Improving the flood resistance of sewer systems through strategic positioning and design of flow controls

Submitted by

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Abstract

Sewer systems are designed and installed to convey stormwater and wastewater from areas where it is collected to a treatment works or a suitable discharge point into a natural watercourse. Over time, however, changes in climate, population growth and urbanisation increase the flows these sewer systems need to convey.

This thesis discusses a method, and developed assessment framework, to propose solutions to address flood risk. The method involves iteratively simulating a sewer system and designing vortex flow controls and orifice plates into the sewer system. These passive flow controls are designed into the sewer system, whilst accounting for sub-catchment flood vulnerability scores, to attenuate potential flood volumes and make use of available storage capacities in the upstream sections of the sewer system. The flow control positioning method uses the SWMM 5 program to simulate the sewer system, a developed hyetograph generator for the rainfall inputs and a flow control design tool. The whole assessment framework was programmed in Microsoft Excel and VBA. Vortex flow controls and orifice plates were chosen as they require no power, have no moving parts and are self-activating. Vortex flow controls are primarily designed into the sewer system, over orifice plates, due to their higher mean flow-rate and reduced blockage risk due to the larger outlet diameters.

Four sewer system models were used to demonstrate the application of the assessment framework, in which one model was hypothetical and three were anonymised. The smallest model consisted of 14 nodes and collected surface runoff from 1.5 hectares. The largest model consisted of over 280 nodes and was a combined sewer system from a town in the South-East of England.

In the application of the assessment framework, it was shown that strategically positioning and designing passive flow controls into the sewer system can have a beneficial effect by reducing flood risk. In one case study, the flood resistance level of a sewer system was increased from a 1 in 3 year return period to a 1 in 108 year return period. In the largest case study, which was of a combined sewer system, the flood resistance level was increased from a 1 in 1 year return period to a 1 in 71 year return period. The results of the analyses also found that installing vortex flow controls, instead of orifice plates only, tended to achieve a greater increase in the flood resistance level. Comparison of the proposed solutions from the method to alternative flood alleviation methods shows that the strategic positioning of passive flow controls to be a competitive and feasible solution to reduce flood risk.

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Contents

List of publications

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Newton, C J, Jarman, D S, Memon, F A, Andoh , R Y & Butler, D. (2013). *Implementation and assessment of a critical input hyetograph generation methodology for use in a decision support tool for the design of flood attenuation systems*. International Conference on Flood Resistance. Exeter: University of Exeter. 5th-7th September 2013.

Newton, C J, Jarman, D S, Memon, F A, Andoh, R Y & Butler, D. (2014). *Development of a decision support tool for the positioning and sizing of vortex flow controls in existing sewer systems.* Procedia Engineering, 70, 1231-1240.

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Abbreviations

CIH	Critical input hyetograph
CS	Collection system
CSO	Combined sewer overflow
DfE	Designing for Exceedance
DWF	Dry weather flow
FR level	Flood resistance level
FSR	Flood Studies Report
FVS	Flood vulnerability score
OAT	One-factor-at-a-time
OP	Orifice plate
RFSWIM	Risk of flooding from surface water interactive map
RMSD	Root mean square difference
SEPA	Scottish Environment Protection Agency
SWMM	Storm Water Management Model
VBA	Visual Basic for Applications
VFC	Vortex flow control

Notations

Parameter	Description	Units
A_h	Area of storage as a function of head	m^2
$A_{n,i}$	Internal cross-sectional area of assessed node	m^2
Cap	Total used volumetric capacity of the sewer system	
Cap_D	Greatest acceptable ratio of sewer system fullness	-
Cap_S	User selected ratio of used sewer system capacity before increasing the volumetric capacity of a manhole chamber.	-
C_B	Capital budget for the retrofit works to the sewer system	£
C_{BF}	Increase in the value of the financial budget stop condition to expand search space.	-
C_C	Consultancy fee	%
C_d	Coefficient of discharge	-
C_{FC}	Cost of the flow control	£
C_I	User desired cost to install a flow control.	£
C_R	User defined cost to increase the volumetric capacity of a manhole chamber.	£
C_S	Cost of installing storage.	£
C_T	Total cost of the design	£

D	Cross-sectional diameter	m
D_d	Design head of water for the flow control.	m
D_i	Flow control invert level	m
d_j	Internal diameter of the conduit	m
$d_{o,min}$	Minimum flow control outlet diameter.	mm
$D_{W,i}$	Depth of water in node.	m
FR_F	User selected increase in the value of the FR level stop condition to expand search space.	-
FR_L	Targeted FR level quantified as 1 in 'x' years return period.	years
g	Acceleration due to gravity	m/s^2
h	Head of water.	m
H_S	Head left between maximum design head of the flow control and the cover level of the manhole chamber.	m
L_j	Length of the conduit.	m
$M5\text{-}60$	Expected depth of rainfall to fall in 60 minutes with a return period of 1 in 5 years.	mm
$\overline{P_f}$	Mean of the pipe full ratios of the conduits	-
$P_{f,j}$	Pipe full ratio of the conduit.	-
Q	Flow-rate	l/s
Q_C	Maximum desired outflow-rate of the sewer system	l/s
$Ratio\text{-}R$	Ratio of the M5-60 value and M5-2880 value	-
S_V	Flood vulnerability score	-

V_F	Flood volume	m^3
V_{in}	Volume of water entering the storage chamber.	m^3
$V_{l,j}$	Volume available in the conduit	m^3
$V_{n,i}$	Volume available in the node	m^3
V_{out}	Volume of water leaving the storage chamber.	m^3
V_T	Total available upstream volume	m^3
V_W	Weighted total available upstream volume	m^3

Chapter 1

Introduction

1.1 Background, rationale and justification

Sewer systems are designed and constructed in catchments to provide an essential health and wellbeing service by conveying unwanted wastewater and/or surface water runoff to treatment works and suitable discharge locations (Butler & Davies, 2011). Ponding surface water runoff and wastewater are undesirable in both rural and urban locations as: wastewater contains human waste and possibly diseases; and surface water runoff potentially contains toxic contaminants collected from the catchment. Excessive volumes of wastewater and/or surface water runoff can also cause flooding, which can pose a risk to human lives and cause damage to infrastructure.

Sewer systems, in most modern civilisations, are belowground assets belonging to the local authority or the local sewerage company. These systems typically consist of manhole chambers, conduits, pipes, pumps and storage chambers. The majority of the sewer system infrastructure, in major cities, was designed and installed over a hundred years ago (Hughes, 2013). As in London's case, it became compulsory for homes to connect to sewers in the 1840's. In the time since these sewer systems were installed, increases in urbanisation, population and changes in the climate and weather patterns have meant that certain sections of the sewer system have been stressed and can no longer adequately convey the required volumes of water. When a section of a sewer system becomes overly stressed, flooding and pollution incidents can occur either at street level or in basements and belowground properties. Urbanisation and population growth, however, can also be beneficial as increased population concentrations can reduce the cost of services per capita (e.g. potable water, sewerage services, utility infrastructure and council services) (Cruickshank & Fenner, 2007).

The drivers to reduce the risk and frequency of flooding are numerous (for example: health implications; damage to the economy; damage to buildings; loss of life; deposited debris and pollution; etc.). Current industry practices to reduce the risk of sewer systems flooding and spilling can be categorised into two strategies, termed 'grey' and 'green'. Grey strategies refer to the extension of the sewer system infrastructure through the construction of: by-pass pipes; additional storage chambers; large pipes and combined sewer overflows. These solutions are typically costly and provide the sole benefit of reducing the risk of flooding in unwanted locations and storing the water out of the public's view. Green strategies refer to the development of more natural water management strategies, for example 'water sensitive urban design' (WSUD), 'sustainable drainage systems' (SuDS) and 'low impact development (LID). These strategies use natural processes, such as infiltration and evapotranspiration, to reduce the volumes of surface runoff entering the sewer system and return it back to the natural water cycle. The benefits of employing green strategies over grey strategies are:

1) The infrastructure is typically above ground and, therefore, easy to inspect and maintain;
2) Added amenity benefits;
3) At source water treatment; and
4) Use of sustainable infrastructure such as vegetation (Woods-Ballard *et al.*, 2015).

Issues with implementing green strategies into already urbanised locations are: the availability of above ground space, the required infiltration potential of the soil, as well as the lack of adequate and undisturbed blue corridors to convey the surface water runoff to natural water bodies or safe discharge locations.

Both of the grey and green strategies mentioned above have benefits and issues regarding their application and installation when applied in existing urbanised catchments. In highly urbanised areas, it is becoming more difficult for 'grey' or ‘green’ solutions to be viable due to the lack of above and below ground space, leading to high construction costs. This issue is expected to intensify as urbanisation and the population in the urban areas are predicted to increase (Mott MacDonald, 2011). There is, therefore, a need for a solution that can be viable and does not require a major re-design and construction of the existing infrastructure.

This project describes the development and the application of an alternative method, termed the ‘flow control positioning method’. The method involves positioning vortex flow controls (VFCs) and orifice plates in existing manhole chambers and aims to improve the hydraulic performance of the sewer system. This method iteratively:

- Runs simulations of the sewer system model;
- Locates available un-used in-pipe capacities to attenuate potential flood volumes;
- Designs a bespoke flow control to attenuate the volumes and maximise the in-pipe capacity used; and
- Assess the impact of installing the flow control by quantifying the change in flood risk and cost of installing the solution.

The benefit achieved from installing the flow controls is quantified by both the change in flood risk and cost of installing the proposed solutions. Within this thesis, the flood risk of the sewer system is quantified as by the ‘flood resistance level’. The term ‘flood resistance level’ (abbreviated to ‘FR level’) is defined as the highest return period of rainfall, quantified as 1 in ‘x’ years, which does not cause the sewer system to behave beyond its design parameters. This includes: physical failure; surface water flooding; and breach of the sewer system’s discharge consents (Newton *et al*., 2014).

The process of searching for un-used capacities and positioning flow controls is repeated until a design limitation is reached (maximum budget and achieved FR level) or all of the available un-used in-pipe capacities are used. The proposed solutions from the flow control positioning method, unlike the grey and green strategies described, require little construction in comparison as the flow controls are installed in existing manhole chambers.

1.2 Project question, aim and objectives

The research question addressed in this thesis is, that even though SuDS are a preferred method of flood risk management but are not always a viable solution, is there a design method or process that can tailor a sewer system's hydraulic behaviour to help meet the predicted future needs of the system without constant user/computer software interaction?

The primary aim of the project is to establish a protocol for increasing the FR level of catchments where typical runoff reducing measures, such as sustainable drainage systems, are impractical or applying powered in-sewer real-time control strategies are unfeasible. The protocol will enable decision makers to increase the FR level of the catchment and reduce detrimental effects on the environment due to the accumulation of pollutants or increased combined sewer overflow (CSO) spills. The aim will be achieved by developing a decision support tool that will advise decision makers on retrofit solutions that will improve the behaviour of their sewer systems. The decision makers can then use a cost against FR level increase relationship output to support their decisions.

The objectives of the research undertaken are as follows:

1) Conduct a literature review of current knowledge regarding the use of flow attenuation devices and existing methods of improving the performance of sewer systems;
2) Develop an algorithm which can be used to select potential flow control locations and produce outputs for a decision maker;
3) Automate the developed algorithm into an assessment framework to demonstrate the potential benefits of positioning flow controls into the sewer system;

4) Use new case study data to demonstrate the application of the method; and
5) Compare the outputs from the algorithm to other flood alleviation methods to determine the benefits the can be achieved by implementing flow attenuation devices into the sewer system.

1.3 Originality of work

The originality of this research is in the following areas:

- An automated iterative method for positioning and designing both VFCs and orifice plates into sewer systems using a deterministic method;
- Comparison of the hydraulic benefits achieved when multiple VFCs or orifice plates are installed into a sewer system;
- Introduction of flood vulnerability scores for flow control positioning; and
- Use of a simplified critical input hyetograph to hydraulically stress the sewer system and then design the flow controls to be positioned.

1.4 Contribution to knowledge

The contribution to knowledge from the outputs of this thesis are:

- A new method for increasing the FR level of sewer systems by increasing the total capacity utilised during rainfall events through the positioning of flow controls in strategic locations (Newton *et al*., 2013b);
- Developed sewer system retrofit designs based on the available volume within the sewer system and assigned flood vulnerability scores; and
- Application of a simplified critical input hyetograph method and applying the hyetographs as the rainfall inputs when simulating the sewer system, thereby, reducing the required number of simulations per return period (Newton *et al*., 2013a).

1.5 Outline of the thesis

The thesis contains eight chapters in total. Chapter 2 contains a review of the current literature around the topic of positioning flow controls and alternative flood risk reduction measures, such as storage.

Chapter 3 of the thesis outlines the flow control positioning method and the 29 steps required to complete the analysis of the sewer system. The rationale for selecting to use vortex flow controls in this project, over orifice plates and active flow controls, is also presented. This chapter also argues and presents the definitions of terms used throughout this piece of work.

Chapter 4 describes how an assessment framework was developed to demonstrate the potential benefits from the application of the flow control positioning method. This chapter also discusses how the outputs from the assessment framework can be applied and used in a real-life scenarios to improve the behaviour of an existing sewer system.

Chapter 5 discusses and presents the application of the flow control positioning method on four case study sewer system models. In Chapter 5, all of the flood vulnerability scores are equal in each described sewer system analysis,

Chapter 6 continues by presenting the sewer system analyses when the flood vulnerability scores were not equal for each sewer system subcatchment. The outputs from the application of the method are also compared to alternative design methods.

Chapter 7 takes the proposed solutions from the flow control positioning method analyses in Chapters 5 and 6 and compares these to alternative flood alleviation methods used in the UK water industry. A 'one-factor-at-a-time' analysis is also completed to assess the effect of changing the input variables into the assessment framework decision support tool.

Finally, Chapter 8 presents the conclusions from the research and discusses the potential recommendations for further work respectively.

Chapter 2

Literature Review

2.1 Introduction

This body of work investigates a method of improving the hydraulic performance of a sewer system through the implementation of non-powered passive flow control devices. The drivers and objectives for improving a sewer system's hydraulic performance is to reduce flood risk by managing flow-rates across the sewer system being considered. This in-turn can help meet water quality targets, with the aim of reducing the amount of pollutants and debris being deposited into receiving water bodies when the sewer system over-spills or treatment facilities are overwhelmed. Water quality drivers have received significant attention in recent years, within Europe, with the stringent targets set in the European Union's Water Framework Bathing Water Directive (WFD, 2000/60/EC) being an example.

