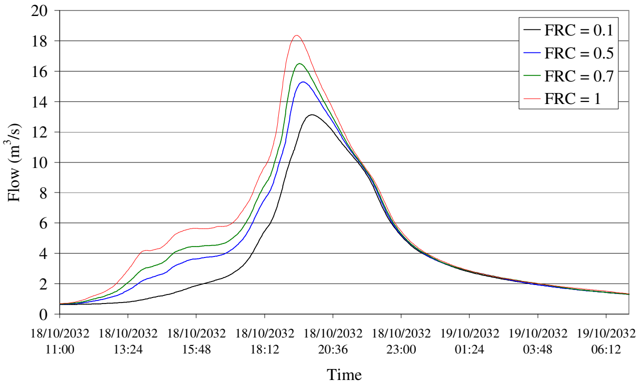
Common's road river gauge in 2050

Figure 7.1. Comparison between river flows at the two river gauges when the Fixed Runoff Coefficient (FRC) varies from 0.1 to 1.0 for the rainwater event 25th of August 1986.

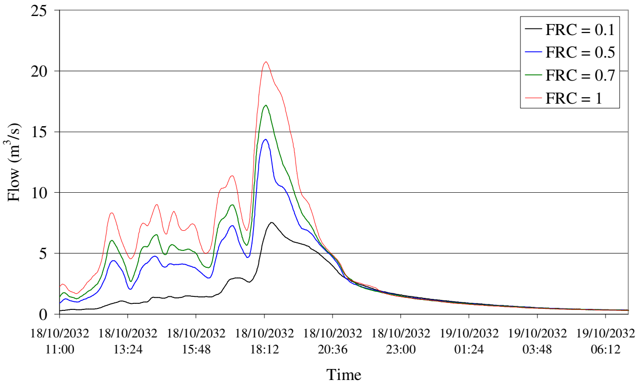
Carrickmines river gauge in 2002



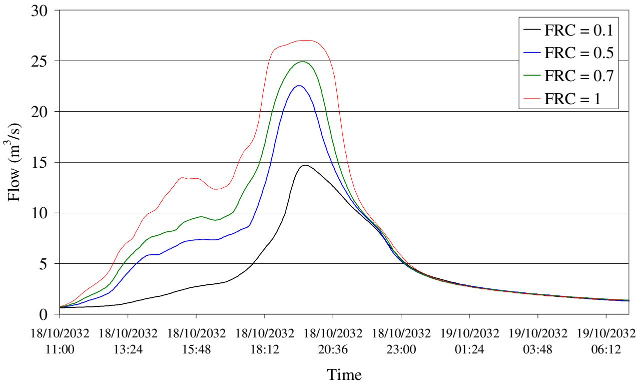
Common's road river gauge in 2002



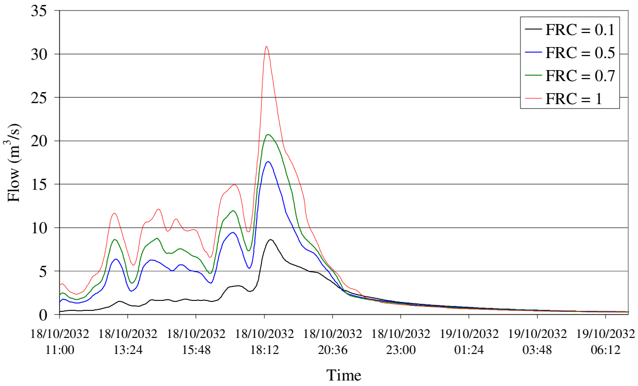
Carrickmines river gauge in 2010



Common's road river gauge in 2010



Carrickmines river gauge in 2050



Common's road river gauge in 2050

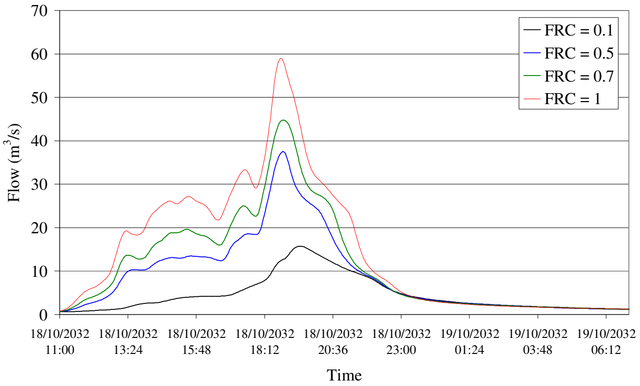
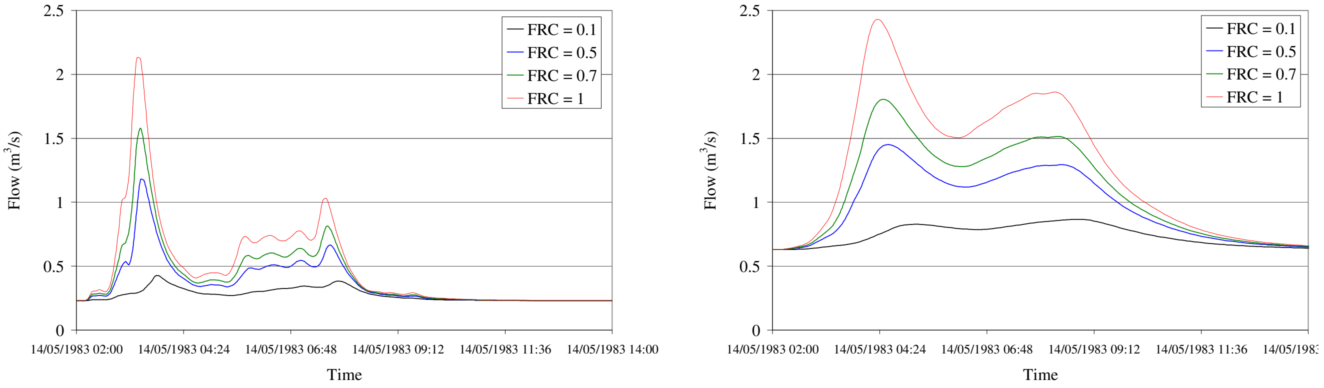
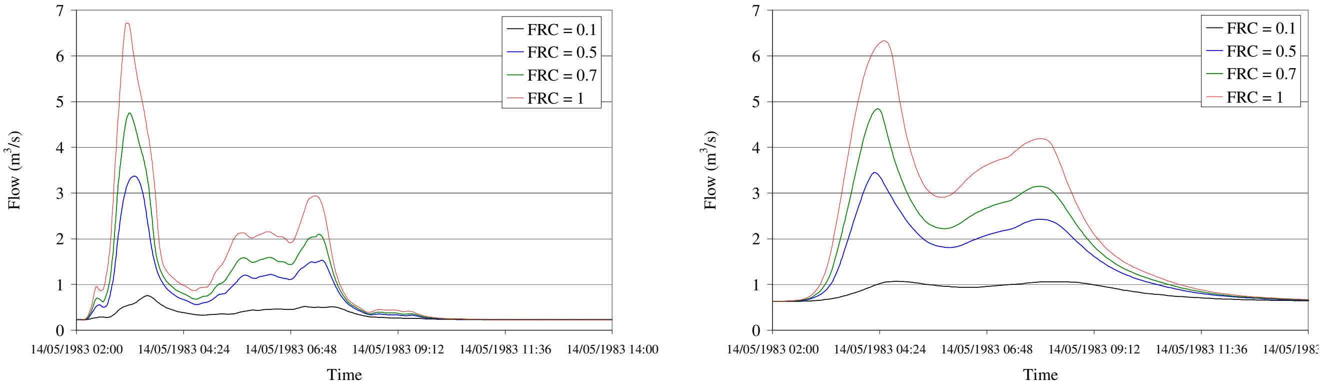


Figure 7.2. Comparison between river flows at the two river gauges when the Fixed Runoff Coefficient (FRC) varies from 0.1 to 1.0 during a 100 year return period event.



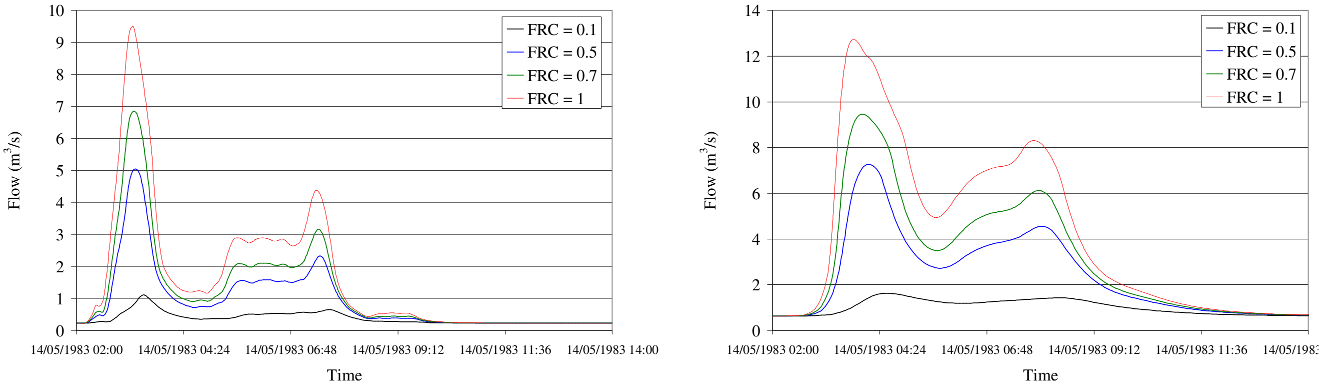
Carrickmines river gauge in 2002

Common's road river gauge in 2002



Carrickmines river gauge in 2010

Common's road river gauge in 2010



Carrickmines river gauge in 2050

Common's road river gauge in 2050

Figure 7.3. Comparison between river flows at the two river gauges when the Fixed Runoff Coefficient (FRC) varies from 0.1 to 1.0 during a 5 year return period event.

The Nash-Sutcliffe coefficients (E_{NS}) obtained are reviewed within Table 7.3, Table 7.4 and Table 7.5.

Table 7.3. Nash-Sutcliffe coefficient analysis results obtained when FRC parameter was tested for the 2002 development.

	Rainfall simulation					
	1986		100 year return		5 year return	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
FRC=0.1	0.993	0.960	0.872	0.863	0.154	0.875
FRC=0.5	0.999	0.996	0.986	0.985	0.897	0.986
FRC=1	0.998	0.990	0.972	0.966	0.766	0.964

Table 7.4. Nash-Sutcliffe coefficient analysis results obtained when FRC parameter was tested for the 2010 development.

	Rainfall simulation					
	1986		100 year return		5 year return	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
FRC=0.1	0.920	0.771	0.402	0.513	0.079	0.007
FRC=0.5	0.991	0.974	0.935	0.946	0.896	0.878
FRC=1	0.981	0.943	0.854	0.884	0.776	0.735

Table 7.5. Nash-Sutcliffe coefficient analysis results obtained when FRC parameter was tested for the 2050 development.

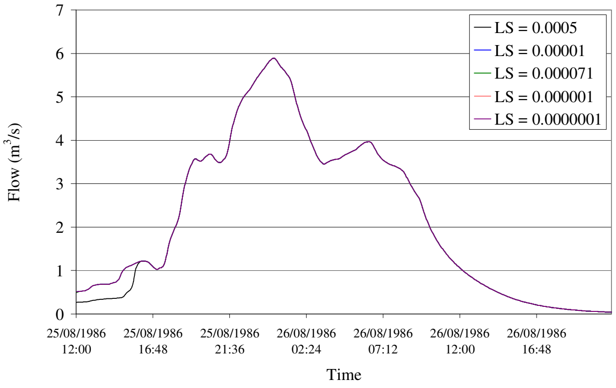
	Rainfall simulation					
	1986		100 year return		5 year return	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
FRC=0.1	0.538	0.495	0.294	0.199	0.090	0.018
FRC=0.5	0.949	0.943	0.923	0.917	0.899	0.882
FRC=1	0.888	0.876	0.819	0.830	0.783	0.747

First, increasing the value of FRC results in increase scenarios in the peak flow intensity for the three rainfall events and three urban development scenarios. The influence of FRC variation is more important under the 2010 and 2050 developments than the 2002 base scenario. Under 25th of August 1986 rainfall event and 100 year return period events, a variation in the river peak flow is observed at both river gauges and for each urban development. However, under the 5 year return period event, for a value of FRC equal to 0.1, Figure 7.3 reports a big influence on river flow at the two river gauges, the flows observed are really close to zero. The variation of the fixed runoff coefficients influences the value of E_{NS} within the three developments under the three rainfall events.

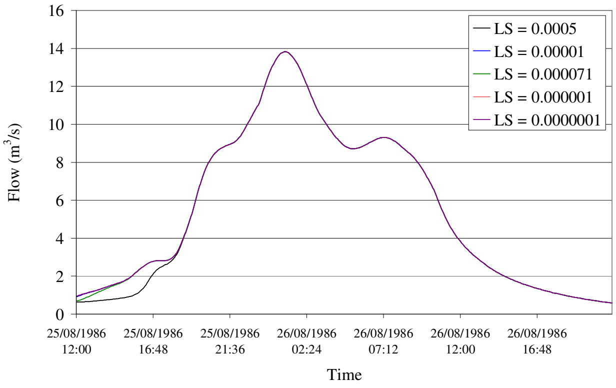
7.2.2 Influence of the Initial Loss (LS) on the hydrology

Figure 7.4, Figure 7.5 and Figure 7.6 review the hydrographs obtained under the 25th of August 1986 rainfall event, 100 year return period event and 5 year return period event. The results only identify a slight delay in the when LS increase under 25th of August 1986 rainfall event, 100 year return period event, the same peak flow intensity was observed. However under 5 year return period events, delay and intensity lower.

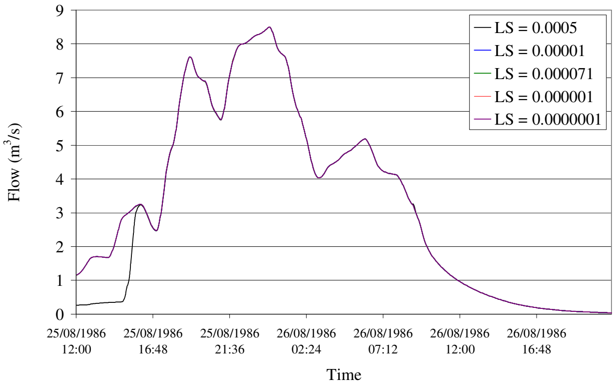
Carrickmines river gauge in 2002



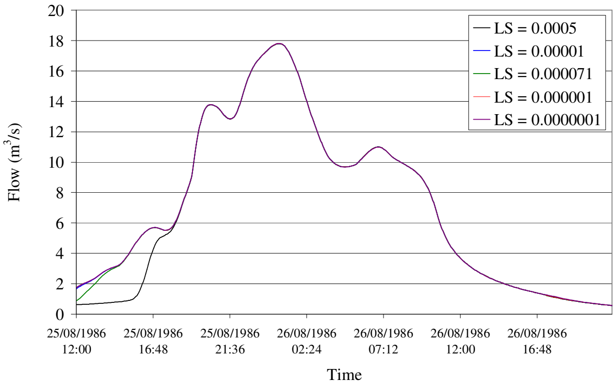
Common's road river gauge in 2002



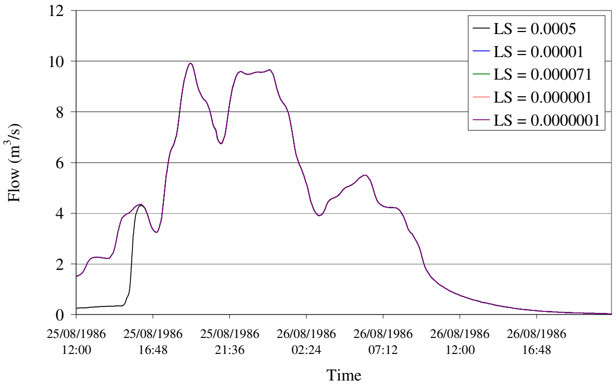
Carrickmines river gauge in 2010



Common's road river gauge in 2010



Carrickmines river gauge in 2050



Common's road river gauge in 2050

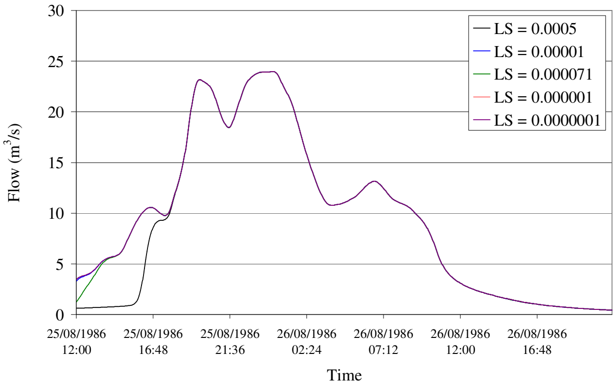
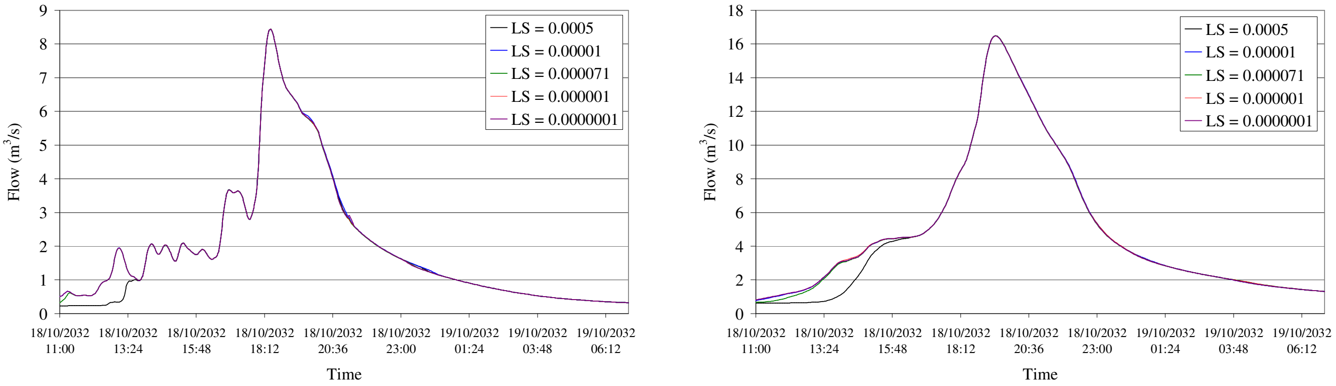
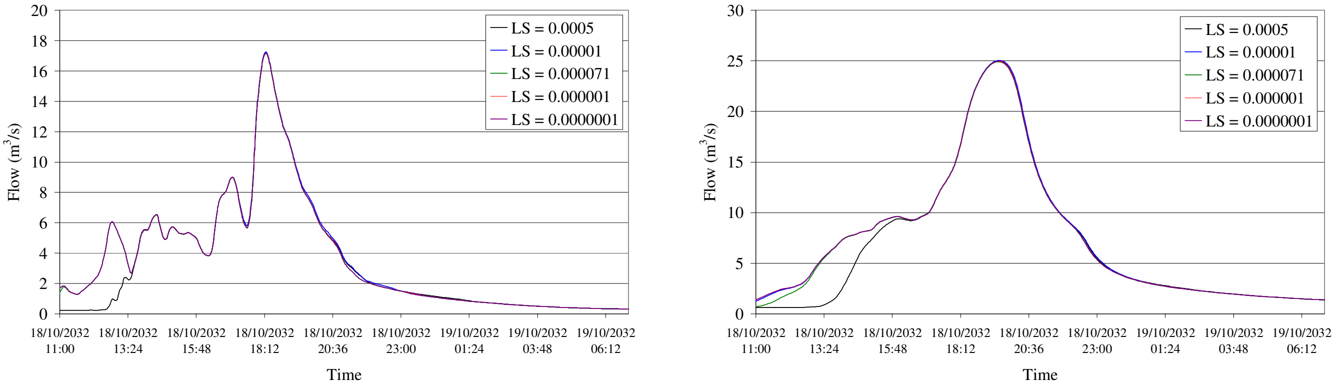


Figure 7.4. Comparison between river flows at the two river gauges when the Initial Loss (LS) varies from 1 10-7 to 5 10-4 for the event 25th of August 1986.

Carrickmines river gauge in 2002 **Common's road river gauge in 2002**



Carrickmines river gauge in 2010 **Common's road river gauge in 2010**



Carrickmines river gauge in 2050 **Common's road river gauge in 2010**

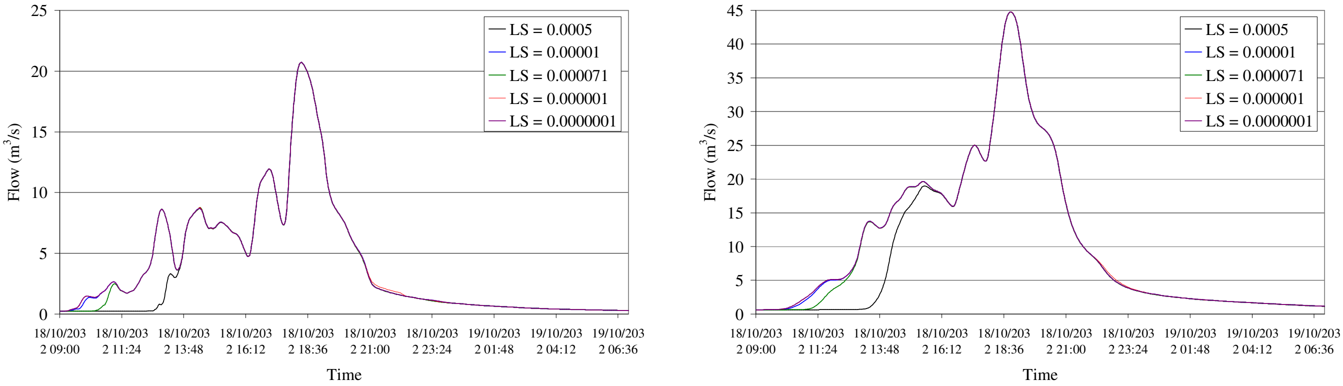
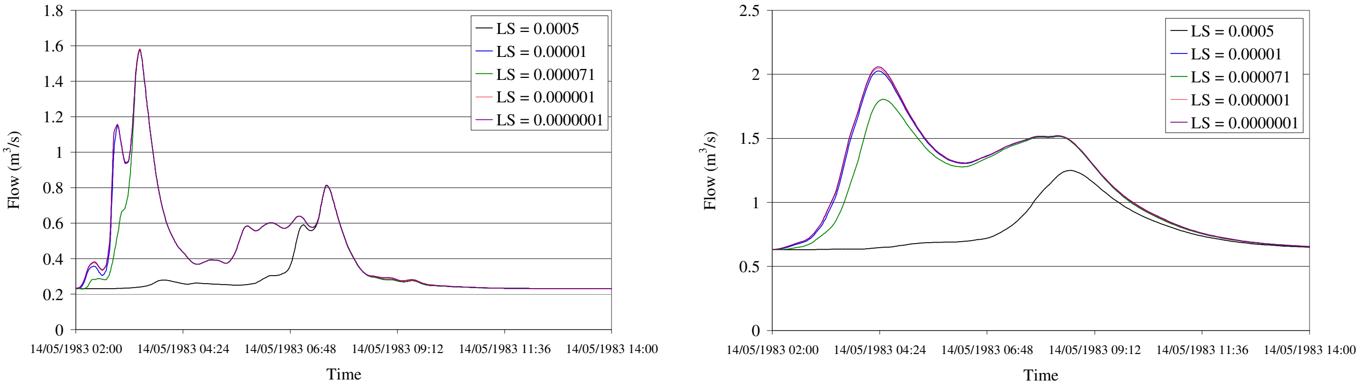
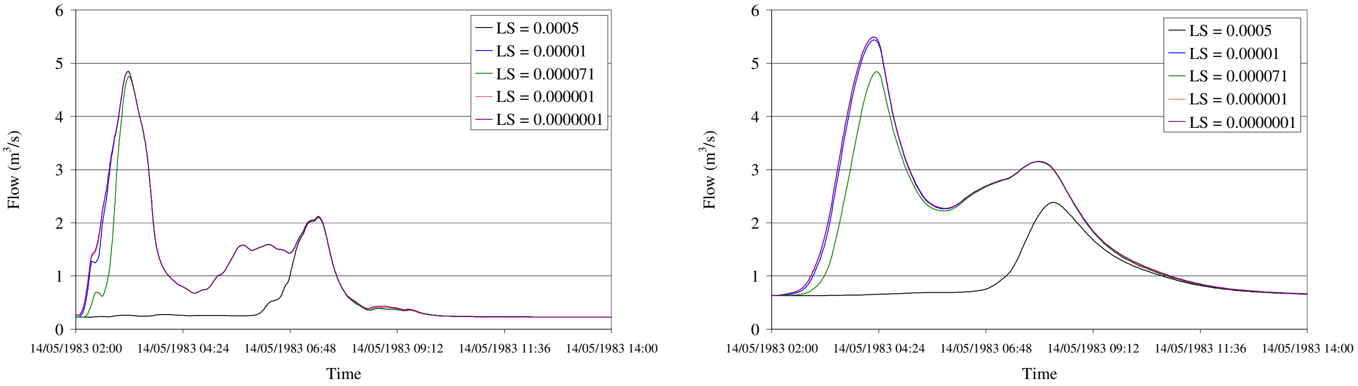


Figure 7.5. Comparison between river flows at the two river gauges when the Initial Loss (LS) varies from 1 10^{-7} to 5 10^{-4} during a 100 year return period event.

Carrickmines river gauge in 2002 Common’s road river gauge in 2002



Carrickmines river gauge in 2010 Common’s road river gauge in 2010



Carrickmines river gauge in 2050 Common’s road river gauge in 2050

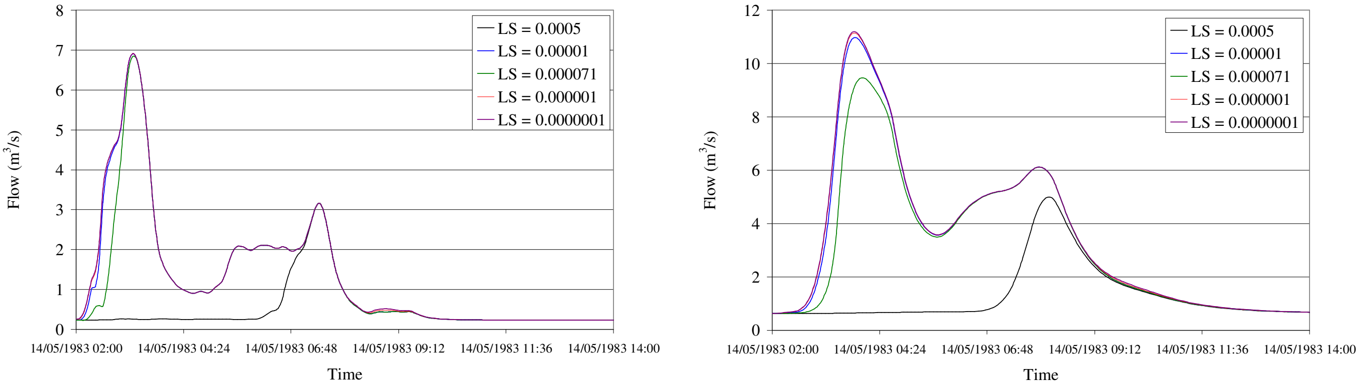


Figure 7.6. Comparison between river flows at the two river gauges when the Initial Loss (LS) varies from 1 10^{-7} to 5 10^{-4} during a 5 year return period event.

Table 7.6, Table 7.7 and Table 7.8 review the Nash-Sutcliffe coefficients (E_{NS}) obtained for the variation of the initial loss (LS).

Table 7.6. Nash-Sutcliffe coefficient analysis results obtained when LS parameter was tested within 2002 development.

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
LS=0.0005	0.996	0.996	0.984	0.989	0.105	0.090
LS=0.00001	0.999	0.999	0.999	0.999	0.916	0.960
LS=0.000001	0.999	0.999	0.999	0.999	0.901	0.951
LS=0.0000001	0.999	0.999	0.999	0.999	0.899	0.947

Table 7.7. Nash-Sutcliffe coefficient analysis results obtained when LS parameter was tested for the 2010 development.

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
LS=0.0005	0.972	0.982	0.943	0.966	0.029	0.010
LS=0.00001	0.999	0.999	0.998	0.999	0.931	0.952
LS=0.000001	0.998	0.999	0.998	0.999	0.915	0.939
LS=0.0000001	0.998	0.999	0.998	0.999	0.912	0.937

Table 7.8. Nash-Sutcliffe coefficient analysis results obtained when LS parameter was tested for the 2050 development.

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
LS=0.0005	0.960	0.959	0.930	0.941	0.021	0.033
LS=0.00001	0.997	0.998	0.998	0.998	0.922	0.944
LS=0.000001	0.997	0.998	0.997	0.998	0.907	0.927
LS=0.0000001	0.997	0.998	0.997	0.998	0.905	0.923

Under 25th of August 1986 rainfall event, LS influence on peak flow is really minimal, a delay in peak flow is observed when LS = 0.0005 at both river gauges and LS = 0.00001 and 0.000071 at Common's road river gauges. The same observation was made for 100 year return period events. However, under 5 year return period events, for a value of LS. The variation of the fixed runoff coefficients influences the value of E_{NS} within the three developments under the three rainfall events.

7.2.3 Influence of the Runoff Routing Value (RRV) on the hydrology

Figure 7.7, Figure 7.8 and Figure 7.9 review the hydrographs obtained under 25th of August 1986 rainfall event, 100 year return period event and 5 year return period event. A small variation of the two peak flow is observed under the two following rainfall events: 25th of August 1986 rainfall event, 100 year return period event. However, under 5 year return period event the delay and intensity of the two peak flow is more influence than under the two other rainfall events. Moreover, the sensitivity analysis highlights a smaller variation of the peak flow when RRV varies than with LS and FRR.

The Nash-Sutcliffe coefficients (E_{NS}) obtained are reviewed within Table 7.9. Nash-Sutcliffe coefficient analysis results obtained when RRV parameter was tested for the 2002 development. Table 7.9, Table 7.10 and Table 7.11.

Table 7.9. Nash-Sutcliffe coefficient analysis results obtained when RRV parameter was tested for the 2002 development.

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
RRV=0.2	0.999	0.999	0.998	0.999	0.967	0.997
RRV=2.0	0.999	0.999	0.998	0.999	0.968	0.996
RRV=4.0	0.999	0.999	0.990	0.998	0.816	0.972
RRV=6.0	0.998	0.999	0.984	0.996	0.650	0.930

Table 7.10. Nash-Sutcliffe coefficient analysis results obtained when RRV parameter was tested for the 2010 development.

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
RRV=0.2	0.999	0.999	0.995	0.999	0.975	0.999
RRV=2.0	0.999	0.999	0.994	0.999	0.970	0.999
RRV=4.0	0.995	0.998	0.970	0.994	0.821	0.9952
RRV=6.0	0.988	0.995	0.944	0.986	0.663	0.9889

Table 7.11. Nash-Sutcliffe coefficient analysis results obtained when RRV parameter was tested for the 2050 development.

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
RRV=0.2	0.999	0.999	0.995	0.999	0.977	0.993
RRV=2.0	0.999	0.999	0.994	0.998	0.971	0.989
RRV=4.0	0.993	0.995	0.968	0.988	0.823	0.926
RRV=6.0	0.984	0.988	0.938	0.971	0.667	0.843

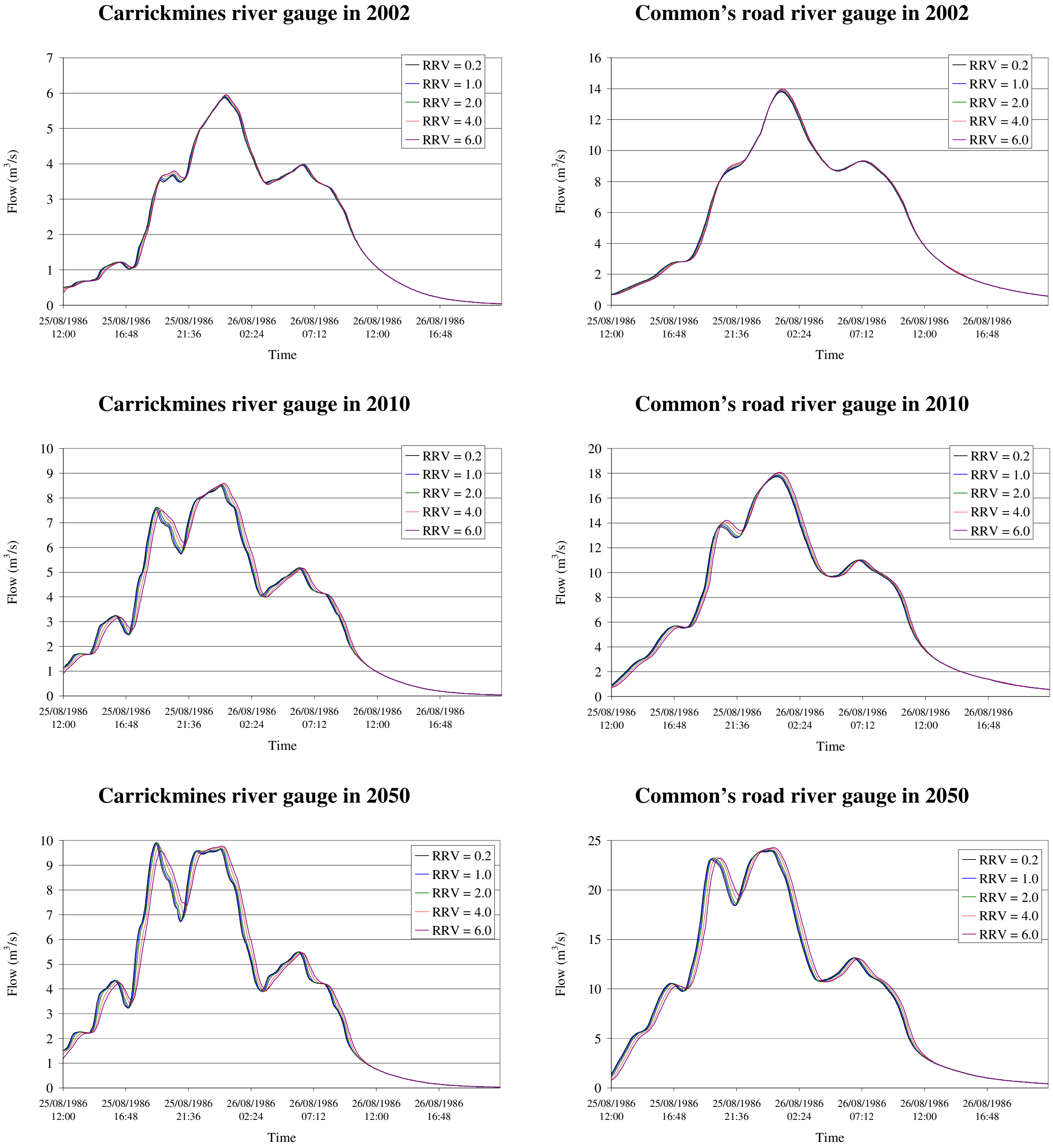
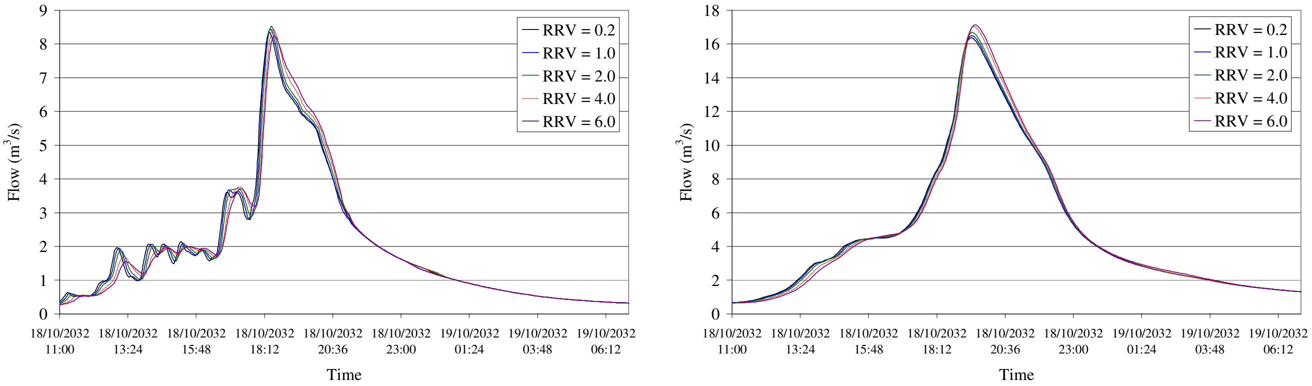


Figure 7.7. Comparison between river flows at the two river gauges when the Runoff Routing Value (RRV) varies from 0.1 to 6.0 for the event 25th of August 1986.