There are a number of methodologies in the literature that also aim to improve the hydraulic performance of a sewer system. This literature review summarises the current knowledge regarding the use of in-sewer source control and flow attenuation. The literature review is separated into the following sections:

1) Sewer system modelling and design;
2) The use of source control and flow attenuation in the industry; and
3) Existing methods for determining the positions and designs for flow controls.

2.2 Sewer system modelling and design

In the last 30 years, sewer system modelling and design has developed and evolved in parallel with the improvements in sewer system monitoring, computer technology and computer processing power. Sewer system modelling software can be used to predict the performance of a sewer system to achieve a number of objectives, such as, reduce flood risk and optimise pump operation. The performance of a sewer system is represented in a number of ways including:

- Flow-rates;
- Head levels;
- Flood volumes;
- Water quality parameters;
- Economic criteria;
- Environmental criteria; and
- Social criteria (Foxon *et al.*, 2002).

Foxon *et al.* presented criteria and example indicators of how economic, environmental and social criteria could be quantified as part of the Sustainable Water Industry Asset Resource Decisions (SWARD) project.

Sewer systems are increasingly no longer modelled in isolation but are integrated with other urban water systems (Bach *et al.*, 2014). Other systems that are now part of these integrated models are the river catchment, overland flow models, stormwater drainage, wastewater treatment works and environment components (e.g. natural watercourses, groundwater, ponds, etc.). One aim of using these types of models is to understand the impacts the systems have on each other and apply Water Sensitive Urban Design (WSUD) principles and achieve the vision of the Water Sensitive City (Wong and Brown, 2009). Other functions of using integrated models discussed by Bach *et* al. (2014) are:

- Flood and flood risk management;
- Drought risk management;
- Ecological health management;
- Urban growth assessment;

- Asset management; and
- Operation and process optimisation.

Integrated models for predicting flood times, durations, volumes, water quality parameters, etc., however, are now being used in research to investigate their use to predict damages from flooding, impacts to infrastructure from flooding, estimating the vulnerability of assets, health impacts and hydro-epidemiology (Hammond *et al.*, 2015). These integrated models explore risk (function of consequence and frequency) and are used to argue whether implementing measures to reduce the frequency of flooding are feasible; quantifying whether resources are actually needed to prevent flooding or a sewer system failing is acceptable in these tough economic climates. The uncertainties with these models, however, is how do you accurately and effectively quantify or monetarise the health impacts and change in hydro-epidemiology due to flooding? (Hammond *et al.*, 2015).

Some integrated models are used to assess possible changes made to a system and the effect the changes have on the whole wider water system. For the purpose of proposing solutions to specific engineering and water management issues (e.g. flood management problems, pump operation optimisation and development planning), these integrated models are too computationally intensive for practical use (Pleau *et al.*, 2005). This is, however, changing with further developments in computer technology.

Models, whether they are integrated or not, are only of use if they are built to or have the capacity to address the user's problems (Lerer *et al*., 2015). Lerer *et al*. found that many models that aid decision makers in WSUD planning and design are context, location and initial user purpose specific. Their review was not able to cover all types of planning decisions that are considered in the design process. The review did show, however, that no decision making model that is initially focused on a WSUD design and planning context, is currently capable of taking all necessary considerations into account and it is up to the model user to consider the remaining considerations omitted from each respective model.

Many sewer system models will have been used in response to growing pressures on the local sewer systems. Climate change and urbanisation are two issues that are having a negative impact on the level of service provided by existing sewer systems. Two effects of climate change are variable hydrological patterns and an increase in sedimentation due to wet and dry seasons (Yazdanfar & Sharma, 2015). It is also documented that the intensity of same return period rainfall events are increasing within the UK (Jones *et al*, 2013). The effects of urbanisation are an increase in the surface run-off rate from impervious surfaces, an increase in rainfall due to the urban heat island effect and a reduction in aboveground runoff storage areas (i.e. ponds and basins) (Yazdanfar & Sharma, 2015).

Yazdanfar & Sharma's (2015) review outlines possible steps to adapt a sewer system to respond to changing climates and levels of urbanisation. The steps involve:

- Sustainable management approaches;
- In-depth uncertainty analysis;
- Integrated decisions with multiple stakeholders; and
- Accounting for spatial and temporal variations in rainfall (Yazdanfar & Sharma, 2015).

In this context the sewer system models can be used as decision support tools. Some legislation also forces sewer system designs to consider future predicted climate change as part of the hydraulic quantity assessments (e.g. Sewers for Scotland: 3rd Edition (2015)).

Using sewer system models for design and decision support purposes are, however, no longer restricted to purely technical issues but also institutional and social issues (Brown & Farrelly, 2009, Elliot & Revitt, 2010). Both Brown and Farrelly's and Elliot and Revitt's papers argue that, within the UK, the legal issues of ownership and responsibility of the sewer system are the predominant issues in proposing and implementing integrated water management solutions. Spiller *et al.*, (2015) also argues that implementing flexible design within the water industry is not as important, as the sector is driven by slow changing variables, such as: climate change; population growth; and urbanisation.

Brown & Farrelly (2009), Elliot & Revitt (2010) and Yazdanfar & Sharma (2015) highlight the differences between the desired best management of water (sustainable management approaches, in-depth uncertainty analysis and integrated decisions with multiple stakeholders) and the realistic implementation of these designs. This indicates that designs are selected based on institutional and social issues regarding ownership and legal issues rather than the hydraulic performance of the designed system.

This section has so far focused on the reasons for sewer system simulation and the assessment of its impacts within the wider water catchment. Sewer system models that focus on assessing impacts are analysis tools that, in some cases, are used to provide data to support decision making (e.g. InfoWorks ICM). Sewer system design tools are used to investigate different sewer configurations and propose:

- Concept and preliminary designs for networks (e.g. SWMM);
- Geometries of sewer system infrastructure alongside designing for SuDS (e.g. Micro Drainage);
- Real-time control design (e.g. Mike Urban).

The aim of the sewer system design tools is to aid engineers in the process of designing and proposing solutions that increase the sewer system's performance to meet an expected level of service (e.g. no flooding for a given return period of rainfall). The selection of sewer system modelling tools will tend to depend on suitability of the tool for the modelling purpose, accessibility of the tool to the user, and the usability and layout of the tool's user interface.

Within the UK, an industry derived sewer system modelling standard has been widely accepted (Wastewater Planning Users Group, 2002). The *Code of practice for hydraulic modelling of sewer systems*, which incorporated the views of “expert” modellers, covers model building, model testing, flow surveys, model verification and documentation. It is also accepted that modellers within the industry follow these guidelines to maintain a continued quality of sewer system model.

InfoWorks ICM

InfoWorks ICM is a commercially available integrated catchment modelling program commonly used to model and run simulations of existing river and sewer systems. The program uses the Saint Venant equations to model water flow through the river and sewer systems. The modelling program can be used for numerous applications, including:

- River, drainage and sewerage master planning studies;
- Surface Water Management Plans;
- Urban drainage storm runoff control and retention design;
- Development of solutions to existing flooding problems;
- Assessment of catchment future needs under growth or climatic changes;
- Flooding and pollution prediction under complex urban and river interaction;
- Flood flow planning and management;
- Impact of intermittent discharges from sewerage systems (UID's, CSO's or SSO's) on river environments; and
- Combined / wastewater interceptor system design and analysis.

InfoWorks ICM, however, does not produce sewer system designs for the user. The user has to input potential sewer system solutions into the model and simulate the solutions impact on the receiving system.

Mike Urban

Similarly to InfoWorks ICM, Mike Urban is an integrated urban water modelling program developed by DHI. Mike Urban, which is a descendant from the MOUSE drainage modelling program, also uses the Saint Venant equations to model the sewer system. Applications of the program include:

- Master planning;
- Capacity management;
- Wet weather management and overflows;
- Evaluation of storm water best management practices and low impact development; and
- Design and optimisation of real-time controls.

MOUSE

MOUSE, the previous embodiment of Mike Urban, has also been used as the hydraulic simulation package within non- commercially developed sewer system modelling tools such as the CORAL tool (Puig *et al*., 2009). In the CORAL tool, MOUSE is used to model and enable global control of the Riera Blanca Catchment in real time using hydraulic data collected from the site using a SCADA system. The model within MOUSE is required to:

- Represent the hydraulic and hydrologic behaviour of the sewer system whilst maintaining model simulation stability and mass balance;
- Be simple and able to complete simulations within required short periods of time; and
- Be amenable to on-line calibration and optimisation.

Micro Drainage

The Micro Drainage program is specifically marketed for sewer system and surface water runoff sewer design (XP Solutions, 2015). The Micro Drainage program, unlike InfoWorks ICM, is able to propose dimensions for sewer system designs through an automated algorithmic design process, CASDeF. The user selects the locations of the manholes and conduits, and the Micro Drainage program, using its CASDeF optimiser module, sizes the manholes, conduits and orifice plates for a given set of selected return periods and storm durations of design rainfall hyetographs. The use of optimisation techniques for the design of sewer systems, however, have been widely used within academic applications but, as of yet, have not been accepted in day-to-day use within the real world sewer industry (Guo *et al*., 2008). Reasons for the lack of uptake of optimisation sewer system design methods are:

- Optimised sewer solutions provide modest cost savings compared to conventional design methods;
- Costing models are overly simplified and unrealistic;
- Sewerage companies err on the side of caution and conservativeness when considering flooding issues; and
- Sewer system models themselves contain high levels of uncertainty and simplifications, and therefore, compromise the solutions from the optimisation program.

Storm Water Management Model

The Storm Water Management Model (SWMM) is an open source hydraulic modelling program developed in the United States of America (Rossman, 2004). The program is a 1D sewer and channel hydraulic modelling package and, like the other modelling and design programs discussed above, uses the Saint Venant equations to model flow through the system. SWMM's primary intended use was for detailed planning and preliminary designs of drainage systems (Elliott & Trowsdale, 2007). Since SWMM's inception, the program has been commercialised by other modelling companies (e.g. XP Solutions, Innovyze and DHI) by improving the users experience with the graphical user interface (GUI). SWMM allows users to model and design a variety of products and hydraulic structures into the drainage network. Unlike Micro Drainage and it's CASDeF optimiser module, SWMM is not able to size pipes or orifice plates. As SWMM is open source, the program is able to be linked with alternative code packages (e.g. C++, MATLAB and Visual Basic for Applications) to create custom sewer system design and modelling tools (e.g. Atkinson, 2013, Lim *et al.*, 2014, and Sun *et al.*, 2011).

2.3 Use of source control and flow attenuation

The sewer system modelling and design programs can be used to design sewer system designs to manage water quality and quantity. Two types of solutions that can be designed into sewer systems are source control and flow attenuation solutions. Source control and flow attenuation are terms used when discussing the slowing of water in safe areas to prevent flooding or damage in downstream sections of the system (Andoh & Declerck, 1999). Flow attenuation is the reduction in flow-rate to prevent too great a volume of water causing flooding in downstream vulnerable sections. Source control is used, especially when discussing the use of SuDS, to manage surface runoff from subcatchments and to manage rainfall where it has landed (Andoh & Declerck, 1999). Both source control and flow attenuation solutions require a form of flow control and storage volume to retain excessive volumes of water. Controlling and attenuating flows is a possible solution when retrofitting systems, in preference to increasing the volumetric capacity of the system (Digman *et al.*, 2012). Implementing control and attenuation strategies are typically more beneficial than increasing the system's capacity (Digman *et al*., 2012, Woods-Ballard *et al*., 2015) because of:

1) Reduced construction costs;
2) At source and on surface management of the flow;
3) Potential treatment of the collected surface runoff;
4) Greater future adaptability of attenuation components; and
5) Potential additional amenity and biodiversity benefits from different attenuation strategies.

Digman *et al*. (2009) summarises the selection of retrofit strategies, including source control and attenuation, for various source, pathway and receptor related flooding problems. They show that 32 of the 34 available surface water management measures are positioned aboveground. Positioning these methods aboveground, especially in areas that are heavily urbanised and have a high population density, can be difficult due to the lack of space and the disruption from construction activities. Increases in urbanisation have also been noticed in peri-urban catchments. In one case study, it was observed that the area of impervious surfaces had increased 400%, from 11% to 44%, in approximately 50 years (Miller *et al*., 2014).

SuDS can also be difficult to position within the UK due to low infiltration potential of the soil, as well as, the increase in the area of impervious surfaces. In the UK, 34.5% of the land is probably compatible for the use of infiltration SuDS and 20.7% of the land poses significant constraints for the implementation of infiltration SuDS (Dearden *et al.*, 2013).

Implementing source control and attenuation, however, can be both a logistically and politically intensive process in already urbanised catchments due to existing infrastructure and reluctance of local residents. Challenges to the implementation of attenuation systems can include:

1) Land uptake;
2) Existing above and belowground infrastructure;
3) Soil conditions effecting infiltration and run-off; and
4) Reluctance of local residents to both co-habit with the solution and the construction of the solution.

The implementation of different attenuation strategies can be achieved using different methods depending on different targets and the preferred form of the solution. A number of design methodologies have been developed in recent years in academia with a commercial bias, showing that the designer's concerns and use of the methodology have been considered in the development of the methodology. Changes made to the urban water systems to reduce the risk of flooding, improve water quality and achieve and implement WSUD concepts, for example can be designed using decision support tools. The types of changes designed are increasing the physical sewer capacity (Atkinson *et al.*, 2014, Fu *et al.*, 2010, Lim et al, 2014, and XP Solutions, 2015) or increasing the used capacity of sewer systems through the positioning of flow controls or source control attenuation (Chow *et al.*, 2014, Petrucci & Tassin, 2015, Phillippon *et al*, 2015, and XP Solutions, 2015).

In-sewer real-time control strategies are currently being researched and some solutions being implemented within the water industry (Butler & Schutze, 2005, Puig *et al.*, 2009, Weijers et al, 2012, for example). Real-time control schemes typically include the automatic operation of electro-mechanical penstocks or gates strategically positioned within the sewer system to manage flows. These topics have, however, been omitted from this literature review as the project aims to investigate the implementation of passive non-powered flow controls (Section 1.2). In this body of work, passive flow controls require:

- No power requirements;
- No moving parts;
- No external signal for activation;
- Reduced amounts of maintenance;
- No external controlling hardware or software program;
- No collection of sewer flow-rate and flow depth data; and
- No maintenance or calibration of automation equipment, for example (Newton *et al.*, 2015).

2.4 Existing methods of improving the performance of sewer systems

Design methods (e.g. hydrograph method, rational method and time-area method) are applied with the primary focus on achieving a desired hydraulic quantity target for a drainage system (Butler & Davies, 2011). They are used to assess flooding volumes and flow-rates within the sewer system. These can either be assessed throughout the system or at selected nodes. The design methods are then used to assess possible amendments or changes to the sewer system so that the hydraulic quantity targets can be met. Such amendments may include, but are not restricted to, increasing conduit diameters, increasing storage volumes and adding additional conduits. The literature discussed in this section all aim to meet hydraulic quantity targets for sewer systems. The solutions, if implemented, can require large construction projects and incur large project costs to replace existing infrastructure or increase its capacity. A project commissioned by Ofwat, the water industry regulator in the UK, found that the cost of removing a property from the DG5 flood risk register was between £15,000 and £58,000 (Babtie Ltd & Ofwat, 2003).

There are numerous tools for designing solution for increasing a sewer system's capacity. As previously discussed in Section 2.2, CASDeF is an automated sewer system design package within Micro Drainage and is used to optimise the designs of sewer systems (XP Solutions, 2015). CASDeF optimises a sewer system's design by altering the system's physical geometry with the aim of preventing flooding from occurring. It does this in response to a user selected rainfall return period and rainfall durations, providing the user with a single design solution, which only accounts for hydraulic performance and not costings. During the analysis, CASDeF alters the following parameters of the sewer system:

1) Storage volume;
2) Conduit dimensions;
3) Pond dimensions; and
4) Control dimensions such as orifice outlet diameters.

CASDeF completes the optimisation of the sewer system by: checking the setup of the sewer system model for sections where the analysis may become unstable; modifying the controls installed in the system; modifying the pipe dimensions; adding additional storage to prevent flooding or overflow activation.

Fu *et al.* (2010) developed a method of positioning and sizing storage tanks within sewer systems with the aim of mitigating the additional pollution of natural watercourses from the construction of new residential developments. This method utilised an integrated model (sewer system, wastewater treatment plant and the river) and the Non-dominated Sorting Genetic Algorithm II (NSGA II) optimisation technique to design a solution to optimise the water quality targets whilst maintaining good hydraulic performance. The conclusions from Fu *et al.*'s work were that an improved sewer system design could be achieved from the positioning of storage tanks within the sewer system and that these designs are insensitive to a change in population (± 20%) as well as longer rainfall series.

Atkinson's work focused on both water distribution systems and foul sewer systems (2013). In Atkinson's work, foul sewer systems only collected sewage and no stormwater runoff volumes. The aim of the work was to develop design methodologies that could be applied to the two hydraulic systems so that the two systems could meet customer demands in the future. The design methodologies used developed reliability indicators and a genetic algorithm optimisation technique to redesign the geometry of the systems to meet predicted future hydraulic quantity targets. The concept of ranking retrofit solutions to meet a design purpose is useful, however, optimising the geometries of all the existing infrastructure and implementing the design is potentially impractical and unfeasible.

The work completed by Lim *et al*. (2014) is another example of optimised offline storage positioning and design within an existing sewer system. Lim *et al.* developed a SWMM based multi-objective optimisation tool and demonstrated its application on a case study based in South Korea. The tool was constrained to select only five locations for storage whilst minimising the cost of constructing the storage and minimising total over-flow volumes. Lim *et al*. found that installing storage chambers can help reduced overflow volumes, but the user of the tool would have to already consider the use of the existing sewer system for attenuation. The tool does not consider attenuation within the existing sewer system infrastructure.

The tools discussed above all look to position storage. An alternative solution is to position flow controls within the sewer system to control flow volumes. Retrofit source control and flow attenuation in existing sewer systems is not a new concept in the water industry (Lamb, 1983, Andoh, 1994, and Andoh & Declerck, 1997 & 1999). In these examples, passive flow controls were manually designed into the sewer system to reduce the frequency of flooding. In-sewer source control and flow attenuation solutions are becoming more considered due to the change in weather patterns. Lamb, 1983, Andoh, 1994, and Andoh & Declerck, 1997 & 1999, however, did not discuss how their ideas could be implemented into an automated method proposing possible solutions to reduce flood risk.

Other authors have looked into the positioning of flow controls. Work by Philippon *et al*. (2015) developed a method that analysed a sewer system model using an in-sewer volume calculation method. The tool ranked the greatest available storage capacities that could be used within the existing sewer geometries for the design of real-time control devices into the sewer system manholes. The top locations were selected based on the greatest volume of storage that could be achieved and that the storage volumes do not overlap (i.e. same manholes and conduits used to calculate two storage volumes). The findings from this research, demonstrated on a combined sewer system in Berlin, showed that a decrease in the CSO volumes (minimum reduction of 10%) and a reduction in biological oxygen demand (BOD_5) load (minimum reduction of 2%) could be achieved. The limitations in the method presented by Philippon *et al*. are:

1) The method presented only calculated the available storage capacities during dry weather flow. This method does not account for the stormwater considerations in the design of the combined sewer system;
2) The method is not an iterative process enabling the user to see how the storage volumes interact with each other during storm events. This issue has been circumnavigated by implementing the real-time control devices and adjusting their controlled behaviours to increase the enabled storage capacities; and
3) The method has not been developed to consider a maximum desired design target for the proposed storage solutions. Implementing the solution to make use of the storage capacities may exceed considered adequate design targets (e.g. no flooding during a 1 in 100 year return period rainfall event).

Designing flow control measures to attenuate flow volumes is possible either by computing the available volumes within the sewer system, as shown by Philippon *et al.* (2015), or by assessing the characteristics of the flow-rate hydrographs entering the sewer system (Petrucci & Tassin, 2015). Petrucci & Tassin developed a simplified top-down numerical approach for a sewer system to assess the impact of applying attenuation strategies at regions within the catchment at various travel time bands away from the sewer system outlet. Two attenuation strategies were assessed, volume reduction and flow-rate reduction, and the simulation outputs compared to determine where in the catchment the strategies were more effective. The simulations showed that the greater the travel time between the attenuation structure and the outlet of the sewer system, the greater the beneficial impact seen from the application of the volume reduction strategy. This finding complements current state-of-the-art attenuation practices in that applying attenuation strategies at the top of the catchment provides a cheaper and more beneficial solution (Andoh & Declerck, 1997, Ashley *et al.*, 2011, and Woods-Ballard *et al.*, 2015).

Petrucci & Tassin's model (2015) does inform users where within their catchment different attenuation strategies (flow-rate reduction or volume reduction) would be most beneficial. As a top-down approach, the strategic locations determined by the model require substantial further additional engineering design (e.g. type of attenuation, specific location in the catchment, size, cost, effect of the wider catchment hydraulics, etc.).

In the literature discussed in this review only the decision and positioning of orifice plates, weirs, gates and storage chambers are discussed. The design of these flood alleviation options have been optimised in various works. These structures are selected for use in optimisation problems as they contain one variable in their design:

- Orifice plate – outlet diameter;
- Weir – height;
- Gate – height; and
- Storage – volume.

VFCs, in contrast to the orifice plates, weirs, gates and storage chambers, have three variables required for their design: outlet diameter; aspect ratio; and slot ratio (Jarman *et al.*, 2014). The aspect ratio and slot ratio determine the flow characteristics within the chamber and, hence, the characteristic behaviour of the VFC.

2.5 Gap in knowledge

The discussed literature, in Sections 2.2 to 2.4, presents a number of possible solutions that can be implemented to reduce level of flood risk of a sewer system by positioning non-powered flow controls. An increase in the sewer system's flood resistance level is achieved by either increasing the capacity of the sewer system (e.g. enlarging pipes and positioning storage) or preventing the flow from entering the sewer system (e.g. SuDS). Both of these methods can be unfeasible and unviable in the current layout of urbanised areas, especially when also considering future pressures (further urbanisation, population growth and climate change). SuDS and above ground solutions can be difficult to implement due to the lack of green/unconstructed areas in urban catchments and increasing urbanisation (Miller *et al*., 2014). Low soil infiltration values can also mean that infiltration SuDS structures cannot be utilised to their full potential (Dearden *et al.*, 2013). Belowground structures and solutions can also be difficult to implement in urban areas due to the layout of both the above and belowground infrastructure and services.

Even though SuDS are a preferred method to reduce flood risk levels, SuDS may not be possible or plausible solutions in every case. So one question that arises is: 'is there a design method or process that can change or tailor a drainage or water system's hydraulic behaviour to help meet the predicted future needs of the system without constant user/computer software interaction?'.

This literature review has highlighted the following gaps in knowledge from the field.

1) A method incorporating the concept of flood vulnerability into the decision making process; and
2) A methodology designing a VFC for installation into an existing sewer system and the aim of reducing flood risk.

Chapter 3

Method for positioning and designing flow controls

This chapter describes a method of improving the hydraulic behaviour of a sewer system to increase the system's flood resistance level, which fills the above knowledge space.

Water quantity targets can refer to different levels of flood resistance or resilience that might want to be achieved. In this project, the term 'flood resistance level' is used to define the hydraulic behaviour of the sewer system. Different definitions of the terms 'flood resistance' have been derived (Gouldby & Samuels, 2005, Department for Communities and Local Government, 2009, Sun, 2010, and Butler *et al*, 2014). Most of the definitions of flood resistance are accompanied with definitions of flood resilience. Flood resilience is not considered in this study, however, as the aim of this work is to improve the performance of the sewer system in isolation and not assess flood consequences, damages or recovery times. Existing flood resistance definitions are:

> *"the ability of a system to remain unchanged by external events". (Gouldby & Samuels, 2005).*
>
> *"Constructing a building in such a way as to prevent flood water entering the building or damaging its fabric. This has the same meaning as flood proof." (Department for Communities and Local Government, 2009)*
>
> *"The resistance of the system is a drainage system to carry the rainfall water" (Sun, 2010).*
>
> *""The degree to which the system minimises level of service failure frequency over its design life when subject to standard loading" (Butler*

et al., 2014)

The four definitions all state their opinion of what flood resistance is defined as, but do not explicitly state how the flood resistance level of a system should be measured or quantified to allow comparisons of sewer system designs. The definitions above were used to help derive the term flood resistance level, with a quantifiable measure, and is used as the definition of flood resistance level throughout this body of work:

> *"The term 'flood resistance level' is defined as the highest return period of rainfall, measured as 1 in 'x' years, which does not cause the sewer system to perform beyond its design parameters (flooding, over-discharge or structural failure)" (Newton et al., 2014)*

Having defined and quantified what this project aims to increase, a method of increase can be investigated. This method for increasing a sewer system's flood resistance (FR) level is discussed in the remainder of the chapter.

The method developed to strategically position and design flow controls into an existing sewer system contains 29 Steps (Figure 3.0-1). The 29 Steps consist of 11 decisions, shown as diamonds, and 18 actions, shown as rectangles or trapeziums. In the following chapter, the method is described and details of the calculations presented. Figure 3.0-1 contains cross-references to sub-sections in this document that explain each of the steps in the design and positioning method in further detail; for example, *S3.1* refers to 'Section 3.1'.

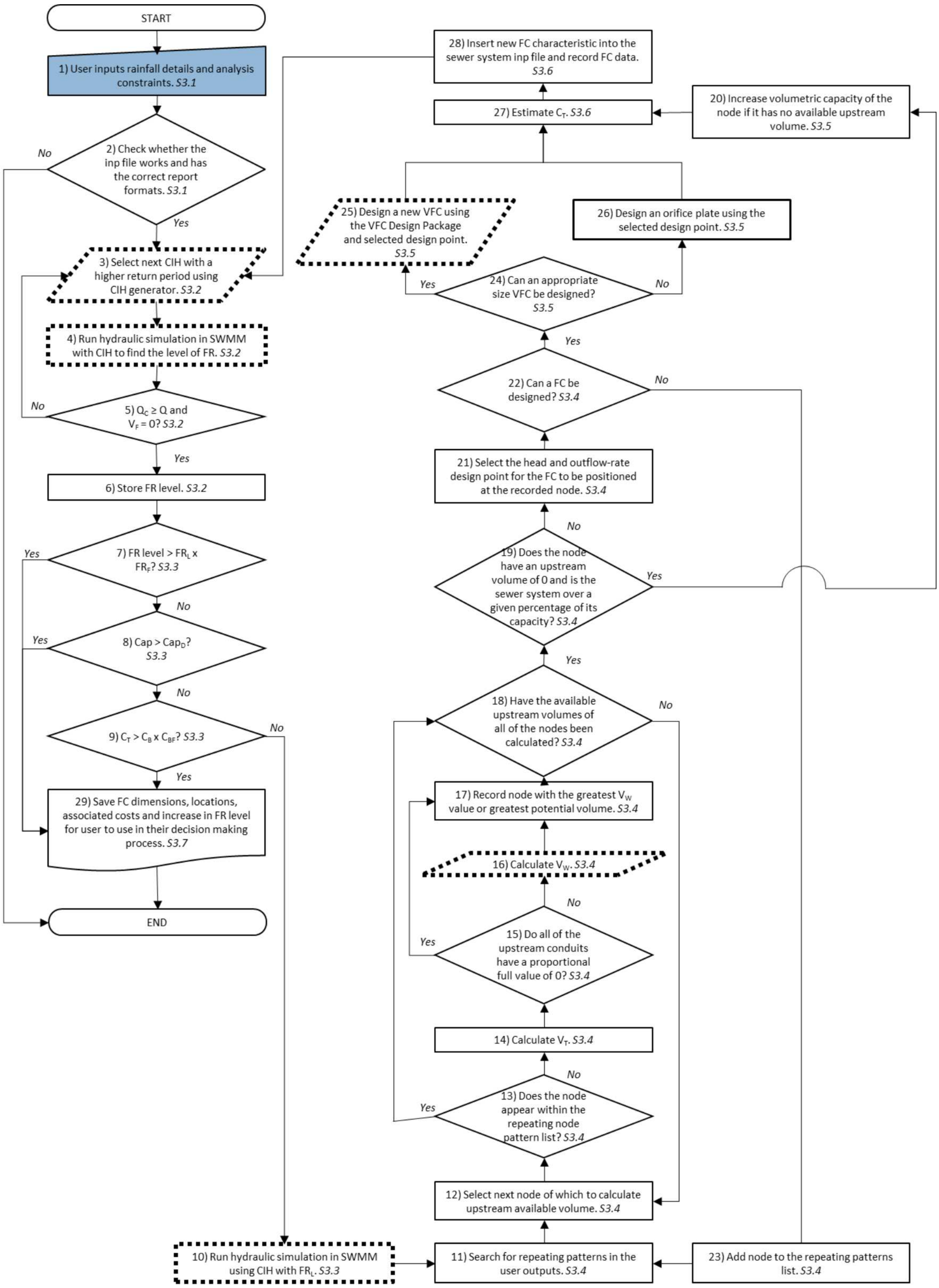


Figure 3.0-1: Flow diagram of the method of positioning and designing flow controls into existing sewer systems.