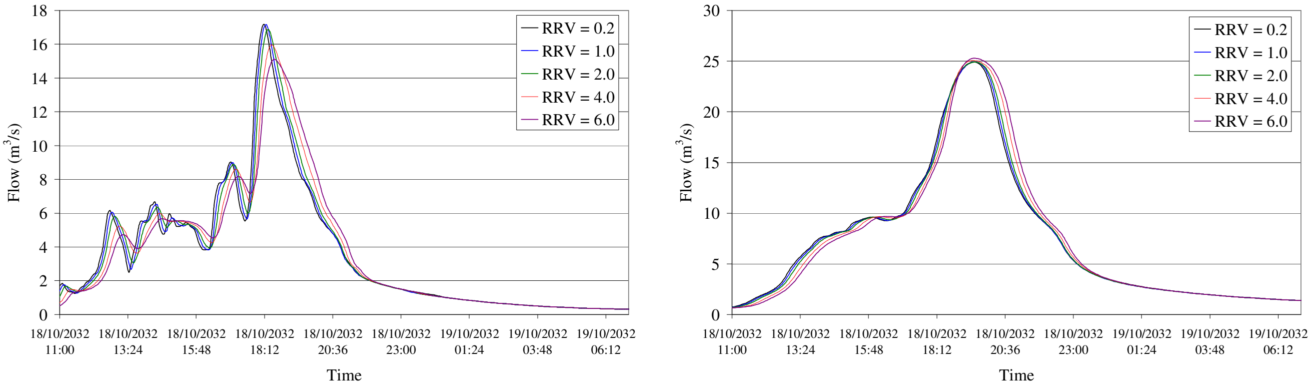
Carrickmines river gauge in 2002

Common's road river gauge in 2002



Carrickmines river gauge in 2010

Common's road river gauge in 2010



Carrickmines river gauge in 2050

Common's road river gauge in 2050

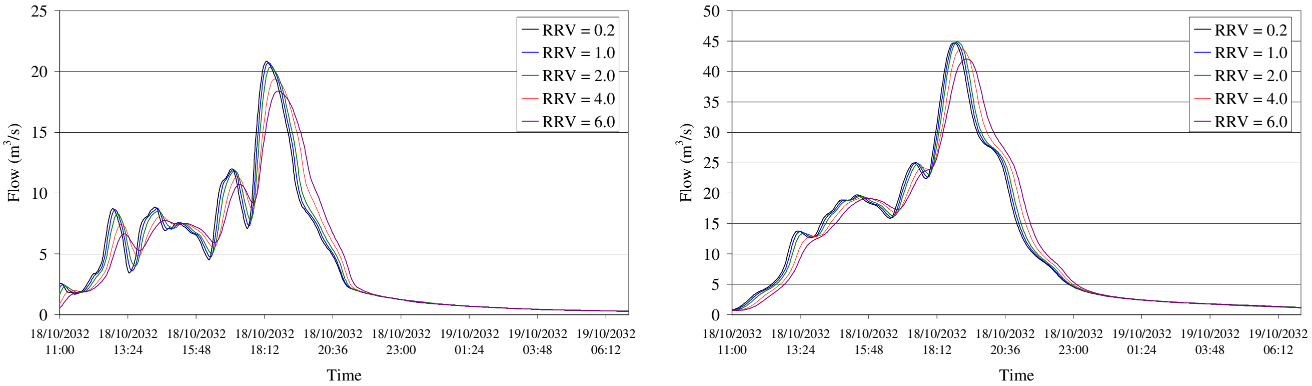
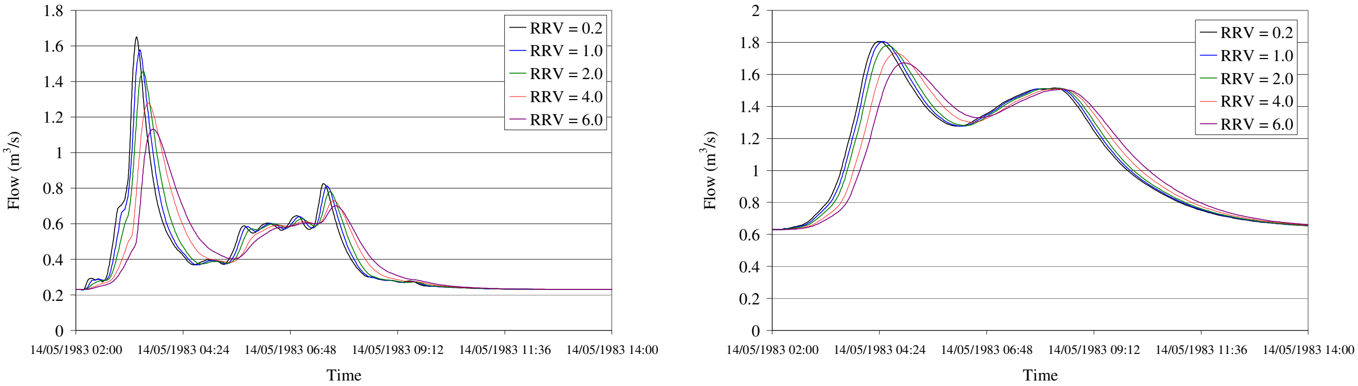
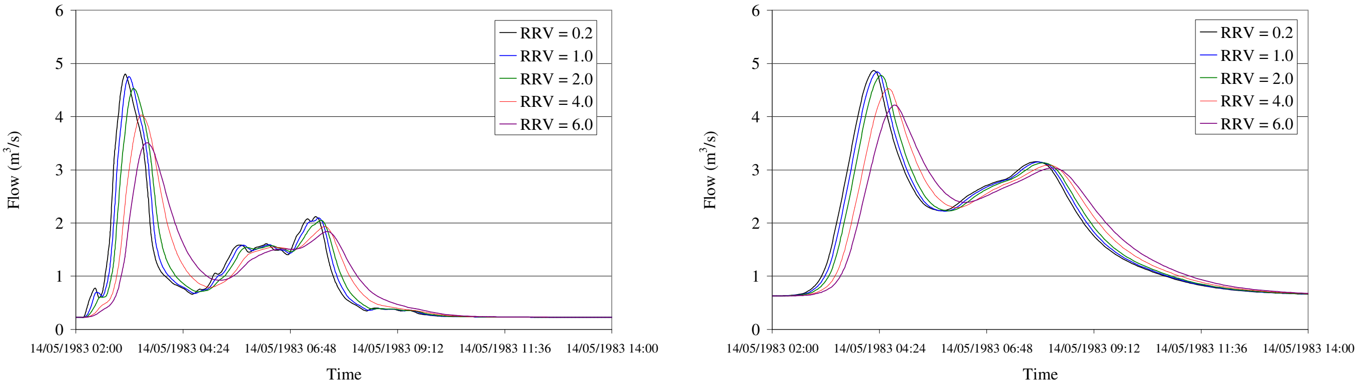


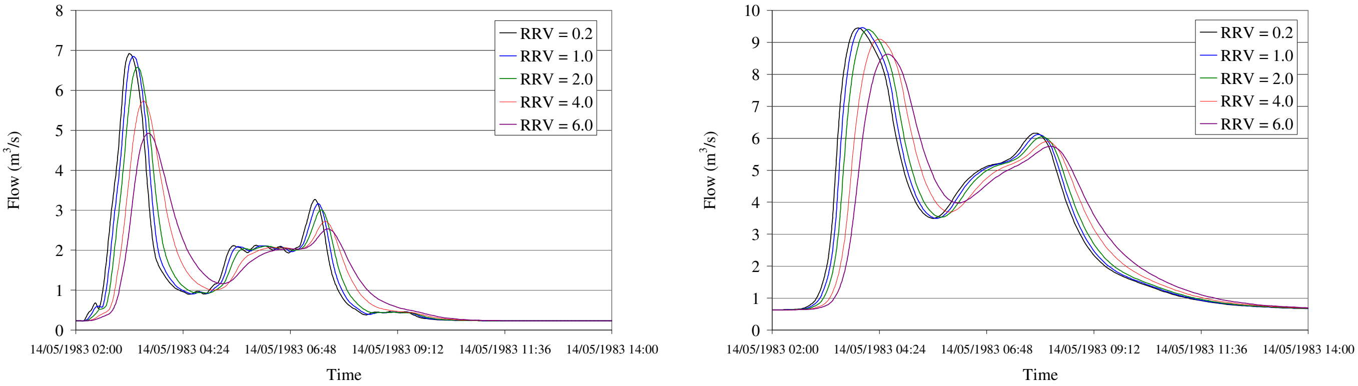
Figure 7.8. Comparison between river flows at the two river gauges when the Runoff Routing Value (RRV) varies from 0.1 to 6.0 during a 100 year return period event.


Carrickmines river gauge in 2002

Common's road river gauge in 2002


Carrickmines river gauge in 2010

Common's road river gauge in 2010


Carrickmines river gauge in 2050

Common's road river gauge in 2050

Figure 7.9. Comparison between river flows at the two river gauges when the Runoff Routing Value (RRV) varies from 0.1 to 6.0 during a 5 year return period event.

The routing runoff value variation shows little variation of peak flow, the peak flow are slightly delayed when RRV increase. Under the 25th of August 1986 rainfall event and 100 year return E_{NS} always exceed 0.900 for the three urban developments at both river gauges. However, under the 5 year return period event, E_N observed is bigger and 0.650 E_{NS} is identified for RRV = 6.0 under the 2002 development.

7.3 Influence of three urban design parameters on the hydrological network

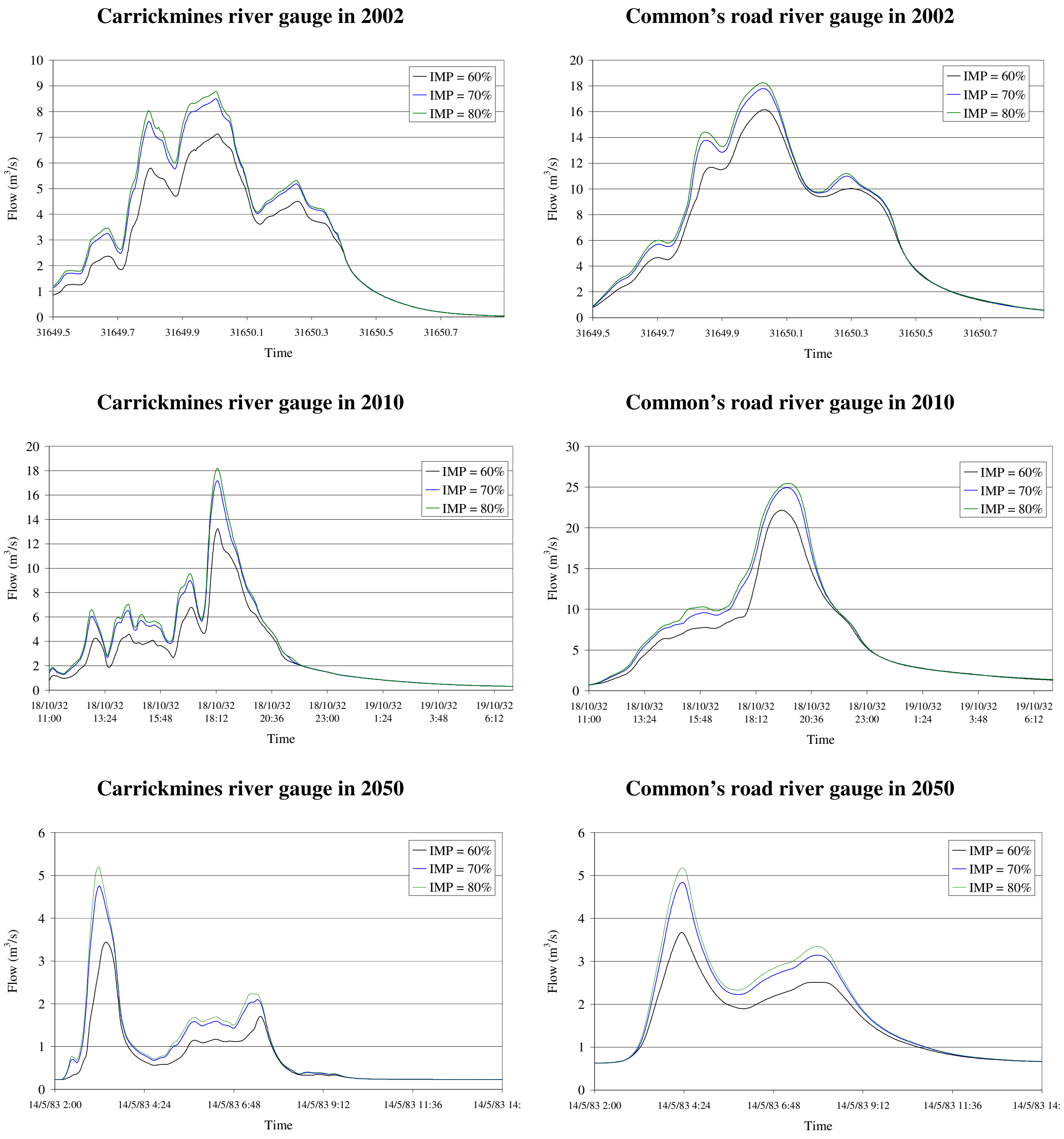
In order to assess the parameters selected to design the urban development, impervious area value, roof area surface and roof area contributing to the sewer network have been modified as shown in Table 7.12. The method followed to assess the sensitivity analysis is similar to the one describe in Table 7.12 at the exception that not only peak flow at the river gauges were compared but also peak flow of two conducts present within the urban development 2050.

Table 7.12. Hydrological default value typical for impervious area

Parameters	Default value	Value changed to
Impervious area	70% of new urban are	60 and 80%
Roof area surface	40% of impervious area	30 and 50%
Roof area contributing	5% of roof area	0 and 10 %

7.3.1 Sensitivity of hydrological results to changes in impervious area

Figure 7.10 introduces the results relating to the important of varying the impervious surface area between 60 and 80% of the total new urban area as measured by flows at the two river gauges.



Carrickmines river gauge in 2002

Common's road river gauge in 2002

Carrickmines river gauge in 2010

Common's road river gauge in 2010

Carrickmines river gauge in 2050

Common's road river gauge in 2050

Figure 7.10. Comparison between river flows at the two river gauges when the % of impervious area in new development is varied from 60% to 80%

The E_{NS} values are introduced within Table 7.13.

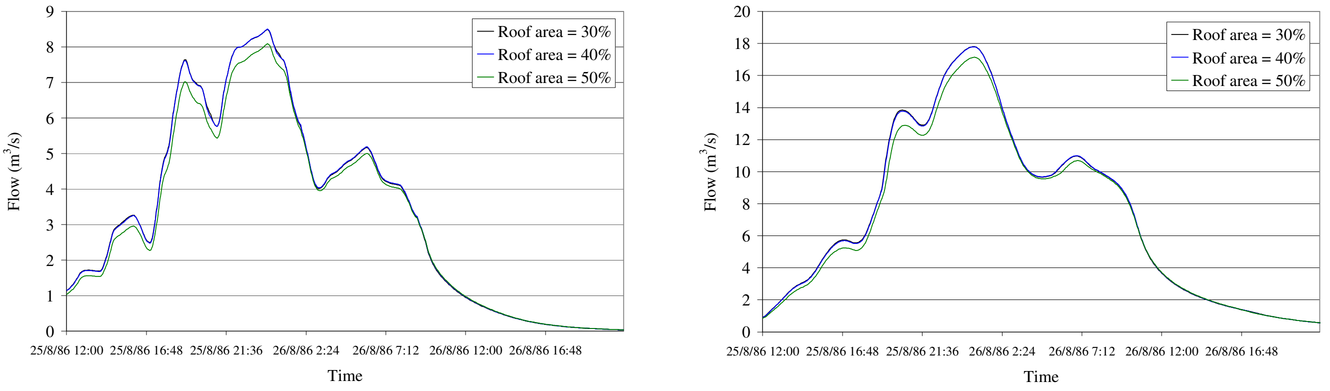
Table 7.13. Nash-Sutcliffe coefficient analysis results obtained when impervious area varies

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
IMP = 60%	0.938	0.999	0.995	0.959	0.848	0.918
IMP = 80%	0.997	0.999	0.994	0.898	0.990	0.991

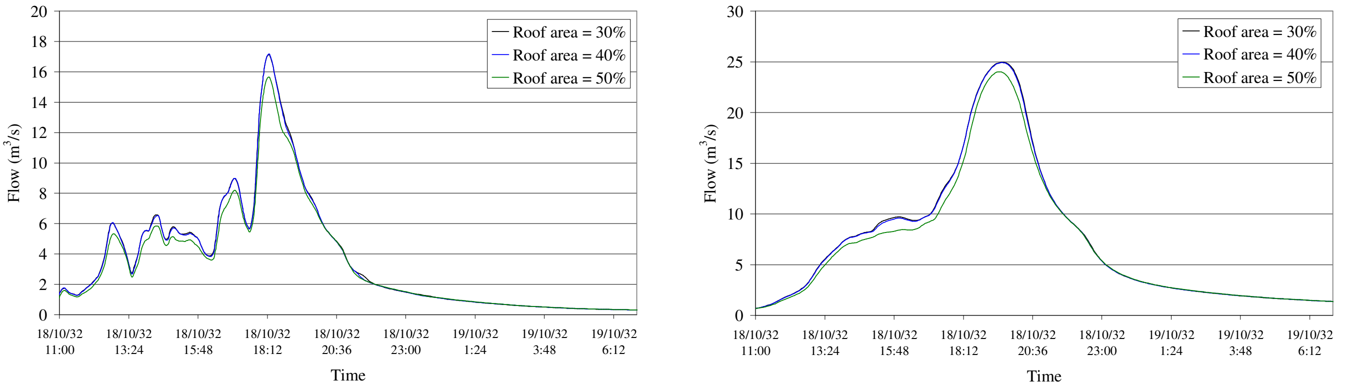
The variation of runoff percentages influences the peak flow at both river gauges under the three rainfall events. A more important difference is observed between 60% and 70% impervious area and between 70% and 80% impervious areas. However, the E_{NS} coefficients obtained when compared to the initial results obtained for always exceed 0.898. Therefore, the percentage impervious of new development has an influence on river peak flow however the sensitivity analysis shows that the influence is negligible.

7.3.2 Sensitivity of hydrological results to changes in roof area

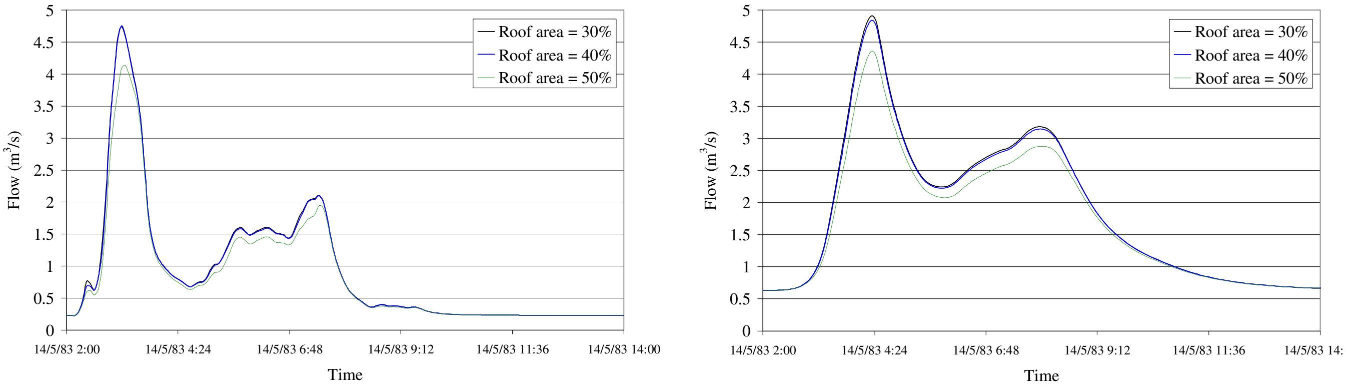
Figure 7.11 and Table 7.14 introduce the results obtained when roof surface area varies between 30 and 50% of the total imperious area on the river peak flow at Carrickmines and Common's road river gauges.


Carrickmines river gauge in 2002

Common's road river gauge in 2002


Carrickmines river gauge in 2010

Common's road river gauge in 2010


Carrickmines river gauge in 2050

Common's road river gauge in 2050

Figure 7.11. Comparison between river flows at the two river gauges when the roof area varies from 30% to 50%

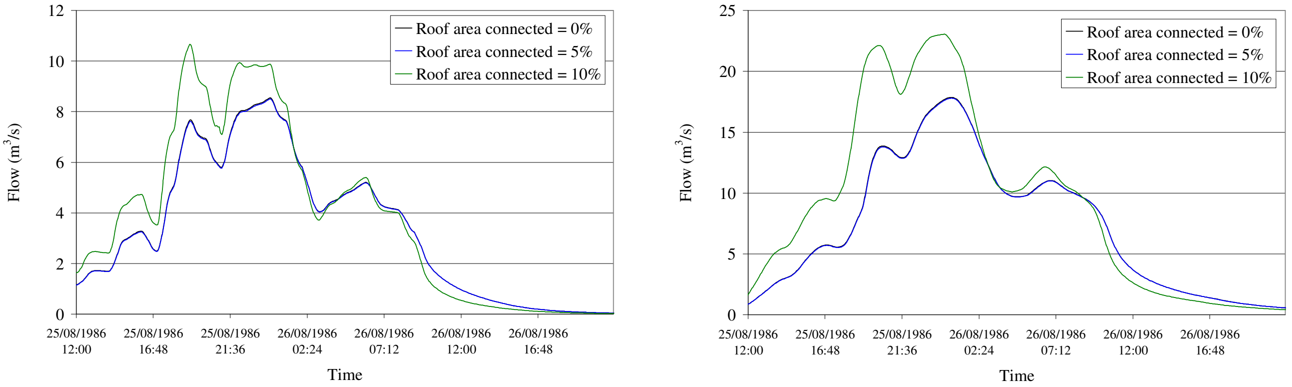
Table 7.14. Nash-Sutcliffe coefficient analysis results obtained when roof area

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
Roof area = 30%	0.999	0.999	0.999	0.999	0.999	0.999
Roof area = 50%	0.994	0.999	0.988	0.992	0.982	0.983

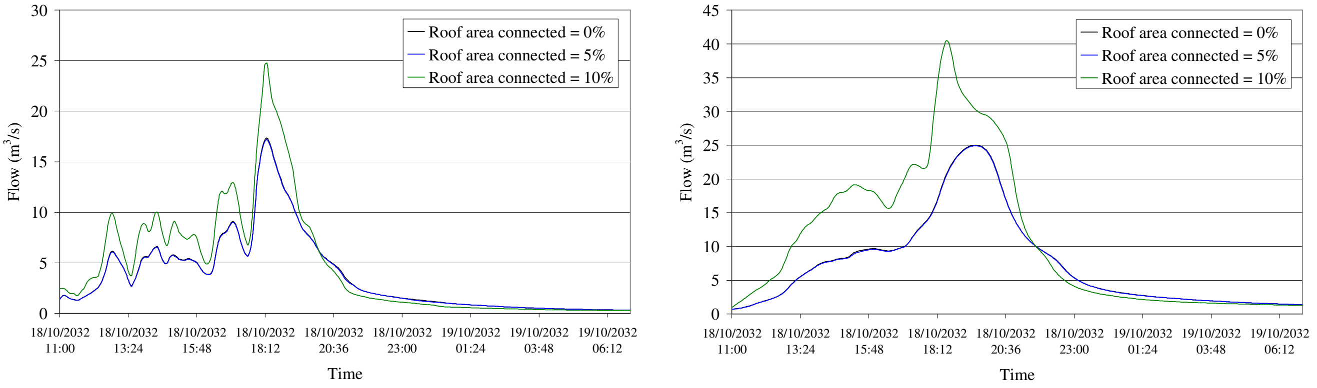
The variation of roof area surface from 30 and 40% same influence on peak flow at the two river gauges. 50% more influence however the E_{NS} coefficients are exceeding 0.980 for the three rainfall events. Therefore, the percentage of roof area of new development has a small influence on river peak flow as shown by the sensitivity analysis.

7.3.3 Sensitivity of hydrological results to changes in connected roof area

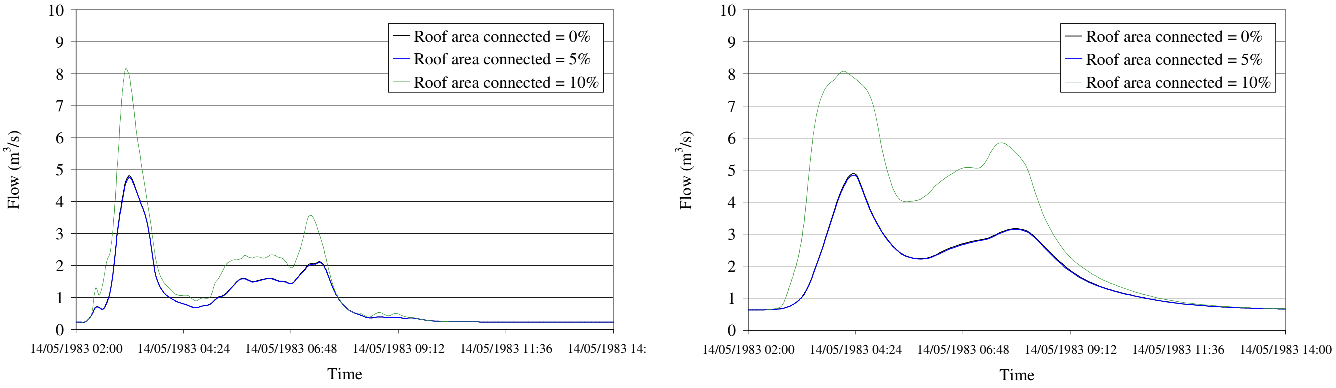
Figure 7.12 and Table 7.15 introduce the results obtained when contributed roof surface area varies between 0 and 10% of the total imperious area on the river peak flow at Carrickmines and Common's road river gauges.


Carrickmines river gauge in 2002

Common's road river gauge in 2002


Carrickmines river gauge in 2010

Common's road river gauge in 2010


Carrickmines river gauge in 2050

Common's road river gauge in 2050

Figure 7.12. Comparison between river flows at the two river gauges when the roof area connected varies from 0% to 10%.

Table 7.15. Nash-Sutcliffe coefficient analysis results obtained when roof area connected

	Rainfall simulation					
	1986		100 year		5 year	
	Carrickmines	Common	Carrickmines	Common	Carrickmines	Common
Roof connected = 0%	0.999	0.999	0.286	0.999	0.999	0.999
Roof connected = 10%	0.887	0.999	0.739	0.999	0.536	0.742

The variation of roof area surface between 0% and 5% does not show influence on river peak flow. With 10% roof area surface more influence however the E_{NS} coefficients are exceeding 0.980 for the three rainfall events.

7.4 Influence of the three parameters on the sewer network

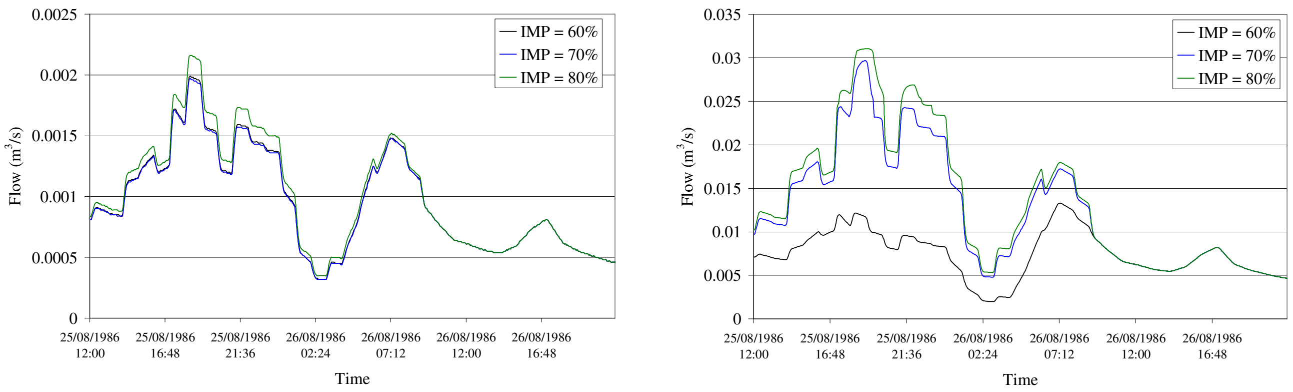
The method followed to assess the sensitivity analysis is similar to the one describe in Figure 7.13 at the exception that not only peak flow at the river gauges were compared but also peak flow of two conducts present within the urban development 2050.

7.4.1 Sensitivity of hydrological results to changes in impervious surface area

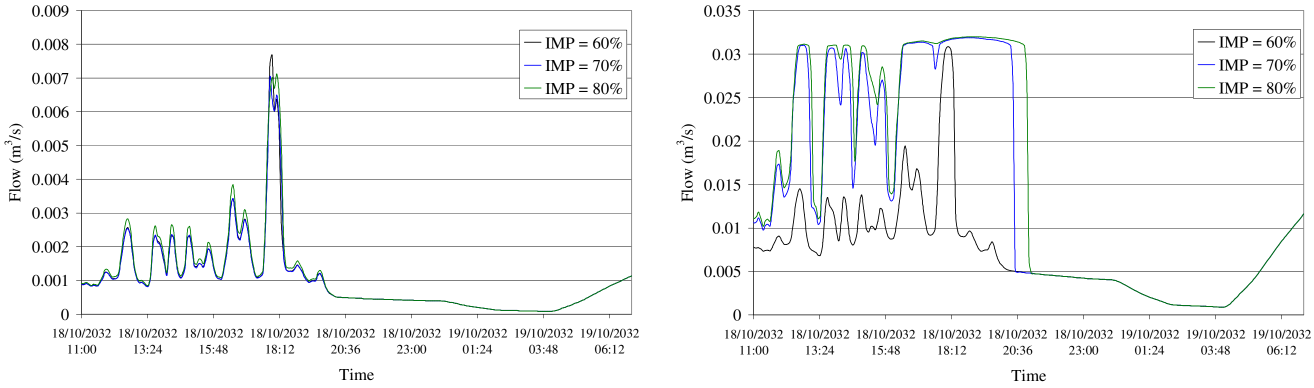
Figure 7.13 and Table 7.16 introduce the results obtained when impervious surface area varies between 60 and 80% of the total new urban area on the sewer network.

1986

Pipe 1 **Pipe 2**



100 year return period (M100)



5 year return period (M5)

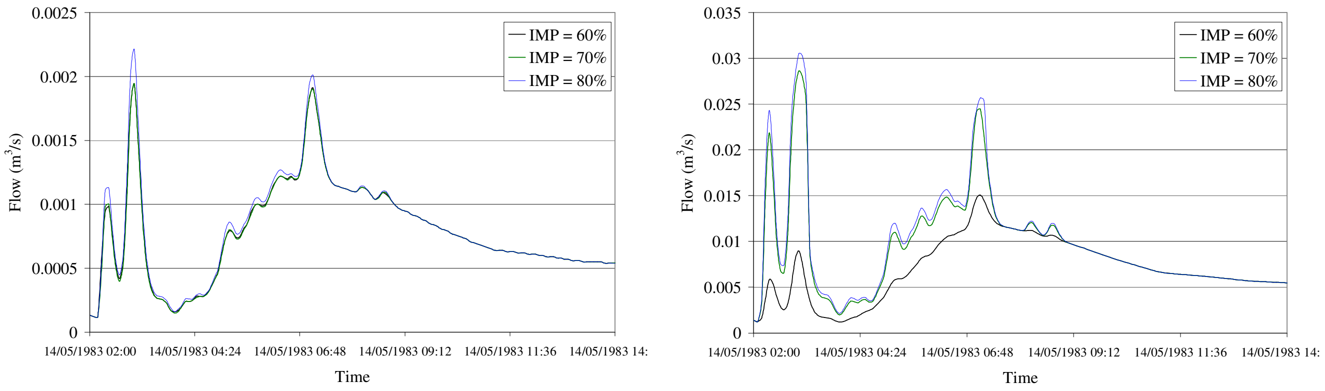


Figure 7.13. Comparison between pipes flows at the two river gauges when the % of impervious area in new development varies from 60% to 80%.

Table 7.16. Nash-Sutcliffe coefficient analysis results obtained when impervious area varies

	Rainfall simulation					
	1986		100 year		5 year	
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2
IMP = 60%	0.999	0.208	0.985	0.165	0.999	0.449
IMP = 80%	0.999	0.968	0.980	0.870	0.988	0.986

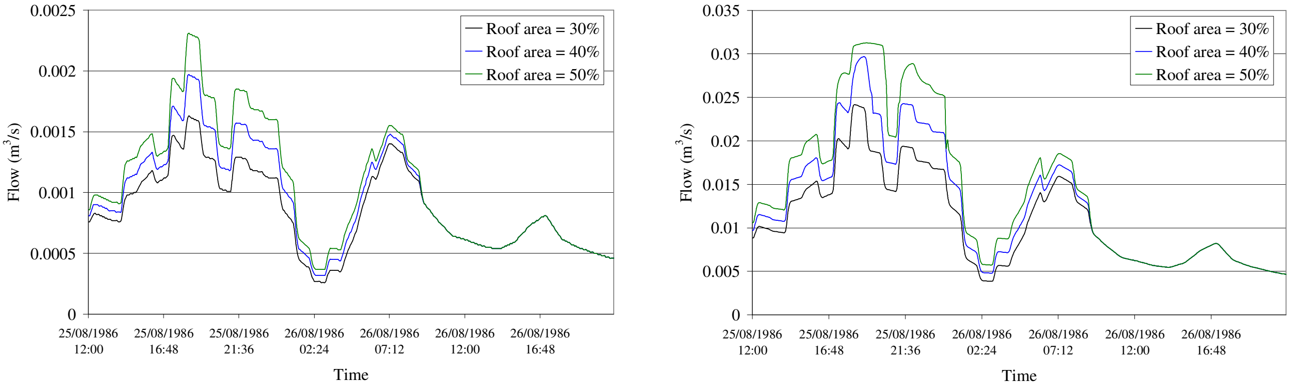
Different results are observed between the two conducts. The peak flow variation within the two conducts is varying a lot between the three rainfall events. For example floods occur for pipe 2 under 100 return period rainfall events when 60 and 70% of the new urban area is impervious. Therefore the volume of stormwater entering the sewer network is really dependent to the approach follow to design the new urban area. The E_{NS} coefficients confirm the finding from Figure 7.13, with values going from 0.999 and 0.165. E_{NS} coefficients obtained for pipe 1 are always exceeding 0.980 whereas for pipe 2 reach the low value of 0.165. Therefore the sensitivity of sewer peak flow due to urban development impervious area variation is different for each pipes of the sewer network.

7.4.2 Sensitivity of hydrological results to changes in roof area

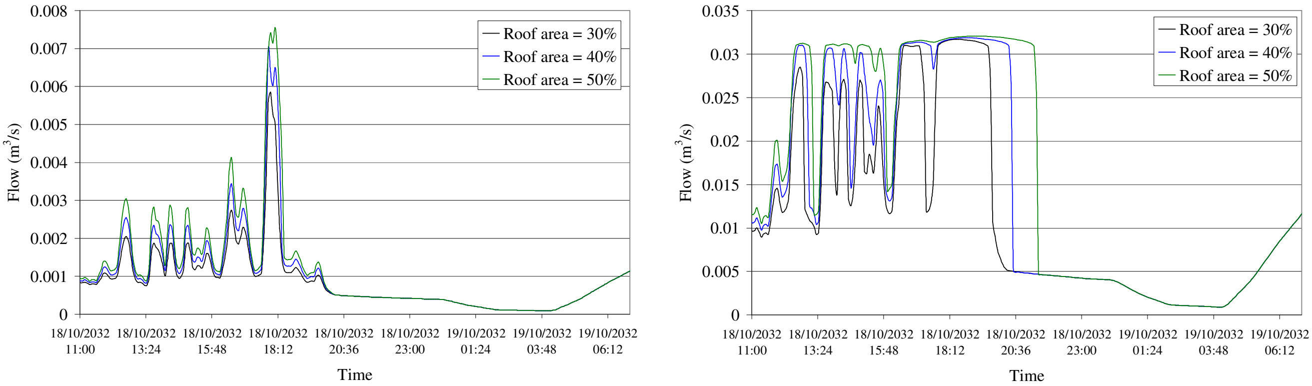
Figure 7.14 and Table 7.17 introduce the results obtained when roof surface area varies between 30 and 50% of the total imperious area on the sewer network.