The method for the positioning of flow controls aims to improve the overall FR level of the sewer system. This is achieved by attenuating potential flood volumes within previously unused capacities of the sewer system, thereby, optimising storage use during rainfall events that may exceed the sewer system's current FR level. The positioning of the flow controls is dependent on the location of the greatest volume of unused capacity and the assigned flood vulnerability score (FVS) of the sewer system's subcatchments.

The description of the method has been dissected into sections:

1) The tool set up (Section 3.1);
2) Predict the system's FR level (Section 3.2);
3) Assessing whether the FR level, maximum system capacity or cost have exceeded the user defined values (Section 3.3);
4) Positioning the flow control (Section 3.4);
5) Designing the appropriate flow control (Section 3.5);
6) Estimating the total financial cost of the design (Section 3.6); and
7) Presenting the user with the outputs from the analysis of the sewer system model (Section 3.7)

The method has been coded into an assessment framework to automate the method for demonstration. The tool enables automated sewer system searching to select the positions of flow controls and determine appropriate flow control designs at each chosen location. The assessment framework has been developed in Microsoft Excel® and includes:

1) Microsoft Visual Basic for Applications (VBA);
2) A bespoke hyetograph generator;
3) The Storm Water Management Model (SWMM) version 5; and
4) A vortex flow control (VFC) design program.

The hyetograph generator and VFC design program have also been developed in Microsoft Excel and the SWMM 5 program can be called using VBA. Within the method diagrams, steps that require a different program to Microsoft Excel or Microsoft VBA are displayed in trapeziums with dashed borders.

3.1 Tool set-up

The first step of the method is to set up the assessment framework by defining the method's constraints, which are maximum financial budget, maximum sewer system capacity and desired FR Level, Figure 3.1-1. This step requires the user to input simulation and analysis constraints (Table 3.1-1) before the method can begin. The information in Table 3.1-1 is needed for:

1) The hyetograph generator (Section 3.2 and 3.4);
2) Setting the sewer system behaviour constraints (Section 3.3);
3) Setting the analysis constraints (Section 3.3); and
4) Estimating the cost of the proposed designs (Section 3.6).

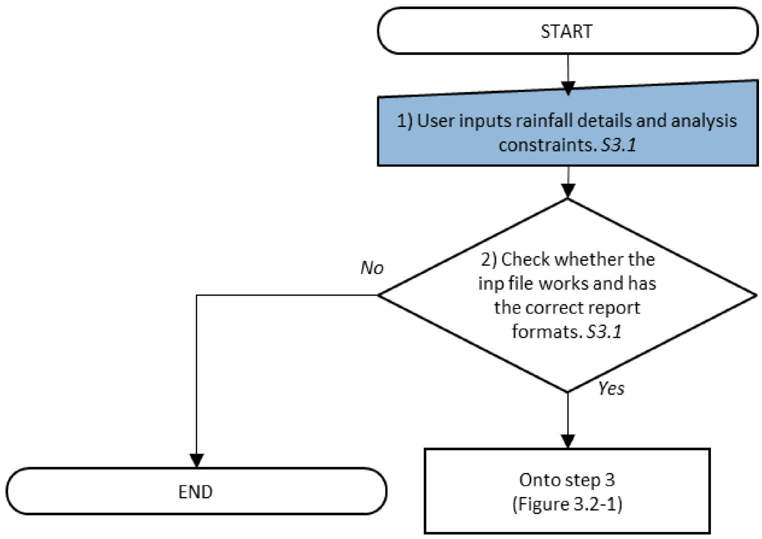


Figure 3.1-1: Step 1 to 2 of the method for positioning and designing VFCs into sewer systems required to set the constraints of the sewer system analysis and check that the sewer system model can be simulated in SWMM 5.

The hyetograph generator requires 'Flood Studies Report' (FSR) rainfall descriptors to derive the hyetograph to be used (Newton *et al.*, 2013a), as shown in Table 3.1-1a. The sewer system behaviour constraints and analysis constraints, as listed in Table 3.1-1b&c, are values that are used to determine when a sewer system model under consideration has exceeded the analysis constraints of FR level, maximum sewer system capacity and total estimated cost. These constraints are further discussed in Section 3.3. Finally, the costs also entered in Step 1 allow user-specified costs to be applied to calculate the overall budget requirements of the sewer system modifications, Table 3.1-1d. Once the user has entered all of the required data, the user has no further interaction during the operation of the method beyond Step 1. As with Figure 3.0-1, Table 3.1-1 also has the relevant sub-sections of the chapter referenced to which the constraints relate.

Table 3.1-1: List of simulation and analysis constraints required from the user for the assessment framework in Step 1 of the method where: a) is the hyetograph generator constraints; b) is the sewer system behaviour constraints; c) is the analysis constraints; and d) are the assigned costings.

a): List of hyetograph analysis constraints for the assessment framework.

Hyetograph generator constraints	**Description**
M5-60 (mm)	Expected depth of rainfall to fall in 60 minutes with a return period of 1 in 5 years. *S3.2* & *S3.3*
Ratio-R	Ratio of the M5-60 value and M5-2880 value, where the M5-2880 value is the expected depth of rainfall to fall in 2880 minutes with a return period of 1 in 5 years. *S3.2* & *S3.3*
Area (km^2)	Total area of all subcatchments in the sewer system model. *S3.2* & *S3.3*
Climate change (%)	Percent increase in rainfall to account for climate change. *S3.2* & *S3.3*
Location	Location of sewer system within the British Isles. Select ‘1’ for England and Wales or ‘2’ for Ireland and Scotland. *S3.2* & *S3.3*

b) List of sewer system behaviour parameters for the assessment framework.

Sewer system behaviour parameters	Description
Freeboard, H_S, (m)	User selected value of head left between maximum design head of the flow control and the cover level of the manhole chamber. *S3.4* & *S3.5*
Discharge consent, Q_C, (l/s)	Maximum desired outflow-rate of the sewer system. *S3.2*
Increase storage ratio, Cap_S	User selected ratio of used sewer system capacity before increasing the volumetric capacity of a manhole chamber. *S3.3*

c): List of analysis constraints for the assessment framework.

Analysis constraints	Description
Desired FR level, FR_L, (years)	Targeted FR level quantified as 1 in 'x' years return period. *S3.3*
FR level factor, FR_F	User selected increase in the value of the FR level stop condition to expand search space. *S3.3*
Maximum desired capacity full, Cap_D	Greatest acceptable ratio of sewer system fullness. *S3.3*
Financial budget, C_B, (£)	Capital budget for the retrofit works to the sewer system. *S3.3*

d) List of assigned costings for the assessment framework.

Assigned costings	**Description**
Cost of installing a flow control through the manhole cover, C_I, (£)	User defined cost to install a flow control. *S3.6*
Cost of installing a flow control by removing the manhole lid, C_I, (£)	User defined cost to install a flow control. *S3.6*
Cost of installing manhole with the flow control, C_R, (£)	User defined cost to install a larger manhole chamber. *S3.6*
Cost of installing storage, C_S, (£)	User defined cost to install additional storage within the sewer system. *S3.6*

The user can also specify FVSs within the sewer system model. The FVSs are used to prioritise the flood protection of vulnerable subcatchments during the positioning of the flow control (Section 3.4). The values entered range from -1, to indicate the subcatchment has a low priority for flood protection, to 1, to indicate the subcatchment has a high priority for flood protection. An example of assigned priority for flood protection rankings are presented by Balmforth *et al.* (2006). This is further explored in Section 4.4.

Once the user has entered all of the required constraints in Step 1, the method checks whether a successful simulation of the sewer system model can be run in Step 2. If a simulation of the sewer system model cannot be successfully run, an error message is sent to the user and the method ends. This is so the user can fix the errors encountered. The errors that caused the simulation failure require being addressed manually by the user in either SWMM 5 or using a text editing program, such as 'Notepad' in Windows. The method and framework have not been designed to self-diagnose and fix errors or issues within the sewer system model. The user is then required to restart the method from the start once the errors have been corrected.

Step 2 also checks the reporting formats in the sewer system model file so that the required simulation outputs (e.g. depths of flow and flow-rates in the links and nodes) can be retrieved for later use in the positioning and design of the flow control. The reporting formats within SWMM 5 allow the users to only record simulation outputs for specific objects within the sewer system model that are of interest. The available objects are links, nodes and subcatchments. For the method to be able to complete the analysis, all links and nodes need to be reported on. If the reporting formats are unsatisfactory, they are changed without confirmation from, or notification, to the user. If a simulation is successfully run and once the reporting formats are satisfactory, the method moves onto Step 3 to find the FR level of the sewer system.

Beyond Step 2, the method repeats Step 3 to Step 28, positioning and designing flow controls into the sewer system model to attenuate potential flood volumes without user interaction. The method is continued until the analysis constraints (FR level, maximum used sewer system capacity and maximum cost), assessed in Section 3.3, are exceeded.

3.2 Predict the flood resistance level

Section 3.2 of the method quantifies the FR level of the sewer system model. This is completed to measure the change in the FR level of the sewer system as flow controls are designed into the sewer system model and sewer system model modifications are made. The FR level of the sewer system model is found by repeatedly running simulations of the sewer system model with a critical input hyetograph (CIH) for an increasing return period value (Figure 3.2-1). The FR level is deemed to be with the highest return period level, 1 in ‘x’ years, which does not cause the sewer system model to flood or exceed discharge consents (Newton *et al.*, 2014). The CIH is generated using the FSR rainfall constraints, entered in Step 1, and the method presented by Newton *et al.* (2013a).

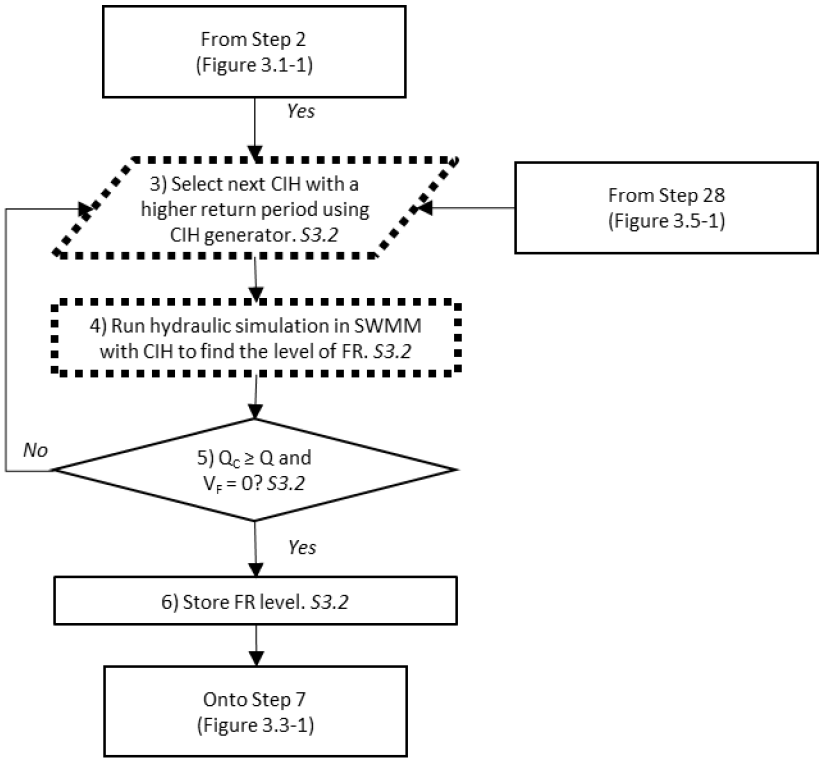


Figure 3.2-1: Finding and storing the FR levels of the sewer system model (Step 3 to 6 of the method for positioning and designing VFCs into sewer systems).

Using a given CIH, a hydraulic simulation of the sewer system model is run in Step 4 to find the FR level of the sewer system. In Step 5, the method checks whether the FR level has been found by assessing whether $Q_C \geq Q$ and $V_F = 0$, where Q_C is the sewer system's discharge consent (l/s), Q is the maximum total discharge flow-rate from the sewer system model (l/s) and V_F is the total flood volume from the system (m^3). If the FR level has not yet been found, the method moves back to select a CIH with a higher return period, and the process is repeated. Once either of the conditions $Q_C \geq Q$ or $V_F = 0$ are no longer valid, the algorithm moves onto Step 6 to record the FR level. The FR level is reported in the 'User Outputs' at the end of the sewer system model analysis, Section 3.7. After the FR level is recorded in Step 6, the method moves onto assess the stopping criteria of the analysis, Step 7.

3.3 Assessing whether the FR level, maximum system capacity or solution costs have exceeded the user defined values

In Section 3.2, the FR level of the sewer system was quantified to measure the changes in the FR level as modifications are made to the sewer system model after each iteration of the method. After the FR level has been quantified, Section 3.3 assesses whether the method can continue with the analysis by considering the analysis constraints input by the user in Step 1 (Figure 3.3-1). These conditions are:

1) The FR level (Step 7);
2) The total used capacity of the sewer system (Step 8); and
3) The user's financial budget (Step 9).

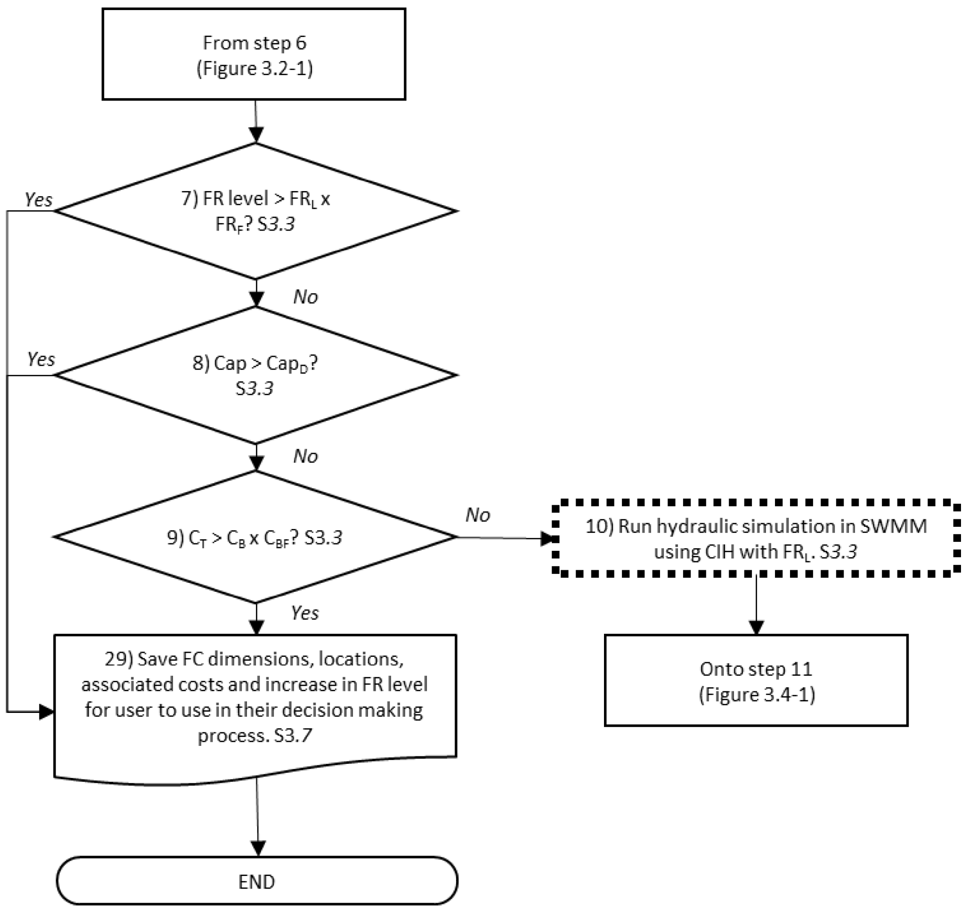


Figure 3.3-1: Step 7 to 6 and 29 of the method for positioning and designing VFCs into sewer systems assessing whether the analysis of the sewer system model is within the user's set constraints.