1986

Pipe 1 **Pipe 2**



100 year return period (M100)



5 year return period (M5)

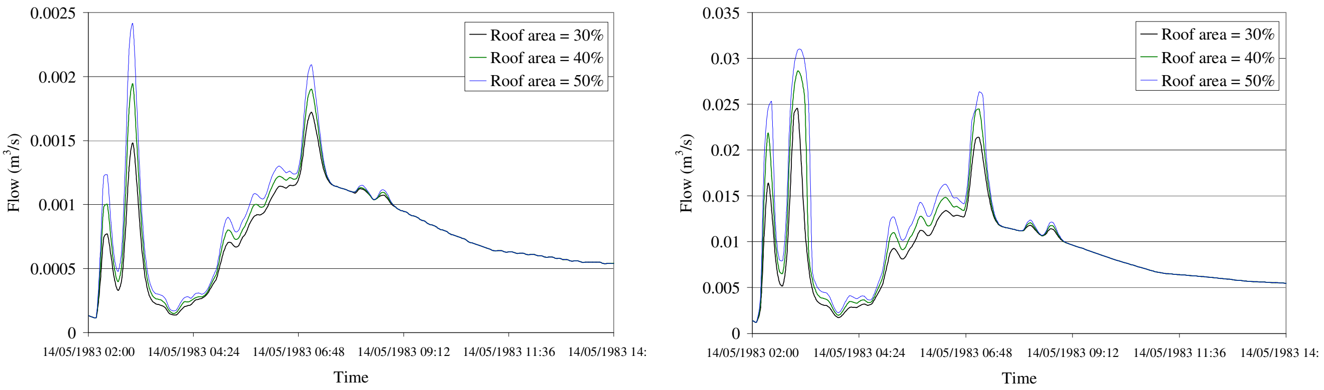


Figure 7.14. Comparison between pipe flows at the two river gauges when the roof area varies from 30% to 50%.

Table 7.17. Nash-Sutcliffe coefficient analysis results obtained when roof area

	Rainfall simulation					
	1986		100 year		5 year	
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2
Roof area = 30%	0.999	0.910	0.924	0.768	0.964	0.915
Roof area = 50%	0.999	0.901	0.927	0.738	0.963	0.916

The variation of roof area surface between 30 and 50% influence the sewer peak flows within the two pipes and for the three rainfall events. The variation observed is proportional of the roof area variation. However the E_{NS} coefficients are exceeding 0.910 for pipe 1 and 0.738 for pipe 2. Therefore, the variation of roof area is less significant than the impervious area observed in 7.4.2.

7.4.3 Sensitivity of hydrological results to changes in connected roof area

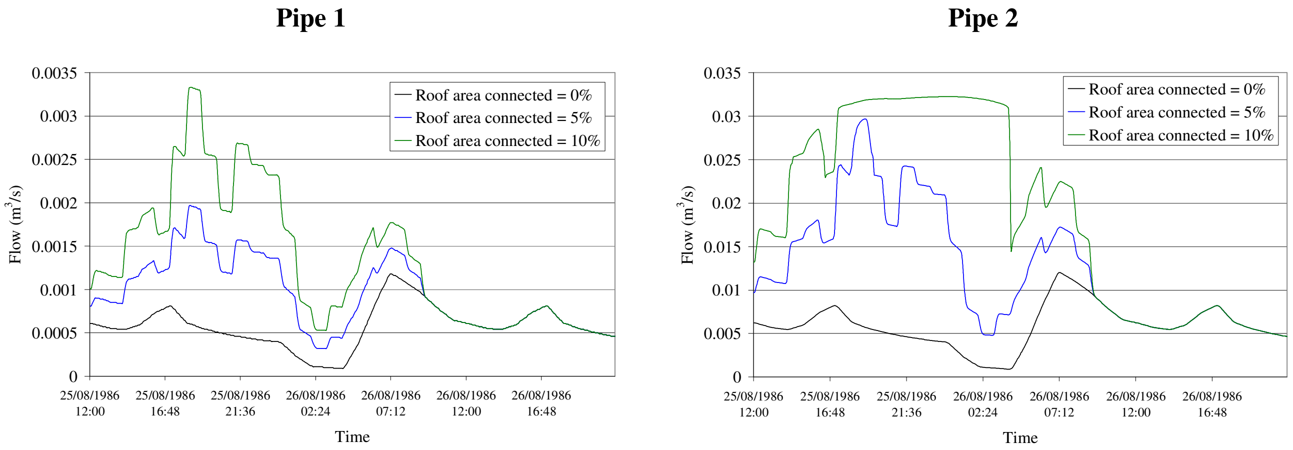
Figure 7.15 and Table 7.18. Nash-Sutcliffe coefficient analysis results obtained when roof area connected introduce the peak flow observed when contributed roof surface area varies between 0 and 10% of the total imperious area on two pipes present on the 2050 urban development.

Table 7.18. Nash-Sutcliffe coefficient analysis results obtained when roof area connected

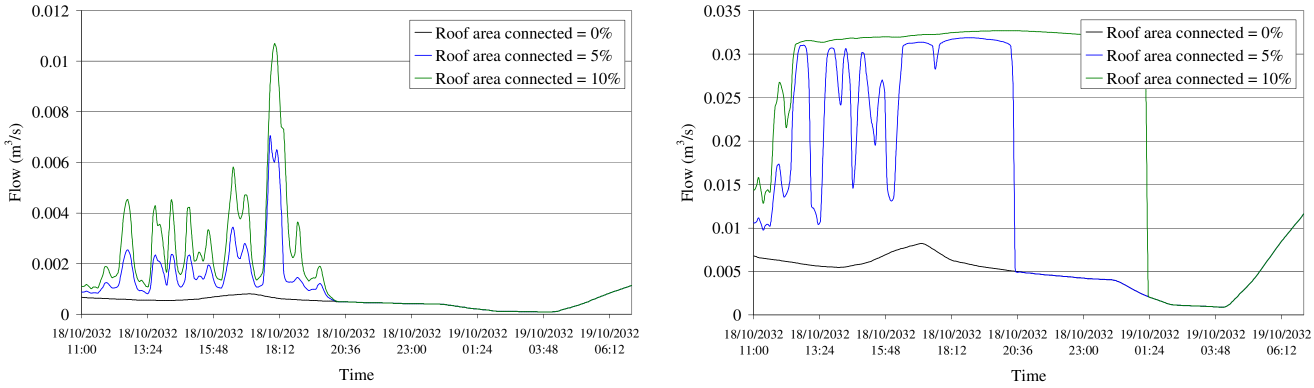
	Rainfall simulation					
	1986		100 year		5 year	
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2
Roof connected = 0%	-0.0987	-0.412	-0.052	0.129	0.439	0.410
Roof connected = 10%	-0.0978	-0.523	-0.355	-0.449	0.449	0.057

Results in two pipes different, flood occur within the second pipes under 25th August 1986 and 100 year return period events when 5 and 10% roof area surface contributing to the sewer network. The sewer network has been designed for 5% roof area contribution to the network. Therefore the E_{NS} coefficients are exceeding 0.910 for pipe 1 and 0.738 for pipe 2. Negative values of E_{NS} observed for both pipes under 25th August 1986 and 100 year return period events. The negative value of E_{NS} is due to the pipe flooding during the extreme events (25th August 1986 and 100 year return period events).

1986



100 year return period (M100)



5 year return period (M5)

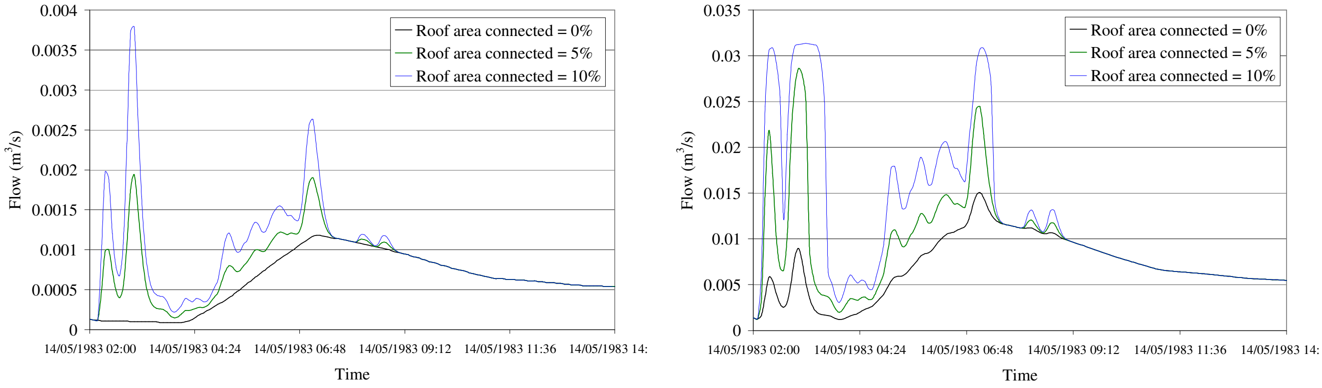


Figure 7.15. Comparison between pipe flows at the two river gauges when the roof area connected varies from 0% to 10%.

7.5 Summary

Many simulations have been carried out. A sensitivity analysis has been performed. Due to the lack of data available, the Nash coefficient (E_{NS}) has been calculated comparing modelled data obtained with the initial or default parameters with results obtained with changed parameters.

The analysis carried out on the runoff parameters on the hydrological network identified that the three parameters tested (Runoff Routing Value RRV, Initial Loss LS and Fixed Runoff Coefficient FRC) have influences on the river flow results. However, the influence has been observed to be minimal for LS under extreme events. However, under frequent rainfall event (5year return period), the flow obtained was reduced substantially when compared to the initial flow. This observation is true for the three parameters, under 5 year return period event, the Nash coefficient (E_{NS}) value dropped for each simulation. Therefore, this finding highlights weaknesses of the model under small rainfall events.

The sensitivity analysis then focused on the hydraulic network and identified the influence of the urban development designed scenarios. The results show a net variation of the flow volume within the sewer network for the three parameters under the three tested rainfall events. Unlike previously, extreme rainfall events are causing the biggest variation in flow and E_{NS}. The findings can be explained by the occurrence of sewer floods within the very extreme rainfall events (100 year return event). These floods occurred as the sewer network (pipe size) has been designed for the selected urban sewer network constructed. To conclude, the results obtained within the sewer network are very sensitive to sewer network design.

Finally, the sensitivity analysis identified model weaknesses under frequent rainfall events tested (5year return period or smaller events) and also the assumptions made to design the sewer network have an important influence on the sewer results obtained. To conclude, it has to be mentioned that the lack of monitored data available to compare with the simulation results obtained limit the conclusions that can be drawn from the sensitivity analysis achieved.

Chapter 8 Discussion and conclusions

Growing population and climate change exert stress on water supply and increase the risk of floods. Supplying sufficient water to consumers without damaging the environment is and will be a problem for many cities around the world. The benefits of implementing innovative recycling technologies in new urban areas to increase water efficiency and to reduce the frequency and intensity of floods from rivers and sewers overflows in order to support integrated water resource management (IWRM), has been highlighted in Chapters 4, 5 and 6. New urban developments, rainwater harvesting and recycling water technologies and climate changes scenarios have been represented within InfoWorks^{TM} CS and applied to the Carrickmines catchments in Ireland. The modelling activities have enabled us to quantify the variation of wastewater and sewer flood volumes as well as the river flow and flood volumes. Furthermore for each scenario, the volume of drinking water saved was quantified. The purpose of this Chapter is to identify and discuss the influence of implementing these technologies within the Carrickmines catchment. First of all, the influence of the technologies on the hydraulic network will be discussed for the greywater recycling, the rainwater harvesting and combined scenarios, followed by a brief general discussion about the sewer network designed. Then, the influence of the technologies on the hydrological networks is introduced. The discussion will then focus on the ability of the technologies to support drinking water supply. Finally, the Chapter concludes on the ability of the technologies to identify the hydraulic and hydrologic impacts of scaling up greywater recycling and rainwater harvesting at catchment scale. The chapter ends by providing some suggestions for further research activities.

8.1 Summary of thesis objectives

The aim of the study carried out in this thesis was to identify the hydraulic and hydrologic impacts of implementing greywater recycling and rainwater harvesting technologies at catchment scale. The main following steps have been achieved:

- collection of the data available about the Carrickmines catchment,
- adaptation and extension of the provided Carrickmines model by HR Wallingford (design of sewer network, urban development and urban drainage present in new developments),

- calibration and validation of the model designed using the data available,
- analysis of the scenarios using a comparison approach designed,
- sensitivity analysis of the model has been carried out.

The following research questions will be answered:

RQ1) How does the scale up and configuration of greywater recycling systems influence flooding within the sewer network?

RQ2) How does the scale up and configuration of rainwater harvesting systems influence flooding within the sewer network?

RQ3) How does the scale up and configuration of greywater recycling systems influence river flows and flooding?

RQ4) How does the scale up and configuration of rainwater harvesting systems influence river flows and flooding?

RQ5) To what extent does the scale up and configuration of greywater recycling and rainwater harvesting systems reduce and support the stress on drinking water supply to a growing population?

RQ6) How are the responses to RQ1-5 influenced by climate change?

RQ7) What combination of technologies and configurations provide robust performance over different climate scenarios?

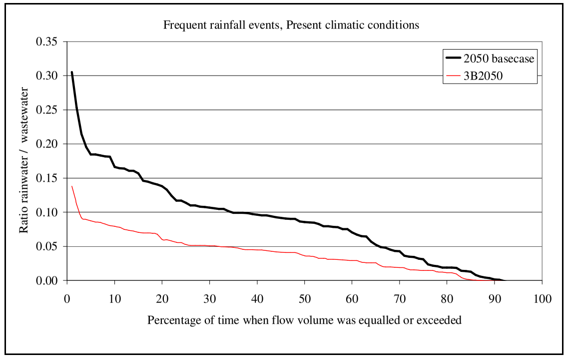
8.2 Summary of scenarios

For each simulations run, the following parameters have been assessed: i) total wastewater volume produced, ii) total wastewater flood, volume, depth and location, iii) total river flow, iv) river flow at the two river gauges, v) river flood volume, depth and location, and vi) volume of water re-used. The obtained results have been processed to produce: i) hydrographs, ii) radar charts, iii) flood maps. Table 8.1 resumes the outputs produced for each set of rainfall events tested and cross referenced the tables and figures produced per scenarios and set of rainfall events.

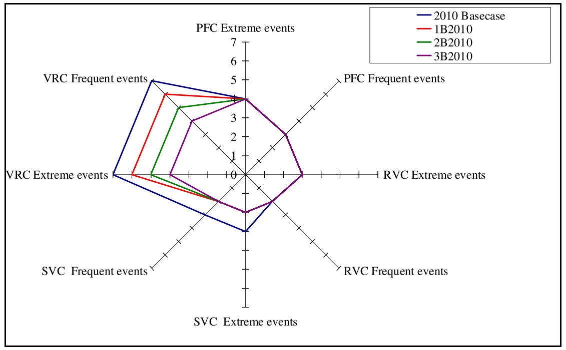
Table 8.1. Reviews of scenarios outputs obtained for the three types of rainfall events used and lists the respective of tables and figures across the thesis.

	Outputs	Simulations
Real rainfall event used (4 sets of top 100 events)	see below	see below

Outputs



Example of flow hydrograph of river and sewer



Example of radar charts combining and comparing hydraulic and hydrological results obtained

Simulations

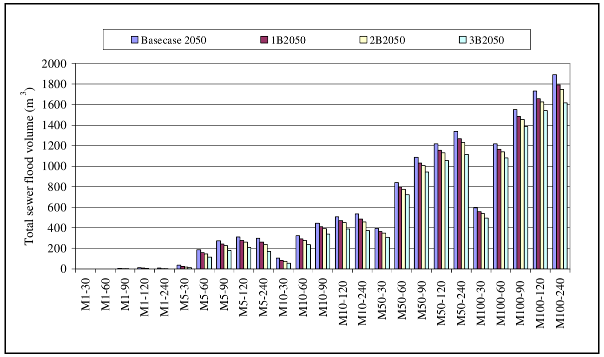
Sewer and river flow hydrographs

	Sewer Hydrograph	River hydrograph
1,2,3B2010 G	Figure 4.1	Figure 4.11
1,2,3B2050 G	Figure 4.2	Figure 4.12
1,2,3M2010 R	Figure 5.1	Figure 5.14
1,2,3M2050 R	Figure 5.2	Figure 5.15
Scenario 1, 2, 3 and 4	Figure 6.1	Figure A3.1, A23.2 and A3.3

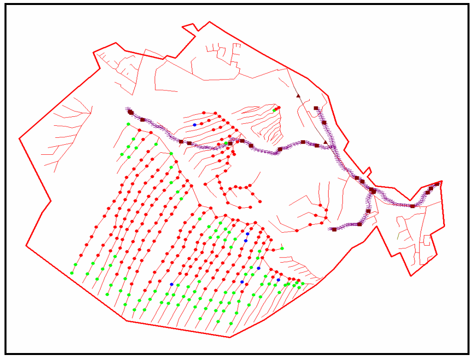
Comparison analysis radar chart

	Radar chart
1,2,3B2010 G	Figure 4.15, 4.16
1,2,3B2050 G	Figure 4.17, 4.18
1,2,3M2010 R	Figure 5.28, 5.29
1,2,3M2050 R	Figure 5.31, 5.32
Scenario 1, 2, 3 and 4	Figure 6.9, 6.10

Design storm event (M1, M5, M10, M50, M100)



Example of quantification of river, sewer and flooding volume



Example of river and sewer flooding location maps

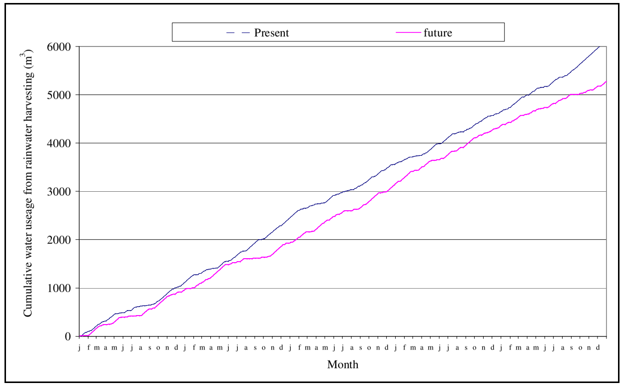
Sewer and river flow quantification

	Sewer flow	River flow
1,2,3B2010 G	Figure 4.5	Figure 4.13
1,2,3B2050 G	Figure 4.6	Figure 4.13
1,2,3M2010 R	Figure 5.5	Figure5.22
1,2,3M2050 R	Figure 5.6	Figure5.22
Scenario 1, 2, 3 and 4	Figure 6.3	

Sewer flood analysis results

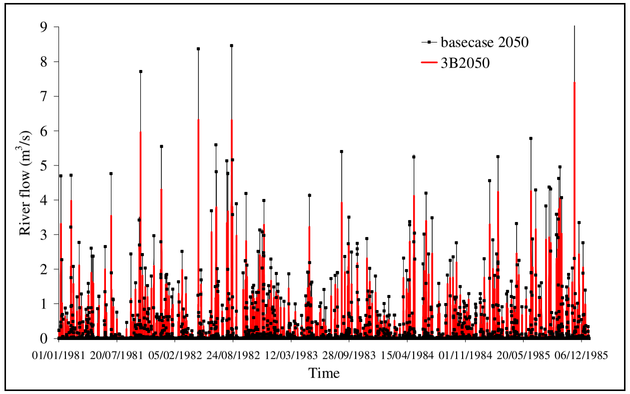
	RPA analysis	Flood maps
1,2,3B2010 G	Table 4.2, Table A1.1	Figures 4.7, 4.8
1,2,3B2050 G	Table 4.2, Table A1.2	Figures 4.7, 4.8
1,2,3M2010 R	Table 5.3	Figure 5.7
1,2,3M2050 R	Tables 5.3, 5.4	Figures 5.7, 5.9, 5.10; 5.11
Scenario 1, 2, 3 and 4	Table 6.3	Figures 6.4, 6.5, 6.6, 6.7, 6.8.

5 years continuous simulation s present and future conditions



Example of cumulative rainwater re-use volume for a 5 years duration period

	Drinking volume saved
1,2,3M2010 R	Figure 5.26 and Table 5.7
1,2,3M2050 R	Figures 5.27, 5.8, 5.9
Scenario 1, 2, 3 and 4	Table 6.4



Example of river flow graph for a 5 years duration periods

	River flow and baseflow analysis
1,2,3M2050 R	Figures 5.24, 5.25 and Table 5.6

8.3 The influence of the technologies on the hydraulic network

This Section will discuss the influence of the technologies on the hydraulic network. Results obtained will be compared to and discussed against the background of the existing literature, introduced in Chapters 1 and 2 of this thesis.

8.3.1 Greywater recycling systems

A constant decrease of total wastewater volume present in the sewer network for both greywater recycling under all simulated climatic conditions has been observed. Moreover, decreases in sewer flood frequencies were observed. Results show that the wastewater flow volume was reduced for all the scenarios simulated. A maximum of 24% and 15% reduction were observed for 2010 and 2050 developments when greywater recycling systems were implemented (Section 4.1.1). Similar results were obtained by Rueedi *et al.* (2005) who report a decrease of 14% in sewage volumes when greywater system was implemented to flush the toilet. Previous research even shows a possible reduction of up to 30% in sewer flow volume (Diaper *et al.*, 2001). These differences can be explained by the fact that in the study reported here, greywater technologies were only applied to a maximum of 80% of the new habitations. Moreover, houses already present in the 2002 development are still producing 150l wastewater per person per day. Therefore, a smaller reduction in wastewater volumes has been found by the modelling carried out within the Carrickmines catchment compared to the results found by Diaper *et al.* (2001) and Rueedi *et al.* (2005).

One of the aims of implementing greywater recycling was to assess their impacts at different scales and configuration. The representation of different size technology within the sewer network has not been achieved by the modelling activities. Within InfoWorks^{TM} CS, water supply is not represented within the hydraulic network, only wastewater production. As a result, the representation of greywater at different scales was not possible. Therefore the influence of greywater recycling systems on the hydraulic network has not been assessed. However, three greywater configuration scenarios were tested for the two urban development scenarios. The results identified a proportional reduction of wastewater produce when the number of greywater recycling technologies increases within the Carrickmines catchment. The results obtained highlight the importance of the implementation of many technologies in order to reduce issues caused by centralised wastewater management. Nevertheless, since the uptake of greywater recycling technologies is currently still limited, their influences on total wastewater production and flood sewer have not been observed and reported yet, which makes it difficult assess and discuss the relevance and validity of the results obtained.

Moreover, the greywater scenarios assumed that water consumption patterns were similar in all types of accommodation and that none of the greywater systems implemented encountered any technical problems. These assumptions were made to avoid extra complexity in the design of the network within the software. However, water consumption varies according to personal habits and technical problems commonly occur in greywater recycling systems (Fittschen and Niemczynowick, 1997). Therefore, results obtained are likely to have overestimated the total wastewater reduction.

Findings further suggest that the implementation of greywater recycling systems contributes to a reduction of sewer floods. The intensity of flood volume decreases by up to 27% for the 2010 development and 65% for the 2050 development (Section 4.1.4, Figures 4.5 and 4.6). The frequency of flooding, however, remains the same. Damage caused by sewer floods in the Carrickmines catchment will therefore be eased but will still occur even if most of the blocks are connected to greywater recycling technologies. An analysis of the flood locations indicated that they predominantly occurred at junction nodes. Therefore, technical optimisation of these specific pipes will be needed during the design of the sewer network. Moreover, the modelling activities carried out also identified the limitation of the software to model flooding under extreme rainfall events. This is a possible source of errors in the results. Therefore, it is very difficult to draw any confident conclusion regarding the extent to which greywater recycling systems reduce sewer floods. Moreover, no other empirical studies addressing the influence of greywater recycling systems on sewer floods could be found in the existing literature. Therefore results obtained could not be compared.

RQ1-How does the scale up and configuration of greywater recycling systems influence flooding within the sewer network?

The modelling activities carried out to assess whether greywater recycling systems influence flooding within the sewer network suggest they contribute to a reduction of sewer floods. Nevertheless, results show the capacity of greywater technologies of reducing sewer flooding problems is limited under heavy rainfall conditions. Whilst findings suggest that the volume of wastewater flooding can be reduced by up to 65% under extreme rainfall events, floods still occur with the same frequency. However, the modelling activities did not succeed in identifying the impact of greywater recycling systems when they are implemented at different size scales. Therefore, further investigations need to be undertaken to assess the efficiency of greywater to control flooding within sewer network. Different researches will have to be carried out in order to assess the impact of sizing greywater as so far no clear results are available.

In summary, the implementation of greywater recycling systems contributes to a useful reduction of wastewater flow volume which will in turn result in a reduction of sewer flood intensity; they will not, however, totally eliminate the occurrence of floods. As a result of flood intensity reduction, the implementation of greywater recycling system will generally reduce the economical and material damage caused by floods.

8.3.2 Rainwater harvesting systems

The results obtained show that rainwater harvesting systems on catchment hydraulics contribute considerably to a reduction of wastewater volumes. The study estimated that a wastewater reduction of 7% under frequent events of 12% under extreme events for the 2050 development (Section 5.1.2). These results suggest that the extent to which wastewater volumes are reduced depends on the severity of the rainfall events in this scenario. The results obtained for the 2010 development scenario are a reduction of 10% (for a five year return period event) and of 18% respectively (for a 100 year return period event). The finding highlights the fact that the reductions in wastewater volume are dependent on the rainfall event intensity and duration. In other words, the more it rains the more reduction is likely to occur. Comparable studies investigating the interrelationship between wastewater volume and reduction caused by rainwater harvesting systems could not be identified in the literature.

The size scaling of the rainwater harvesting system has not been possible within the sewer network, for the same reason explained in Section 8.3.1. Nevertheless, to achieve the aim of the study, rainwater harvesting systems have been implemented to three different extents for the two urban development stages used for the study: 2010 and 2050. The study showed a proportional reduction of wastewater flow volume depending on the number of technologies present and the rainfall event frequency and duration. Findings show that the more technologies present within the catchment, the greater reduction of rainfall intrusion into the sewer network.

To conclude, the maximum wastewater volume reduction observed has been quantified to be 26% for a 100 year return period event of 240min (Section 5.1 Table 5.1). The volume is substantial considering the fact that the sewer network modelled has the following characteristic: it is a non-combined network (ie. 5% of the total roof area connected to the sewer network). In other words, implementing rainwater harvesting model in areas where combined sewer systems are present will result in a higher reduction of wastewater volume.

Further analyses showed that when up to 80% of the habitations are connected to rainwater harvesting technologies, sewer volumes are reduced by 100% in both urban development scenarios. In other words, no sewer flood occurred under any of the tested rainfall events. These results imply that the reduction observed is enough to stop sewer floods during any rainfall event. This depends, however, on the number of rainwater harvesting technologies implemented throughout the catchment. The study also illustrates the location of floods depends on the position of rainwater harvesting technologies within the studied catchment. The junction nodes (where pipes are connected to each other) within the sewer network are sensitive nodes where floods occur frequently and floods volume exceeding 25m^3. The analysis also shows that the locations of floods are linked to the geographical position of the harvesting technologies. The agglomeration of harvesting technologies in a specific area will reduce the surcharge and stress caused by rainwater intrusion and therefore limit or control floods within this specific area. Moreover, the maximum flood intensity observed for the four scenarios tested identified an important difference between the scenario, the maximum value is 205m^3 and the lower 113m^3 (Section 5.1.4.1). Therefore, it can be concluded that the geographical position of rainwater harvesting systems is likely to influence the flood intensity of certain nodes. As a result flood severities occurring within the Carrickmines catchment are linked to both the location and the number of technologies present. Harvesting water is a very successful strategy to control sewer floods in non-combined sewer system.

RQ2-How does the scale up and configuration of rainwater harvesting systems influence flooding within the sewer network?

Results presented in the above section quantified and analysed the influence of implementing rainwater harvesting systems within the Carrickmines catchment. The study shows a complete control of sewer flooding in non-combined sewer system when 80% of the houses present are harvesting rainfall for any rainfall events. Moreover, a net reduction of flood intensity has been observed, 91% under frequent events and 40% under extreme events (Section 5.1.4). Therefore, harvesting rainwater is a very effective technology to control and reduce sewer flooding issues. However, to observe a complete reduction of sewer flooding, most of the habitations have to be connected to a harvesting system. To conclude, there is no doubt about the importance of implementing rainwater harvesting systems in order to control sewer floods.

8.3.3 Combined scenarios

Four scenarios have been designed for the purpose of the study combining greywater recycling and rainwater harvesting systems. For the purposes of the study, both wastewater flow volume and flood have been quantified to estimate the impact of scaling up and different configurations of the both technologies on the hydraulic network. The results show that the combination of greywater and rainwater harvesting systems contributes to a significant reduction of wastewater volume. The following results have been obtained, under scenario 2 (80% rainwater and 80% greywater), a maximum reduction of 26% can be achieved under extreme events for development

2050 under extreme rainfall event (See Section 6.1.3 in Figure 6.3). Concerning the three other scenarios, 5% reduction was obtained for Scenario 1 (20% rainwater and 20% greywater), 19% for Scenario 3 (20% rainwater and 80% greywater) and 11% reduction for Scenario 4 (80% rainwater and 20% greywater). The four scenarios have a different influence on the volume of wastewater produce within the Carrickmines catchment. The current literature only reports studies focusing on combining greywater and rainwater to assess the potable water saved when technologies are implemented and not the volume of wastewater reduction. Therefore it is difficult to assess the relevance and validity of the volume quantified by the modelling activities.

The reduction of wastewater involves a reduction of total flood volume. Sewer flood volumes are reduced by 100% for Scenarios 2 and 4 (both scenarios have 80% of rainwater harvesting systems implemented) for all the tested rainfall events. However, for Scenarios 1 and 3, sewer floods are still present in the case of frequent rainfall event (five year return) but the total sewer volume has been decreased by up to 91%. Floods exceeding 25m^3 are still occurring at the junction nodes. The flood mapping carried out with the four set of data, show that the implemented technologies fail to successful to control floods in Scenarios 1 and 3. Even though, Scenario 3 assumes 80% of the habitation to be connected to a greywater system and 20% to rainwater harvesting technologies. Considering the number of technologies implemented the results obtained can be considered as disappointing. To conclude, combining technologies is a good option to enhance wastewater management, however the most appropriate combination will need to be designed according to the hydraulic characteristic of each catchment. For the Carrickmines catchment, Scenario 4 (80% rainwater and 20% greywater) presents the most suitable technology combination and implementation scale to control sewer flood as it is able to avoid floods for all the tested rainfall events. It should also be noted that in terms of investment, the payback period will be comparatively shorter as it contains fewer technologies than Scenario 2 (80% rainwater and 80% greywater).

It should be noted, though, that socio-economic factors and public attitudes were not taken into account in the design of the scenario. For example, such technologies are fairly expensive (Jefferson *et al.*, 1999), and their payback period is extremely long

(Nolde, 2005, Ghisi and Mengotti de Oliveira, 2007). Therefore, implementing both technologies at such a scale might not be feasible due to the financial implications.

8.3.4 Summary of the sewer network modelling

The sensitivity analysis introduced in Chapter 7 describes the design of the sewer network and outlines the assumptions made about the pervious area of the new urban area. The results identified extreme variations within the flow in the pipe. Within the two pipes selected, the second pipe shows a complete change of the hydraulic flow for the three rainfall events and for the three parameters tested. Floods are occurring more often and negative values of E_{NS} are observed. As mentioned earlier, the coefficient value should be above zero to indicate minimally acceptable performance. However, the results can be explained by the fact that the sewer network has been designed for the selected parameters (70% impervious area, 40% roof area and 5% roof area contributing to the sewer network). In other words, with different parameters selected to design the sewer network, different sewerage data would have been produced by the modelling activities. More optimistic results would have been obtained with smaller roof contributions and bigger pipes diameters and visa-versa.

Finally, concerning the effect of scaling the technologies, the approach designed and selected to represent the re-use systems did not allow to represent the different scaled-up systems. As a result, the study cannot draw any conclusions about the impact of the technologies on the Carrickmines catchment hydraulic system.

8.4 The influence of the technologies on the hydrological network

The modelling activities also focused on quantifying the river flow, flood volumes, as well as the volume of drinking water saved. The results suggest that the total river flood volume is highly influenced by urban development and rainfall events. Indeed, under the 2002 urban development scenario, river flooding sets in with 50 year return period events, whereas for the 2010 and 2050 urban development scenarios, floods are observed from the one year return period events.

8.4.1 Greywater recycling systems

The implementation of greywater recycling systems within the sewer network has no influence on the catchment surface runoff and therefore will not influence the river flow and drainage system applied. However, the modelling activities did not identify any change in the river flow and flooding when greywater recycling systems are implemented. Nevertheless, the analysis shows a net increase of the peak flow due to the intense urbanisation that took place within the catchment, namely 40% increase under frequent events and 67% under extreme events. In other words, the urban development will alter considerably the catchment surface hydrology, and the river flow patterns will be very different from the Greenfield observation (2002 catchment) hydrology currently present.

However, the implementation of greywater recycling technologies at catchment scale influences the water cycle by reducing the volume of drinking water and wastewater produced by approximately 30% of the total domestic water use (Birks *et al*., 2004). As a result, the hydrological catchment will be affected indirectly due to reduction of abstraction and discharge water from Wastewater treatment work. Those two hydrological parameters will also influence phenomenon such groundwater recharge for example (See Section 2.1 Figure 2.1). In the aim of assessing the influence of greywater recycling schemes at catchment scale, abstraction and discharge locations have to be implemented with the InfoWorks CS model studied.

RQ3-How does the scale up and configuration of greywater recycling systems influence river flows and flooding?

Greywater systems applied at any scale and under any configuration will support urban surface management as the implemented technology focuses on recycling household wastewater only. The modelling activities carried out identified the limited capacity of greywater recycling systems to control runoff. It can then be conclude that greywater recycling at any scale and configuration will not enhance urban drainage at a catchment scale, therefore the technology should be considered as a suitable solution to control river flows and flooding.

8.4.2 Rainwater harvesting systems

In Chapter 5, rainfall harvesting systems scaling-up and configuration has been analysed to identify the influence on catchment runoff, river flow and flood within the river catchment.

As part this analysis, the modelling carried out within the Carrickmines catchment quantified a net reduction of total runoff volume; the maximum volume observed was 30% under frequent events when 80% of the new urban development assumed for year 2050 are connected to rainwater harvesting systems. Moreover, for scenarios 1B2010, 2B2010 and 3B2010, the total runoff is forecast to decrease by 2, 4 and 11% respectively. A previous study carried out by Kellagher and Maneiro (2005) illustrate the potential limitations of reducing runoff through rainwater harvesting. The study concludes that the runoff decrease they obtained for a 100mm event was 40% compared to only 20% for a 180mm rainfall event. However, the analysis carried out on runoff reduction within 2050 urban development with four sets of designed rainfall events (M5-30, M5-240, M100-30 and M100-240) did not confirm the findings from Kellagher and Maneiro (2005). Indeed, the analysis identifies very similar reduction of urban runoff for the four tested rainfall events. The runoff volume computed and used in order to assess the results, considered all the sub-catchments of the model, in other words the runoff volume of the total catchment. The Carrickmines catchment area is 32km^2 (3,200ha) whereas the catchment used by Kellagher and Maneiro was 0.4ha (0.2ha roof surface area and 0.2ha road area) and thus much smaller. Therefore, in a bigger size catchment the influence of the rainfall event on limiting the runoff volume will be minimized.

The study further focused on the influence of scaling up and implementing a large number of rainwater harvesting technologies within the 2010 development. The analysis concludes that the implementation of rainwater harvesting systems at different scales does neither enhance nor reduce the total volume of runoff within the Carrickmines catchment. Therefore, the study carried out within the Carrickmines catchment shows that scaling up rainwater harvesting systems is irrelevant for their ability to control the total runoff control. Previous study carried out by Herrmann and Schmida (1999) concluded that the control of urban drainage is better at multi storey building scale and in densely populated districts. Herrmann and Schmida's findings are based on the hypothesis that rainwater harvesting tanks in multi storey scale building will be larger than tanks used for household harvesting schemes, as a result a bigger amount of rainfall will be collected which will result in a greater control of urban runoff. However, in the modelling activities carried out in this study, the tanks were designed according to the number of people connected (e.g. 0.75m^3 per habitant connected). As a result, the designed tanks are proportional, which explains why results differ from those reported by Herrmann and Schmida. The analysis also identified the reduction of runoff volume according to the number of houses connected to harvesting systems, showing that the reduction is proportional to the number of technology.