The first condition assessed, in Step 7, checks whether the found FR level of the sewer system is greater than the desired FR level, FR_L, multiplied by the user's desired FR level factor, FR_F. The desired FR level factor, further discussed in Table 3.1-1c, is included to allow the user to explore possible designs beyond the user's original desired FR level target. A solution beyond the user's desired FR level may provide a greater benefit at a lower cost in some cases and is, therefore, may be of additional interest to the user. If the found FR level $> FR_L$ x FR_F, the method ends, via Step 29, as the analysis constraints have been exceeded and the user has indicated any further information is not of interest. The method's analysis of the sewer system model is completed in Step 29 and Step 29 is discussed in further detail in Section 3.7. If the found FR level $< FR_L$ x FR_F, the method moves onto check the total used volumetric capacity of the sewer system (Cap), which is quantified as a ratio.

The total capacity of the sewer system is found by calculating the mean of the pipe full ratios of the conduits, $\overline{P_f}$, within the sewer system model. The pipe full ratios are read from the output file from the hydraulic simulation, completed in Step 4, and the values range from 0 to 1. If a pipe full ratio of 1 is read, this indicates that the pipe is surcharged and there is no additional capacity within the pipe to be used. If a pipe full ratio of 0 is read, this indicates that the pipe has no water flowing through it and none of the capacity is used. If the mean of the pipe full ratios is less than 1, this shows there is still available capacity within the sewer system to be used and not all of the pipes are surcharged. If the mean of the pipe full ratios is equal to 1, this shows there is no more available capacity within the sewer system to be used and all of the pipes are surcharged. If the user's maximum capacity of the sewer system has been exceeded ($Cap > Cap_D$), the method moves to present the user outputs and end the method. If $Cap < Cap_D$, the method moves to assess whether the total estimated cost of the design, C_T, has exceeded the user's maximum financial budget (Step 9).

The costs accounted for in the method include:

1) The cost of purchasing the flow control;
2) The cost of shipping and installing the flow control; and

3) The cost of increasing the diameter of any existing manhole chambers to install a flow control or provide additional storage.

The user's financial budget, C_B, is multiplied by a budget factor, C_{BF}, which increases the user's budget to allow the method to explore possible sewer system designs that could provide a greater cost-benefit ratio. If $C_T < C_B \times C_{BF}$, the method continues to then select the position for the next flow control as the current sewer system design has not exceeded any of the three analysis constraints. If $C_T > C_B \times C_{BF}$, the method ends as the total estimated cost has exceeded the analysis constraint.

If the budget limit is found to have not been exceeded in Step 9, the method continues onto begin positioning and designing the flow control into the sewer system model (Figure 3.3-1). Firstly, the sewer system model is re-simulated, Step 10, with a CIH with the desired return period (FR_L), input by the user in Step 1. This was found to be necessary when developing the method as, when a CIH with the previously achieved FR level was used, the flow controls designed were overly restrictive. This is due to the flow controls being designed from the flow-rate measured in the sewer system (see Section 3.5). This was found to prevent the method from achieving a higher FR levels as the flow controls were designed to store greater volumes of flow. Once the simulation of the sewer system model with a CIH for the desired return period has been completed, the method moves onto select the position to install the next flow control within the sewer system model (Section 3.4).

3.4 Selection of the flow control's position

As discussed in the introduction, the aim of the method is to position and design flow controls into the sewer system model to attenuate potential flood volumes and improve the sewer system model's FR level. The positioning of the flow controls is a key part of the method and requires 12 steps to search the sewer system for the maximum available capacity that can be used to attenuate potential flood volumes, Figure 3.4-1.

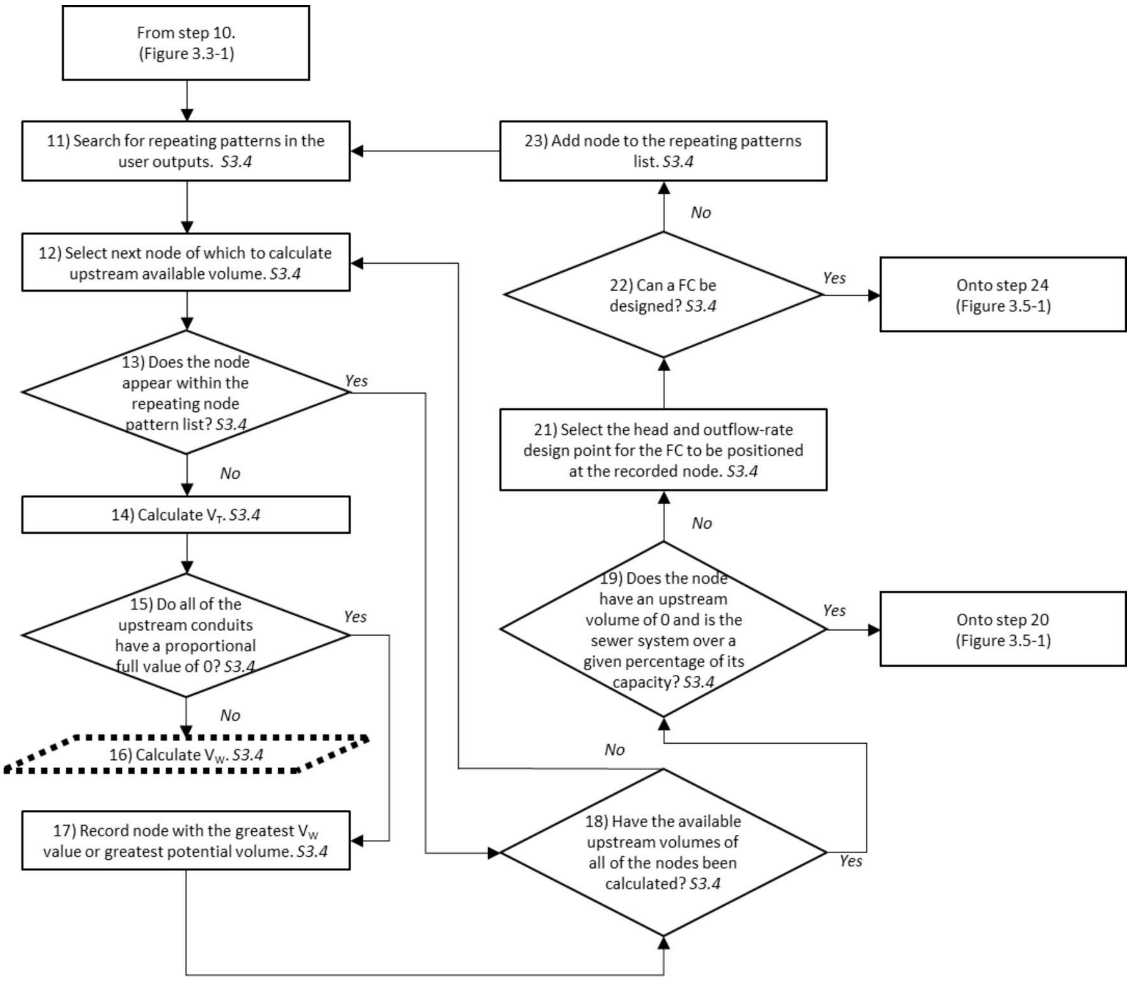
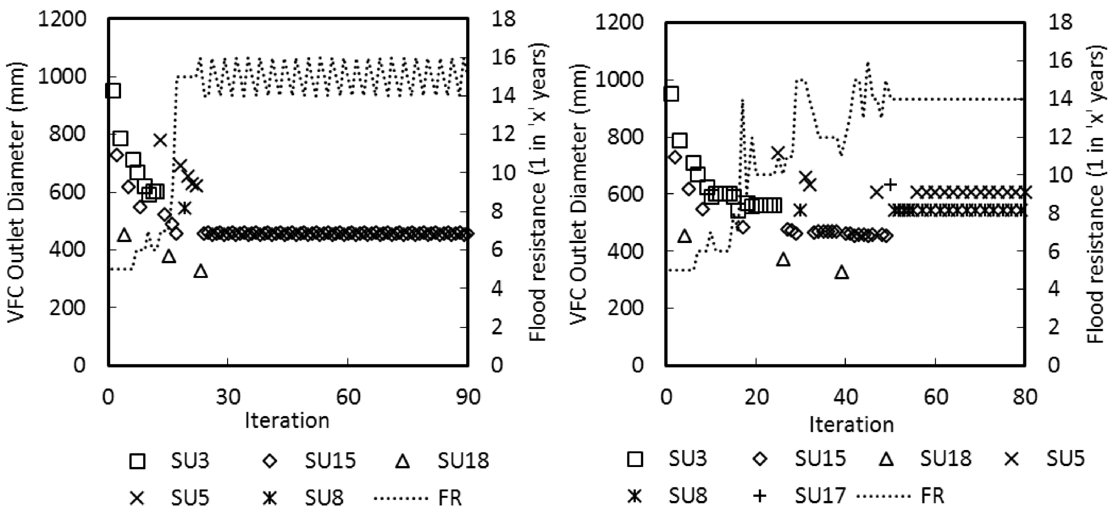


Figure 3.4-1: Step 11 to 23, of the method for positioning and designing VFCs into sewer systems, for selecting the position for the next flow control to be installed.

The first step in the positioning of the flow control, Step 11, requires the method to search for patterns of any flow control designs that have been repeated in the flow control positioning method, in previous iterations of the method. If fewer than three flow controls have been previously designed, this step is ignored. Searching for patterns of flow controls designed is completed before selecting the position for the next flow control so, if a pattern is found, those nodes can be overlooked in the flow control positioning process. The pattern searching step was introduced into the method to prevent the positioning algorithm continuously repeating a number of flow control design configurations, which was found to prevent progress of the algorithm in some scenarios. This phenomenon caused an uninterruptable loop in the operation of the method, examples shown in Figure 3.4-2a & b. Figure 3.4-2a & b both show separate analyses of a sewer system model where an uninterruptable loop was observed before the introduction of a pattern searching method. The points of the plots show the outlet diameters of the VFCs designed into the sewer system model for the given iteration of the method. The plots also show the locations of the VFCs positioned in the sewer system model in the legend, as well as, the achieved FR level of each proposed solution.



a) Plot of an analysis completed by the assessment framework before the introduction of the pattern matching algorithm.

b) Plot of an analysis completed by the assessment framework before the introduction of the pattern matching algorithm.

Figure 3.4-2: Plots comparing the outlet diameters of VFCs designed into sewer system models, at different nodes, by the method before the introduction of the FAST pattern matching algorithm. Both a) and b) show uninterruptable loops where the same size flow controls were being repeatedly designed into the sewer system model.

The plots of the VFC outlet diameters show a decrease in the outlet diameters of the positioned flow controls as the number of iterations of the method increases. This trend is caused by additional flow controls in the upstream sections of the sewer system being designed and enabling the reduction in diameter of the flow controls downstream. This trend continues until approximately 25 and 50 iterations of the method respectively, where after no change is observed in the flow controls outlet diameters in the proceeding iterations. Figure 3.4-2a & b both show the method continued with the analysis, as none of the analysis constraints have been exceeded, in Step 7 to 9, and therefore have not stopped the analysis. On the secondary axis of both plots, the dashed black line shows the FR level achieved at each iteration of the method. Evidence of the method being in a repeating loop is further demonstrated by the repeating values of the FR levels either oscillating in Figure 3.4-2a or an unchanging value in 3.4-2b. Both of these analyses using the method in Figure 3.4-2a & b were manually prevented from continuing due to the developed loop. It was deemed necessary to introduce a pattern matching algorithm to prevent this loop from occurring.

The method of searching for patterns within the already positioned and designed flow controls is based on a FAST pattern matching algorithm (Sheik *et al.*, 2004). The FAST pattern matching algorithm has a search phase, which completes a character-character comparison of a string of data to find repeating patterns. The FAST pattern matching algorithm was presented to search through the listed data from left to right. The FAST pattern matching algorithm was adapted for use in this project and was adapted to search the listed data in reverse order from right to left instead. This is because the concern is in the pattern of flow controls more recently positioned and designed in the analysis. Making this adaptation to the FAST pattern matching algorithm also reduces the computational time of searching for repeating patterns. In the event of a repeating pattern of flow controls being found, the relevant node names are recorded to prevent the method positioning the next flow control into those nodes. If no repeating pattern is found in the list of designed flow controls, the method is able to select any of the nodes in the sewer system model to position the next flow control, Step 12 to Step 18 (Figure 3.4-1).

After completing the pattern matching algorithm, the method searches the sewer system model for the node with the greatest volume of upstream capacity, Figure 3.4-1. This is completed by iteratively assessing all of the nodes in the sewer system for their total available upstream volume, V_T, Figure 3.4-3.