The hydrograph analysis shows a reduction of the peak flow from 10m^3/s for the 2050 basecase scenario to 9m^3/s for the 1M2050 and 6m^3/s for scenarios 2M2050 and 3M2050. This decrease might be attributed to the runoff volume which is reduced by the rainwater harvesting technologies. According to the results, technology implementation at the municipal scale seems to be less effective to reduce river flow than an application at the neighbourhood and household scale. Further investigations have been carried out to understand the non-linearity of the river volume reductions by analysing the river peak flow at the two river gauges. The results show a peak flow increase at the Carrickmines bridge river gauge for many scenarios at the three tested scales. The increase of river peak flow under extreme event conditions might be a result of overflowing rainwater tanks. However, the hydrograph highlights the appearance of another peak caused by over-flooding of the municipal rainwater harvesting system. The peak observed is delayed when compared to the initial peak observed for the 2050 basecase scenario but more intense for 3M2040 where a peak flow of 14m^3/s is indicated. Therefore, multi-scale technologies (municipal) have a bigger impact on the peak flow than smaller scale systems (household and municipal scales). Therefore, concerning the peak flow of the river, the tank overflow and thus the scale of the technology might influence the river peak flow.

The cumulative effect of harvesting rainwater may have an impact on downstream water availability within a river basin scale (Ngigi, 2003). The expected shifts in water flows in the water balance would affect both nature and economic sectors depending on direct water withdrawals (Rockstrom *et al.*, 2001). In the Carrickmines catchment, the downstream impact is limited as the catchment is located by the sea. However, river low flow could explain the sizable runoff reduction observed in this study. The modelling activities carried out show a reduction of the river volume and peak flow. However, assessing the low flow due to the rainwater harvesting has been impossible due to the lack of river baseflow data available to carry out long term simulations.

Within 2010 urban development scenario, during frequent storm events (M5-30), a maximum reduction of 90% of the river flood volume was observed if the contributing area is decreased by 15% under neighbourhood and municipal scales. In contrast, if technologies are implemented at the household scale, the river flood volume only reduces by a maximum of 60%. The three sets of data show that larger the scale the bigger the reduction of river floods. Indeed municipal scale shows better results than neighbourhood and households scales. For the 2050 development, the analysis shows that rainwater harvesting systems reduce the river flood volume by up to 40%. However under extreme events, we observe a significantly higher reduction in flood volumes for scenario 3M2050 than in the other scenarios, suggesting that the implemented rainwater harvesting scheme is more likely to mitigate river floods.

Finally, the influence of combining rainwater harvesting and greywater was assessed. However, only the implementation of rainwater harvesting causes variation within the surface hydrology. Therefore, the scenarios 1 and 3 refer to 1M2050 and the scenarios 2 and 4 refer to 3M2050.

RQ4-How does the scale up and configuration of rainwater harvesting systems influence river flows and flooding?

Results obtained for the rainwater harvesting modelling identified the benefit of implementing the technology to support surface water management. A decrease of runoff volume across the entire catchment has been identified. The modelling activities show that the scale of the rainwater harvesting systems does not affect the percentage of runoff reduction. Concerning the ability of rainwater harvesting systems to influence river volume and peak flow, this seems to be influenced by the scale at which the technologies are implemented. Indeed, municipal scale technologies involve a river peak flow increase (when compared to the basecase peak flow obtained) under extreme conditions due to a considerable overflow of the harvesting tanks. However, findings indicate that under frequent events the implementation of rainwater harvesting at any scale and number is a useful technique to control river flow and floods.

8.5 The ability of the technologies to reduce drinking water demand

Saving is an important purpose of implementing recycling technologies. This next Section will discuss the extent to which a reduction of drinking water demand could be achieved by implementing the two technologies in the Carrickmines catchment. **Erreur ! Source du renvoi introuvable.**2 summarises the results obtained in this modelling study.

Table 8.2. Summary of the volume of drinking water saved under present and future conditions

	2050 present conditions		**2050 future conditions**	
	Volume of drinking water saved per year	Average reduction in water supply	Volume of drinking water saved per year	Average reduction in water supply
Greywater 3M2050	1,371Ml	19%	1,371Ml	19%
Rainwater 3M2050	979Ml	14%	815Ml	13%
Scenario 1	585Ml	9%	553Ml	8%
Scenario 2	2,350Ml	36%	2,222Ml	34%
Scenario 3	1,616Ml	25%	1,584Ml	24%
Scenario 4	1,319Ml	20%	1,191Ml	18%

Under present and future conditions drinking water usage was reduced by 19% when 80% of the new habitation of the 2050 development were connected to greywater recycling schemes. The volume of drinking water saved is independent of the frequency or intensity of rainfall events. Concerning rainwater harvesting, a maximum reduction of 14% and 13% of the respective total drinking water used for the 2050 development can be achieved when up to 80% of the houses are connected to a harvesting systems in each development under frequent and future events. Therefore the volume of drinking water saved is i) less than the reduction caused by greywater recycling for the similar configuration and ii) reduction observed is less under future rainfall events. Regarding the four combined scenarios tested, Scenario 1 (20% rainwater, 20% greywater) involves a maximum reduction of 9% in drinking water used, the smallest reduction observed of the four scenarios. In comparison, the biggest reduction is observed in Scenario 2, namely a reduction of 36% under present conditions and 34% for future conditions. The combination of 20% rainwater harvesting and 80% greywater recycling results in a reduction of drinking water demand by 25% and 24% respectively for the following respective rainfall events: present and future conditions. Results for Scenario 4 (80% rainwater, 20% greywater) and Scenario 3M2050 (80% greywater) are quite similar. Therefore it can be concluded that combining many rainwater harvesting technologies with some greywater recycling schemes does not effect a significantly higher reduction in drinking water demand than when many greywater technologies are implemented. Moreover, a difference between present and future events has also been observed for the four combined scenarios. A maximum 2% difference was observed for Scenarios 2, 3 and 4. The modelling activities highlight the efficiency of both recycling and reusing technologies to reduce the volume of water supply required. However, the study identified some technology combinations to be more suitable to control the volume of drinking water needed.

Many studies focus on the influence of recycling and reusing technologies on drinking water demands. Reports of the performance of greywater recycling prototypes at house and hotel scale suggest that water saving can vary between 14 to 36 % (Birks *et al.*, 2004 and Mars, 2004, Ghisi and Mengotti de Oliveira, 2007, Mitchell and Diaper, 2005).

Concerning the reduction caused by rainwater harvesting implementation, published research widely confirms that that rainwater harvesting is an efficient strategy to save drinking water. For example, Villareal and Dixon’s (2005) prediction for a large scale rainwater project to be built in Sweden is rather optimistic: the water demand was forecast to be reduced by almost 40% when low flush toilets were combined with rainwater harvesting system. Other studies have shown a reduction of 30 to 50% potable water usage in Australia (Jeppesen, 1996) and in the driest regions of the UK, where rainwater is collected from a roof area of 20m^2/ person, the daily water demand could reduce by 25l/c/d, which equals a reduction of 17% of the total drinking water

(Kellagher and Maneiro 2005). The results obtained by the modelling activities carried out within the Carrickmines catchment suggest the reduction of drinking water is likely to be comparatively smaller. The difference of results can be explained by different rainwater harvesting scenarios used within the modelling activities. For example, the toilets flush volume assumed for the designed scenarios used ‘normal’ flushing volume (50l per day per person so an average of 10l per flush) rather than low flush toilets. However, habitation equipped with low flush toilets are likely to be also equipped with high water saving technologies such as water saver showers (see Section 1.2) therefore their water consumption will be less than 150l per day and per person. As a result, different approaches toward domestic water use will involve a difference in rainwater influence.

Combining rainwater and greywater technologies to reduce drinking water have been modelled by a number of authors, such as Ghisi and Mengotti de Oliveira; 2007; Fewkes, 1982. As illustrated before, the volume of reduction varies between studies: Ghisi and Mengotti de Oliveira (2007) report reductions between 34 and 36% of potable water. However, Dixon *et al.’* (1999) study focuses on the collection of rainwater in addition to greywater in a single store reuse system, which, as their findings suggest, show to offer little improvement in water saving efficiency. A previous study carried out by Fewkes (1982) suggests modest improvements in water saving efficiency (greywater only bath and washing machine). The variations between the findings of the studies can be partly explained by the average household water consumption the authors most likely assumed. Fewkes published their study in 1982 and by 1999, the year when the second study was published; household water consumption had increased considerably. Secondly, greywater recycling systems available nowadays are able to recycle a bigger volume of household water than 25 or even ten years ago. Therefore, the volume of rainfall collected by the combined systems is minimal compared to the greywater recycled, which could explain the observation made by Dixon *et al.*. The result obtained under Scenario 3 confirms the result found by Dixon *et al.;* for this specific scenario, the combination of rainwater harvesting with greywater recycling technologies does not increase the total volume of drinking water saving.

The volume of water saved when rainwater harvesting systems are implemented is directly related to the size of the harvesting tank available to collect the water. However, the size of the rainwater harvesting tanks represented under neighbourhood and municipal conditions are rather big: 960m^3 for neighbourhood scale and 49,920 m^3 (for municipal scale). A tank volume equating to 0.75m^3 per person was selected from the literature (Kellagher and Maneiro, 2005). Therefore the size of the tank was scaled up according to the number of people connected to it.

RQ5-To what extent does the scale up and configuration of greywater recycling and rainwater harvesting systems reduce the stress on drinking water supply to a growing population?

Results obtained for both technologies show their effectiveness in supporting the conservation of drinking water. Findings further illustrate under which conditions the different technologies are most appropriate. Greywater recycling systems can achieve consistent water savings as the production of greywater is not linked to rainfall event patterns, whereas the amount of drinking water saved when rainwater harvesting is implemented is dependent on the rainfall patterns. Therefore, during wet periods harvested water will be available whereas over drought periods, re-used water can make an important contribution to enhancing water availability.

The volume of water available for consumption is directly linked to the size of the recycling or re-using system, therefore scaling-up and increasing the number of technologies will insure a bigger reduction in freshwater usage.

8.6 Climate change

In the future, due to the expected effects of climate change, water stress and flood problems may increase. A 50% reduction in rainfall events and an increase of between 1 to 6° C has been forecast by UKCIP by the summer of 2100 (Hulme *et al.*, 2002). Therefore to assess how climate change might influence the results previously reviewed in questions 1 to 5, climate change scenarios have been designed and run within InfoWorks^{TM} CS. The analysis assessed the impact of climate change on i) sewer flow volume, ii) river peak flow and iii) drinking water saved.

For greywater recycling, the sewer flow volume analysis carried out for present and future rainfall conditions identified a maximum difference of 20% and an average increase of the total sewer volume of 4.5%. Similar results were observed for rainwater harvesting systems: under Scenario 3M2050 the total sewer volume increases from 20,000m^3 to up to 22,000 m^3 equalling a 10% increase due to a change in rainfall intensity. In the literature, Seladeni-Davies *et al.* (2008) estimate that the impact of climate change and urbanisation on a combined sewer system could results in a 318% increase in total overflow volume and 450% in sewer volume. The sewer modelled in this study is non-combined which explains the comparatively lower increase of sewer volume for the Carrickmines catchment.

For greywater recycling, peak flow increases considerably under the predicted climate change scenarios For example, under present conditions the peak flow exceeds 6.9m^3/s for 40% of the time but 67% of the time under future conditions, i.e. larger urban development and more rainfall events, in 2050. Therefore, under climate change more severe river floods can be expected.

Concerning rainwater harvesting, the peak flow is reduced under both present and future rainfall conditions when technologies are implemented at small scale. However, results indicate that when rainwater harvesting technologies are implemented at municipal scale the peak flow intensity for the 1M2050 Scenario, the 2M2050 Scenario and the 3M2050 Scenario exceeds the basecase peak flow for urban development 2050, under future conditions. In other words, the implementation of rainwater harvesting systems at municipal scale combined with the predicted climate change impacts influences and causes river flooding. Therefore, the efficiency of large scale technologies to reduce river flood can be questioned. However, the modelling data obtained shows that the larger the implementation scale the bigger the river flood reductions which can be achieved; indeed municipal scale shows better results than neighbourhood and households scales. For the 2050 development, a 40% reduction of the river flood volume can be obtained under extreme rainfall events (Section 5.2.2).

The variation of drinking water savings achievable by implementing the assessed technologies has been introduced in Section 8.5. It was shown that the performance of greywater recycling systems is not linked to rainfall patterns. Therefore, the volume of drinking water is constant and will not be influenced by climate change. When rainwater harvesting was implemented, the modelling activities carried out to assess the drinking water saved compared the total volume of water saved over a 10 years tested (five years present and five year future) and estimated the percentage of the time when rainwater harvesting was available for toilet flushing. The study illustrated that under present conditions, the total volume of drinking saved was higher than under future conditions. For example, 974Ml of drinking water were saved under present conditions compared to only 851Ml under future conditions (in both cases 80% of the habitation are connected to harvesting technology within 2050 urban development), the difference equals 1% of the total drinking water saved. Therefore, the reduction is directly linked to the quantity and frequency of rainfall in the catchment. However, the study also showed that the amount of water collected and re-used per year does not vary too much across the 10 year period. Concerning the percentage of time the toilet flushing was using rainwater, results vary considerably over the 10 years studied. The analysis indicates that the percentage pumping time is varying considerably along the seasons. In general, during summer time the worst results are obtained except from the year 1981. And the autumn/winter period is the time of the year where rainwater is the most available. These findings illustrate that rainwater availability significantly varies from one season to another. In the best case, rainwater is available 95% of the time during winter time under present condition and in the worst case only 35% of the time this time during summer time under present conditions. Other results show that during the summertime of year 1 under present conditions (in 1981) and year 2 under future conditions (2076) rainwater was available for re-use less than 40% of the time. In contrast the same period in year 2 under present condition was rather wet and therefore rainwater was available for re-use 78% of the time. Therefore, whilst rainwater harvesting is a good technique to control drinking water demand, its efficiency is highly dependent on rainfall frequency and intensity. Therefore, the impact of climate change will largely depend on the rainfall patterns.

Finally, the comparison of the two sets of rainfall events simulated highlight the fact that the designed rainfall events are more intense than the four sets of top 100 events. The results highlight the influence of rainfall on the volume present in the sewer network. When results obtained for the top 100 events under frequent and extreme conditions (both under present conditions) were compared, a maximum increase of 34% of total wastewater volume was observed between frequent and extreme events; however the observed average increase was only 6.6%. Similar analysis was carried out between present and future rainfall condition and a maximum difference of 20% was calculated; the average difference observed was 4.5%.

RQ6-How are the responses to RQ1-5 influence of climate change?

The modelling outputs illustrate the potential influence of climate change on the results obtained for question 1 to 5. The change in rainfall patterns is most likely to influence the volume of sewer reduction, the river flow and drinking water saved in most cases. Only the volume of drinking water saved when greywater recycling systems are implemented is not influenced by climate change.

The biggest impacts observed of climate change are i) the reduction of drinking water saved in general and ii) the increase of peak flow volume when rainwater harvesting technologies have been implemented at neighbourhood and municipal scales.

RQ7-What combination of technologies and configurations provide robust performance over different climate scenarios?

The results identified that the combination of rainwater harvesting with greywater recycling technologies does not increase the total drinking water saving. Moreover, the climate change scenarios tested forecast a reduction in drinking water saving (approximately 2% of the total drinking water volume). Therefore, the modelling activity carried out highlighted a poor performance of the combination of technologies under future climatic conditions.

Concerning, river peak flow control, no benefits have been identify within the combination of the two technologies as greywater recycling technique does not affect urban drainage. Moreover, similar observation can be assessed for sewer flooding control. The tested configurations did not identify benefits of combining the technologies to control sewer flooding under any rainfall events.

We can then conclude that combining rainwater harvesting and greywater recycling under different configurations in order to enhance urban water management has not show much benefit under climate change conditions.

8.7 Greywater recycling and rainwater harvesting as elements of integrated water management strategies

This section will review the prospect of implementing new technologies found in the study in order support integrated water management both within the Carrickmines catchment and in general. **Erreur ! Source du renvoi introuvable.**1 summarises the modelling findings and suggests technology approaches to support issues faced in urban areas.

In order to discuss and asses the best scenario to support integrated water management within the Carrickmines catchment, the results obtained for the 2050 basecase scenario, as well as the four scenarios (which combine greywater and rainwater) with the 3M2050 for greywater and rainwater technologies (scenarios which represent 80% of houses connected within 2050 development) have been compared. Figure 8.1 and Figure 8.2 present the findings. The results identified the benefits of implementing technologies to reduce peak flow, runoff volume, sewer volume as well as the increase of re-used volume. Under both present and future conditions, the biggest index variation observed between the tested scenarios is the volume of water re-used.

Figure 8.1. Combination of the comparison hydraulic and hydrological performance obtained for the combine scenarios, greywater recycling and rainwater harvesting technologies under present conditions.

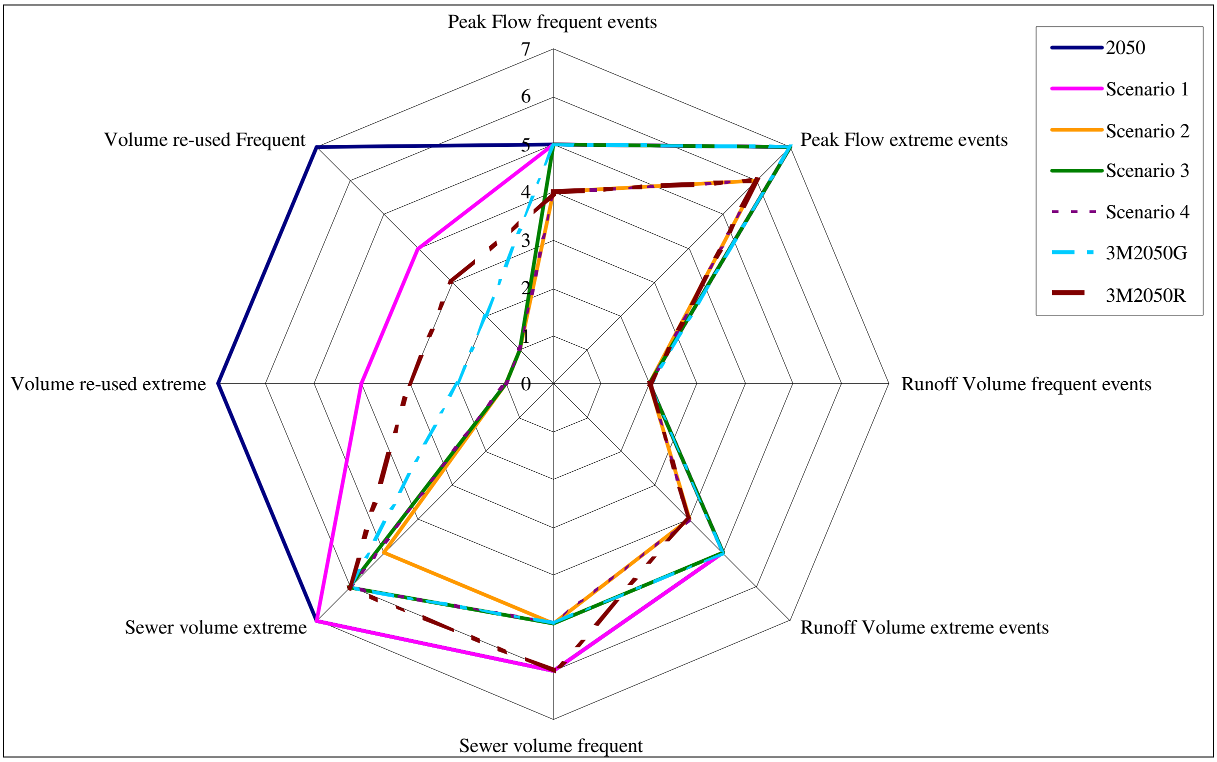


Figure 8.2. Combination of the comparison hydraulic and hydrological performance obtained for the combine scenarios, greywater recycling and rainwater harvesting technologies under future conditions.

Moreover, Figure 8.1 and Figure 8.2 also show reduction of the index for sewer volume and peak flow for some scenarios. The results highlight that the sewer flow volume is controlled by the implementation of technologies. The comparison analysis also highlighted that under frequent events, greywater recycling technologies contribute to a bigger reduction in sewer volume than rainwater harvesting system for the respective scenarios. However, under extreme events, the reduction of greywater recycling is decreasing due to rainfall intrusion and the index of sewer volume obtained is equal to the rainwater harvesting index. To conclude, the installation of re-using and recycling technologies within the Carrickmines catchment will support the demands of a growing population and the increase in volume of drinking water. Concerning the use of the technologies to save drinking water, greywater recycling technology implementation has shown to decrease drinking water by up to 20%. Moreover, the amount of water re-used is independent of the rainfall events. Thus, drinking water saving is potentially constant all year long. However rainwater harvesting results show that the volume of water saved is directly linked to the rainfall pattern and below that achieved through greywater recycling systems. Moreover, the results indicate that the amount of water saved per year does not vary significantly from one year to another for the five years tested within the model. However, under future rainfall conditions, the volume of rainwater available for re-use was significantly smaller than the volume available under current conditions. Therefore tank size may have to be upgraded in order to increase the volume of water for re-use. Finally, as expected, combining both technologies will increase the amount of drinking water saved. Scenario 2 and 4 will involve the highest reductions. However, Ireland and the Carrickmines catchment are not facing any water scarcity issue; the average rainfall event is 726.9mm. Therefore, drinking water control may not be the main purpose for re-using and recycling water. As a result, Scenario 4 (which combined 80% of greywater recycling schemes with 20% rainwater harvesting) might not be the most appropriate for the Carrickmines catchment.

Floods within the sewer network have been assessed as a recurrent issue within the Carrickmines catchment. The implementation of greywater recycling technologies at catchment scale shows that flood volumes (flood intensity) can be significantly reduced. However, the frequency of floods and nodes surcharges has shown to decrease only slightly. Therefore, although floods will still be experienced, the implementation of greywater technologies might help to reduce the severity of floods and the damages they cause. Concerning the implementation of rainwater harvesting in the Carrickmines catchment, the implementation of a large number of technologies shows a 100% sewer volume reduction. As a result, rainwater harvesting technologies are comparatively more effective to control sewer floods. Floods, however, still occur even when rainwater harvesting systems and greywater recycling technologies are combined and implemented at large scale. For example, in Scenario 3 (with 80% of households connected to greywater and 20% to rainwater systems), sewer floods are only marginally reduced and floods still occur all over the catchment. Against this background, we can conclude that rainwater harvesting systems are comparatively more effective than greywater recycling techniques to reduce flood frequency and intensity. Therefore, in a catchment where sewer flooding is a major problem, the installation of rainwater harvesting system is more recommended than greywater recycles schemes in order to support and control flooding problems. Moreover, the benefit of combining the two technologies to support sewer surcharge can be questioned as rainwater harvesting implementation is sufficient to solve the sewer issues.

River flood issues have been a problem within the Carrickmines catchment. Therefore, the main purpose of implementing new technologies will be to support surface drainage. The results have shown that the implementation of greywater water recycling is an in-efficient technique to control urban runoff. As a result, greywater recycling technology is not an adequate method to enhance urban water management. Contrary to greywater recycling system, the implementation of rainwater harvesting systems proved efficient to control runoff volume to a certain extent. The reduction of runoff volume has shown to influence river peak flow and floods significantly. However, when the rainfall intensity increases the efficiency of rainwater harvesting to reduce runoff volume is decreasing. Moreover, the modelling activities highlighted that the peak flow reduction depended on the scale of the rainwater technology. Indeed, neighbourhood and municipal scale technologies show an increase of river peak flow under extreme rainfall events. This increase of the river peak flow is due to a considerable overflow from the harvesting tanks. As a result, rainwater harvesting systems may cause river flood due to an overflow of rainwater. With regards to the

Carrickmines catchment, the implementation of rainwater harvesting systems support and enhance urban drainage. The efficiency of controlling urban runoff and river flood is depending on the rainfall events. Therefore, in order to control river flood due to heavy runoff, the urban drainage should be enhanced to avoid flood. Other technologies and measures such as pervious car parks or Sustainable Urban Drainage Systems (SUDS, see Section 1.2) could be implemented to support surface water management. Finally, given that greywater recycling systems have shown only a marginal influence on the catchment hydrology, there is no benefit of combining the two technologies in order to control urban drainage.

To conclude, within the Carrickmines catchment, there is no doubt that rainwater harvesting systems are the most suitable technology to support: i) urban drainage by controlling the urban runoff and ii) stopping sewer surcharge and flooding occurrence. A possible scheme could be the installation of rainwater harvesting systems at household scale spread over the catchment and along the junctions' nodes where heavy floods have been observed (as shown in Figure 8.3). With a total of 50% of household connected to the rainwater harvesting systems, at this extension stage only few flood spots have been observed. Therefore, public places such as school, shopping centre and offices will be connected to rainwater harvesting systems set up at bigger scale. In order to avoid the problem related to the tank overflowing, harvesting tank must drain to a retention ponds part of a SUDS system which could form part of park (see Figure 8.3). Moreover, in order to control urban runoff and diffuse hydrocarbons pollutants, impervious car parks could be implemented across the catchment.

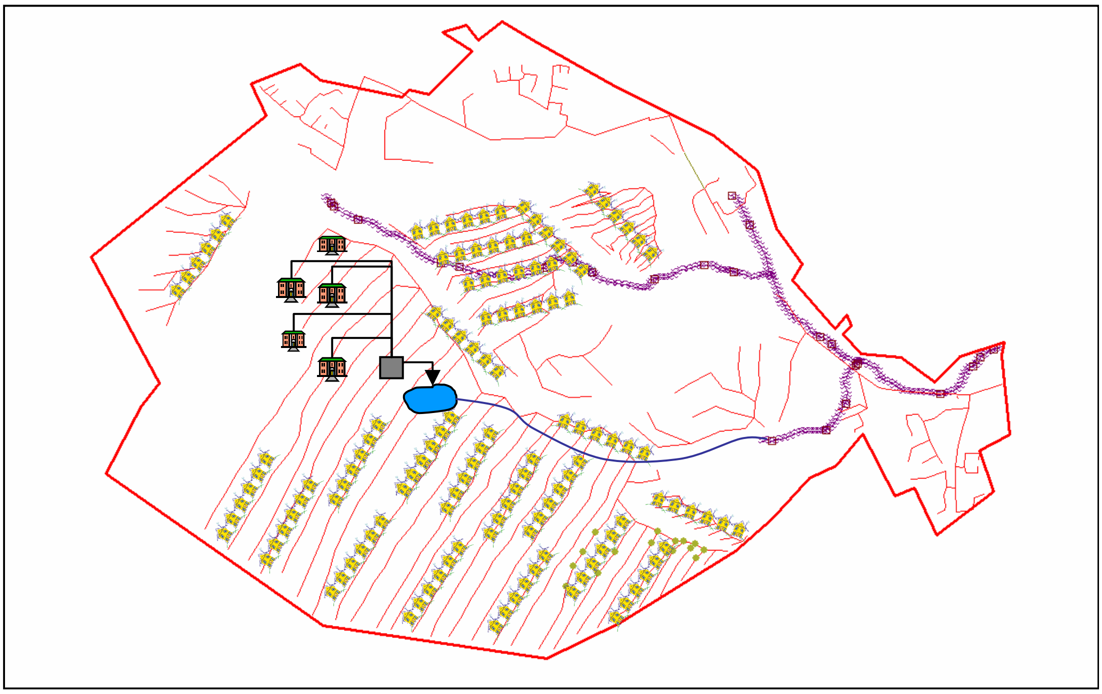


Figure 8.3. Example of rainwater harvesting scenario to enhance sewer floods and urban drainage within the Carrickmines catchment.

8.7.1 Policy to support IWRM

The study identified the interest and benefits of considering the use of recycling and re-using technologies within new urban development to support the hydraulic and hydrological systems at catchment scale in order to reach a more sustainable water management. With the output of the comparison analysis (See Section 3.6.2 and radar charts Figures 8.1 and 8.2) a Multi-criteria Decision Analysis (MCDA) can be produced in order to support IWRM. Within urban area, the main policy objectives to support the IWRM are: i) cost effectiveness, ii) environmental protection, iii) flood prevention and iv) enhance centralised water network. The following section will identify the importance between the modelling activities carried out and the policy through stakeholder participation. Finally a ranking of the scenarios will be established in response to the policy objectives listed above.

The results obtained by the modelling activities highlight the importance of implementing policies in order to support and enhance the water management. For example, the findings concerning the consistent sewer flooding at some locations of the Carrickmines catchment (Section 5.1.4) show the importance role of policies and stakeholder participation. Indeed, policies to prevent flooding are and must be implemented to response to climate change for example and therefore decision to support the flooding issues must be taken. In this particular case, the role of stakeholders is also essential to prevent flooding; implementing rainwater harvesting technologies at the right locations will support flooding issues. Therefore science (in this case the modelling activities) must be used to support implemented policies in order to enhance IWRM. As a result, the modelling outputs from Figure 8.1 and Figure 8.2 have been classified in response to the four policies listed. Table 8.3 reviews the six scenarios present in the final comparison analysis and ranked them from 1 to 6, where 1 represent the 'best' option or scenario to support to the respective policies.

Table 8.3. Ranking scenarios according to policy objectives.

Ranking scenario	Cost	Environmental Protection	Flood prevention	Water treatment
1	3M2050 R	Scenario 2	Scenario 2	Scenario 2
2	3B2050 G	3M2050 R	3M2050 R	Scenario 3
3	Scenario 1	Scenario 1	Scenario 3	Scenario 1
4	Scenario 3	Scenario 4	Scenario 1	Scenario 4
5	Scenario 2	Scenario 3	Scenario 4	3B2050 G
6	Scenario 4	3B2050 G	3B2050 G	3M2050 R

To conclude, ranking the scenarios in response to different policy objectives able to integrate all the tested parameters (future development scenarios in relation to urban development, climate change and technologies) to support IWRM. Moreover, the looking at the obtained ranking, Scenario 2 is the 'best' scenarios out of the six, expect the fact that a very high payback period. The ranking also identified the poor performance of Scenario 4 compared to its high cost. However, Scenario 3M2050 R (when 80% of the houses are connected to a rainwater harvesting systems within development 2050) performance to support environmental protection and flood prevention is interesting when compared to the cost of the installation.

The last section identifies the importance of carrying out modelling activities, analysing the findings, integrating with occurring issues in order to enhance water management. However, further ranking and multi criteria analysis can be designed in order to integrate and provide essential interpretation of modelling results to policy developers in participatory process and integrated water resource management.

Table 8.4 summarises more general findings which can also be used to support IWRM.

Table 8.4. Summary of the technology options performance for urban water management

		Technology support to enhance urban water management			
	Issues	Greywater	Rainwater	Combined	Others
Hydraulic	Water supply	✓✓✓	✓	✓	
	Sewer surcharge	✓	✓✓	✓✓✓	SUDS
	Sewer flooding	✓	✓✓✓	✓✓	SUDS
	Wastewater treatment	✓✓	✓	✓✓✓	
Hydrological	Runoff volume control	✗✗✗	✓✓	✓	SUDS
	Peak flow increase	✗✗✗	✓✓✓	✓	SUDS
	River flooding	✗✗✗	✓✓✓	✓	SUDS
	Drought/ Low river flow	✓✓✓	✓✓	✓	
	Freshwater abstraction	✓✓✓	✓✓	✓	

✓✓✓ Very good technology, ✓✓ good technology, ✓ useful technology,
✗✗✗ Not efficient technology

Difficulties to represent the scaling-up effects on the sewer network for both technologies were faced during the modelling activities. Therefore it is now difficult to analyse and conclude the impact caused by municipal scale greywater recycling at urban catchment scale. However, there is no doubt that the energy required at municipal scale to pump the greywater or harvested rainwater out and back will be significantly higher than the energy used at smaller scale (household scale). Therefore, for household purposes implementation at a smaller scale should be considered. Moreover, smaller scale technology for household purposes might also engender public awareness. Indeed, habitants would have to maintain their system and therefore would be more concerned and aware of their daily water use. This may result in a reduction of water consumption. Consequently, scaling-up technology within public places such as schools or offices which have the necessary space to hold bigger recycling or harvesting tanks (more space available and bigger roof area) and therefore enhance the re-use volume for example.

The main outcome of this study is the realisation that the implementation of one of the two greywater recycling and rainwater recycling at a large number across a catchment is not enough to support all the hydrological and hydraulic issues faced nowadays.

Therefore in the close future with the increasing stress caused by climate change, the benefits of the technologies may be even more reduced. However, the combination of greywater and rainwater harvesting investigated in this study clearly showed the limitations of the technologies in terms of increasing drinking water saving as well as controlling sewer floods and urban drainage. As a result, sustainable urban drainage systems require a mix of technologies and measures such as permeable car parks, retention ponds and swales.

To conclude, the decentralisation of the existing water system by combining technologies could enhance the urban surface hydrology, the sewer flooding issues, save consistent volume of drinking water and limit the effect of climate change when the appropriate combination is implemented.

This research focused on quantifying hydraulic and hydrological data only therefore further research needs to be carried out to support the implementation of the most appropriate technology. The following section proposes topics for further research.

8.8 Further research

In order to improve the results of the modelling activities, appropriate data of the respective catchment are necessary. The WFD monitoring programs will provide an extra source of data available to design, calibrate and validate future model. Moreover, a more sophisticated way to represent the technologies will also improve the quality of the modelling results. For example, different tank sizes could be tested; the representation of pumping rate could be improved in a way that makes the water reuse profile more realistic (hourly pumping, instead of twice a day). Also, the robustness of the technologies could be tested.

In order to investigate the influence of implementing technologies at different scales and in different quantities, water quality issues require further attention. For example, the concentration of heavy metals or hydrocarbons present in runoff water raises the question whether implementing technologies could result in environmental hazards. Water quality modelling activities should be carried out in order to i) the effects of the dilution of wastewater due to the implementation of the technologies to determine the possible difficulties that may be faced at the water treatment work and ii) investigate the concentration of pollutant in sewer system due to the reduction of wastewater volume when greywater recycling technologies are implemented.

REFERENCES

Albek, M., Ögütveren. Ü.B., Albek. E. 2004. Hydrological modelling of Seydi Suyu watershed (Turkey) with HSPF. *Journal of Hydrology*, vol 285, pp 260-271.

Albrechtsen, H. 2002. Microbiological investigations of rainwater and graywater collected for toilet flushing. *Water Science and Technology*, vol 46, no 6-7, pp311-316.

Andersen, H. E., Kronvang, B., Larsen, S.E., Hoffmann, C.C., Jensen, T.S. and Rasmussen, E.K. 2006. "Climate-change impacts on hydrology and nutrients in a Danish lowland river basin", *Science of the Total Environment,* vol. 365, no. 1-3, pp. 223-237.

Aradas, R.D., Ivanissevich Machado, L., Maurino, M. and Norton, M.R. 2004. Urban Drainage: System Modelling for Integrated Catchment Management. Available at: http://www.ciwem.org/groups/wapug/.

Arnold, G.E., Lange, W.J., Blind. M.W. 2005. The concerted action Harmoni-CA: Facilitating the dialogue and bridging the gap between research and the WDF implementation. *Environmental Science and Policy*, vol 8, pp 213-218.

Artina, S., Bolognesi, A., Liserra, T. and Maglionico, M. 2007. Simulation of a storm sewer network in industrial area: Comparison between models calibrated through experimental data. *Environmental Modelling & Software,* vol. 22, no. 8, pp. 1221-1228.

Beary. B. 2007. Why Ireland's Economic Boom Is No Miracle. *The Globalist*. Available at: http://www.theglobalist.com/StoryId.aspx?StoryId=6172. (Assessed: 07/08).

Beekman, G.B. 1998. Water conservation, recycling and reuse. *Water resources development*, vol 4, no3, pp 353-364.

Beven, K. 2001. How far can we go in distributed hydrological modelling ? *Hydrology and Earth System Sciences*, vol 5, no 1, pp 1-12.

Beven, K. 2000. Rainfall-runoff modelling: the primer. Wiley: London.

Birks, R., Colbourne, J., Hills, S. and Hobson, R. 2004. Microbiological water quality in a large in-building, water recycling facility. *Water Science & Technology,* vol 50, no 2, pp 165–172.

Booij, M.J. 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. *Journal of Hydrology,* vol. 303, no. 1-4, pp. 176-198.

Boughton, W.C. 2006. Effect of data length on rainfall-runoff modelling. *Environmental Modelling and Software,* vol. 22, no. 3, pp. 406-413.

Brewer, B., Brown, R., and Stanfield, G. 2000. Rainwater and grey water in buildings: project report en case studies.

Brown, R.R., Sharp. L., and Ashley. R.M. 2006. Implementation impediments to institutionalising the practice of sustainable urban water management. *Water Science and Technology*. vol 54, no 6, pp 415-422.

Burkhard, R., Deletic, A., Craig. A. 2000. Techniques for water and wastewater management: a review of techniques and their integration in planning. *Urban Water*, vol 2, pp 197-221.

Butler, D., McEntee, B., Onof, C. and Hagger, A. 2007. Sewer storage tank performance under climate change. *Water Science & Technology*, vol. 56, no. 12, pp. 29-35.

Cariboni, J., Gatelli, D., Liska, R. and Saltelli, A. 2007. The role of sensitivity analysis in ecological modelling. *Ecological Modelling,* vol. 203, no. 1-2, pp. 167-182.

CIRIA. 2001. Rainwater and greywater use in buildings, Best practice guidance. CIRIA: London.

Communities and Local Government. 2008. The Code for Sustainable Homes, Setting the standard in sustainability for new homes. Crown Publication. Available at: http://www.communities.gov.uk/documents/planningandbuilding/pdf/codesustainhomesstandard.pdf.

Coombes, P.J. and Kuczera, G. 2002. Integrated water cycle management: Moving towards systems understand. In: *2nd International Water Sensitive Urban Design Conference.*

DDC. 2006a. Carrickmines Phase 2 (Storm). Model preparation, verification and System Assessment Report.

DDC .2006b. Final Carrickmines Phase 3 Report: Needs, Options and Strategy report.

Defra. 2008. Future Water: the government's water strategy for England. Crown publication. Available at: http://www.defra.gov.uk/environment/water/strategy/pdf/future-water.pdf.

Diaper C., Jefferson B. and Parsons S.A., Judd S.J. 2001. Water-recycling technologies in the UK. *Journal Of The Chartered Institution Of Water And Environmental Management*, vol 15, no 4, pp 282-286.

Dibike, Y.B. and Coulibaly, P. 2007. Validation of hydrological models for climate scenario simulation: The case of Saguenay watershed in Quebec. *Hydrological Processes,* vol. 21, no. 23, pp. 3123-3135.

Dixon,A., Butler, D., Fewkes, A. and Robinson, M. 1999. Measurement and modelling of quality changes in stored untreated grey water. *Urban Water*, vol 1, pp 293-306.

Environment Agency. 2001. Conserving Water in Buildings: Water Efficient WC's and Retrofits, Available at: http://environmentagency.gov.uk/subjects/waterres (accessed December 2005).

EPA. 2008. Evaluation and Interpretation of hydrometric data on Rivers and Lakes in Ireland and future implication to include climate change and water resources. Available at: http://www.epa.ie/downloads/pubs/other/corporate/oea/research/research-closedcalls/tech%20desc%20-%20erc%20surfacewater.pdf. (Assessed 06/08).

Ettrich, N., Steiner, K., Thomas, M. and Rothe, R. 2005. Surface models for coupled modelling of runoff and sewer flow in urban areas. *Water Science & Technology*, vol. 52, no. 5, pp. 25-33.

Fewkes, A. 1999. The use of rainwater for WC flushing: The field testing of a collection system. *Building and Environment,* vol. 34, no. 6, pp. 765-772.

Fewkes, A. 2000. Modelling the performance of rainwater collection systems: towards a generalised approach. *Urban Water,* vol. 1, no. 4, pp. 323-333.

Fleischbein, K., Lindenschmidt, K. and Merz, B. 2006. Modelling the runoff response in the Mulde catchment (Germany). *Advances in Geosciences,* vol. 9, pp. 79-84.

Francos, A., Elorza, F.J., Bouraoui, F., Bidoglio, G. and Galbiati, L. 2003. Sensitivity analysis of distributed environmental simulation models: Understanding the model behaviour in hydrological studies at the catchment scale. *Reliability Engineering and System Safety,* vol. 79, no. 2, pp. 205-218.

Friedler, E. 2004. Quality of individual domestic greywater streams and its implication for on-site treatment and reuse possibilities. *Environmental Technology,* vol. 25, no. 9, pp. 997-1008.

Friedler, E., Kovalio, R., and Galil, N,I. 2004. Proceedings of the 1st International Conference on Onsite Wastewater Treatment & Recycling. Fremantle, Western Australia. February 11-13, 2004.

Fittschen, I. and Niemczynowicz, J. 1997. Experiences with dry sanitation and greywater treatment in the ecovillage toarp, Sweden. *Water Science and technology*. vol 35, no 9, pp 161-170.

GDSDS. 2005. Greater Dublin Strategic Drainage Study. Available at: http://www.irishsuds.com/information/60824co1rk.pdf. (Assessed: 06/08).

Gerba, C. P., Straub, T.M., Rose, J.B., Karpiscak, M.M., Foster, K.E. and Brittain, R.G. 1995. Water quality study of graywater treatment systems. *Water Resources Bulletin,* vol. 31, no. 1, pp. 109-116.

Ghisi, E., Mengotti de Oliveira. S. 2007. Potential for potable water savings by combining the use of rainwater and greywater in houses in southern Brazil. *Building and Environment*, vol 42, pp 1731-1742.

Giupponi, C. 2007. Decision Support Systems for implementing the European Water Framework Directive: The MULINO approach. *Environmental Modelling and Software,* vol. 22, no. 2, pp. 248-258.

Gӧtzinger, J., Jagelke, J., Barthel, R. and Bárdossy, A. 2006. Integration of water balance models in Rivertwin. *Advances in Geosciences,* vol. 9, pp. 85-91.

Gough, M. and Cremins, R. 2004. Economic development plan 2004-2010. Dun Laoghaire: Dundrum.

Guitierrez Andres, J., Rayner, C., Udale-Clarke, H., Kellagher.R. and Reeves, M. 2008. 2D Flooding Analysis in Scotland. In: 11th International Conference on Urban Drainage, 2008, Edinburgh, Scotland.

GWP TAC. 2000. Integrated Water Resource Management. Available at: http://www.connectedwater.gov.au/water_policy/integrated_mgt.html. (Assessed 08/08).

Haile, A. T. and Rientjes, T.H.M. 2005. Effects of LIDAR DEM Resolution in Flood Modelling: A model sensitivity study for the city of Tegucigalpa, Honduras. *In: ISPDS WG III/3, III/4, V/3, Workshop "Laser scanning 2005.* 12-14 September 2005. Enschede, The Netherlands.

Herrmann, T. and Schmida, U. 1999. Rainwater utilisation in Germany: Efficiency, dimensioning, hydraulic and environmental aspects. *Urban Water,* vol. 1, pp. 308-316.

Hulme, M.**,** Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S. 2002. Climate change scenarios for the UK: the UKCIP02 scientific report. Tyndall Centre, UEA, Norwich, UK.

HR Wallingford. 2001. South Eastern Motortway- River Catchment Study.Carrickmines / Shanganagh Catchment Report. Report EX4377 Howbery Park: Wallingford.

HR Wallingford. 2005. Rainfall, Runoff and Other Inflows, training manual. Howbery Park: Wallingford.

HR Wallingford. 2007. Water cycle management for New Developments (WaND) Elvetham Health Case study-Testing of sustainability measures for stormwater drainage. HR Wallingford Limited.

Jang, S.; Cho, M., Yoon, J., Yoon, Y., Kim. S., Kim, G., Kim, L. and Aksoy, H. 2007. Using SWMM as a tool for hydrologic impact assessment. *Desalination*, vol 212, pp 344-356.

Jefferson, B., Laine, A., Parsons, S., Stephenson, T. and Judd, S. 1999. Technologies for domestic wastewater recycling. *Urban Water*, vol 1, pp285-292.

Jefferson, B., Gray, S. and Dixon, D. 2007. Special issue: Membranes. *Water Research,* vol. 41, no. 17, pp. 3793-3793.

Jeon, J., Yoon, C.G., Donigian, A.S., Jung, K. 2007. Development of the HSPF-Paddy model to estimate watershed pollutant loads in paddy farming regions. *Agricultural Water Management*, vol 90, pp 75-86.

Jeppesen, B. 1996. Domestic greywater re-use: Australia's challenge for the future. *Desalination*, vol 106, pp311-315.

Jia, Y.; Niu, N.; Wang, H. 2007. 2007. Integrated modeling and assessment of water resources and water environment in the Yellow River Basin. *Journal of Hydro-Environment Research.* Vol 1, pp 12-19.

Kellagher, R.B.B., and Maneiro Franco, E. 2005. Rainfall collection and use in developments; benefits for yields and stormwater control. HR Wallingford.

Kim, R., Lee, S. and Kim, J. 2005. Application of a metal membrane for rainwater utilization: filtration characteristics and membrane fouling. *Desalination,* vol. 177, no. 1-3, pp. 121-132.

Leister, J., Roberts, M. and Turnley.M. 2007. Entire Catchment Flood Modelling as a Planning Tool - River Trent Case Study. *In: 5th flood management conference*, 9-12 October 2007, Warmanbool.

Legesse. D., Vallet-Coulomb. C., Gasse. F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology*, vol 275, pp 67-85.

Liu, Z., Martina, M.L.V. and Todini, E. 2005. Flood forecasting using a fully distributed model: Application of the TOPKAPI model to the Upper Xixian Catchment. *Hydrology and Earth System Sciences,* vol. 9, no. 4, pp. 347-364.

Mark, O., Weesakul, S., Apirumanekul, C., Aroonnet, S. B. and Djordjević, S. 2004. Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology,* vol. 299, no. 3-4, pp. 284-299.

Mars, M. (2004). Proceedings of the 1st International Conference on Onsite Wastewater Treatment & Recycling. Fremantle, Western Australia. February 11-13, 2004.

McIntyre, N., Wheater, H. and Lees, M. 2002. Estimation and propagation of parametric uncertainty in environmental models. *Journal of Hydroinformatics*, vol 4, no 3, pp 177-198.

Menzel, L., Thieken, A.H., Schwandt, D. and Bürger, G. 2006. Impact of climate change on the regional hydrology - Scenario-based modelling studies in the German Rhine catchment. *Natural Hazards,* vol. 38, no. 1-2, pp. 45-61.

Merz, R., Blöschl, G. and Humer, G. 2008. National flood discharge mapping in Austria. *Natural Hazards,* vol. 46, no. 1, pp. 53-72.

MDSF notes. 2008. Modelling and Decision Support Framework. Available at: http://www.mdsf.co.uk/. (Assessed 07/08).

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J. and Wilke, K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change,* vol. 49, no. 1-2, pp. 105-128.

Mignot, E., Paquier, A. and Haider, S. 2006a. Modeling floods in a dense urban area using 2D shallow water equations. *Journal of Hydrology,* vol. 327, no. 1-2, pp. 186-199.

Mignot, E., Paquier, A. and Ishigaki., T. 2006b. Comparison of numerical and experimental simulations of a flood in a dense urban area. *Water Science and Technology*. vol 54, no 6, pp 65-73.

Mitchell, V. G. 2007. How important is the selection of computational analysis method to the accuracy of rainwater tank behaviour modelling? *Hydrological Processes,* vol. 21, no. 21, pp. 2850-2861.

Mitchell, V.G., Diaper, C. 2005. Simulating the urban water and contaminant cycle. Environmental Modelling and Software.

Mitchell, V.G., Diaper, C., Gray, S.R., Rahilly, M. and CSIRO Manufacturing and Infrastructure Technology. 2003. UVQ: Modelling the Movement of Water and Contaminants through the Total Urban Water Cycle. In: 28th International hydrology and water resources symposium, 10-14 November 2003, Wollongong, NSW.

Mitchell, V.G., Mein, R.G. and McMahon, T.A. 2001. Modelling the urban water cycle. *Environmental Modelling and Software,* vol. 16, no. 7, pp. 615-629.

Mustow, S., Grey, R., Smerdon, T., Pinney, C., and Waggett, R. 1997. Water conservation: implications of using recycled greywater and stored rainwater in the UK. Bracknell: BSRIA.

Ngigi, S. N. 2003. What is the limit of up-scaling rainwater harvesting in a river basin? *Physics and Chemistry of the Earth,* vol. 28, no. 20-27, pp. 943-956.

Niemczynowicz, J. 1999. Urban hydrology and water management - present and future challenges. *Urban Water,* vol. 1, no. 1, pp. 1-14.

Nolde, E. 2005. Greywater recycling systems in Germany results, experiences and guidelines. *Water Science & Technology*, vol 51, no 10, pp 203-210.

Park, S.Y.; Lee. K. W; Park. I.H.; Ha, S.R. 2008. Effect of the aggregation level of surface runoff fields and sewer network for a SWMM simulation. *Desalination*, vol 226, pp 328-337.

Pascual, P., Steiber, N., Sunderland, E .2003. Draft Guidance on Development, Evaluation and Application of Regulatory Environmental Models**.** The Council for Regulatory Environmental Modeling. Office of Science Policy, Office of Research and Development. US Environmental Protection Agency, Washington DC 60 pp.

Pidou, M., Avery, L., Stephenson, T., Jeffrey, P., Parsons, S. A., Liu, S., Memon, F.A. and Jefferson, B. 2008. Chemical solutions for greywater recycling. *Chemosphere,* vol. 71, no. 1, pp. 147-155.

Pohlert, T., Huisman, J. A., Breuer, L. and Frede, H. 2007. Integration of a detailed biogeochemical model into SWAT for improved nitrogen predictions-Model development, sensitivity, and GLUE analysis. *Ecological Modelling,* vol. 203, no. 3-4, pp. 215-228.

Powell, S.J., Letcher, R. A. and Croke, B.F.W. 2007. Modelling floodplain inundation for environmental flows: Gwydir wetlands, Australia. *Ecological Modelling,* vol. 211, no. 3-4, pp. 350-362.

Prudhomme, C. and Davies, H. 2008. Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 1: baseline climate. *Climatic Change,* pp. 1-19.

Reed R, A. (1995). Sustainable Sewerage, Guidelines for community schemes. Intermediate technology Publications: London.

Refsgaard, J.C., and Henriksen, H.J. 2004. Modelling guidelines – terminology and guiding principles. *Advances in Water Resources*. vol 27, pp 71-82.

Refsgaard, J.C., Henriksen, H.J., Harrar, W.G., Scholten, H., Kassahun, A. 2005. Quality assurance in model based water management – review of existing practice and outline of new approaches. *Environmental Modelling and Software*. Vol 20, pp 1201-1215.

Refsgaard, J.C., Van der Sluijs, J.P., Højberg, A.L., Vanrolleghem, P.A. 2007. Uncertainty in the environmental modelling process - A framework and guidance. *Environmental Modelling & Software*, vol 22, pp 1543-1556.

Renwick, M.E., Archibald, S.O. 1998. Demand side management policies for residential water use: Who beans the conservation burden? *Land Economics*, vol 74, no3, pp. 343-359.

Rockström, J., Kaumbutho, P., Mwalley; P., and Temesgen, M. 2001. Conservation farming among small-holder farmers in E. and S. Africa: adapting and adopting innovate land management options. *Conservation,* vol. 1, pp. 363–374.

Rodda, J.C. and Smith, S.W. 1986. The significance of the systematic error in rainfall measurement for assessing wet deposition. *Atmospheric Environment,* vol. 20, no. 5, pp. 1059-1064.

Rueedi, J., Cronin, A., and Moon, B. 2005. Effect of different water supply and drainage strategies on water and contaminant fluxes in Doncaster, United Kingdom.

Saltelli, A., Tarantola, S. and Chan, K. P. 1999. A quantitative model-independent method for global sensitivity analysis of model output. *Technometrics,* vol. 41, no. 1, pp. 39-56.

Santala, E., Uotila, J., Zaitsev, G., Alasiurua, R., Tikka, R., and Tengvall, J. 1998. Microbiological greywater treatment and recycling in an apartment building.

Proceedings of the Advanced Wastewater Treatment, Recycling and Reuse conference, Milano, Italy. 14-16 Sept. 1998

Sauri, D. 2003. Lights and Shadows of Urban Water Demand Management: The Case of the Metropolitan Region of Barcelona.

Schmitt, T.G., Thomas, M. and Ettrich, N. 2004. Analysis and modeling of flooding in urban drainage systems. *Journal of Hydrology,* vol. 299, no. 3-4, pp. 300-311.

Segond, M., Wheater, H. S. and Onof, C. 2007. The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK. *Journal of Hydrology,* vol. 347, no. 1-2, pp. 116-131.

Semadeni-Davies, A., Hernebring, C., Svensson, G. and Gustafsson, L. 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Suburban stormwater. *Journal of Hydrology,* vol. 350, no. 1-2, pp. 114-125.

Siang, L. C., Abdullah, R., Zakaria, N.A., Ghani, A.A. and Kiat, C.C. 2007. Modelling Urban River Catchment: A Case Study of Berop River, Tanjong Malim, Perak. In: 2nd International Conference on *Managing Rivers in the 21st Century: Solutions Towards Sustainable River Basins*, 6-8 June 2007, Kunching, Malaysia.

Sieber, A. and Uhlenbrook, S. 2005. Sensitivity analyses of a distributed catchment model to verify the model structure. *Journal of Hydrology,* vol. 310, no. 1-4, pp. 216-235.

Sim, P., McDonald, A., Parsons, J., and Rees, P. 2005. The Options for UK Domestic Water Reduction: A Review. University of leeds.

Smith, T. 2007. Integrated Urban Drainage Lessons from the Birmingham Pilot. *WaPUG Autumn Conference 2007.*

Stransky, D., Bares, V. and Fatka, P. 2007. The effect of rainfall measurement uncertainties on rainfall-runoff processes modelling. *Water Science & Technology*, vol. 55, no 4, pp. 103-111.

Sullivan, A., Ternan, J.L. and Williams, A.G. 2004. Land use change and hydrological response in the Camel catchment, Cornwall. *Applied Geography,* vol. 24, no. 2, pp. 119-137.

Surendram, S. and Wheatley, A.D. 1998. Greywater reclamination for non-potable reuse. *Journal CIWEM*. Vol 12. pp 406-413.

Thames Water. (2005). Thames Gateway: A New Water Supply for London.
Available at:
http://www.thameswateruk.co.uk/UK/region/en_gb/content/Section_Homepages/Section_Homepage_000516.jsp?SECT=Section_Homepage_000516. (Accessed : December 2005).

Thorndahl, S. and Willems, P. 2008. Probabilistic modelling of overflow, surcharge and flooding in urban drainage using the first-order reliability method and parameterization of local rain series. *Water Research,* vol. 42, no. 1-2, pp. 455-466.

Tjandraatmadja, G., Burn, S., McLaughlin. M., Biswas. T. 2005. Rethinking urban water systems – revisiting concepts in urban wastewater collection and treatment to ensure infrastructure sustainability. *Water Science and Technology*. vol 5, no 2, pp 145-154.

Todini, E. 2007. Hydrological catchment modelling: Past, present and future. *Hydrology and Earth System Sciences,* vol. 11, no. 1, pp. 468-482.

Udale-Clarke, H.and Kellagher, R.B.B. 2007. Sustainability measures applied to an urban stormwater drainage system. In: Combined International Conference of Computing and Control for the Water Industry (CCWI2007) and Sustainable Urban Water Management (SUWM2007), 3-5 September 2007, Leicester, UK. (2007)

Van Waveren, R.H., Groot, S., Scholten, H., Van Geer, F.C., Wösten, J.H.M., Koeze, R.D., Noort, J.J. 2000. Good Modelling Practice Handbook. STOWA Report 99-05. Utrecht, RWS-RIZA, Lelystad, The Netherlands. Available at: http://waterland.net/riza/aquest.

Villarreal, E. L. and Dixon, A. 2005. Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrköping, Sweden. *Building and Environment,* vol. 40, no. 9, pp. 1174-1184.

Ward, R.C. and Robinson. M. 2000. Principles of Hyrdology. McGraw Hill: London.

Willems, P. 2003. Methodology for integrated catchment modelling. The International IMUG Conference, Tilburg, 23-25 April 2003.

WWF. 2003. Water and Wetland Index – Critical issues in water policy across Europe November 2003. Available at: http://assets.panda.org/downloads/wwiireland.pdf. (Assessed: 06/08).

Young, A. R. 2006. Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. *Journal of Hydrology,* vol. 320, no. 1-2, pp. 155-172.

Zhang, G.P., Savenije, H.H.G., Fenicia, F. and Pfister, L. 2006. Modelling subsurface storm flow with the Representative Elementary Watershed (REW) approach: Application to the Alzette River Basin. *Hydrology and Earth System Sciences,* vol. 10, no. 6, pp. 937-955.

Zoppou, C. 2001. Review of urban storm water models. *Environmental Modelling and Software,* vol. 16, no. 3, pp. 195-231.

Annex 1 Additional results from greywater simulations

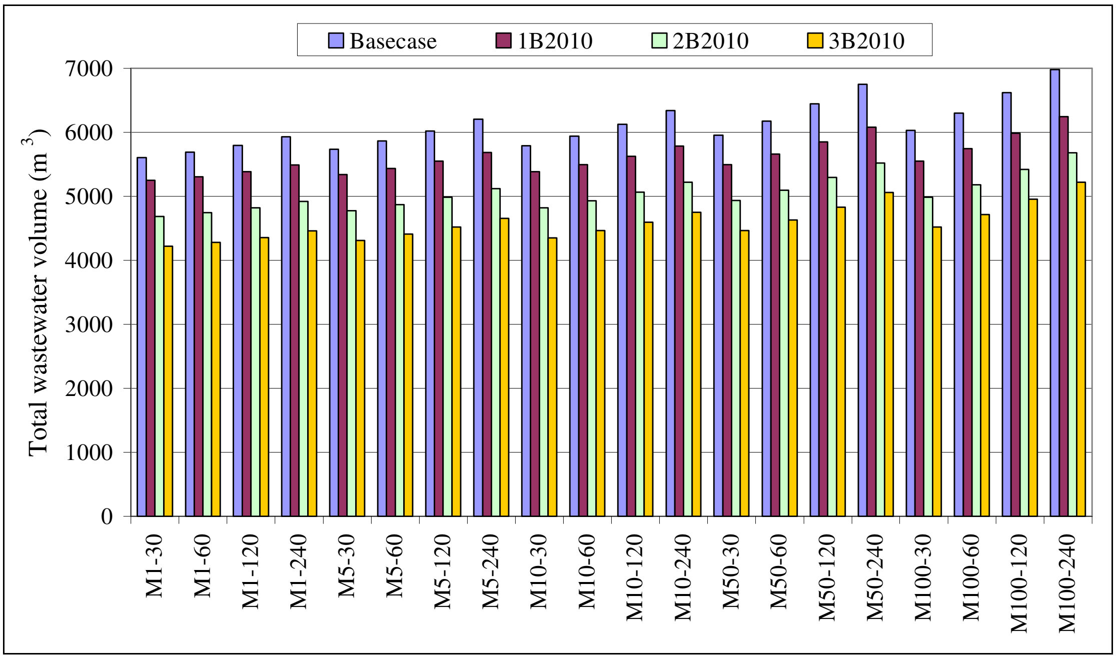


Figure A1.1. Total wastewater volume production variation during various design storm from M1 to M100 with a duration of 30min to 240min, 2010 development during winter conditions.

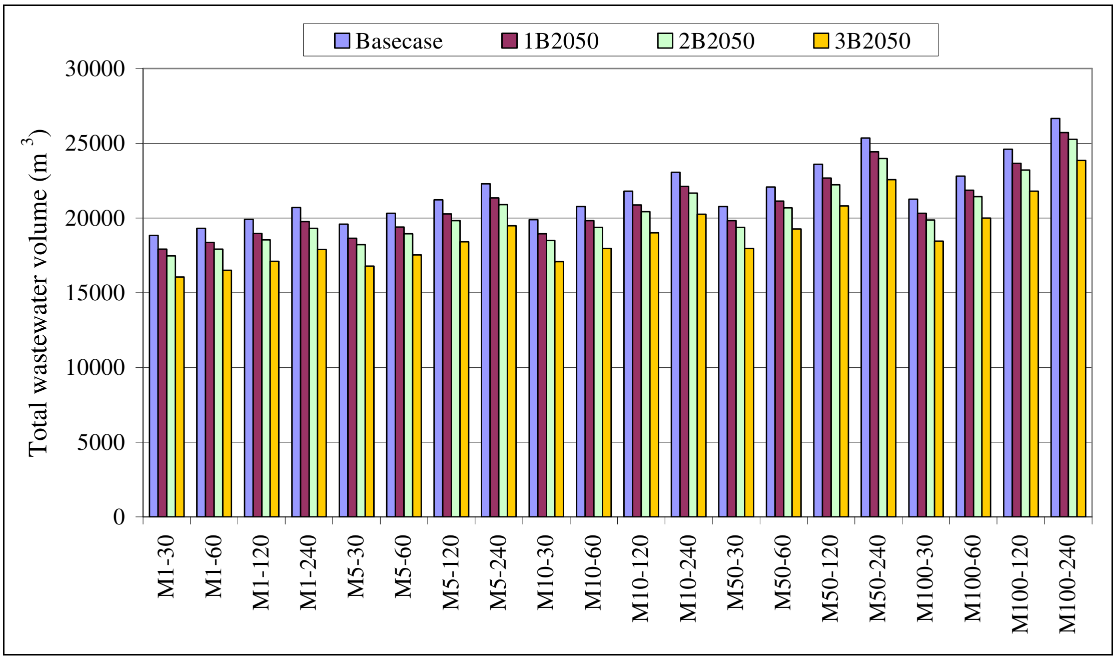


Figure A1.2. Total wastewater volume production variation during various design storms from M1 to M100 with a duration of 30min to 240min, 2050 development.

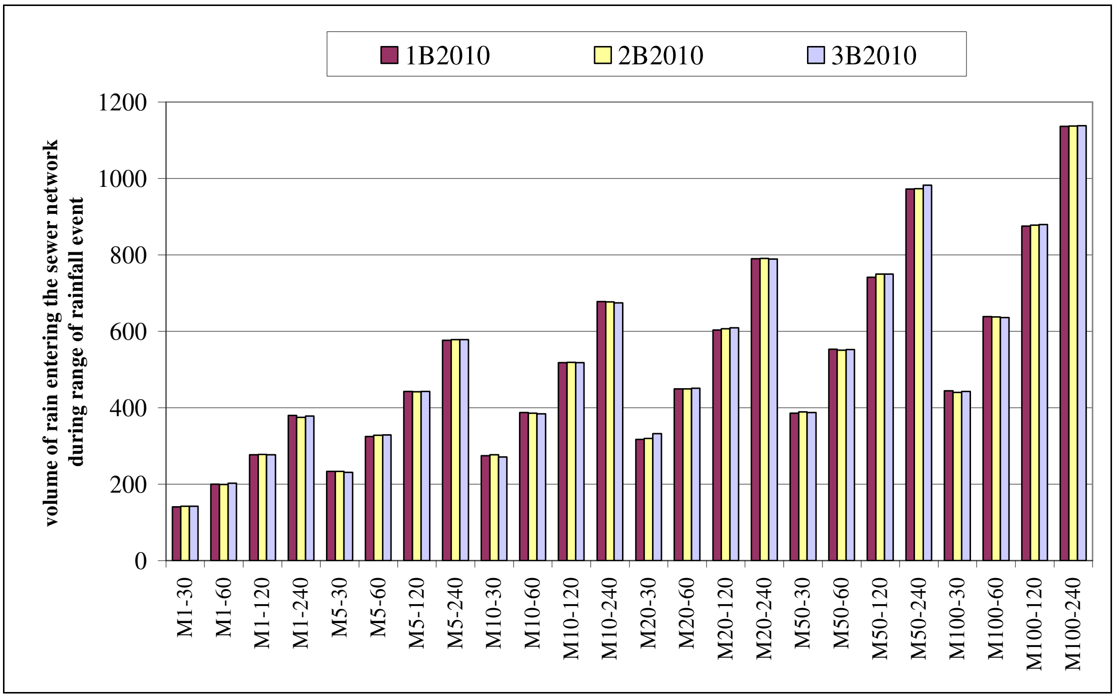


Figure A1.3. Volume of rainwater entering the sewer network during design storm event for scenarios 1B2010, 2B2010 and 3B2010.

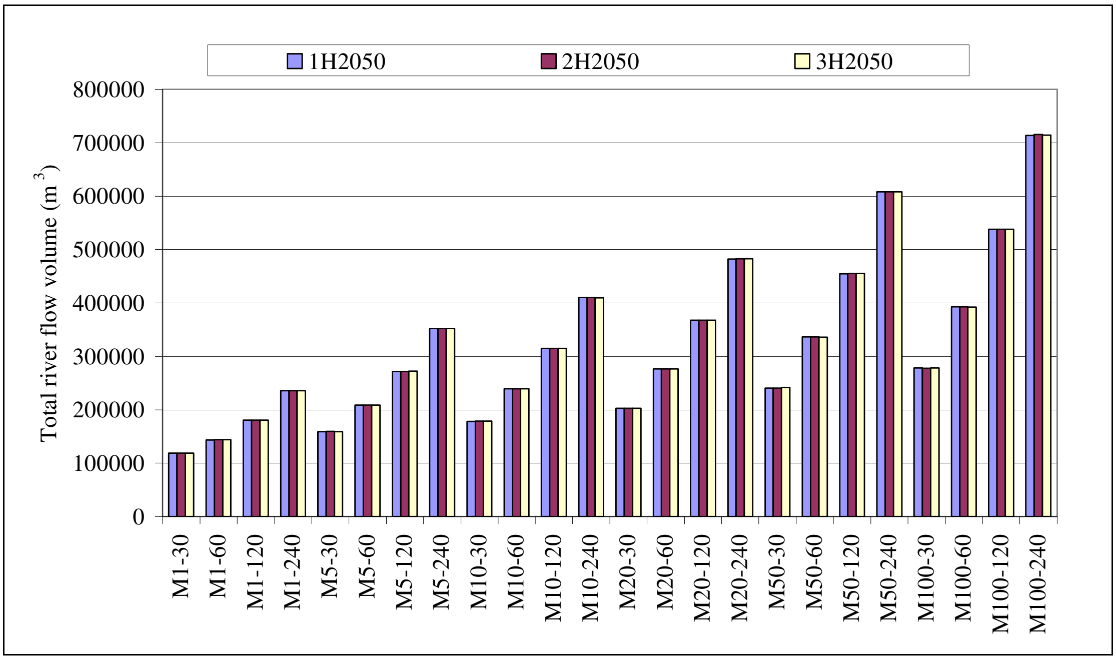


Figure A1.4. Variation of the river flow volume during many rainfall events in development 2050.

Table A1.1. Review flood occurrence and variation in 2050 development during 100 year return period events

Node	Total floods volume (m^3)				% reduction sewer flood			Recycling or not		
	basecase	20%	50%	80%	20%	50%	80%	20%	50%	80%
D1H163	312	296	280	276	5	10	12	yes	yes	yes
D1H103	171	145	114	113	15	33	34	yes	yes	yes
D1H178	156	149	138	131	4	12	16	yes	yes	yes
D1H191	130	125	114	101	3	12	22	yes	yes	yes
D1H296	109	108	106	94	1	3	14	yes	yes	yes
D1H245	102	101	98	85	1	4	17	yes	yes	yes
D1H149	99	93	91	91	6	8	9	yes	yes	yes
D1H294	98	97	95	87	1	3	11	yes	yes	yes
D1H285	92	91	89	78	1	3	15	yes	yes	yes
D1H295	89	88	86	78	1	3	12	yes	yes	yes
D1H307	78	77	75	71	1	3	9	yes	yes	yes
D1H232	77	75	72	62	2	6	19	yes	yes	yes
D1H259	76	75	73	64	1	4	16	yes	yes	yes
D1H273	68	67	65	57	1	3	15	yes	yes	yes
D1H218	63	62	58	49	2	7	21	yes	yes	yes
D1H133	62	59	57	57	6	8	8	yes	yes	yes
D1H205	53	51	46	37	3	12	30	yes	yes	yes
D1H272	50	49	47	38	2	5	24	yes	yes	yes
D1H118	38	36	35	35	6	8	8	yes	yes	yes
D1H148	38	28	25	25	25	33	35	yes	yes	yes
D1H258	33	32	30	20	3	10	39	yes	yes	yes
D1H244	30	29	25	12	5	17	61	yes	yes	yes
D1H177	29	24	15	11	18	48	63	yes	yes	yes
D1H15	29	27	27	27	7	9	9	yes	yes	yes
D1H297	29	28	26	17	4	10	42	yes	yes	yes
D1H315	28	28	27	26	1	3	9	yes	yes	yes
D1H284	28	27	25	15	3	10	45	yes	yes	yes
D1H323	28	27	27	25	2	4	10	yes	yes	yes
D1H231	26	24	21	10	6	19	59	yes	yes	yes
D1H132	21	17	15	15	21	28	29	yes	yes	yes
D1H143	19	17	16	16	13	13	13	yes	yes	yes
D1H43	18	18	17	17	0	7	7	No	yes	yes
D1H271	18	17	15	6	6	17	66	yes	yes	yes
D1H49	17	17	14	14	0	19	19	No	yes	yes
D1H44	17	17	15	15	0	12	12	No	yes	yes
D1H50	16	16	13	13	0	18	18	No	yes	yes
D1H158	15	14	14	14	7	11	11	yes	yes	yes
D1H46	15	15	13	13	0	14	14	No	yes	yes
D1H142	15	14	14	14	9	9	9	yes	yes	yes
D1H9	14	14	12	12	3	14	14	yes	yes	yes
D1H47	14	14	12	12	0	15	15	No	yes	yes
D1H141	13	12	12	12	10	10	10	yes	yes	yes
D1H48	13	13	11	11	0	18	18	No	yes	yes
D1H45	13	13	11	11	0	13	13	No	yes	yes
D1H144	13	11	11	11	12	13	13	yes	yes	yes

D1H157	13	12	11	11	9	10	10	yes	yes	yes
D1H42	12	12	12	12	0	6	6	No	yes	yes
D1H159	12	11	10	10	6	15	16	yes	yes	yes
D1H162	12	7	3	3	44	71	77	yes	yes	yes
D1H156	12	10	10	10	10	10	10	yes	yes	yes
D1H66	11	11	9	9	0	17	17	No	yes	yes
D1H51	11	11	10	10	0	14	14	No	yes	yes
D1H112	11	10	10	10	11	11	11	yes	yes	yes
D1H65	11	11	9	9	0	17	17	No	yes	yes
D1H64	10	10	9	9	0	18	18	No	yes	yes
D1H67	10	10	8	8	0	16	16	No	yes	yes
D1H113	10	8	8	8	16	16	16	yes	yes	yes
D1H111	9	8	8	8	12	12	12	yes	yes	yes
D1H127	9	8	8	8	13	13	13	yes	yes	yes
D1H160	9	8	7	7	9	23	23	yes	yes	yes
D1H81	9	9	8	8	0	14	14	No	yes	yes
D1H140	9	8	8	8	11	11	11	yes	yes	yes
D1H155	9	8	8	8	11	11	11	yes	yes	yes
D1H98	9	9	8	8	1	16	16	yes	yes	yes
D1H62	9	9	8	8	0	12	12	No	yes	yes
D1H82	9	9	7	7	0	15	15	No	yes	yes
D1H41	9	9	8	8	0	6	6	No	yes	yes
D1H63	8	8	7	7	0	13	13	No	yes	yes
D1H331	8	8	8	7	3	8	16	yes	yes	yes
D1H172	8	8	7	7	0	15	15	No	yes	yes
D1H126	8	7	7	7	14	14	14	yes	yes	yes
D1H60	8	8	7	7	0	9	9	No	yes	yes
D1H110	8	7	7	7	12	12	12	yes	yes	yes
D1H171	8	8	7	7	0	14	14	No	yes	yes
D1H97	8	8	7	7	0	16	16	yes	yes	yes
D1H61	8	8	7	7	0	11	11	No	yes	yes
D1H80	8	8	6	6	0	16	16	No	yes	yes
D1H99	8	7	6	6	4	18	18	yes	yes	yes
D1H96	7	7	6	6	0	17	17	No	yes	yes
D1H128	7	6	6	6	14	14	14	yes	yes	yes
D1H109	7	6	6	6	12	11	11	yes	yes	yes
D1H161	7	5	4	3	24	46	49	yes	yes	yes
D1H145	6	6	6	6	10	10	10	yes	yes	yes
D1H114	6	5	5	5	12	12	12	yes	yes	yes
D1H125	6	5	5	5	14	14	14	yes	yes	yes
D1H253	6	6	6	5	0	0	17	No	No	yes
D1H79	6	6	5	5	0	18	18	No	yes	yes
D1H59	6	6	5	5	0	8	8	No	yes	yes
D1H170	6	6	5	5	0	13	13	No	yes	yes
D1H139	6	5	5	5	13	13	13	yes	yes	yes
D1H95	5	5	5	5	0	16	16	No	yes	yes
D1H169	5	5	4	4	0	17	17	No	yes	yes
D1H68	5	5	4	4	0	15	15	No	yes	yes
D1H173	5	5	4	4	0	15	15	No	yes	yes
D1H52	5	5	4	4	0	13	13	No	yes	yes