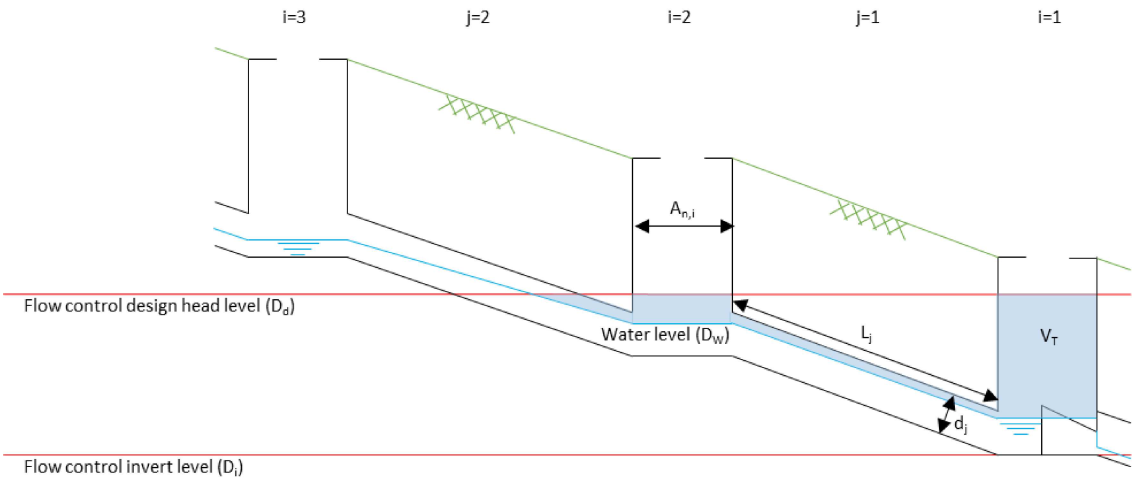


Figure 3.4-3: Schematic of a sewer system showing the calculated available storage volumes that are calculated in Step 14 of the method.

The method to calculate the available storage volume follows the following steps:

Step 12. A node in the sewer system model is selected to then begin calculating its available upstream capacity. The selected node must have a conduit upstream of it to allow for attenuation.

Step 13. The selected node is compared to any nodes recorded in the pattern matching algorithm. If the selected node is found in the list of recorded nodes, the next node is selected.

Step 14. The volume available in the nodes, $V_{n,i}$, is calculated using

$$V_{n,i} = (D_d - D_{W,i})A_{n,i} \tag{3.1}$$

where D_d is the design head of water for the flow control (m), $D_{W,i}$ is the depth of water in node (m) and $A_{n,i}$ is the internal cross-sectional area of any available upstream node (m^2). The volume of the conduits, $V_{l,j}$, between the nodes is calculated by,

$$V_{l,j} = \frac{P_{f,j} L_j \pi {d_j}^2}{4} \tag{3.2}$$

where $P_{f,j}$ is the pipe full ratio of the conduit, L_j is the length of the conduit (m) and d_j is the internal diameter of the conduit (m). The total available volume upstream of the node, V_T, is the sum of the volumes in the upstream i nodes and the upstream j conduits between the maximum water level, D_W, and the maximum design depth of the flow control, D_d,

$$V_T = \sum V_{n,i} + \sum V_{l,j} \quad (3.3)$$

Whilst the method searches for the upstream nodes and conduits from the selected node, the method checks that the node or conduit has not already been accounted for. This is necessary due to possible flow and pipe loops within sewer systems.

Step 15. If V_T equals 0 then the method moves onto decide whether the node name needs to be recorded as a potential location to increase the sewer system capacity by adding storage. If V_T is found to be greater than 0, the method moves onto consider the user's assigned FVS. The FVSs for each subcatchment should have been applied to the sewer system model during its construction.

Step 16. If there is an available volume upstream of the selected node, the calculated available upstream volume is weighted by the respective FVS using the following chosen relationship:

$$V_w = (1 + V_T)^{(1+S_v)} \quad (3.4)$$

where V_W is the weighted volume and S_V is the relevant FVS between -1 and 1. A S_V value of 1 indicates a subcatchment with a high priority for flood protection and a S_V value of -1 indicates a low priority for flood protection. This relationship was chosen to give a balanced output and to prevent the method from fixating on the positions with the highest S_V values and negligible available storage capacities. For example, when ranking locations with a large value of V_T value and a low S_V value with a position with a small V_T value and high S_V value, the high S_V value position may not be selected as the V_T value does not generate a great enough V_W value.

The FVSs assigned to the subcatchments within the sewer system model are similar to those suggested by Balmforth *et al*. (2006). Balmforth *et al*. present initial flood consequence ratings for different infrastructures and structures (see Section 10.5.1

(Balmforth *et al.*, 2006)). By including a vulnerability score into the method, the method prioritises the attenuation of potential flood volumes upstream of the critical subcatchments. The FVSs are extracted from the sewer system model file where they were input by the user before using the tool. Further details about the FVSs are discussed in Section 4.3.6.

Step 17. The method then records the node with the greatest V_W value. If no previous node has been recorded that has an available upstream volume, the node with the least distance between the maximum water depth and node cover level is recorded as a potential location to install additional storage volumes.

Step 18. Once the available upstream volume of the selected node has been calculated, the method checks if all of the nodes in the sewer system model have been assessed. If this is the case, the method moves onto determine whether to design a flow control or to add additional storage, otherwise, it returns to calculate the available upstream volume of the next node, Step 12.

At this stage of the method, the position of the next flow control to be installed has been selected as the node with the greatest V_W value. The method then moves onto check whether a suitable flow control can be designed into that location and selects the design head and design flow-rate of the flow control. Step 19 of the method checks whether a flow control should be designed or additional storage is required, depending on the node and data recorded in Step 17. If additional storage is to be added to the sewer system model (i.e. none of the available nodes have any available upstream storage volume) the method moves onto add additional storage to the sewer system model, else the method moves onto select the design head and flow-rate of the flow control. The method for adding additional storage is discussed in Section 3.5.

Once the position for the flow control has been selected in Steps 12 to 18, and a flow control is to be designed (Step 19), Step 21 determines the design head and average outflow-rate of the flow control. The flow control is then designed using the method presented by Newton *et al.* (2013b). The flow control design method, presented by Newton *et al.*, designs VFCs to have the same average outflow-rate over the design head range as an orifice plate that was designed in the same position. The aim of this flow control design method is to manage the flow volumes being passed downstream and, therefore, not cause additional flooding issues elsewhere in the sewer system.

This alternative method was chosen due to the complexity of designing VFCs, which has three design parameters (outlet diameter, aspect ratio and slot ratio (Jarman *et al.*, 2014)), compared to designing an orifice plate, which has one parameter (outlet diameter). The design head is calculated as the depth of the node chamber minus the freeboard value, H_S, which is entered by the user in Step 1. The average flow-rate is determined by sizing an orifice plate to attenuate potential flood volumes into the calculated maximum spare capacity and then averaging the outlet flow-rate over the design head. The size of the orifice plate is determined through a storage routing procedure (further explained by Butler & Davies, 2011)

$$V_{in} - V_{out} = A_h \Delta h \tag{3.5}$$

where V_{in} is the volume of water entering the storage chamber over the time period (m^3), V_{out} is the volume of water leaving the storage chamber over the time period (m^3), A_h is the area of storage as a function of head (m^2) and Δh is the change in head level over the time period (m). The value V_{in} was taken from the inflow hydrograph from the hydraulic simulation outputs in (Step 10). V_{out} is determined from large and small orifice theory similarly to Jarman et al. (2011a):

$$V_{out} = Max \begin{cases} 2C_d\sqrt{2g}\left[-\frac{2D}{3}(D-h)^{\frac{3}{2}} + \frac{2}{5}(D-h)^{\frac{5}{2}} + \frac{4}{15}D^{\frac{5}{2}}\right] \\ C_d\frac{\pi D^2}{4}\sqrt{2g\left(h-\frac{D}{2}\right)} \end{cases} \tag{3.6}$$

where C_d is the coefficient of discharge for the orifice plate (the method uses an arbitrary value of 0.6), g is the acceleration due to gravity (m/s^2), D is the cross-sectional diameter of the orifice plate's outlet (m), and h is the head of water upstream of the orifice plate measured from the orifice plate's invert level (m). The area of storage as a function of head, A_h, is used in Equation 3.5 to size the flow control (see Figure 3.4-4). The storage area available is calculated at arbitrary 0.1m intervals above the invert level of the intended position of the flow control (D_i). Figure 3.4-4 shows a theoretical example. The values are then used to calculate the volume of water attenuated upstream of the node that will contain the flow control.

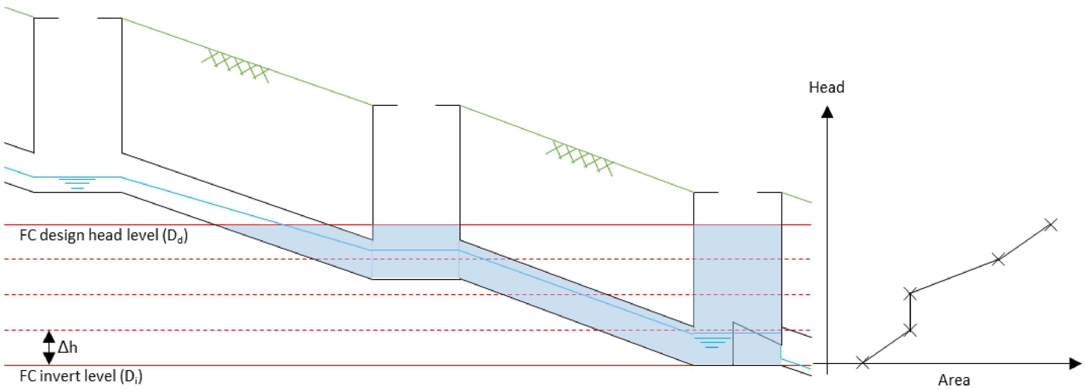


Figure 3.4-4: Schematic of a sewer system showing the upstream volume used to derive the area of storage, as well as, an example head against area plot of total storage.

To determine the orifice plate outlet diameter, D in Equation 3.6, the *GoalSeek* method in VBA is used so that the maximum head of water over the simulation period, calculated in Equation 3.5, is equal to the flow control design head level. After calculating the design head and outlet diameter of the orifice plate in Step 21, Step 22 checks if a flow control can be designed to attenuate the flow in the selected node. The reasons for not being able to design a flow control are:

1) Outlet diameter of the flow control will be less than the user specified minimum flow control outlet diameter, Step 1; or
2) Outlet diameter of the flow control will be greater than the internal diameter of the downstream conduit.

If a flow control cannot be designed for that position, the method adds the previously selected node to the repeating patterns list of nodes (Step 23). This will prevent the next iteration of the positioning metric (Step 11 to 18) from selecting the same node as previously selected. The method then returns to select an alternative position to install a flow control in Step 11. If a flow control can be designed, the method calculates the average outflow-rate of the orifice plate over the design head range and continues onto design the flow control in Section 3.5.

3.5 Design of the flow control or additional storage

In Section 3.4, the method searches for the available storage capacities within the sewer system model, when simulated with a CIH of the desired return period, and determines the average outflow-rate of an orifice plate in the selected position in the sewer system model. The next section of the method designs the flow control to be installed into the sewer system model (Step 24 to 26) as well as updating the outputs of the method by recording the flow control designed and the estimated cost of the solution, C_T (Step 27 to 28).

The flow controls are used to attenuate potential flood volumes within the system. The factors that would impact an engineer's selection of a flow control to be positioned into a system may include:

- Use of moving parts (i.e. passive or active flow control);
- Outlet diameter and risk of blockage;
- Ease of installation;
- Power requirements;
- Sump and chamber geometry requirements;
- Future proofing (can the behaviour of the control be changed at a later date without major construction?);
- Independent performance verification of the flow control;
- Engineer's previous experience with the flow control; and
- Cost of installation.

The flow controls selected to be positioned within the sewer system were vortex flow controls (VFCs) and orifice plates due to various reasons, Table 3.5-1. Orifice plates, picture provided in Table 3.5-1, provide flow attenuation by physically obstructing the flow and reducing the available cross-section area.

Orifice plates are commonly used as they are simple to design, construct and install. They also do not have moving parts or have a power requirement.

Table 3.5-1: List of reasons for selecting vortex flow controls and orifice plates to be used in this research project.

Flow control:	**Vortex flow controls**	**Orifice plates**
Image of flow control:	 *	 **
Reasons for selection:	Passive flow control	Passive flow control
	No power requirements	No power requirements
	Sump may be required	No sump required
	Installed in standard manhole chamber	Installed in standard manhole chamber
	Design may be adjustable	Design not adjustable
	May have independent verification	May have independent verification
	Reduced risk of blockage compared to an orifice plate	Higher risk of blockage compared to a vortex flow control

*Picture of a vortex flow control from Hydro International, http://www.hydro-int.com/uk/products/hydro-brake-optimum, accessed 16th June 2015.

**Picture of an orifice plate from ACO, http://www.aco.co.uk/product_detail.php?id=89, accessed 16th June 2015.

VFCs, on the other hand, are more complex than orifice plates but are still passive flow controls with no moving parts or power requirements. VFCs, picture provided in Table 3.5-1, throttle the flow-rate by generating a vortex within its geometry at increasing upstream head levels. The air core of the vortex reduces the cross-sectional area of the flow at the outlet of the device and, therefore, reduces the downstream flow-rate. In comparison to orifice plates, VFCs have:

1) A lower risk of blockage;
2) Reduced upstream storage requirements;
3) Higher average outflow-rate;
4) Larger physical geometry; and
5) A greater cost (Newton *et al.*, 2013b).

With regard to designing flow controls into the sewer system, the method must first determine whether a VFC or an orifice plate should be designed in Step 25 or Step 26 respectively, Figure 3.5-1. A VFC or orifice plate is selected by comparing the design head and average outflow-rate of the orifice plate, designed in Step 21, to the VFC's design ranges, Table 3.5-2. Two types of VFCs can be designed, cylindrical or conical frustum (Figure 3.5-2a and Figure 3.5-2c respectively). Figure 3.5-2b also shows the hydraulic characteristics of the two types of VFCs. Both curves plotted record three distinct phases of the VFC's behaviour:

1) **Flow through the device when no vortex has been initiated.** At lower head values, there is no vortex yet formed within the VFC and the flow is allowed to pass relatively freely;
2) **The formation of the vortex within the device.** As the head upstream of the VFC increases, the vortex begins to form within the device and is recognised as the section of the hydraulic behaviour curve with a negative gradient; and
3) **The flow being throttled by a stable vortex within the device.** As the upstream head continues to increase, and once the vortex has stabilised within the device, the gradient of the hydraulic behaviour curve becomes positive again.