D1H252	5	5	5	4	0	0	16	No	No	yes
D1H254	5	5	5	4	0	0	17	No	No	yes
D1H186	4	4	4	4	0	15	19	No	yes	yes
D1H108	4	4	4	4	12	12	12	yes	yes	yes
D1H187	4	4	4	3	0	17	20	No	yes	yes
D1H94	4	4	3	3	0	19	19	No	yes	yes
D1H124	4	3	3	3	18	18	18	yes	yes	yes
D1H240	4	4	4	3	0	0	17	No	No	yes
D1H83	4	4	3	3	0	15	15	No	yes	yes
D1H129	4	3	3	3	16	16	16	yes	yes	yes
D1H117	4	3	2	2	31	42	43	yes	yes	yes
D1H239	4	4	4	3	0	0	19	No	No	yes
D1H78	4	4	3	3	0	20	20	No	yes	yes
D1H251	4	4	4	3	0	0	17	No	No	yes
D1H100	3	3	3	3	8	17	17	yes	yes	yes
D1H267	3	3	3	2	0	0	25	No	No	yes
D1H14	3	3	3	3	18	20	20	yes	yes	yes
D1H154	3	3	3	3	18	18	18	yes	yes	yes
D1H185	3	3	3	2	0	16	23	No	yes	yes
D1H40	3	3	3	3	0	11	11	No	yes	yes
D1H268	3	3	3	2	1	3	33	yes	yes	yes
D1H238	3	3	3	2	0	0	21	No	No	yes
D1H188	3	3	2	2	0	18	21	No	yes	yes
D1H213	3	3	3	2	0	0	29	No	No	yes
D1H270	2	2	2	0	8	21	80	yes	yes	yes
D1H174	2	2	2	2	0	17	17	No	yes	yes
D1H77	2	2	2	2	0	25	25	No	yes	yes
D1H214	2	2	2	2	0	0	29	No	No	yes
D1H93	2	2	2	2	0	23	23	No	yes	yes
D1H336	2	2	2	2	3	8	17	yes	yes	yes
D1H123	2	2	2	2	22	22	22	yes	yes	yes
D1H107	2	2	2	2	19	19	19	yes	yes	yes
D1H269	2	2	2	1	3	8	46	yes	yes	yes
D1H227	2	2	2	1	0	0	31	No	No	yes
D1H266	2	2	2	1	0	0	29	No	No	yes
D1H200	2	2	2	1	0	0	30	No	No	yes
D1H184	2	2	2	2	0	17	27	No	yes	yes
D1H168	2	2	2	2	0	24	24	No	yes	yes
D1H199	2	2	2	1	0	0	36	No	No	yes
D1H255	2	2	2	1	4	6	24	yes	yes	yes
D1H226	2	2	2	1	0	0	37	No	No	yes
D1H58	2	2	2	2	0	13	13	No	yes	yes
D1H212	2	2	2	1	0	0	34	No	No	yes
D1H241	2	2	2	1	0	0	23	No	No	yes
D1H250	1	1	1	1	0	0	33	No	No	yes
D1H146	1	1	1	1	15	15	15	yes	yes	yes
D1H76	1	1	1	1	0	32	32	No	yes	yes
D1H265	1	1	1	1	0	0	40	No	No	yes
D1H115	1	1	1	1	17	17	17	yes	yes	yes
D1H314	1	1	1	1	9	22	50	yes	yes	yes

D1H225	1	1	1	1	0	0	47	No	No	yes
D1H198	1	1	1	1	0	0	46	No	No	yes
D1H215	1	1	1	1	0	0	36	No	No	yes
D1H211	1	1	1	0	0	0	49	No	No	yes
D1H92	1	1	0	0	0	42	42	No	yes	yes
D1H201	1	1	1	0	0	-1	40	No	No	yes
D1H291	1	1	1	1	0	0	0	No	No	No
D1H138	1	0	0	0	46	47	47	yes	yes	yes
D1H228	1	1	1	0	0	0	47	No	No	yes
D1H237	1	1	1	0	0	0	59	No	No	yes
D1H69	0	0	0	0	0	29	29	No	yes	yes
D1H256	0	0	0	0	13	35	100	yes	yes	yes
D1H257	0	0	0	0	26	67	100	yes	yes	yes
D1H122	0	0	0	0	58	58	58	yes	yes	yes
D1H290	0	0	0	0	0	0	0	No	No	No
D1H197	0	0	0	0	0	-1	89	No	No	yes
D1H293	0	0	0	0	24	58	100	yes	yes	yes
D1H189	0	0	0	0	0	38	45	No	yes	yes
D1H130	0	0	0	0	43	43	43	yes	yes	yes
D1H106	0	0	0	0	50	50	50	yes	yes	yes
D1H75	0	0	0	0	0	80	80	No	yes	yes
D1H175	0	0	0	0	0	40	40	No	yes	yes
D1H84	0	0	0	0	0	43	43	No	yes	yes
D1H183	0	0	0	0	0	62	100	No	yes	yes
D1H101	0	0	0	0	26	56	56	yes	yes	yes
D1H153	0	0	0	0	83	85	85	yes	yes	yes
D1H342	0	0	0	0	9	23	38	yes	yes	yes
D1H322	0	0	0	0	24	55	100	yes	yes	yes
D1H279	0	0	0	0	0	-1	100	No	No	yes
D1H8	0	0	0	0	17	100	100	yes	yes	yes
D1H306	0	0	0	0	69	100	100	yes	yes	yes

Table A1.2. Review flood occurrence and variation in 2050 development during 5year return period events

Node	Total floods volume (m^3)				% reduction sewer flood			Recycling or not		
	basecase	20%	50%	80%	20%	50%	80%	20%	50%	80%
D1H163	92	81	69	68	12	25	27	yes	yes	yes
D1H296	49	46	42	31	5	14	36	yes	yes	yes
D1H178	45	40	31	28	11	31	38	yes	yes	yes
D1H294	43	41	37	29	6	15	33	yes	yes	yes
D1H285	41	39	36	26	5	14	36	yes	yes	yes
D1H295	39	37	34	26	5	15	35	yes	yes	yes
D1H245	37	35	33	22	5	13	40	yes	yes	yes
D1H149	36	30	25	25	18	31	31	yes	yes	yes
D1H259	31	30	28	20	4	12	36	yes	yes	yes
D1H307	31	29	26	20	7	17	35	yes	yes	yes
D1H273	30	29	26	19	4	13	36	yes	yes	yes
D1H191	21	18	12	9	13	42	59	yes	yes	yes
D1H232	20	18	16	8	6	19	58	yes	yes	yes
D1H133	19	14	11	11	27	44	44	yes	yes	yes
D1H218	11	10	8	4	9	28	66	yes	yes	yes
D1H315	10	9	8	7	8	19	36	yes	yes	yes
D1H323	7	7	6	5	8	21	38	yes	yes	yes
D1H272	7	6	4	1	15	40	84	yes	yes	yes
D1H118	6	4	2	2	37	69	69	yes	yes	yes
D1H15	4	3	2	2	22	38	38	yes	yes	yes
D1H49	3	3	2	2	0	41	41	no	yes	yes
D1H50	3	3	1	1	0	46	46	no	yes	yes
D1H48	2	2	1	1	0	42	42	no	yes	yes
D1H47	2	2	1	1	0	46	46	no	yes	yes
D1H46	2	2	1	1	0	45	45	no	yes	yes
D1H143	2	1	1	1	64	64	64	yes	yes	yes
D1H51	1	1	0	0	0	64	64	no	yes	yes
D1H45	1	1	1	1	0	49	49	no	yes	yes
D1H205	1	1	1	0	21	60	98	yes	yes	yes
D1H144	1	1	1	1	55	56	56	yes	yes	yes
D1H331	1	1	1	1	9	24	42	yes	yes	yes
D1H44	1	1	1	1	0	54	54	no	yes	yes
D1H159	1	1	0	0	40	67	67	yes	yes	yes
D1H158	1	0	0	0	61	80	80	yes	yes	yes
D1H66	1	1	0	0	0	100	100	no	yes	yes
D1H43	1	1	0	0	0	76	76	no	yes	yes
D1H142	1	0	0	0	94	94	94	yes	yes	yes
D1H67	0	0	0	0	0	100	100	no	yes	yes
D1H113	0	0	0	0	100	100	100	yes	yes	yes
D1H65	0	0	0	0	0	100	100	no	yes	yes
D1H160	0	0	0	0	44	83	83	yes	yes	yes
D1H145	0	0	0	0	97	97	97	yes	yes	yes
D1H336	0	0	0	0	14	36	62	yes	yes	yes
D1H114	0	0	0	0	100	100	100	yes	yes	yes

D1H157	0	0	0	0	100	100	100	yes	yes	yes
D1H64	0	0	0	0	0	100	100	no	yes	yes
D1H258	0	0	0	0	95	100	100	yes	yes	yes
D1H112	0	0	0	0	100	100	100	yes	yes	yes
D1H52	0	0	0	0	0	100	100	no	yes	yes
D1H163	92	81	69	68	12	25	27	yes	yes	yes
D1H296	49	46	42	31	5	14	36	yes	yes	yes
D1H178	45	40	31	28	11	31	38	yes	yes	yes
D1H294	43	41	37	29	6	15	33	yes	yes	yes
D1H285	41	39	36	26	5	14	36	yes	yes	yes
D1H295	39	37	34	26	5	15	35	yes	yes	yes
D1H245	37	35	33	22	5	13	40	yes	yes	yes
D1H149	36	30	25	25	18	31	31	yes	yes	yes
D1H259	31	30	28	20	4	12	36	yes	yes	yes

Annex 2 Additional results from rainwater harvesting simulations

Table A2.1. Review of contributing area for the 2010 and 2050 developments for rainwater harvesting technologies scenarios.

							% area contributing reduction	
	storm area (ha)			roof are (ha)			storm	roof
2010 scenarios	R1	R2	R3	R1	R2	R3	R1	R1
2010 Basecase	541	81	2701	3.292	0	0	n/a	n/a
1B2010	517	81	2701	2.652	0	0	4.38	19.44
2B2010	509	81	2701	1.776	0	0	6.03	46.05
3B2010	432	81	2701	0.959	0	0	20.23	70.87
1N2010	503	81	2703	2.664	0	0	7.13	19.08
2N2010	491	81	2703	2.135	0	0	9.35	35.15
3N2010	418	81	2703	0.889	0	0	22.78	73.00
1M2010	508	81	2703	2.896	0	0	6.07	12.03
2M2010	465	81	2703	2.293	0	0	14.14	30.35
3M2010	441	81	2703	1.911	0	0	18.55	41.95
2050 Scenarios	R1	R2	R3	R1	R2	R3	R1	R1
2050 Basecase	1177	82	1898	23.741	0	0	n/a	n/a
1M2050	1164	82	1898	20.128	0	0	1.17	15.22
2M2050	1063	82	1898	14.496	0	0	9.75	38.94
3M2050	980	82	1898	10.262	0	0	16.76	56.78

Table A2.2. Review of contributing area within the 2050 random scenarios of location of rainwater harvesting technologies.

							% area contributing reduction	
	Storm area (ha)			roof area (ha)			storm	roof
Scenario 1	R1	R2	R3	R1	R2	R3		
1M2050	209	0	0	20.711	0	0	4.33	12.76
2M2050	180	0	0	16.007	0	0	17.39	32.58
Scenario 2								
1M2050	203	0	0	20.433	0	0	7.23	13.93
2M2050	179	0	0	15.658	0	0	17.97	34.05
Scenario 3								
1M2050	202	0	0	20.479	0	0	7.30	13.74
2M2050	177	0	0	15.75	0	0	18.75	33.66

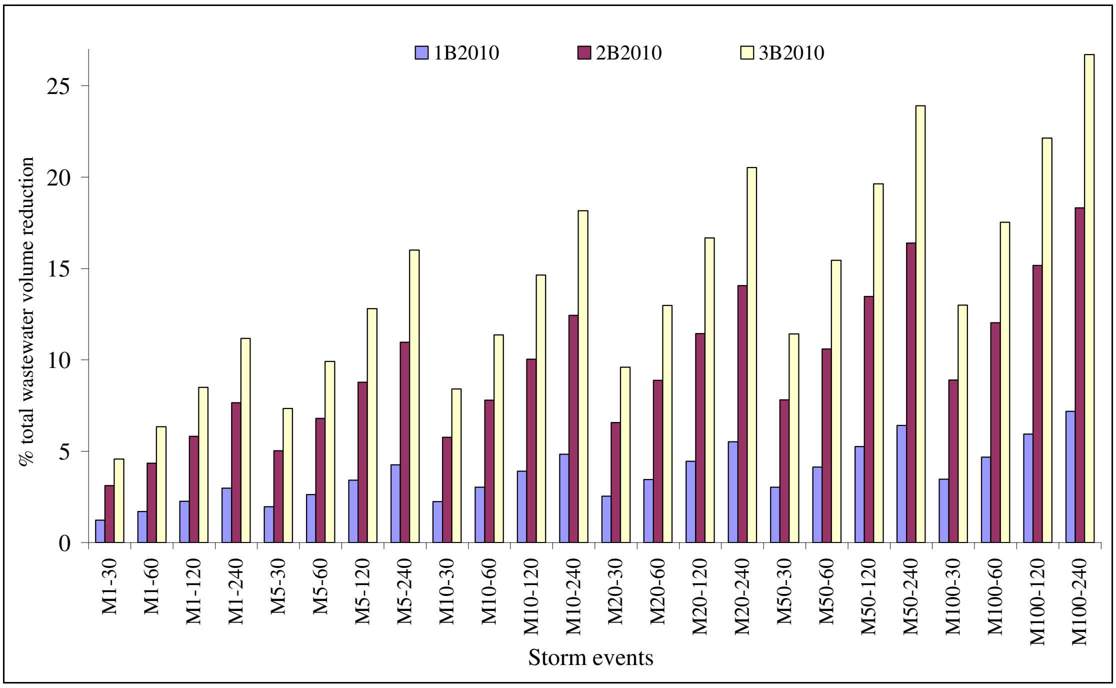


Figure A2.1. Review of the reduction of total wastewater volume within development 2010 when rainwater harvesting technologies are implemented

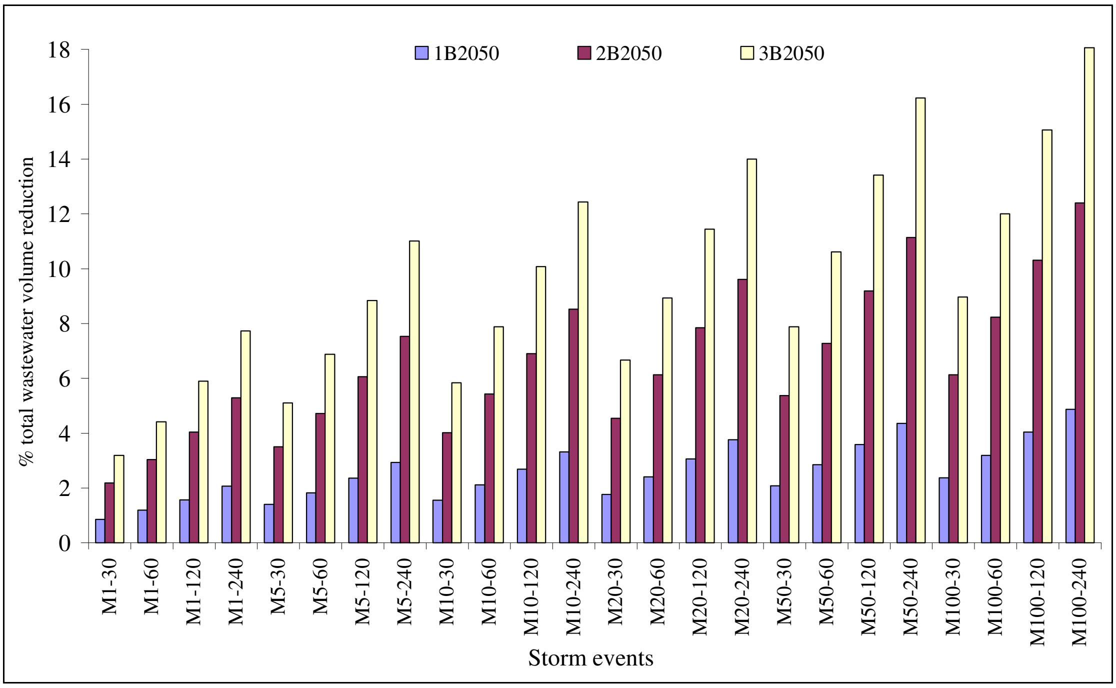


Figure A2.2. Review of the reduction of total wastewater volume within development 2050 when rainwater harvesting technologies are implemented

Table A2.3. Comparison of the total runoff volume (m^3) variation when rainwater harvesting systems are implemented at household scales in development 2010.

	Basecase	1B2010	2B2010	3B2010	% difference 1B2010	% difference 2B2010	% difference 3B2010
M5-30	49510	47955	47121	42192	3.14	4.82	14.78
M5-60	77791	75612	74444	67538	2.80	4.30	13.18
M5-90	97960	95363	93970	85736	2.65	4.07	12.48
M5-120	114107	111189	109623	100368	2.56	3.93	12.04
M5-240	162394	158572	156521	144402	2.35	3.62	11.08
M5-360	198510	194058	191669	177553	2.24	3.45	10.56
M5-480	229733	224760	222092	206327	2.16	3.33	10.19
M100-30	116810	113842	112250	102841	2.54	3.90	11.96
M100-60	188846	184589	182305	168810	2.25	3.46	10.61
M100-90	242003	236883	234136	217902	2.12	3.25	9.96
M100-120	284830	279057	275961	257659	2.03	3.11	9.54
M100-240	407885	400405	396393	372678	1.83	2.82	8.63
M100-360	491190	482657	478079	451023	1.74	2.67	8.18
M100-480	563630	554231	549188	519387	1.67	2.56	7.85

Table A2.4. Comparison of the total runoff volume (m^3) variation when rainwater harvesting systems are implemented at neighbourhood scales in development 2010.

	Basecase	1N2010	2N2010	3N2010	%difference 1N2010	%difference 2N2010	%difference 3N2010
M5-30	49510	47146	46569	41931	4.77	5.94	15.31
M5-60	77791	74536	73722	67190	4.18	5.23	13.63
M5-90	97960	94091	93119	85325	3.95	4.94	12.90
M5-120	114107	109762	108669	99907	3.81	4.77	12.44
M5-240	162394	156710	155279	143800	3.50	4.38	11.45
M5-360	198510	191889	190222	176851	3.34	4.18	10.91
M5-480	229733	222344	220481	205545	3.22	4.03	10.53
M100-30	116810	112262	111163	102331	3.89	4.83	12.40
M100-60	188846	182477	180887	168127	3.37	4.21	10.97
M100-90	242003	234373	232457	217090	3.15	3.94	10.29
M100-120	284830	276234	274073	256746	3.02	3.78	9.86
M100-240	407885	396763	393962	371500	2.73	3.41	8.92
M100-360	491190	478502	475307	449679	2.58	3.23	8.45
M100-480	563630	549671	546150	517912	2.48	3.10	8.11

Table A2.5. Comparison of the total runoff volume (m^3) variation when rainwater harvesting systems are implemented at municipal scales in development 2010.

	Basecase	1M2010	2M2010	3M2010	%difference 1M2010	%difference 2M2010	%difference 3M2010
M5-30	49510	47033	44491	43197	5.00	10.14	12.75
M5-60	77791	74374	70793	68970	4.39	8.99	11.34
M5-90	97960	93896	89624	87449	4.15	8.51	10.73
M5-120	114107	109543	104740	102294	4.00	8.21	10.35
M5-240	162394	156423	150132	146927	3.68	7.55	9.52
M5-360	198510	191555	184227	180494	3.50	7.20	9.08
M5-480	229733	221969	213783	209614	3.38	6.94	8.76
M100-30	116810	112047	107206	104743	4.08	8.22	10.33
M100-60	188846	182160	175167	171606	3.54	7.24	9.13
M100-90	242003	233989	225567	221277	3.31	6.79	8.56
M100-120	284830	275801	266304	261467	3.17	6.50	8.20
M100-240	407885	396201	383890	377619	2.86	5.88	7.42
M100-360	491190	477861	463815	456661	2.71	5.57	7.03
M100-480	563630	548963	533487	525604	2.60	5.35	6.75

Table A2.6. Comparison of the total runoff volume (m^3) variation between the three scales when rainwater harvestings are connected to 20% of the blocks.

Simulation	1B2010	1N2010	1M2010	std	Mean	%difference
M5-30	47955	47146	47033	503	47378	1.06
M5-60	75612	74536	74374	673	74841	0.90
M5-90	95363	94091	93896	796	94450	0.84
M5-120	111189	109762	109543	894	110164	0.81
M5-240	158572	156710	156423	1167	157235	0.74
M5-360	194058	191889	191555	1359	192501	0.71
M5-480	224760	222344	221969	1515	223024	0.68
M100-30	113842	112262	112047	980	112717	0.87
M100-60	184589	182477	182160	1320	183075	0.72
M100-90	236883	234373	233989	1572	235081	0.67
M100-120	279057	276234	275801	1768	277031	0.64
M100-240	400405	396763	396201	2283	397790	0.57
M100-360	482657	478502	477861	2604	479673	0.54
M100-480	554231	549671	548963	2859	550955	0.52

Table A2.7. Comparison of the total runoff volume (m^3) variation between the three scales when rainwater harvestings are connected to 50% of the blocks.

Simulation	2B2010	2N2010	2M2010	std	Mean	% difference
M5-30	47121	46569	44491	1387	46060	3.01
M5-60	74444	73722	70793	1933	72986	2.65
M5-90	93970	93119	89624	2303	92238	2.50
M5-120	109623	108669	104740	2588	107677	2.40
M5-240	156521	155279	150132	3388	153977	2.20
M5-360	191669	190222	184227	3946	188706	2.09
M5-480	222092	220481	213783	4406	218786	2.01
M100-30	112250	111163	107206	2654	110206	2.40
M100-60	182305	180887	175167	3779	179453	2.10
M100-90	234136	232457	225567	4541	230720	1.97
M100-120	275961	274073	266304	5118	272113	1.88
M100-240	396393	393962	383890	6629	391415	1.69
M100-360	478079	475307	463815	7563	472400	1.60
M100-480	549188	546150	533487	8328	542942	1.53

Table A2.8. Comparison of the total runoff volume (m^3) variation between the three scales when rainwater harvestings are connected to 80% of the blocks.

Simulation	3B2010	3N2010	3M2010	Std	Mean	% difference
M5-30	42192	41931	43197	669	42440	1.58
M5-60	67538	67190	68970	944	67899	1.39
M5-90	85736	85325	87449	1126	86170	1.31
M5-120	100368	99907	102294	1266	100857	1.26
M5-240	144402	143800	146927	1659	145043	1.14
M5-360	177553	176851	180494	1933	178299	1.08
M5-480	206327	205545	209614	2159	207162	1.04
M100-30	102841	102331	104743	1271	103305	1.23
M100-60	168810	168127	171606	1843	169514	1.09
M100-90	217902	217090	221277	2221	218756	1.02
M100-120	257659	256746	261467	2504	258624	0.97
M100-240	372678	371500	377619	3247	373932	0.87
M100-360	451023	449679	456661	3704	452454	0.82
M100-480	519387	517912	525604	4082	520968	0.78

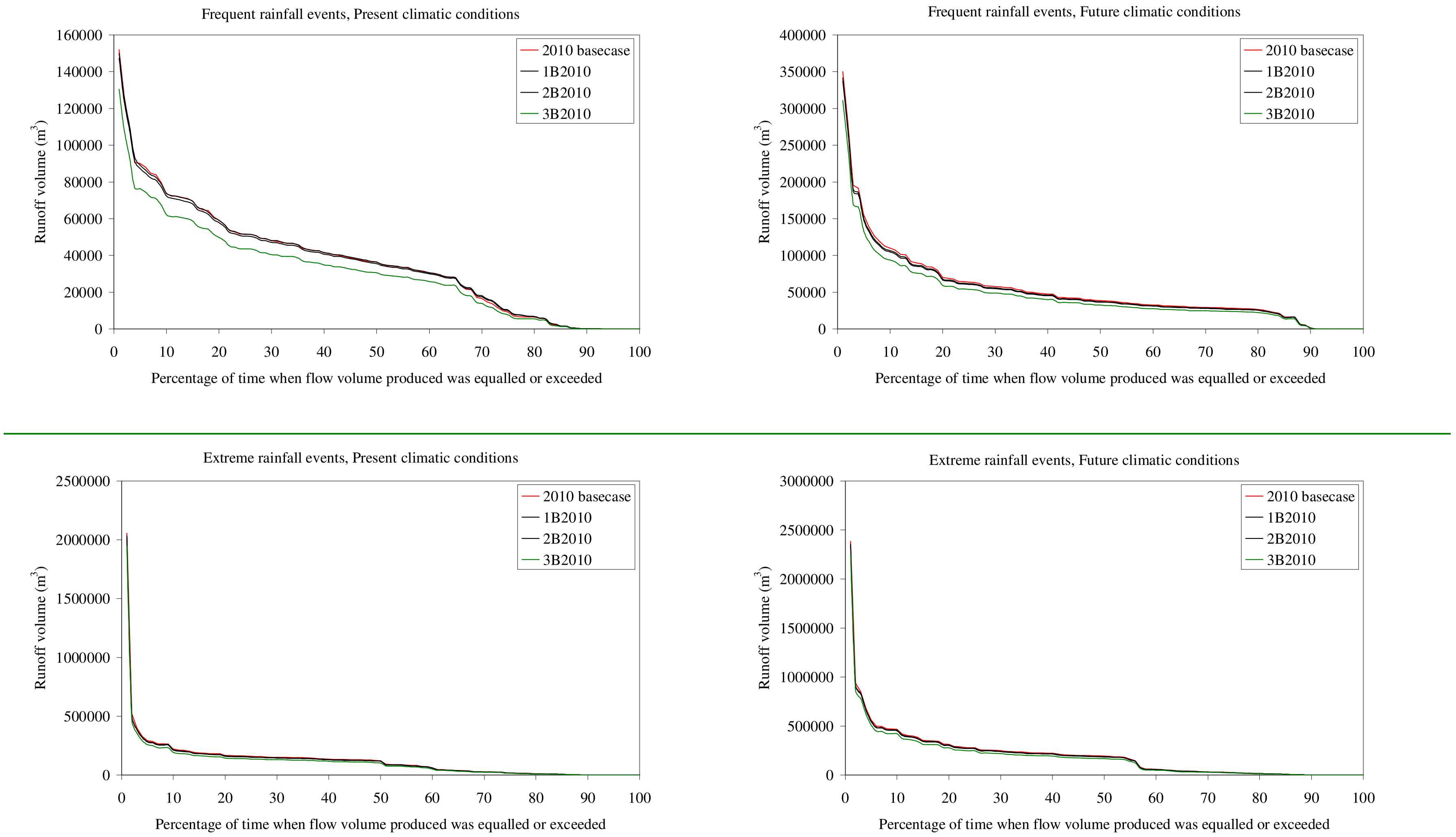


Figure A2.3. Variation of total runoff volume in urban development 2010

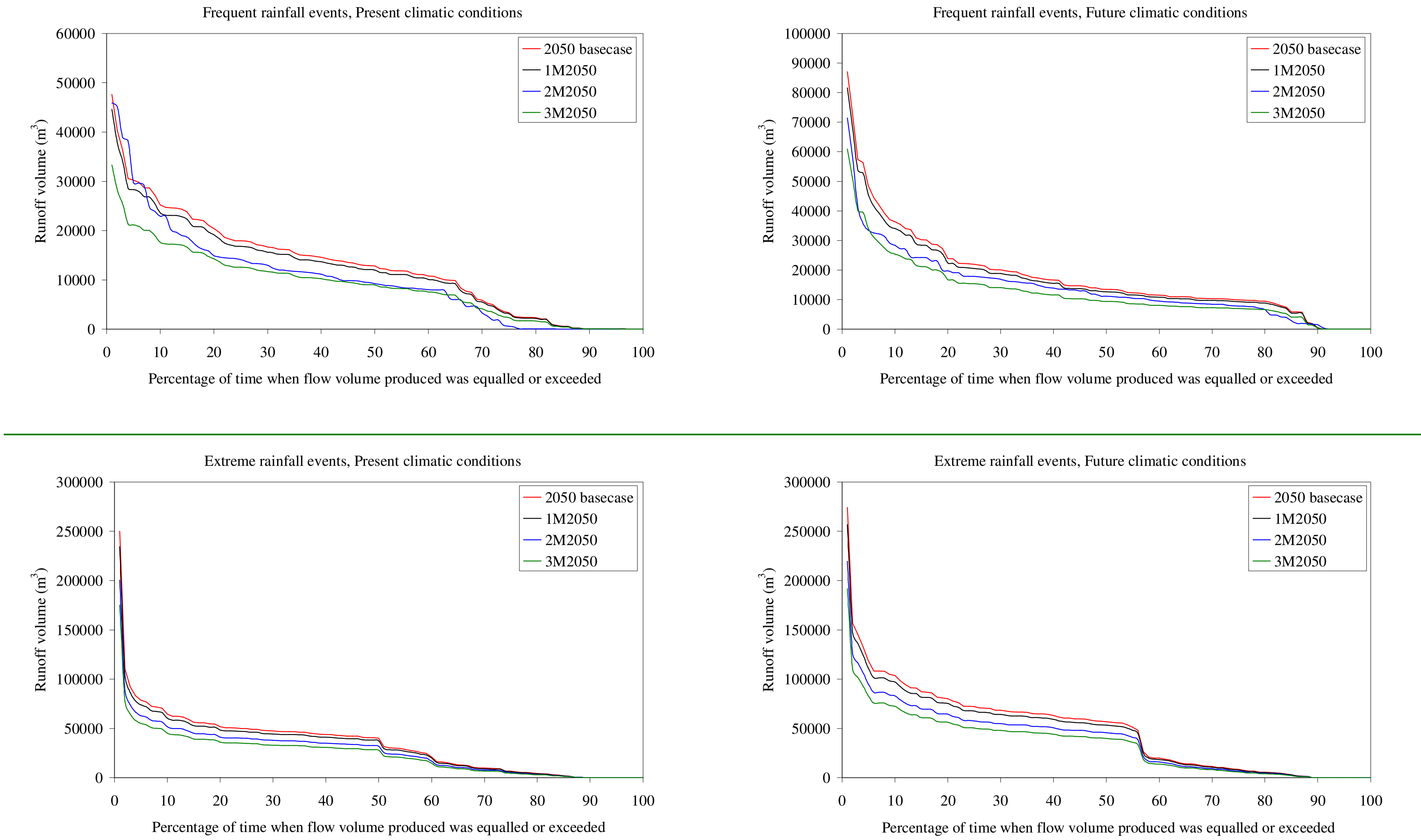


Figure A2.4. Variation of total runoff volume in 2050 urban development

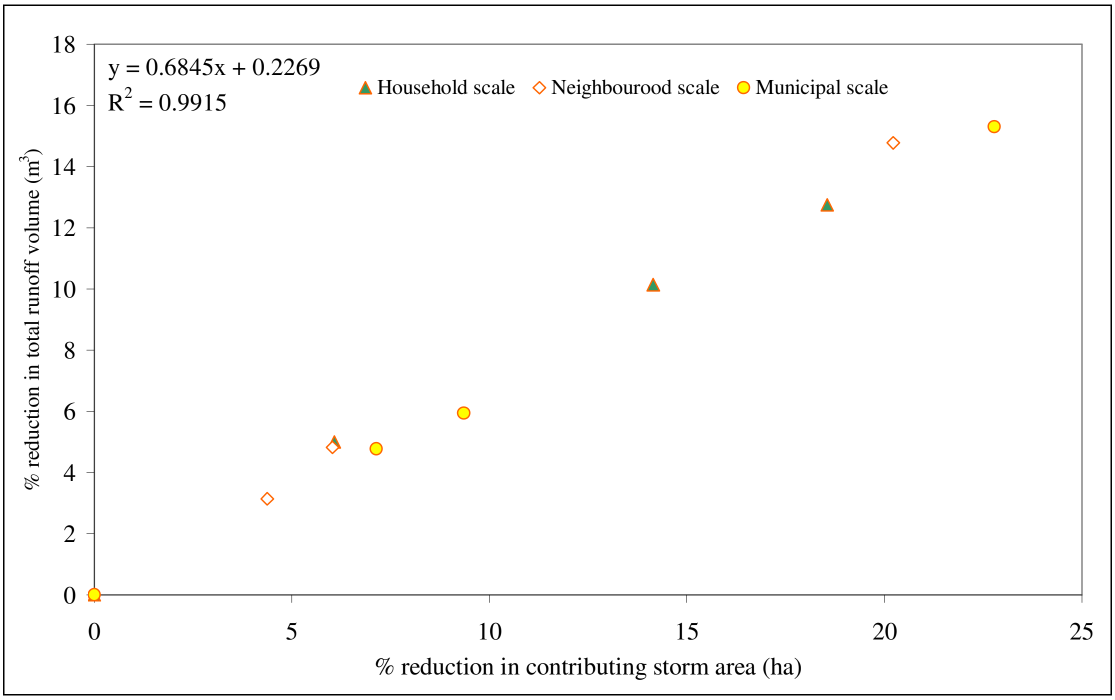


Figure A2.5. Comparison of scaling up rainwater harvesting on the total runoff volume reduction for a M5-30 event

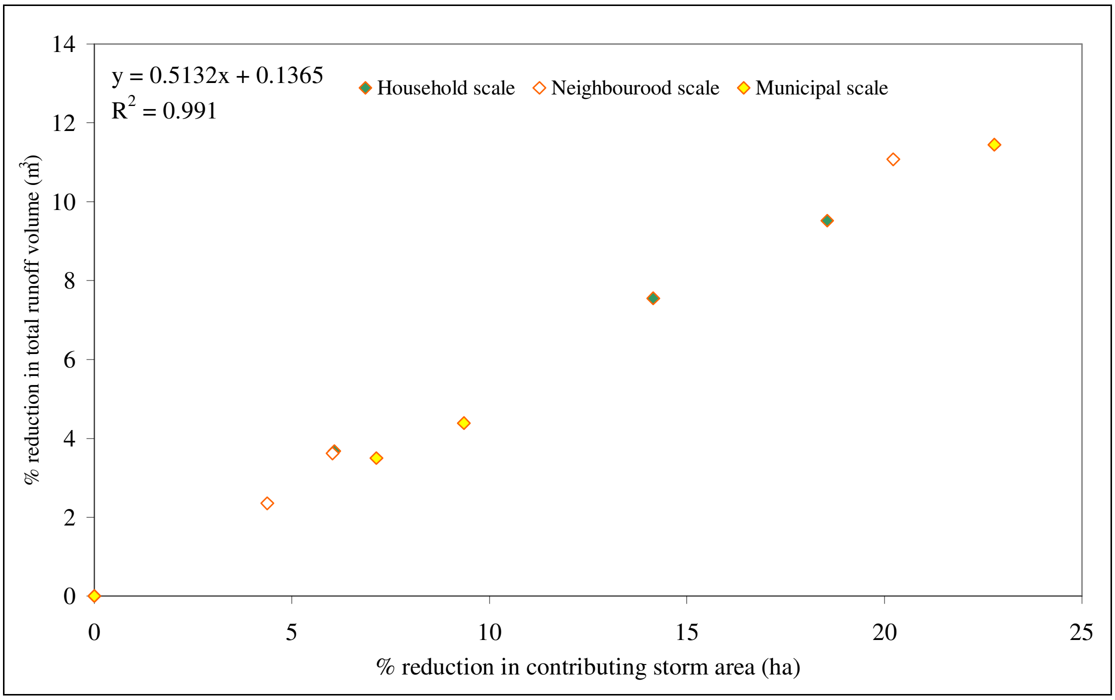


Figure A2.6. Comparison of scaling up rainwater harvesting on the total runoff volume reduction for a M5-240 event

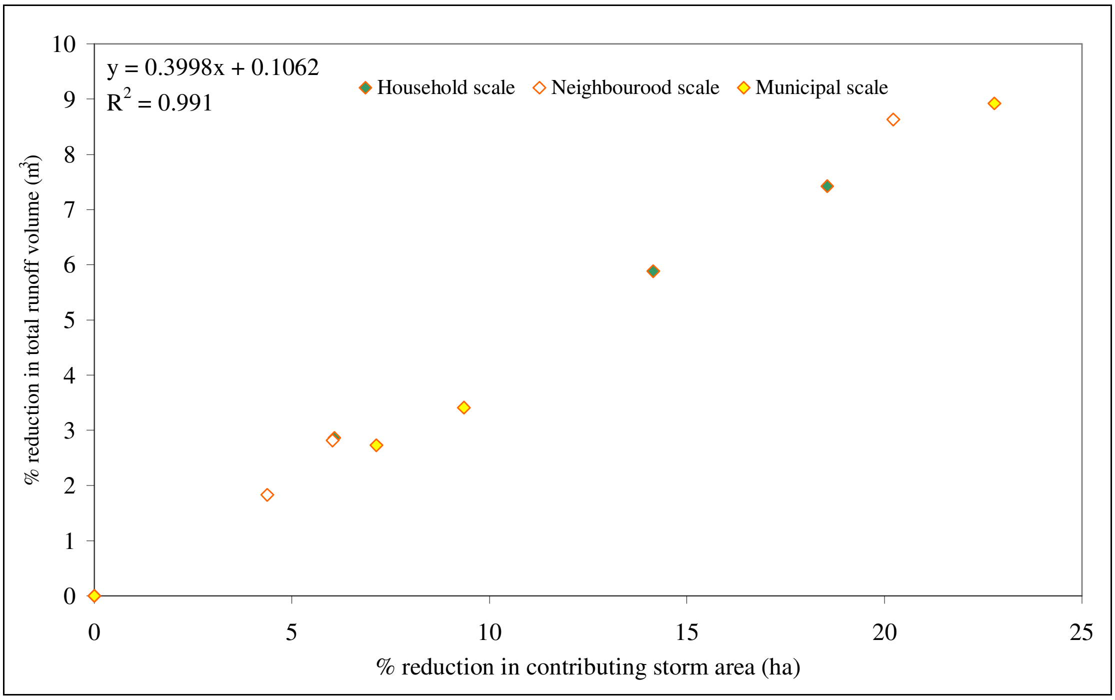


Figure A2.7. Comparison of scaling up rainwater harvesting on the total runoff volume reduction for a M100-240 event

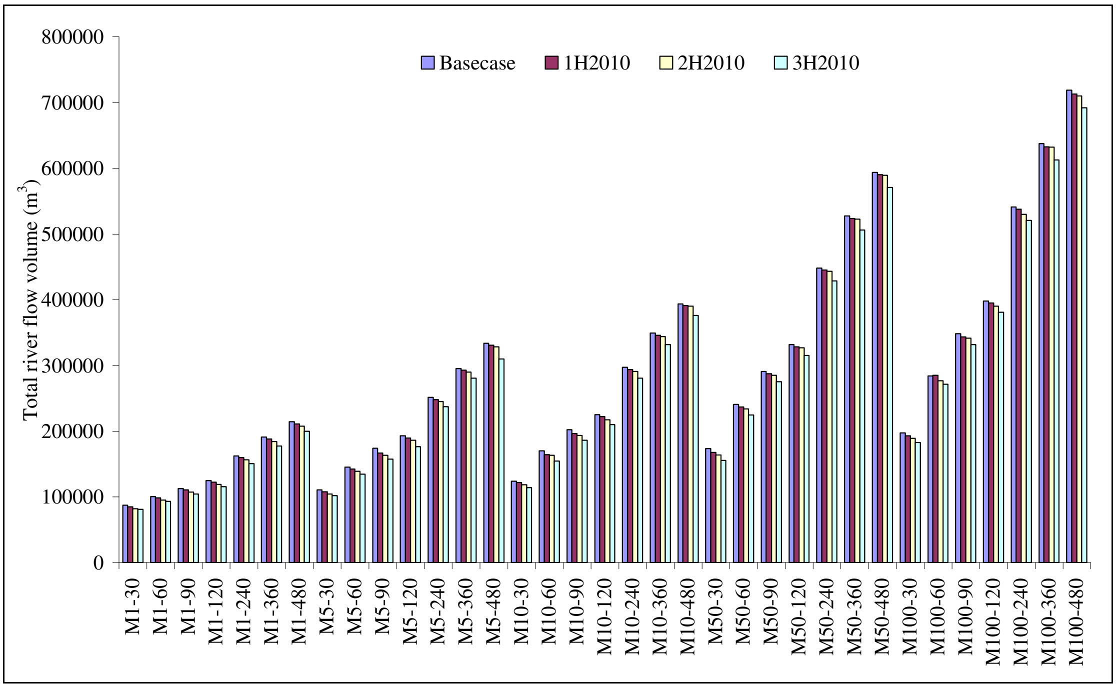


Figure A2.8. Total river flow volume urban development 2010 designed storm events

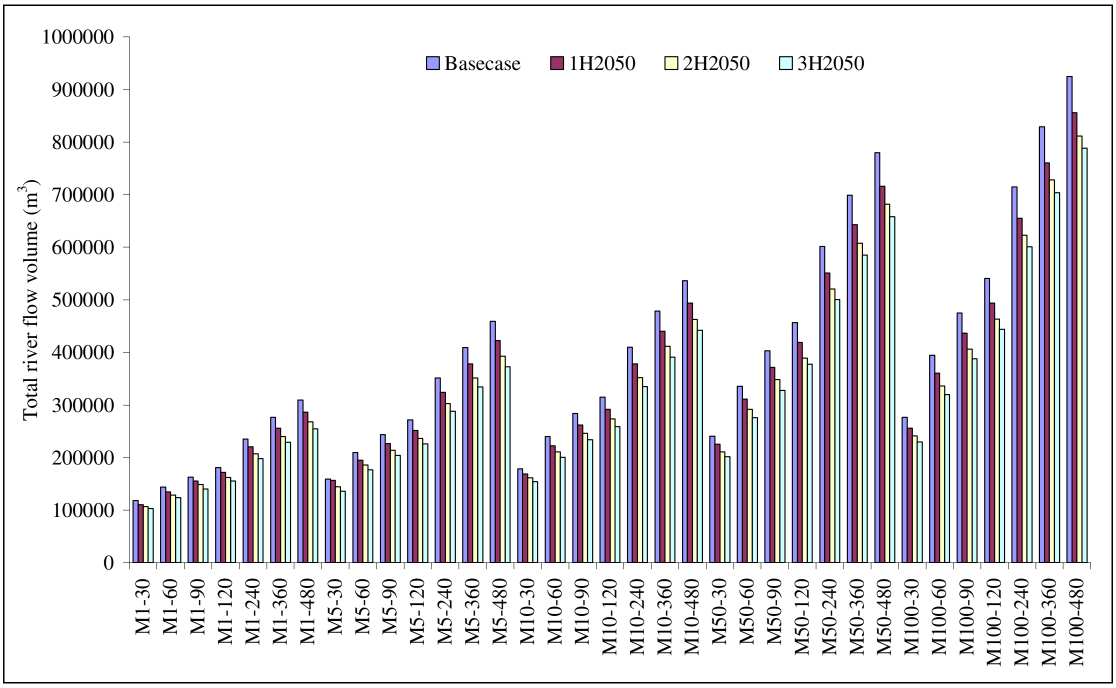


Figure A2.9. Total river flow volume urban development 2050 designed storm events

Table A2.9. Comparison of the total river flow volume (m^3) variation when rainwater harvesting systems are implemented at household scales in development 2010.

	Basecase	1B2010	2B2010	3B2010	%difference 1B2010	%difference 2B2010	%difference 3B2010
M5-30	110889	107684	104201.6	101692	3	6	8
M5-60	145055	142272	138843.4	134640	2	4	7
M5-90	174108	166648	163220.1	157332	4	6	10
M5-120	192878	189451	186136.7	176333	2	3	9
M5-240	251295	248210	245121.5	237169	1	2	6
M5-360	295537	292812	289959.1	280363	1	2	5
M5-480	333426	330498	328396.7	310012	1	2	7
M100-30	197442	192843	189285.7	182959	2	4	7
M100-60	283815	285104	276808.3	271183	0	2	4
M100-90	347980	343352	341564.3	331677	1	2	5
M100-120	398033	394837	390007.9	380894	1	2	4
M100-240	541177	537567	530002.1	520530	1	2	4
M100-360	637667	632535	632055.8	612845	1	1	4
M100-480	718923	712911	710048.5	691900	1	1	4

Table A2.10. Comparison of the total river flow volume (m^3) variation when rainwater harvesting systems are implemented at neighbourhood scales in development 2010.

	Basecase	1N2010	2N2010	3N2010	% difference 1N2010	% difference 2N2010	% difference 3N2010
M5-30	110889	101631	100108	95205	8.35	9.72	14.14
M5-60	145055	129326	127806	121319	10.84	11.89	16.36
M5-90	174108	148950	147052	140020	14.45	15.54	19.58
M5-120	192878	164976	163082	155086	14.47	15.45	19.59
M5-240	251295	216136	214807	202545	13.99	14.52	19.40
M5-360	295537	252412	251918	238525	14.59	14.76	19.29
M5-480	333426	283618	282897	268448	14.94	15.15	19.49
M100-30	197442	170704	168645	158455	13.54	14.59	19.75
M100-60	283815	241979	241862	231901	14.74	14.78	18.29
M100-90	347980	297561	296578	285431	14.49	14.77	17.98
M100-120	398033	338170	355203	328253	15.04	10.76	17.53
M100-240	541177	461140	461476	466493	14.79	14.73	13.80
M100-360	637667	542253	543053	530584	14.96	14.84	16.79
M100-480	718923	612433	613728	600222	14.81	14.63	16.51

Table A2.11. Comparison of the total river flow volume (m^3) variation when rainwater harvesting systems are implemented at municipal scales in development 2010.

	Basecase	1M2010	2M2010	3M2010	% difference 1M2010	% difference 2M2010	% difference 3M2010
M5-30	110889	102141	99759	98755	7.89	10.04	10.94
M5-60	145055	129222	126159	124376	10.91	13.03	14.26
M5-90	174108	149071	145060	143448	14.38	16.68	17.61
M5-120	192878	164450	160479	157656	14.74	16.80	18.26
M5-240	251295	215244	205546	202283	14.35	18.21	19.50
M5-360	295537	251315	239628	235957	14.96	18.92	20.16
M5-480	333426	281985	268325	264612	15.43	19.52	20.64
M100-30	197442	171281	163635	161636	13.25	17.12	18.13
M100-60	283815	240654	234125	230356	15.21	17.51	18.84
M100-90	347980	294025	286001	281351	15.51	17.81	19.15
M100-120	398033	337859	326568	321205	15.12	17.95	19.30
M100-240	541177	456131	444014	439209	15.71	17.95	18.84
M100-360	637667	537866	524084	522526	15.65	17.81	18.06
M100-480	718923	608893	593031	603655	15.30	17.51	16.03

Table A2.12. Comparison of the total river flow volume (m^3) variation between the three scales when rainwater harvestings are connected to 20% of the blocks.

Simulation	1B2010	1N2010	1M2010	std	Mean	%difference
M5-30	107684	101631	102141	3357	103819	3.23
M5-60	142272	129326	129222	7505	133607	5.62
M5-90	166648	148950	149071	10183	154889	6.57
M5-120	189451	164976	164450	14285	172959	8.26
M5-240	248210	216136	215244	18780	226530	8.29
M5-360	292812	252412	251315	23648	265513	8.91
M5-480	330498	283618	281985	27550	298700	9.22
M100-30	192843	170704	171281	12619	178276	7.08
M100-60	285104	241979	240654	25289	255912	9.88
M100-90	343352	297561	294025	27515	311646	8.83
M100-120	394837	338170	337859	32807	356955	9.19
M100-240	537567	461140	456131	45640	484946	9.41
M100-360	632535	542253	537866	53436	570884	9.36
M100-480	712911	612433	608893	59059	644746	9.16

Table A2.13. Comparison of the total river flow volume (m^3) variation between the three scales when rainwater harvestings are connected to 50% of the blocks.

Simulation	2B2010	2N2010	2M2010	std	Mean	%difference
M5-30	106602	100108	99759	3854	102156	3.77
M5-60	141243	127806	126159	8275	131736	6.28
M5-90	165620	147052	145060	11339	152577	7.43
M5-120	188537	163082	160479	15503	170699	9.08
M5-240	247521	214807	205546	22053	222625	9.91
M5-360	292359	251918	239628	27589	261302	10.56
M5-480	330797	282897	268325	32684	294006	11.12
M100-30	191686	168645	163635	14960	174655	8.57
M100-60	279208	241862	234125	24108	251732	9.58
M100-90	343964	296578	286001	30868	308848	9.99
M100-120	394918	355203	326568	34324	358896	9.56
M100-240	539772	461476	444014	50998	481754	10.59
M100-360	634456	543053	524084	59014	567198	10.40
M100-480	716248	613728	593031	65981	641003	10.29

Table A2.14. Comparison of the total river flow volume (m^3) variation between the three scales when rainwater harvestings are connected to 80% of the blocks.

Simulation	3B2010	3N2010	3M2010	std	Mean	% difference
M5-30	101692	95205	98755	3301	98517	3.30
M5-60	134640	121319	124376	7078	126694	5.50
M5-90	157332	140020	143448	9210	146895	6.24
M5-120	176333	155086	157656	11630	162993	7.11
M5-240	237169	202545	202283	20063	214003	9.38
M5-360	280363	238525	235957	24916	251632	9.91
M5-480	310012	268448	264612	23895	283004	8.96
M100-30	182959	158455	161636	13263	167742	7.95
M100-60	271183	231901	230356	23144	244474	9.46
M100-90	331677	285431	281351	27628	299928	9.33
M100-120	380894	328253	321205	32284	343942	9.50
M100-240	520530	466493	439209	44123	469978	8.71
M100-360	612845	530584	522526	49051	556631	9.00
M100-480	691900	600222	603655	51778	632134	8.22

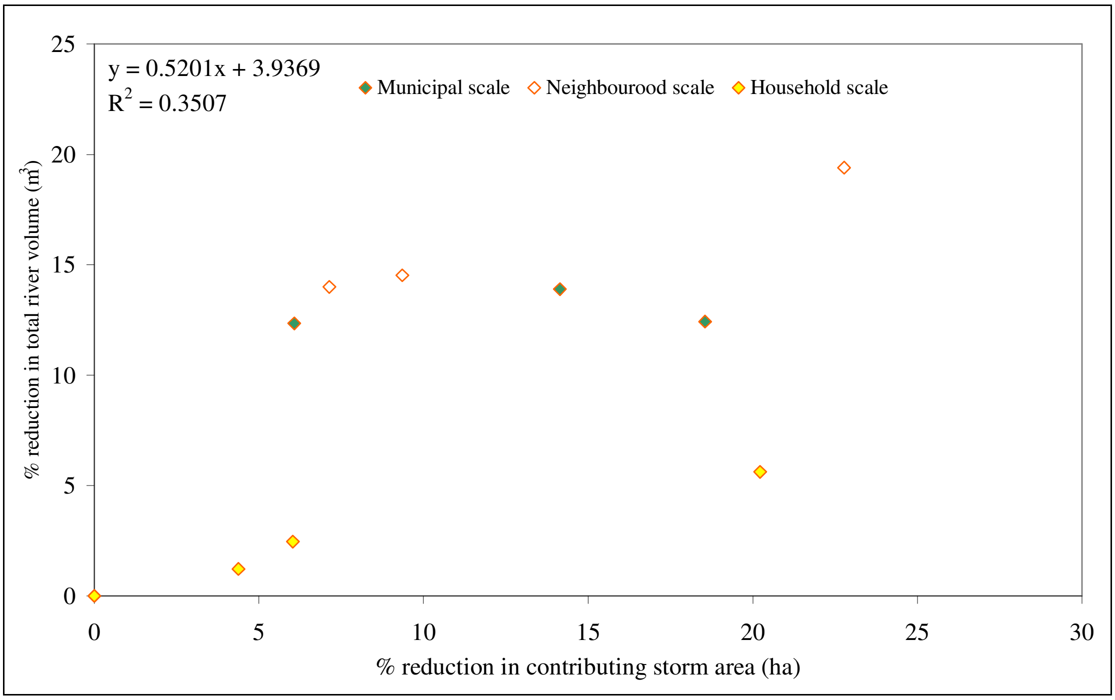


Figure A2.10. Comparison of scaling up rainwater harvesting on the total river volume reduction for a M5-240 event

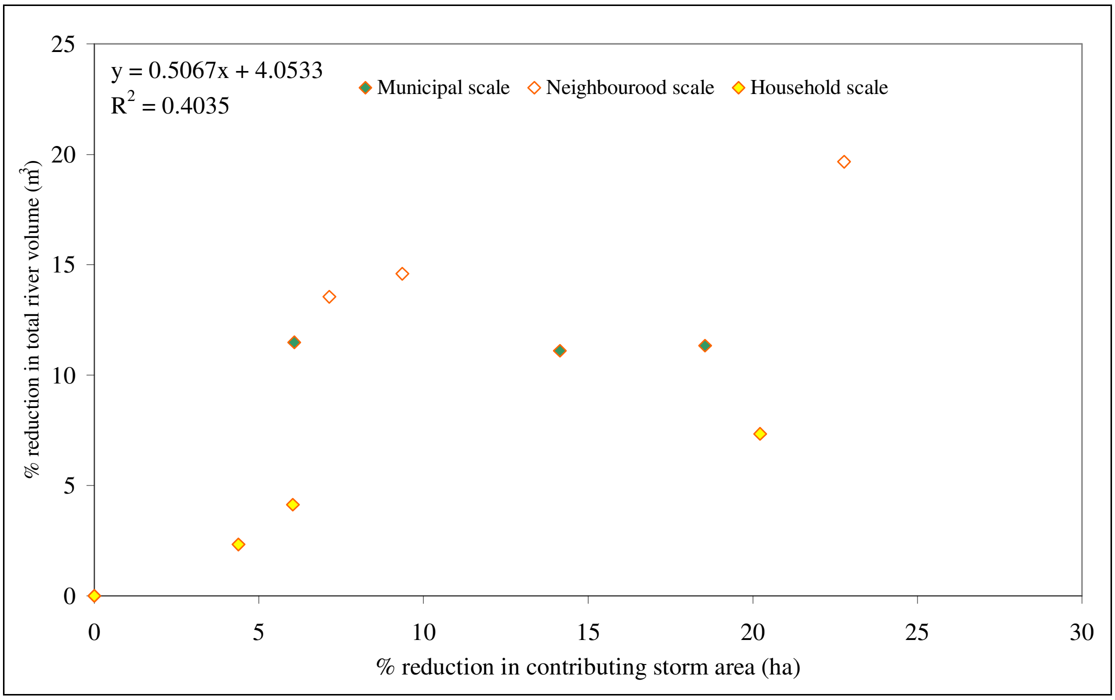


Figure A2.11. Comparison of scaling up rainwater harvesting on the total river volume reduction for a M100-30 event

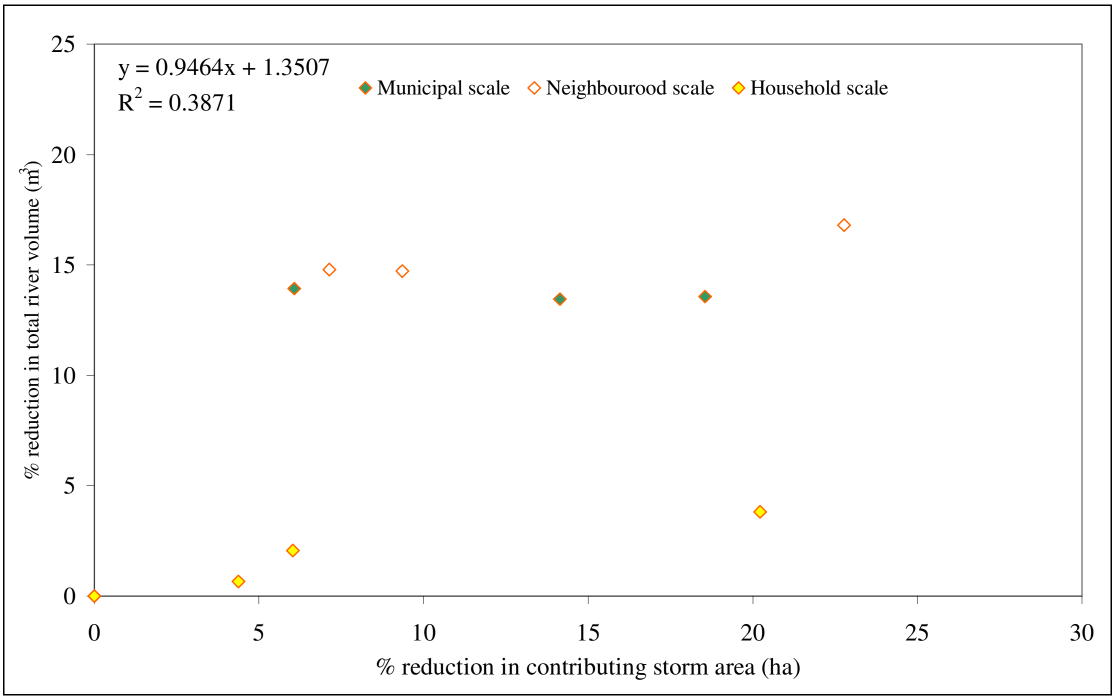


Figure A2.12. Comparison of scaling up rainwater harvesting on the total river volume reduction for a M100-240 event

Table A2.15. Comparison of the total river flow volume (m^3) variation when rainwater harvesting systems are implemented at municipal scales in development 2050.

	Basecase	1M2050	2M2050	3M2050	% difference 1M2050	% difference 2M2050	% difference 3M2050
M5-30	158826	156705	144772	136192	1	9	14
M5-60	209582	195005	185506	176826	7	11	16
M5-90	243768	226564	213655	204437	7	12	16
M5-120	271567	251554	236501	225833	7	13	17
M5-240	351190	323948	302638	288362	8	14	18
M5-360	409377	378123	351661	334367	8	14	18
M5-480	459208	422473	392642	372724	8	14	19
M100-30	276460	255883	241195	229548	7	13	17
M100-60	394383	360696	336337	319373	9	15	19
M100-90	474750	436738	406270	388084	8	14	18
M100-120	540941	493871	463668	443934	9	14	18
M100-240	714508	655256	622991	601044	8	13	16
M100-360	829059	760535	728244	703821	8	12	15
M100-480	924507	856124	811586	788303	7	12	15

Table A2.16. Comparison of the total volume (m^3) variation between the three scales when rainwater harvestings are connected to 20% of the blocks at the Carrickmines bridge river gauge.

	1B2010	1N2010	1M2010	std	Mean	% difference
M5-30	46890	44000	43442	1851	44777	4.13
M5-60	62709	56948	55970	3642	58542	6.22
M5-90	73912	66323	64840	4866	68358	7.12
M5-120	82734	73566	72025	5790	76108	7.61
M5-240	108691	95233	93110	8449	99011	8.53
M5-360	127870	111426	108803	10335	116033	8.91
M5-480	144289	125320	122307	11917	130639	9.12
M100-30	84382	74874	73428	5951	77561	7.67
M100-60	128458	107246	104791	13013	113498	11.47
M100-90	150363	130664	127736	12305	136254	9.03
M100-120	173051	149347	146205	14677	156201	9.40
M100-240	235009	203460	197658	20100	212042	9.48
M100-360	276400	238597	232792	23680	249263	9.50
M100-480	311818.9	269775	263371	26318	281655	9.34

Table A2.17. Comparison of the total volume (m^3) variation between the three scales when rainwater harvestings are connected to 50% of the blocks at the Carrickmines bridge river gauge.

	2B2010	2N2010	2M2010	std	Mean	% difference
M5-30	46712	42758	41247	2822	43572	6.48
M5-60	62705	55468	53067	5017	57080	8.79
M5-90	73957	64340	61060	6703	66453	10.09
M5-120	82878	71498	67914	7813	74097	10.54
M5-240	109114	93168	87393	11250	96558	11.65
M5-360	128500	109554	102114	13605	113389	12.00
M5-480	145213	123449	114805	15669	127822	12.26
M100-30	84694	72917	69094	8131	75568	10.76
M100-60	123262	105179	98094	12978	108845	11.92
M100-90	151591	129709	120153	16117	133817	12.04
M100-120	174108	163672	137471	18875	158417	11.91
M100-240	237846	201742	186253	26474	208614	12.69
M100-360	279709	237795	219799	30741	245768	12.51
M100-480	316231	269002	249154	34457	278129	12.39

Table A2.18. Comparison of the total volume (m^3) variation between the three scales when rainwater harvestings are connected to 80% of the blocks at the Carrickmines bridge river gauge.

	3B2010	3N2010	3M2010	std	Mean	% difference
M5-30	43066	39651	41253	1709	41324	4.13
M5-60	58164	51710	52922	3430	54265	6.32
M5-90	67860	60288	61831	4001	63327	6.32
M5-120	76525	67065	67739	5278	70443	7.49
M5-240	100311	88008	87292	7318	91870	7.97
M5-360	118505	103932	101982	9030	108140	8.35
M5-480	134206	117755	114663	10505	122208	8.60
M100-30	77651	68577	69045	5109	71758	7.12
M100-60	113424	99592	98001	8483	103672	8.18
M100-90	140406	123241	119758	11054	127802	8.65
M100-120	162052	142736	136861	13180	147216	8.95
M100-240	222315	194490	186627	18752	201144	9.32
M100-360	262109	232293	224505	19848	239636	8.28
M100-480	296629	260712	254921	22594	270754	8.35

Table A2.19. Comparison of the total volume (m^3) variation between the three scales when rainwater harvestings are connected to 20% of the blocks at the Common's road river gauge.

	1B2010	1N2010	1M2010	std	Mean	% difference
M5-30	104360	98829	99256	3078	100815	3.05
M5-60	137493	125310	125196	7067	129333	5.46
M5-90	160849	144075	144176	9655	149700	6.45
M5-120	179605	159373	158870	11829	165949	7.13
M5-240	235208	204684	203735	17904	214542	8.35
M5-360	276461	239006	237406	22101	250958	8.81
M5-480	311595	268287	266476	25543	282119	9.05
M100-30	183557	162675	163037	11953	169756	7.04
M100-60	272166	230741	229379	24319	244095	9.96
M100-90	326997	283585	279743	26243	296775	8.84
M100-120	376473	322542	320994	31593	340003	9.29
M100-240	512994	439485	434253	44029	462244	9.52
M100-360	603634	516747	512210	51524	544197	9.47
M100-480	680479	583801	579617	57063	614632	9.28

Table A2.20. Comparison of the total volume (m^3) variation between the three scales when rainwater harvestings are connected to 50% of the blocks at the Common's road river gauge.

	2B2010	2N2010	2M2010	std	Mean	% difference
M5-30	103286	97302	96953	3560	99180	3.59
M5-60	136484	123788	122129	7853	127467	6.16
M5-90	159794	142155	140172	10802	147374	7.33
M5-120	178753	157511	154903	13082	163722	7.99
M5-240	234568	203499	197952	19735	212006	9.31
M5-360	276160	238414	230561	24378	248378	9.81
M5-480	311815	268013	258006	28618	279278	10.25
M100-30	182501	160503	157906	13513	166970	8.09
M100-60	265786	230448	222082	23198	239439	9.69
M100-90	327498	282429	271486	29688	293804	10.10
M100-120	376690	338871	310458	33227	342006	9.72
M100-240	514875	439737	422121	49260	458911	10.73
M100-360	605720	517779	498017	57336	540505	10.61
M100-480	683714	585264	563823	63935	610934	10.47

Table A2.21. Comparison of the total volume (m^3) variation between the three scales when rainwater harvestings are connected to 80% of the blocks at the Common's road river gauge.

	3B2010	3N2010	3M2010	std	Mean	% difference
M5-30	98390	92328	95951	3050	95556	3.19
M5-60	129887	117065	120350	6660	122434	5.44
M5-90	151557	135043	138557	8699	141719	6.14
M5-120	169761	149436	152080	11051	157092	7.03
M5-240	223181	194983	194689	16366	204284	8.01
M5-360	263733	229538	226886	20551	240053	8.56
M5-480	297983	258592	254291	24080	270289	8.91
M100-30	173118	152932	155898	10900	160649	6.78
M100-60	257576	220810	218908	21797	232431	9.38
M100-90	313926	272640	267205	25551	284590	8.98
M100-120	361730	313696	304982	30560	326803	9.35
M100-240	495595	427560	416764	42739	446640	9.57
M100-360	583936	507882	496501	47537	529440	8.98
M100-480	659729	571625	574701	50002	602019	8.31

Table A 2.22. Comparison of the total flow volume (m^3) observed at the Carrickmines bridges river gauge when weir is connect at three different location along the river within development 2050.

	Node where weir is draining					
	E1	GR10	GR20	std	mean	% difference
M100-30	85770	85718	85717	30	85735	0.04
M100-60	125071	120774	120712	2499	122186	2.04
M100-90	145868	148899	149019	1785	147928	1.21
M100-120	166096	174554	174474	4860	171708	2.83
M100-240	222150	244638	244691	12999	237160	5.48
M100-360	257767	289953	290058	18613	279259	6.67
M100-480	289145	334595	328072	24575	317270	7.75

Table A2.23. Comparison of the total flow volume (m^3) observed at the Common's road river gauge when weir is connect at three different location along the river within development 2050.

	Node where weir is draining					
	E1	**GR10**	**GR20**	**std**	**mean**	**% difference**
M100-30	221623	221676	221669	28	221656	0.01
M100-60	313125	308682	308699	2560	310169	0.83
M100-90	374000	374393	374519	271	374304	0.07
M100-120	435602	429167	429144	3722	431304	0.86
M100-240	597448	581258	580763	9493	586490	1.62
M100-360	692488	679998	680007	7209	684164	1.05
M100-480	816146	767815	761377	29936	781779	3.83

Table A2.24. Variation of peak flow for 2010 scenarios for household scale systems. at the Carrickmines bridge river gauge.

	Basecase	**1B2010**	**2B2010**	**3B2010**	**%difference 1B2010**	**%difference 2B2010**	**%difference 3B2010**
M5-30	10	10	10	8	-1.83	0.62	23.50
M5-60	12	12	12	10	-2.40	-3.87	15.05
M5-90	12	12	12	11	-1.65	-3.58	12.70
M5-120	12	12	12	10	-1.20	-3.39	10.81
M5-240	10	10	10	9	-0.09	-2.11	10.53
M5-360	9	9	9	8	0.87	-0.82	10.73
M5-480	8	8	8	7	1.70	0.34	11.07
M100-30	16	16	16	14	-2.33	-2.80	12.56
M100-60	18	19	19	17	-2.27	-3.43	9.49
M100-90	19	19	19	17	-2.36	-3.80	8.15
M100-120	19	19	19	17	-2.51	-4.09	7.42
M100-240	17	17	18	16	-2.50	-4.29	6.70
M100-360	16	16	16	15	-1.68	-3.37	6.46
M100-480	15	15	15	14	-1.07	-2.70	6.26

Table A2.25. Variation of peak flow for 2010 scenarios for neighbourood scale systems. at the Carrickmines bridge river gauge.

	Basecase	1N2010	2N2010	3N2010	%difference 1N2010	%difference 2N2010	%difference 3N2010
M5-30	10	9	9	7	6.63	8.73	29.11
M5-60	12	11	11	9	4.60	4.21	20.71
M5-90	12	12	12	10	3.24	2.13	15.11
M5-120	12	12	12	11	0.60	-0.57	10.06
M5-240	10	11	11	10	-8.29	-8.54	-0.87
M5-360	9	10	10	9	-14.12	-13.53	-6.24
M5-480	8	9	9	9	-16.16	-14.95	-10.78
M100-30	16	15	15	14	4.57	3.41	13.75
M100-60	18	18	18	17	2.92	0.96	8.72
M100-90	19	18	19	18	1.68	-0.44	6.04
M100-120	19	18	19	18	0.54	-1.89	3.64
M100-240	17	18	18	17	-3.87	-6.67	-1.86
M100-360	16	16	17	16	-5.04	-8.26	-3.70
M100-480	15	16	16	15	-4.55	-7.83	-3.38

Table A2.26. Variation of peak flow for 2010 scenarios for municipal scale systems. at the Carrickmines bridge river gauge.

	Basecase	1M2010	2M2010	3M2010	%difference 1M2010	%difference 2M2010	%difference 3M2010
M5-30	10	8	6	6	20.10	34.67	34.67
M5-60	12	10	8	8	15.49	29.58	29.58
M5-90	12	11	9	9	12.35	26.30	26.31
M5-120	12	11	9	9	8.89	23.00	23.01
M5-240	10	10	9	9	-0.49	12.79	12.77
M5-360	9	9	8	8	-7.00	5.56	5.85
M5-480	8	9	8	8	-9.82	2.20	2.66
M100-30	16	14	12	12	12.26	26.31	26.31
M100-60	18	16	14	14	9.85	21.32	21.31
M100-90	19	17	15	15	8.12	19.08	19.09
M100-120	19	17	15	15	6.95	17.72	17.76
M100-240	17	16	15	15	3.28	14.10	14.22
M100-360	16	15	14	14	2.00	12.45	12.61
M100-480	15	15	13	13	2.01	11.07	11.49

Table A2.27. Comparison of the peak flow (m^3/s) variation between the three scales when rainwater harvestings are connected to 20% of the blocks at the Carrickmines bridge river gauge.

	1B2010	1N2010	1M2010	std	Mean	% difference
M5-30	10	9	8	1	9	12.06
M5-60	12	11	10	1	11	9.58
M5-90	12	12	11	1	11	7.45
M5-120	12	12	11	1	11	5.53
M5-240	10	11	10	0	10	4.49
M5-360	9	10	9	1	9	7.02
M5-480	8	9	9	1	9	8.38
M100-30	16	15	14	1	15	7.67
M100-60	19	18	16	1	18	6.30
M100-90	19	18	17	1	18	5.42
M100-120	19	18	17	1	18	4.91
M100-240	17	18	16	1	17	3.76
M100-360	16	16	15	1	16	3.47
M100-480	15	16	15	0	15	3.24

Table A2.28. Comparison of the peak flow (m^3/s) variation between the three scales when rainwater harvestings are connected to 50% of the blocks at the Carrickmines bridge river gauge.

	2B2010	2N2010	2M2010	std	Mean	% difference
M5-30	10	9	6	2	8	20.85
M5-60	12	11	8	2	11	19.39
M5-90	12	12	9	2	11	17.30
M5-120	12	12	9	2	11	15.47
M5-240	10	11	9	1	10	11.02
M5-360	9	10	8	1	9	9.44
M5-480	8	9	8	1	8	9.04
M100-30	16	15	12	2	15	16.84
M100-60	19	18	14	2	17	14.09
M100-90	19	19	15	2	18	13.00
M100-120	19	19	15	2	18	12.50
M100-240	18	18	15	2	17	11.49
M100-360	16	17	14	2	16	10.86
M100-480	15	16	13	1	15	9.79

Table A2.29. Comparison of the peak flow (m^3/s) variation between the three scales when rainwater harvestings are connected to 80% of the blocks at the Carrickmines bridge river gauge.

	3B2010	3N2010	3M2010	std	Mean	% difference
M5-30	8	7	6	1	7	7.88
M5-60	10	9	8	1	9	9.36
M5-90	11	10	9	1	10	8.86
M5-120	10	11	9	1	10	8.51
M5-240	9	10	9	1	9	7.91
M5-360	8	9	8	1	8	9.05
M5-480	7	9	8	1	8	11.13
M100-30	14	14	12	1	13	9.24
M100-60	17	17	14	1	16	8.13
M100-90	17	18	15	1	17	7.88
M100-120	17	18	15	1	17	8.08
M100-240	16	17	15	1	16	8.59
M100-360	15	16	14	1	15	8.68
M100-480	14	15	13	1	14	7.92

Table A2.30. Comparison of the peak flow (m^3/s) variation between the three scales when rainwater harvestings are connected to 20% of the blocks at the Common's bridge river gauge.

	1B2010	1N2010	1M2010	std	Mean	% difference
M5-30	8	7	7	0	7	6.07
M5-60	11	10	9	1	10	9.10
M5-90	13	12	11	1	12	8.40
M5-120	14	13	12	1	13	8.20
M5-240	15	14	14	1	14	5.88
M5-360	15	14	14	0	14	3.26
M5-480	14	14	14	0	14	1.76
M100-30	16	14	14	1	15	8.22
M100-60	21	19	19	1	20	6.77
M100-90	24	22	21	1	22	6.11
M100-120	26	24	23	1	24	5.88
M100-240	29	26	26	2	27	6.35
M100-360	29	27	27	2	28	5.65
M100-480	29	27	27	1	28	4.37

Table A2.31. Comparison of the peak flow (m^3/s) variation between the three scales when rainwater harvestings are connected to 50% of the blocks at the Common's bridge river gauge.