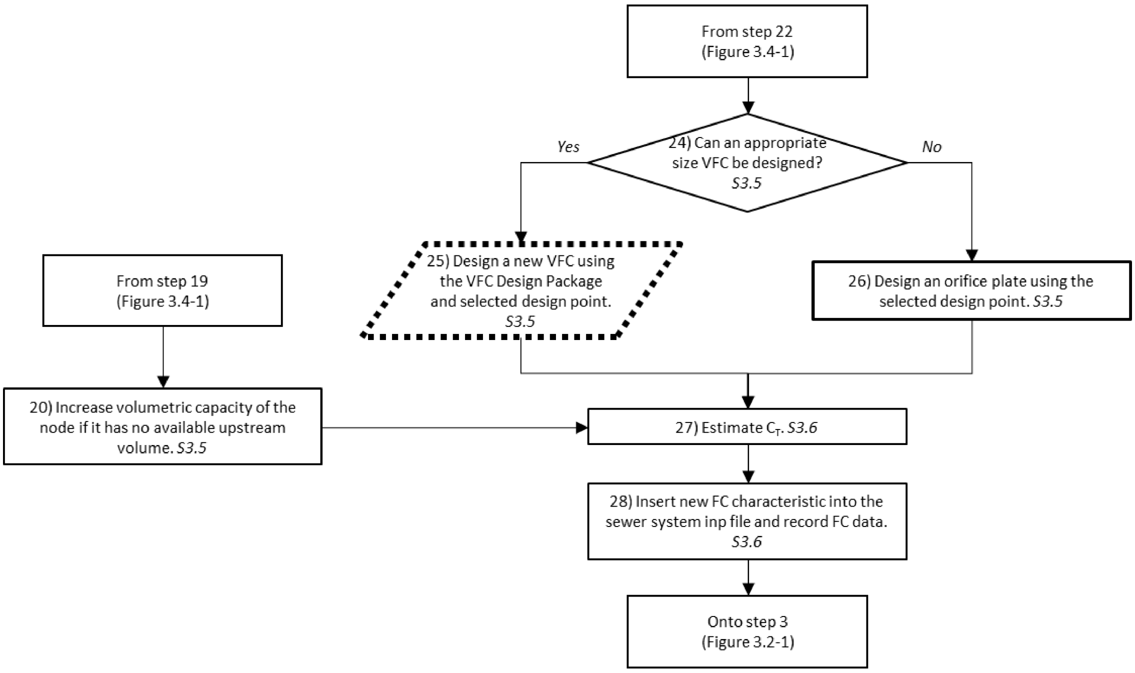
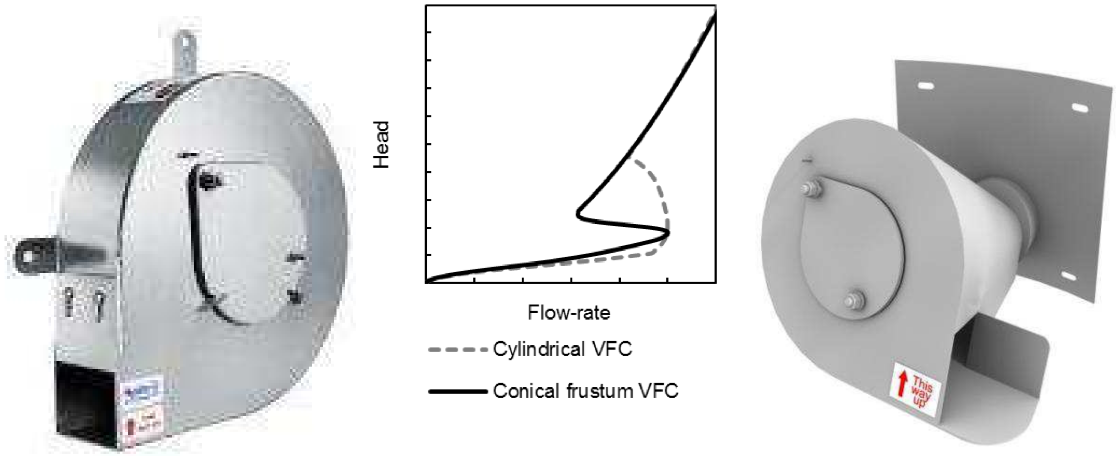


Figure 3.5-1: Step 20 and 24 to 28 of the method for positioning and designing VFCs into sewer systems that selects and designs the appropriate flow control to be installed in the selected node, as well as, calculate the cost, C_T, of the new proposed sewer system design.

Table 3.5-2: Design ranges for the two differing geometry types of vortex flow control (British Board of Agrément, 2012 & 2013).

	Range of values	
Characteristic	Cylindrical VFC	Conical frustum VFC
Design flow-rate (l/s)	0.7 to 250	3 to 550
Average flow-rate (l/s)	0.6 to 214	2.1 to 405
Design head (m)	0.4 to 4	0.25 to 4



a) Image of a VFC with a cylindrical geometry (Hydro International, 2012).

b) Plot of the head across the VFC against the outlet flow-rate for both a cylindrical geometry and a conical frustum geometry VFC.

c) Image of a VFC with a conical frustum geometry (Hydro International, 2012)

Figure 3.5-2: Images of a) a VFC with a cylindrical geometry and c) a VFC with a conical frustum geometry as well as b) a plot showing the hydraulic behaviour curves of both types of VFC.

The targeted design point for the VFC occurs during this third phase of behaviour when the vortex has formed and become stable. The hydraulic characteristic for the cylindrical VFC, shown as a grey dashed curve, typically has a higher flow-rate at lower head values compared to the hydraulic behaviour curve for the conical VFC, shown as the black solid line, Figure 3.5-2b. A cylindrical VFC is used when sumps, with upstream standing water, is acceptable as the inlet invert of the cylindrical VFC is lower than its outlet invert. The conical frustum VFC is used when sumps, and upstream standing water, are not acceptable, for example in a sewerage system. The inlet and outlet of a conical frustum VFC have the same invert level. A cylindrical VFC is generally preferred as they typically require a reduced volume of upstream storage compared to a conical frustum VFC. If the design head and average outflow-rate are outside the specified ranges for a VFC (Table 3.5-2), an orifice plate is designed. If the VFC or orifice plate has an outlet diameter small than the user specified value, the outlet diameter is increased to not conflict with either condition.

If it is determined that a VFC can be designed for the selected design head and average outflow-rate then the flow control is designed in Step 25, else, an orifice plate is designed in Step 26. Step 25 designs a VFC, firstly, using the method of design termed the ‘retrofit design method’ (Newton *et al.*, 2013b) to select the VFC design constraints and the method by Jarman *et al.* (2014) to design the VFC. The method involves designing the VFC to have the same design head and average outflow-rate as an orifice plate designed into the same position, as explained in Section 3.4. This will design a VFC with a lower peak flow-rate at the design head level compared to an orifice plate. Designing the VFC using the average outflow-rate will also reduce the risk of downstream flooding by maintaining a similar volume of water being allowed downstream during the storm event compared to a VFC designed for the same top design head and flow-rate as an orifice plate.

Once the VFC has been designed, the method moves onto estimate the cost of implementing the design, Step 27.

3.6 Assessing the total financial cost of the design

As discussed in Section 3.4, Step 19 determined whether a node within the sewer system model required additional volumetric capacity, Figure 3.4-1. If a node’s volumetric capacity requires increasing, the node’s diameter is increased by an arbitrary factor within the method code (10%) and the increase is recorded in the method’s outputs for the user. The cost of increasing the storage volume of a node is entered by the user in Step 1, C_S, and is taken into account within the method. If the node’s diameter is increased, the tool moves onto calculate the total estimated costs and assess the change in FR level.

Step 27 estimates the total estimated cost of the proposed design changes of the sewer system model. The total estimated cost is given by:

$$C_T = \left(1 + \frac{C_C}{100}\right) \cdot \left(\sum_i C_{FC,i} + \sum_j C_{I,j} + \sum_k C_{R,k} + \sum_n C_{S,n}\right) \quad (3.7)$$

where C_T is the total estimated cost of the proposed design, C_C is the user assigned consultancy fee as a percentage, C_{FC} is the cost of the flow control, C_I is the cost to install the flow control, C_R is the cost to increase a manhole chamber's diameter so the flow control will fit and C_S is the cost of installing storage if flow controls are not beneficial. The cost of the flow controls were supplied by a VFC supplier. All of the user entered costs (consultancy fees, flow control installation costs and manhole chamber construction costs) are further discussed in Section 4.5.

The total estimated cost is displayed in the final user outputs in both the list of flow controls positioned and the plot of the total estimated cost against the change in FR level, further explained in Section 3.7. After the selection and design of the appropriate flow control, the flow control's hydraulic characteristic is inserted into the sewer system model file (Step 28). The method then loops back to Step 3, to quantify the change in the FR level of the sewer system, and continues following the flow control positioning method until either of the stopping criteria in Section 3.3 prevent the method continuing. If the stopping criteria prevent further flow controls being installed into the sewer system model, the method moves onto present the user outputs from the analysis, Section 3.7.

3.7 Presenting the user outputs from the sewer system analysis

The method moves to present the user outputs (Step 29) if either the FR level, the available capacity or the total estimated costs have exceeded the user defined limits in Step 7, 8 and 9. Step 29 saves the user output data from the method in a PDF format for the user's future reference before the method ends. Within the user output data:

1) A copy of the input constraints from Step 1;
2) A list of the flow controls positioned in the sewer system model (example in Figure 3.7-1a); and

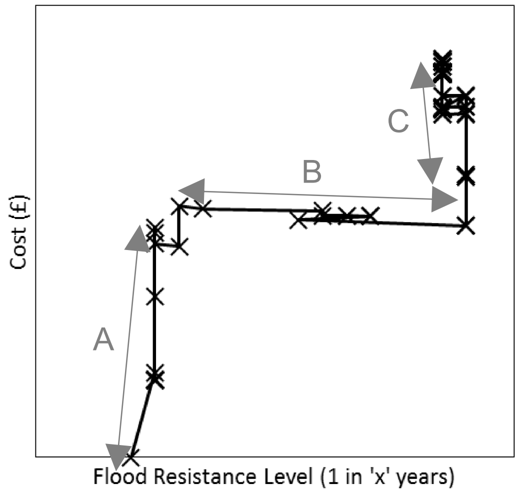
3) A plot of the FR level improvements and estimated costs (example in Figure 3.7-1b) are presented.

The list of flow controls (Figure 3.7-1a) gives details of:

1) The positions of the flow controls (found in Section 3.4);
2) The design constraints of the flow controls (found in Section 3.5);
3) Whether a larger manhole chamber is required (found in Section 3.5);
4) The total estimated cost of the designs (C_T) (found in Section 3.6); and
5) The FR levels achieved after each flow control and storage installation (found in Section 3.2).

Junction #	Q (l/s)	H (m)	Outlet Diameter (mm)	HB Cost (£)	Existing Junction Diameter (m)	Junction Diameter for HB (m)	Junction Costs (£)	Installation Cost (£)	Flood Resistance (1 in 'x' years)	Total Cost (£)
-	-	-	-	-	-	-	-	-	**4**	**0**
SU3	803.43	1.8	944	10566.42	4.830	3.106	0	2558	5	13124.23
SU3	596.42	1.8	844	9526.10	4.830	2.861	0	2558	5	12083.91
SU3	565.96	1.8	824	9318.04	4.830	2.793	0	2558	5	11875.85
SU3	579.71	1.8	833	9411.67	4.830	2.816	0	2558	5	11969.48
SU3	572.76	1.8	829	9370.06	4.830	2.810	0	2558	5	11927.87
SU3	572.78	1.8	829	9370.06	4.830	2.810	0	2558	5	11927.87
SU3	572.78	1.8	829	9370.06	4.830	2.810	0	2558	5	11927.87
SU3	572.78	1.8	829	9370.06	4.830	2.810	0	2558	5	11927.87
SU5	757.86	1.8	924	10358.36	4.530	3.040	0	2558	5	24844.04
SU15	416.37	1.8	719	8225.71	2.840	2.509	0	2558	5	35627.56
SU15	313.18	1.8	642	7424.66	2.840	2.356	0	2558	5	34826.51
SU15	245.82	1.8	579	6769.26	2.840	2.194	0	1489	5	33101.83
SU15	207.23	1.8	539	6353.13	2.840	2.097	0	1489	6	32685.70
SU18	127.73	1.8	439	5312.81	2.290	1.839	0	890	6	38888.42
SU15	176.46	1.8	504	5989.02	2.840	2.011	0	1489	7	38524.31
SU15	149.14	1.8	469	5624.91	2.840	1.918	0	1489	12	38160.20
SU18	86.68	1.8	369	4584.59	2.290	1.62	0	890	12	37431.98
SU15	149.19	1.8	467	5604.1	2.840	1.901	0	1489	13	37411.17
SU15	149.14	1.8	466	5593.7	2.84	1.892	0	1489	13	37400.77

a) Example of a PDF file generated showing the outputs from the method.



b) Example of a plot graphically representing the list in the PDF file.

Figure 3.7-1: Example outputs from the method that are produced in Step 29. a) shows the list of flow controls designed into the sewer system model and b) is a plot graphically displaying the change in FR level and cost of the proposed design.

Accompanying the list, is a plot showing the total estimated cost against the improvement in FR level, C_T (Figure 3.7-1b). The black line on the plot traces the changes in total estimated cost and FR level as the flow controls or changes to the sewer system model are made. Each point on the plot represents the addition or re-design of a flow control in the sewer system model. The example plot shows that in the initial stages of the analysis of the sewer system model, Section A, a lower improvement in the FR level is achieved for a significant cost. As the analysis of the sewer system model continues the method begins re-designing the previously designed flow controls and subsequently reduces the cost of the design and improves the achieved FR level (Section B). The final section of the plot, Section C, shows the method positioning and designing new flow controls, however, no improvement in the FR level is being achieved. This graphically illustrates to the user the improvements in FR levels that can be achieved through attenuating potential flood volumes in the sewer system and allows the user to compare possible solutions proposed by the tool. Once the information is saved, the user is then informed that the method has completed its analysis and the method ends.

The outputs from the flow control positioning method, previously described in this section, are designed to be analysed and assessed by the flow control positioning method's user. The outputs from the flow control positioning method range in different levels of cost and levels of achieved flood resistance.

In the flow control positioning method, there are two analysis constraint parameters named the 'FR level factor' and the 'Financial budget factor', Section 3.1. The aim of these factors is to allow the flow control positioning method to search beyond the user's selected design target, which may be prescribed by legislation. Allowing the flow control positioning method to search beyond the desired analysis constraints, potentially more beneficial or cheaper solutions may be achieved.

A hypothetical example is presented, using Figure 3.7-2, to explain how the user may chose the most beneficial solution for the sewer system. In this instance, the user has set the analysis constraints so that the desired FR level is a 1 in 20 year return period and the total budget is £100,000, Figure 3.7-2. The user has allowed the flow control positioning method to explore solutions beyond those constraints and a greatest achieved FR level and total estimated cost of a 1 in 36 year return period and £195,000 was found respectively. Three solutions proposed by the flow control positioning method that maybe of most interest to the user are highlighted by the red circles (A, B and C).