	2B2010	2N2010	2M2010	std	Mean	% difference
M5-30	7	7	7	0	7	5.61
M5-60	11	10	9	1	10	9.22
M5-90	13	12	11	1	12	8.65
M5-120	14	13	12	1	13	8.35
M5-240	15	14	14	1	14	6.15
M5-360	15	14	14	0	14	3.46
M5-480	14	14	14	0	14	1.92
M100-30	16	14	14	1	15	8.13
M100-60	21	19	19	1	20	6.72
M100-90	24	22	21	1	22	6.19
M100-120	26	24	23	1	24	5.97
M100-240	29	26	26	2	27	6.50
M100-360	30	27	27	2	28	5.83
M100-480	29	27	27	1	28	4.61

Table A2.32. Comparison of the peak flow (m^3/s) variation between the three scales when rainwater harvestings are connected to 80% of the blocks at the Common's bridge river gauge.

	3B2010	3N2010	3M2010	std	Mean	% difference
M5-30	7	6	6	0	7	2.74
M5-60	10	9	8	1	9	7.86
M5-90	12	10	10	1	11	7.96
M5-120	13	11	11	1	12	7.79
M5-240	14	13	12	1	13	6.19
M5-360	13	13	12	1	13	4.40
M5-480	13	13	12	0	13	3.69
M100-30	14	13	12	1	13	9.33
M100-60	20	19	17	1	19	7.30
M100-90	23	21	20	1	22	6.66
M100-120	25	23	22	1	23	6.30
M100-240	28	26	25	2	26	6.77
M100-360	28	27	25	2	27	5.98
M100-480	28	27	25	1	27	5.01

Table A2.33. Comparison of the peak flow (m^3/s) observed at the Carrickmines bridges river gauge when weir is connect at three different location along the river

	Node where weir is draining					
	E1	**GR10**	**GR20**	**std**	**mean**	**% difference**
M100-30	17	17	17	0	17	0.00
M100-60	20	20	20	0	20	0.04
M100-90	21	21	21	0	21	0.00
M100-120	21	21	21	0	21	1.25
M100-240	20	22	26	3	23	12.53
M100-360	19	22	25	3	22	13.81
M100-480	18	22	25	3	22	14.45

Table A2.34. Comparison of the peak flow (m^3/s) observed at the Common's road river gauge when weir is connect at three different location along the river

	Node where weir is draining					
	E1	**GR10**	**GR20**	**std**	**mean**	**% difference**
M100-30	27	27	27	0	27	0.10
M100-60	37	37	37	0	37	0.17
M100-90	41	41	41	0	41	0.18
M100-120	43	43	43	0	43	0.66
M100-240	46	44	44	1	45	1.41
M100-360	44	43	43	1	43	1.96
M100-480	43	42	42	1	42	2.52

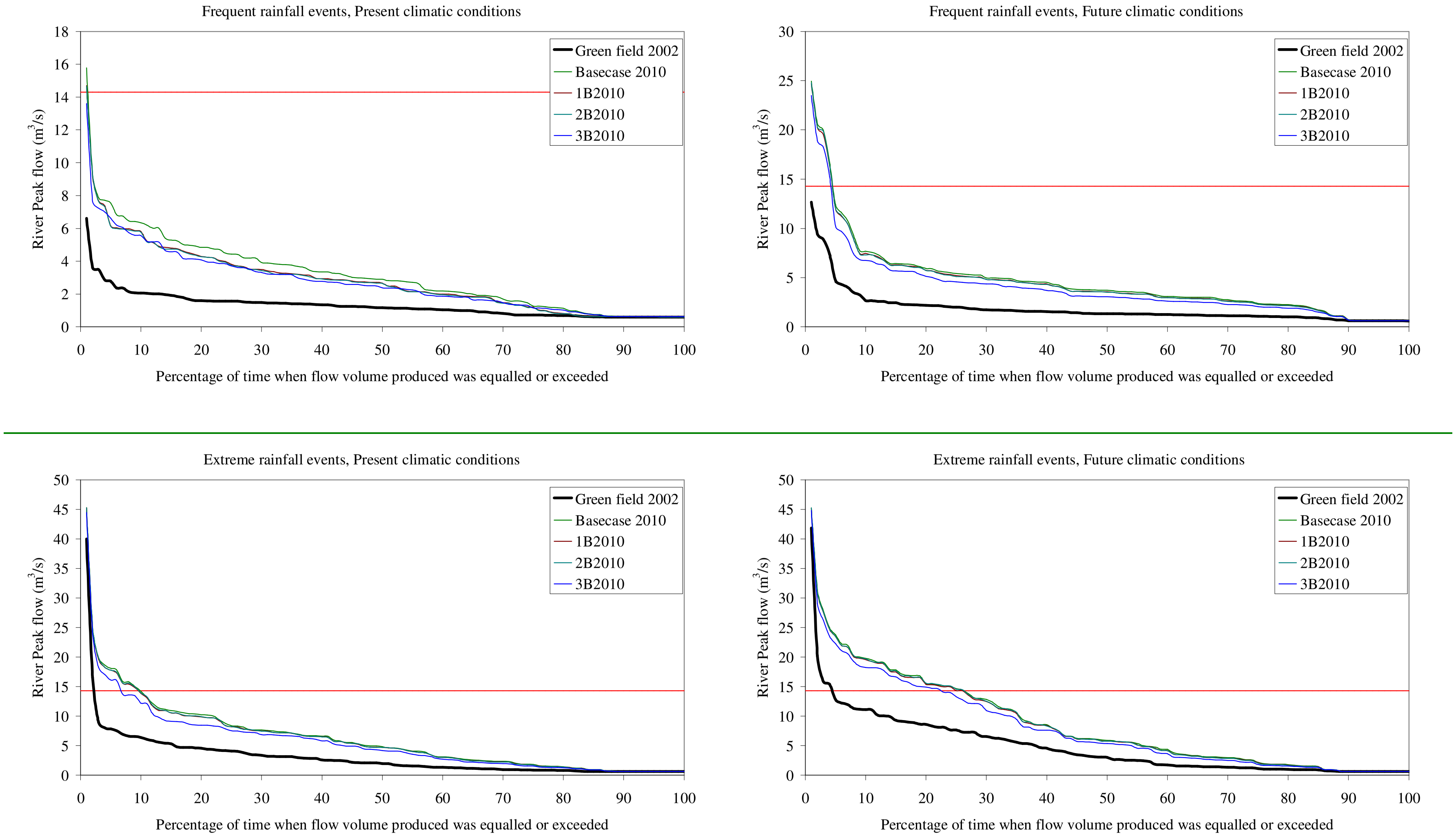


Figure A2.13. Peak flow variation at Common's road river gauges obtained for development 2010.

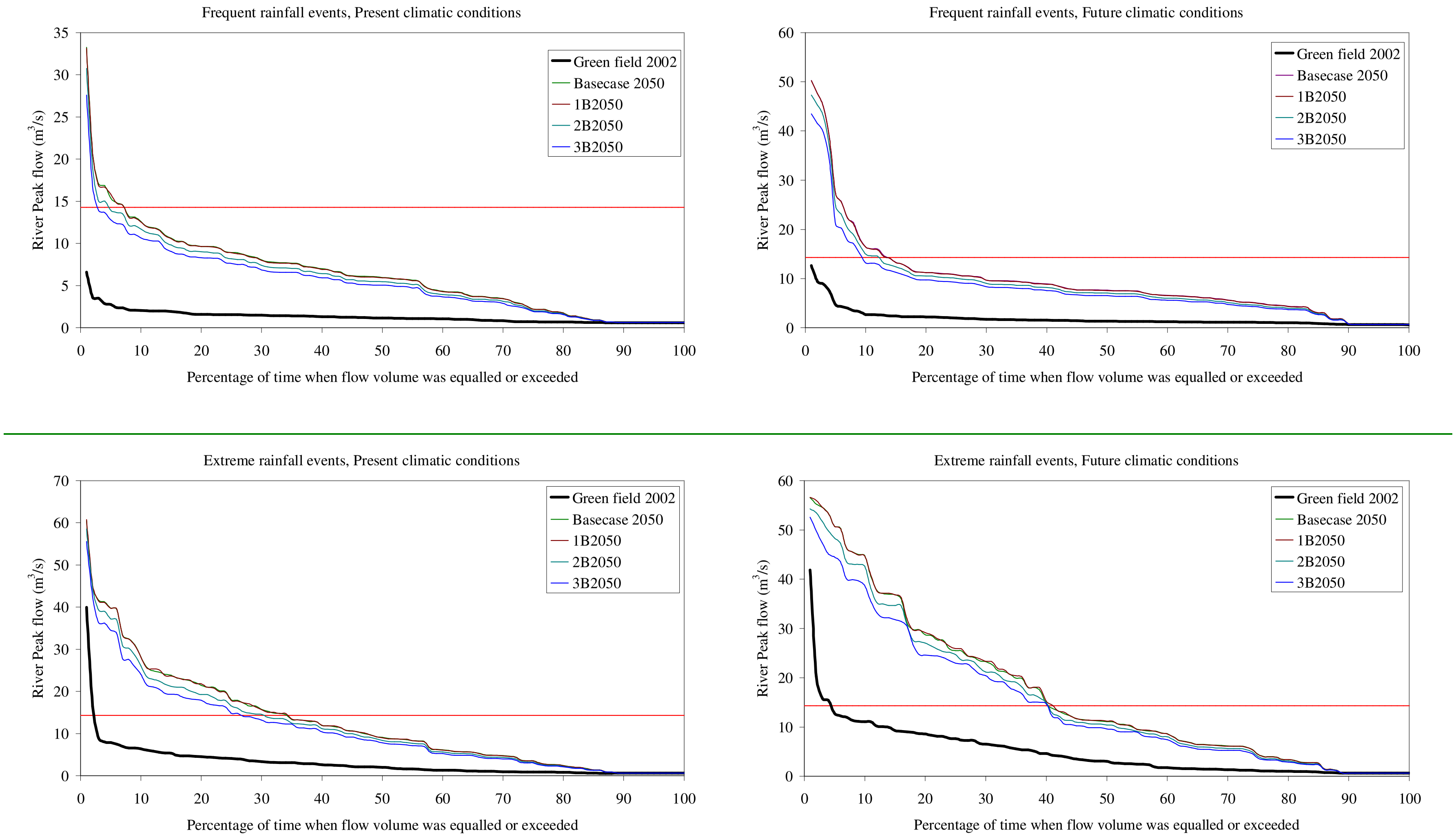


Figure A 2.14. Peak flow variation at Common's road river gauges obtained for development 2050.

Table A2.35. Total weir overflow in m^3 for household scale in 2010.

	1B2010	**2B2010**	**3B2010**
M5-30	0	0	66
M5-60	139	460	441
M5-90	346	713	1087
M5-120	472	1181	1677
M5-240	1243	2735	4184
M5-360	1929	4331	6274
M5-480	2467	5546	8146
M100-30	511	1131	1727
M100-60	1759	4077	5304
M100-90	2649	6048	8971
M100-120	3477	7949	12143
M100-240	5233	12819	19033
M100-360	6433	15334	23328
M100-480	7349	17681	26513

Table A2.36. Total weir overflow in m^3 for neighbourhood scale in 2010.

	1N2010	2N2010	3N2010
M5-30	183	24	233
M5-60	526	414	1339
M5-90	918	600	2050
M5-120	1141	1268	2692
M5-240	2171	3370	6908
M5-360	2873	4971	10613
M5-480	3308	5791	12365
M100-30	1029	1104	3187
M100-60	2734	4389	8845
M100-90	3666	6654	14641
M100-120	4554	19161	17942
M100-240	6552	13266	31451
M100-360	7864	16015	32897
M100-480	8471	18398	36920

Table A2.37. Total weir overflow in m^3 for municipal scale in 2010.

	1M2010	2M2010	3M2010
M5-30	1802	4779	7161
M5-60	2482	6642	10000
M5-90	3024	8439	12062
M5-120	3375	9038	13570
M5-240	4413	11756	19094
M5-360	5156	13604	20784
M5-480	5618	14741	22746
M100-30	3470	8857	12930
M100-60	4940	13068	20256
M100-90	5913	15493	23820
M100-120	6460	17764	26260
M100-240	8912	24872	36340
M100-360	9752	26406	41640
M100-480	10770	29465	44712

Table A2.38. Total weir overflow in m^3 for municipal scale in 2050.

	1M2050	2M2050	3M2050
M5-30	0	0	0
M5-60	0	0	0
M5-90	0	0	0
M5-120	0	0	0
M5-240	0	0	0
M5-360	0	0	0
M5-480	307	0	0
M100-30	0	0	0
M100-60	0	0	0
M100-90	1063	1262	2828
M100-120	2614	5030	8738
M100-240	6389	14690	23698
M100-360	8868	20567	33340
M100-480	10573	24855	38077

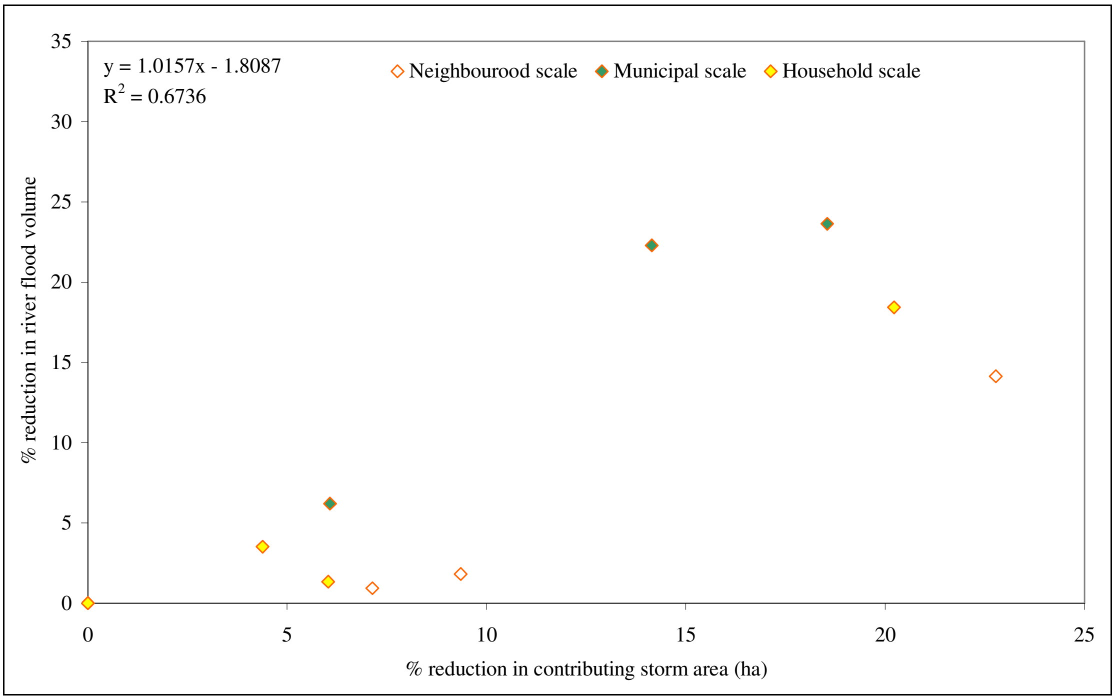


Figure A2.15. Comparison of scaling up rainwater harvesting on the total river flood reduction for a M5-240 event.

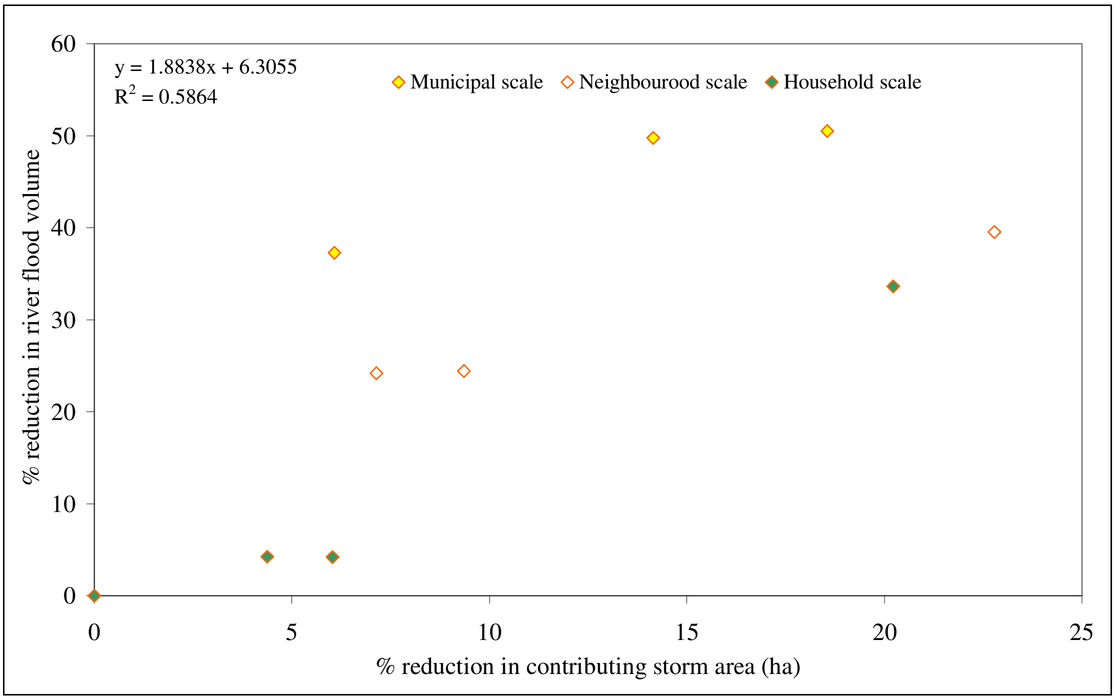


Figure A2.16. Comparison of scaling up rainwater harvesting on the total river flood reduction for a M100-30 event.

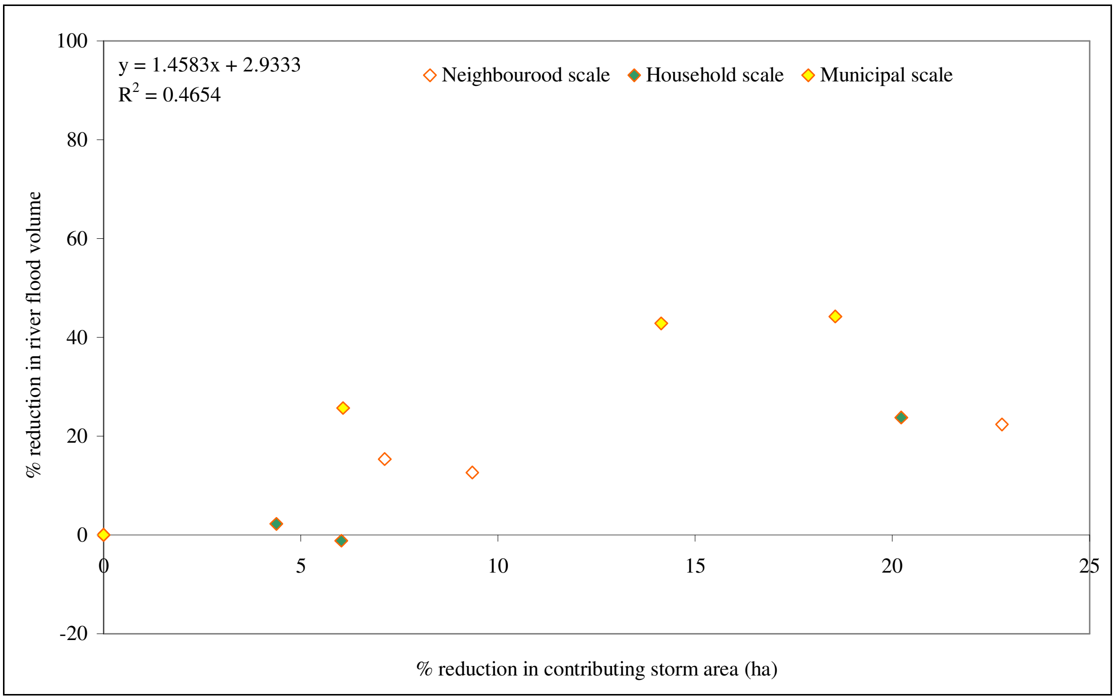


Figure A2.17. Comparison of scaling up rainwater harvesting on the total river flood reduction for a M100-240 event.

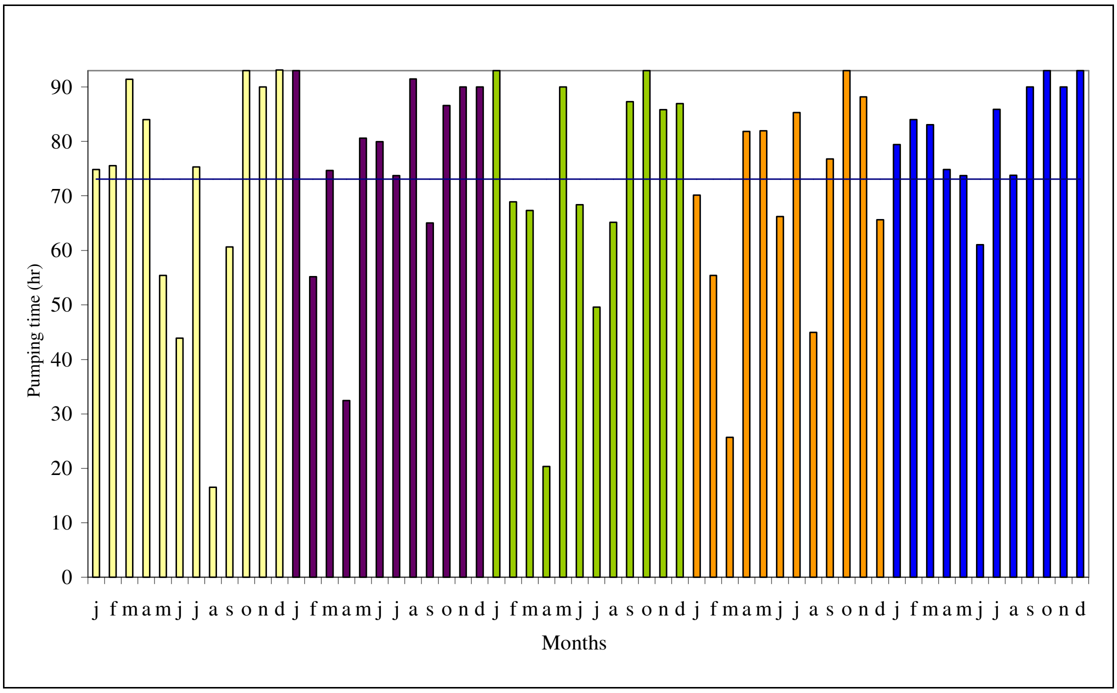


Figure A2.18. Comparison of the pumping hours per month for the 5 year present time (1981-1985).

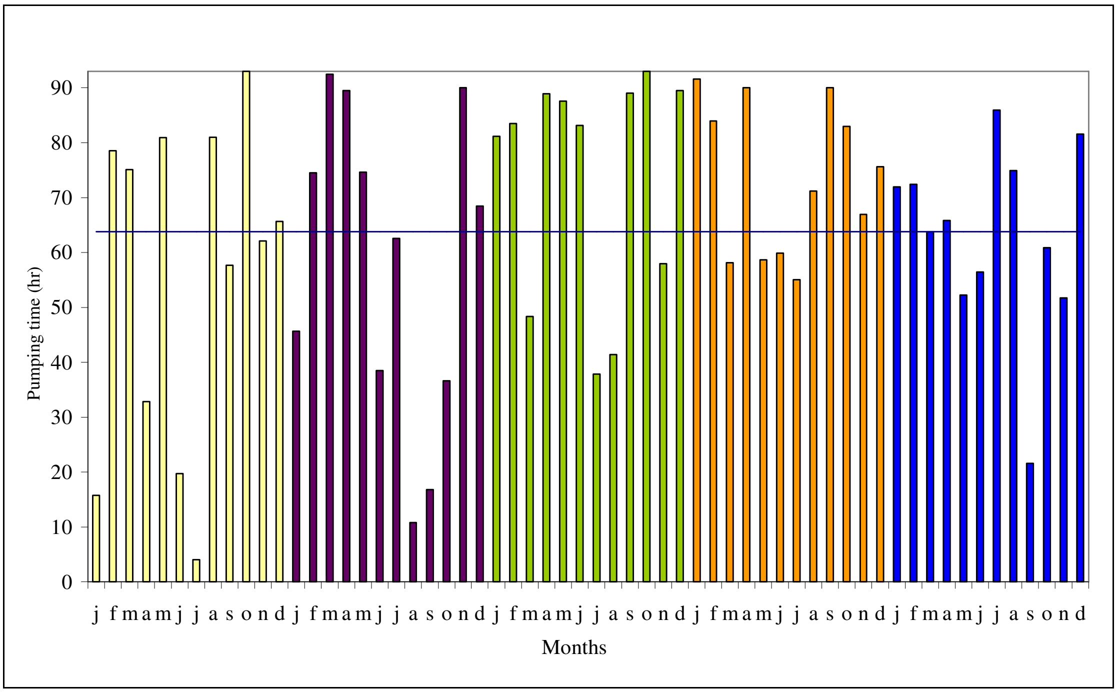
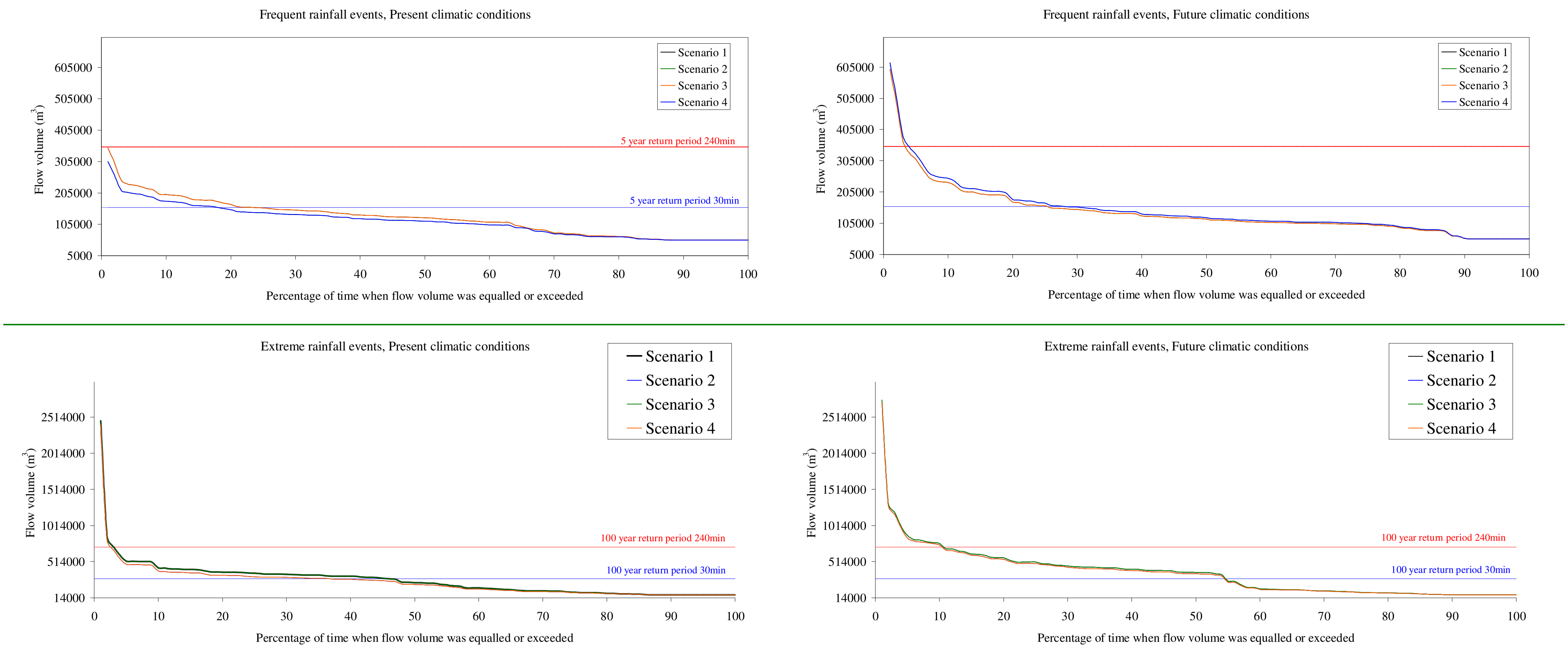


Figure A2.19. Comparison of the pumping hours per month for the 5 year present time (2075-2079).

Annex 3 Additional results from combined technologies simulations


Frequent rainfall events, Present climatic conditions

Frequent rainfall events, Future climatic conditions

Extreme rainfall events, Present climatic conditions

Extreme rainfall events, Future climatic conditions

Figure A 3.1. Total flow volume with the river.

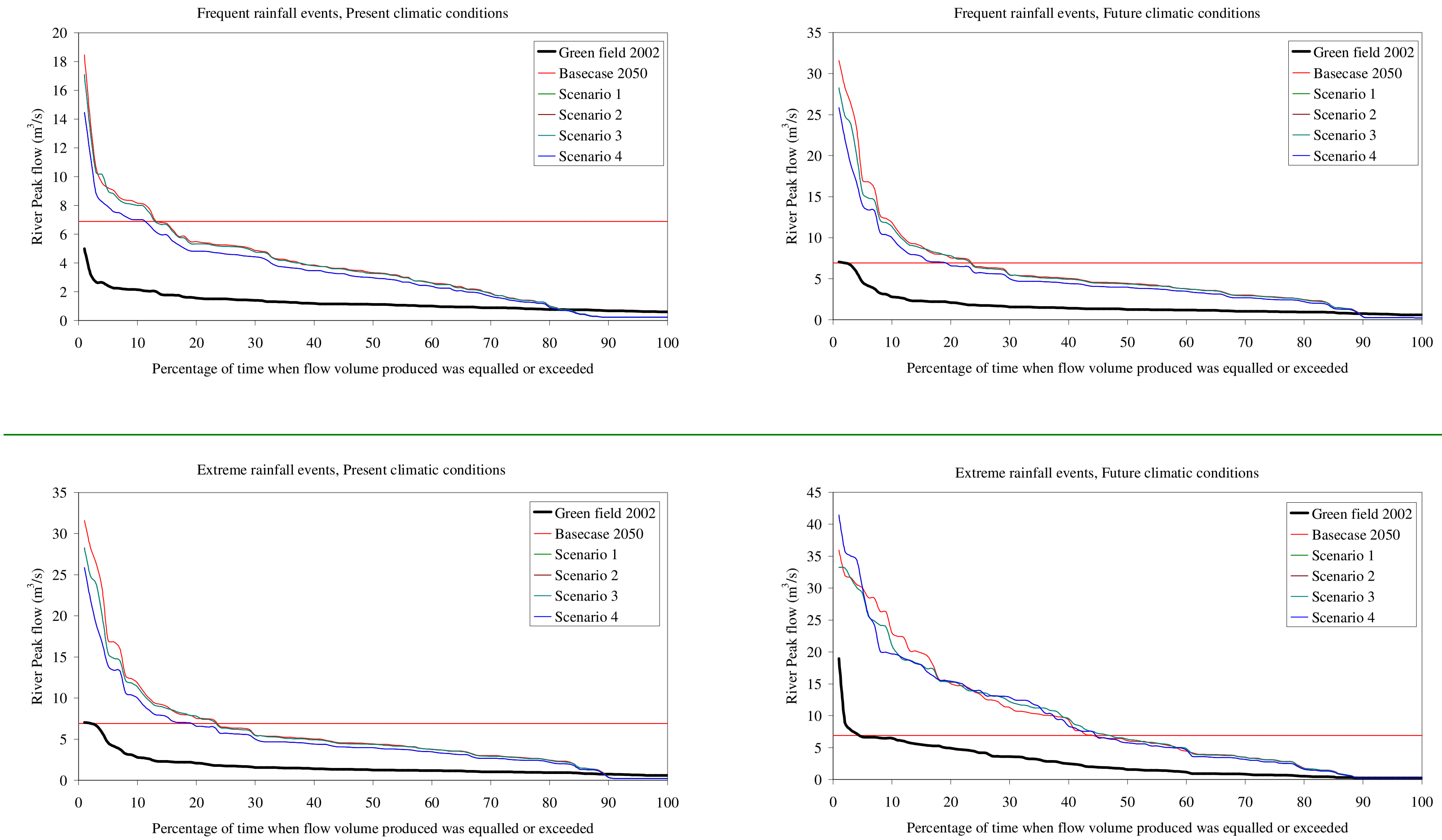


Figure A 3.2. Peak flow variation at Carrickmines Bridge river gauges

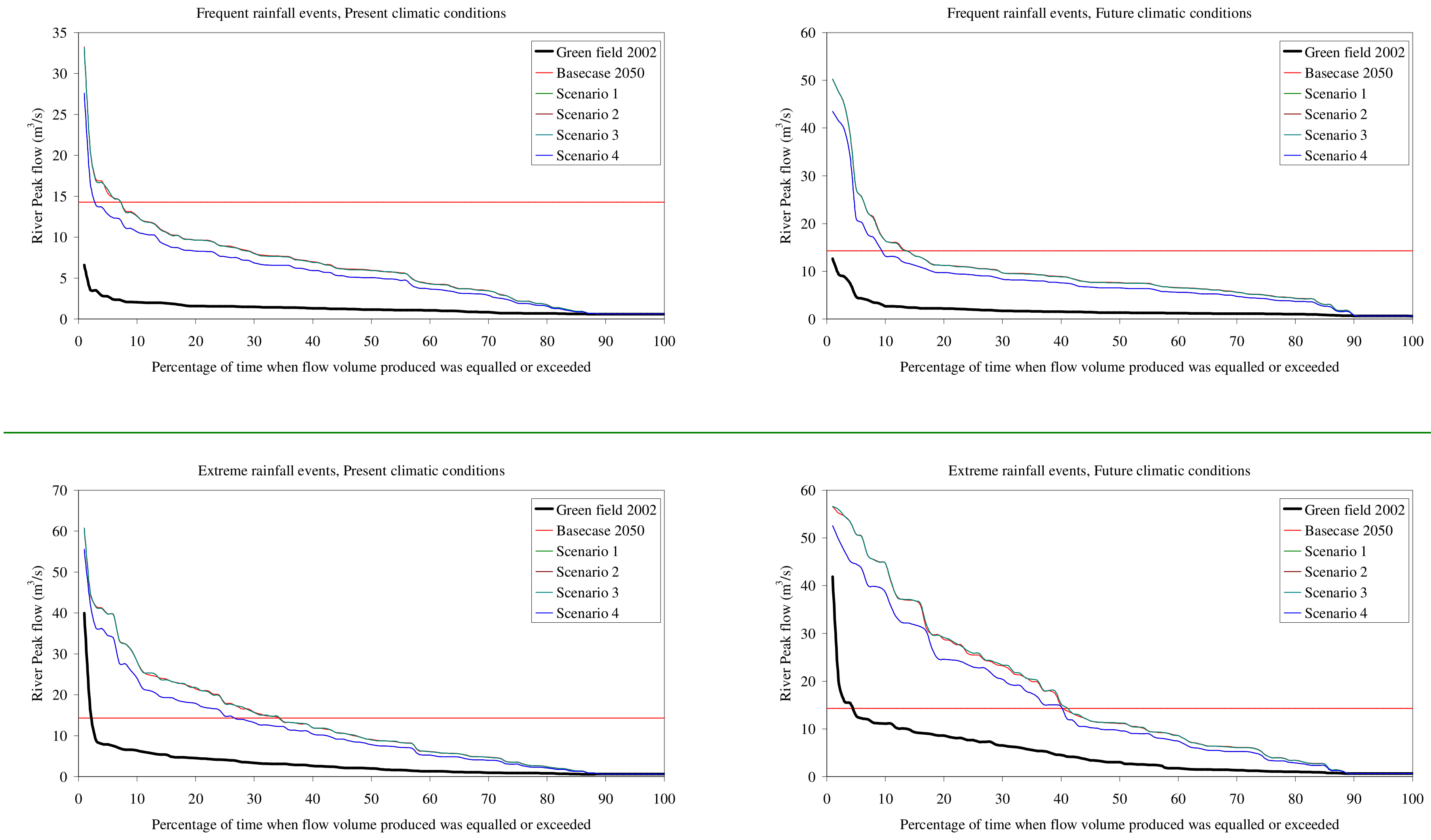


Figure A 3.3. Peak flow variation at Common's road river gauges