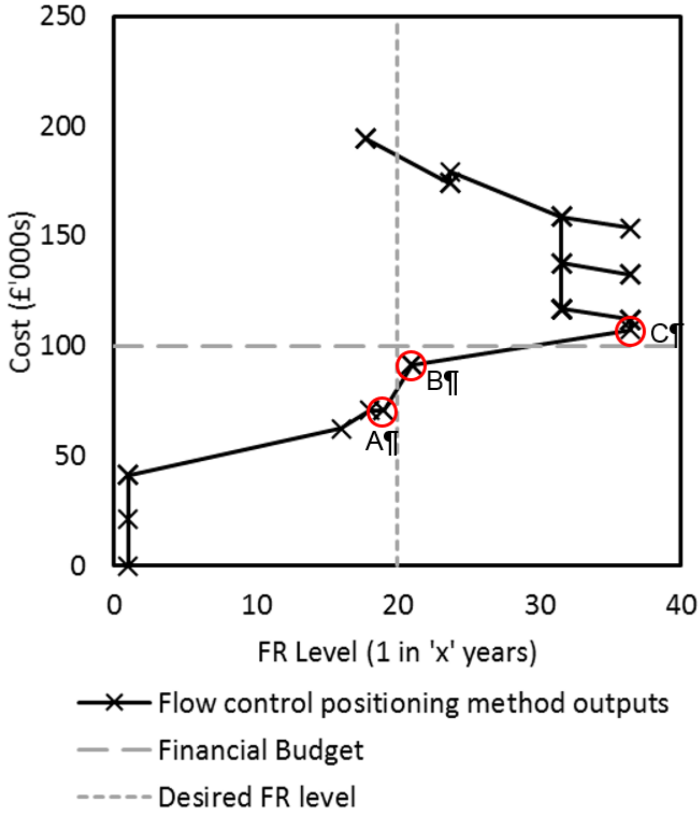


Figure 3.7-2: Hypothetical outputs from the flow control positioning method with the user's financial budget and desired flood resistance level also displayed.

Solution A has an estimated cost of £71,000 but only achieves a FR level of a 1 in 19 year return period. Solution B has an estimated cost of £91,000 and achieves a FR level of a 1 in 21 year return period. Solution C, on the other hand, has an estimated cost of £108,000 but achieves a FR level of a 1 in 36 year return period. If a decision making tool was to select the "best" solution from the flow control positioning method, Solution B would be selected as it is the only solution to be within the user's desired total budget and greater than the user's desired FR level. In this instance, however, Solution C is only £8,000 (+8%) above user's budget and increases the FR level of the sewer system to a 1 in 36 year return period. Compared to the user's constraints, Solution A is £29,000 (-29%) below budget and has a FR level of a 1 in 19 year return period and not a FR level of a 1 in 20 year return period. The user can then build arguments whether Solution

A and C are more beneficial than Solution B due to the cost savings or increased FR level of the design.

3.8 Summary

The method discussed in this chapter is used to strategically position and design flow controls into an existing sewer system model with the aim of improving FR levels. This is achieved by following an iterative method of:

1) Assessing the sewer system's FR level (Section 3.2);
2) Checking that the sewer system and its proposed design are within the user defined analysis constraints (Section 3.3);
3) Selecting the position of the flow control (Section 3.4);
4) Designing and inserting the flow control into the model (Section 3.5);
5) Estimating the financial cost of the proposed design (Section 3.6); and
6) Repeating until the proposed solution is outside the user defined analysis constraints as input in Section 3.1.

Once the method has completed its analysis of the sewer system model, the user is presented with a number of proposed solutions with varying FR levels and estimated installation costs. From these proposed solutions, the user can then select the most appropriate.

Chapter 4

Implementation of the flow control positioning method into an assessment framework

4.1 Introduction

In the third chapter of this thesis, the method for positioning and designing flow controls into existing sewer systems is presented and described. The method requires 29 steps (Figure 3.1-1) to:

- Search for available unused capacities within the existing sewer system geometry;
- Design a flow control to attenuate potential flood volumes into that available capacity during storm events;
- Install the flow control into the sewer system model; and
- Repeat the process until one of the analysis constraints are exceeded (maximum desired FR level, maximum used sewer capacity, maximum desired financial budget).

This chapter follows on by discussing how the flow control positioning method has been implemented into an assessment framework. By implementing the flow control positioning method into an assessment framework, the benefits of positioning flow controls into sewer systems can be quantified and then compared to other industry flood alleviation methods. This chapter will address the following issues:

1) Selection of the components to automate the flow control positioning method;

2) Selection or development of a hyetograph design package if the hydraulic modelling package does not contain one;
3) Explain the application of flood vulnerability scores (FVSs);
4) Further explain the design process for the vortex flow controls; and
5) Quantify the estimated costs for the proposed retrofit solutions used in the assessment framework.

4.2 Purpose of the assessment framework and expected benefits

The assessment framework was constructed to demonstrate the application of the flow control positioning method on sewer system models, as well as quantify the benefits of positioning flow controls into sewer systems (analysis outputs in Chapter 5). The type of sewer system models that will be analysed by the assessment framework are deterministic 1D sewer system models. These sewer system models predict the depths, flow-rates, velocities and volumes of water in links and nodes (pipes and manhole chambers) through mathematical relationships, typically the Saint-Venant equations (Butler & Davies, 2011). Exact flood volumes and surface flood water conveyance across the catchment are not of concern in this project as the aim is to increase the flood resistance (FR) levels and reduce the likelihood of the sewer system flooding. The predicted benefits from the application of the assessment framework on sewer system models are:

1) Proposed designs that improve the FR level of existing sewer systems;
2) A strategic positioning method to locate suitable manhole chambers for flow attenuation;
3) A range of solutions to improve FR levels of the sewer system considering estimated costs and flood vulnerability of subcatchments;
4) Solutions that only require minimal construction within existing sewer assets; and
5) Attenuate potential flood volumes in the sewer system to reduce the number of CSO spills and pollution incidents.

The predictions listed above are revisited in the summary of the case study outputs to see if the predictions were in agreement with the found outputs from the assessment framework, Section 5.7 and 6.5.

4.3 Assessment framework construction and components

As discussed, the assessment framework has been constructed to demonstrate the application of the flow control positioning method. The assessment framework consists of four components that are called and operated using *Visual Basic for Applications* (VBA) in Microsoft Excel®:

1) The hydraulic modelling package;
2) The hyetograph generator;
3) The flood vulnerability score; and
4) The VFC design package, Figure 4.3-1.

The components are called at different steps in the flow control positioning method and these steps are indicated by the italic text in Figure 4.3.1. Sections in which the components are discussed are shown in square brackets in Figure 4.3-1. In this section of the chapter, the different components are discussed and reasons for their selection presented. The components application and use are also related back to the flow control positioning method in Chapter 3.

4.3.1 Microsoft Excel as a data management portal

The main component required for the implementation of the assessment framework is a data management portal and Microsoft Excel was selected. Microsoft Excel was used to construct the assessment framework, facilitate the interaction between the components and enable the transfer of required data. Some of the components of the assessment framework are already in a Microsoft Excel and VBA format (hyetograph generator and the VFC design package, Section 4.3.3 and 4.3.5 respectively). Microsoft Excel is also compatible with VBA, Section 4.3.2, which is able to transfer data between and operate the selected hydraulic modelling package (discussed in Section 4.3.3).

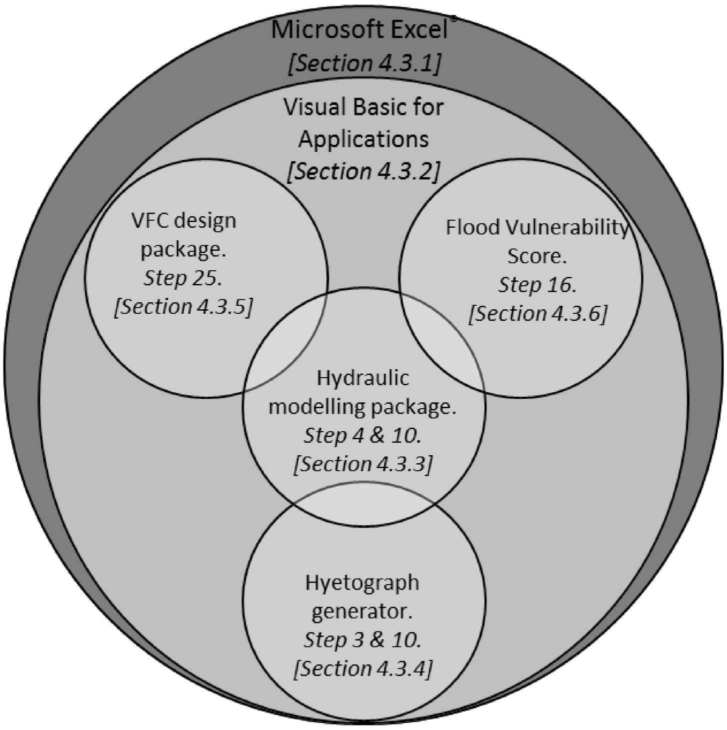


Figure 4.3-1: Extended diagram of the components used in the flow control positioning method assessment framework with reference to the steps they are called at (adapted from Newton et al, 2014).

4.3.2 Visual Basic for Applications

To automate the method, the assessment framework was coded using VBA within Microsoft Excel®. The reasons for opting to use VBA were:

1) Ease of use and connection with Microsoft Excel, Section 4.3.1.
2) The selected hydraulic modelling package, SWMM 5, was executable from the VBA environment, Section 4.3.3.
3) The VFC design package had already been constructed using Microsoft Excel and VBA, Section 4.3.5.
4) Computational time was not a concern as VBA is only capable of using a single processor for computations, unlike Microsoft Excel itself that can use four.

The automation of the flow control positioning method required one Microsoft Excel workbook that contained 20 Microsoft Excel spreadsheets and 173 pages of code in VBA. The majority of the VBA code is available in Appendix A1. The code for the design of the VFC, Step 25 (Section 3.5), has been omitted as a request from the VFC manufacturer and supplier.

4.3.3 Hydraulic modelling package

Sections 4.3.3 to 4.3.6, discuss the additional components called within the method (the hydraulic modelling package, the hyetograph generator, the VFC design package and the flood vulnerability scores).

The hydraulic modelling package is the fundamental component for the integration of the flow control positioning method into an assessment framework. Within the flow control positioning method itself, the hydraulic modelling package is required in Step 2, Step 4 and Step 10, Figure 3.1. The hydraulic modelling package is first used in Step 2 to run a simulation of the sewer system model and check the input file (inp file) can be simulated before continuing with the analysis, Section 3.1. If a successful simulation cannot be completed, an error message is sent to the user and the flow control positioning method does not continue. In Step 4, the hydraulic modelling package is used to predict the FR level of the sewer system. This is completed using an iterative process that completes simulations of the sewer system with rainfall hyetographs of increasing levels of return periods until flooding or over-discharge is predicted, Section 3.2. The process of finding the sewer system’s FR level requires the most number of simulations compared to Step 2 and Step 10. In Step 10, the hydraulic modelling package is used to re-simulate the model using a rainfall hyetograph with the desired return period before the position of the next flow control is selected, Section 3.3. The requirements of the hydraulic modelling package for use in the assessment framework were to be able to:

1) Accurately replicate passive flow control hydraulic behaviour, specifically orifice plates and vortex flow controls;
2) Predict flow attenuation behaviour in medium and large sewer system models using dynamic flow routing and allow for storage; and

3) Communicate with other software packages that are used for the design and selection of rainfall hyetographs and the design of passive flow controls.

A comparison of three hydraulic modelling packages was conducted at the beginning of this project. The three hydraulic modelling packages selected for comparison were: the InfoWorks 'Combined Sewer' package (CS); the 'Storm Water Management Model' version 5 (SWMM 5); and WinDes (Newton, 2012). InfoWorks CS, SWMM 5 and WinDes were selected as they were all used in the UK water industry. The InfoWorks CS package version 12.0.3 was compared in this research project. The InfoWorks CS hydraulic modelling package has the capacity to model combined, foul and stormwater sewer systems. The package is used by a large number of the UK sewerage companies to model their existing sewerage assets. The package is a closed code software package, which is also unable to replicate the transition phase of the vortex flow control's hydraulic behaviour (the section of the characteristic curve where the head increases and the outflow-rate decreases, as shown in Figure 4.3-2).

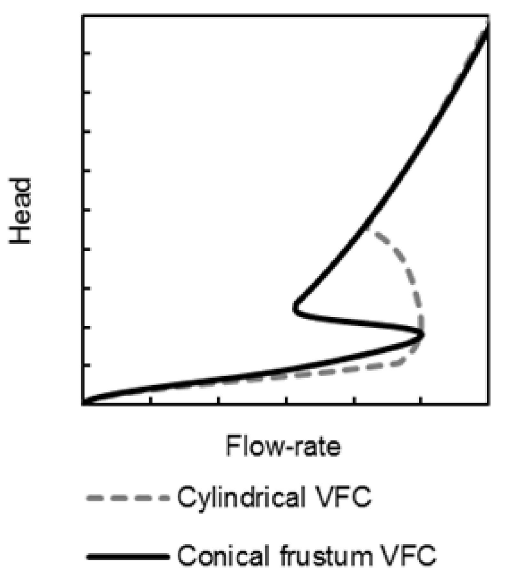


Figure 4.3-2: Plot of the outlet flow-rate against the head across the VFC for both a VFC with a cylindrical geometry and a VFC with a conical frustum geometry.

The SWMM 5 hydraulic modelling package was developed in the USA by the Environment Protection Agency (EPA) (Rossman, 2004). SWMM version 5.0.022 was used in this comparison. The SWMM 5 package has less modelling capabilities than InfoWorks CS, for example, SWMM 5 has fewer subcatchment routing models (one model compared to eight). SWMM 5, on the other hand, is able to accurately model the full characteristic behaviour of the vortex flow control. SWMM 5 is also a freely downloadable software package* and has open source code.

WinDes version 12.6 is a sewer system design package that is also closed code like InfoWorks CS. WinDes was developed by Micro Drainage, in the United Kingdom, and uses the Rational Method to predict volumes of surface runoff and then design sewer systems. WinDes is able to model the behaviour of the vortex flow control but does restrict the number of data points used, to 52 data points, to describe the characteristic. The WinDes hydraulic modelling package also contains a vortex flow control design engine within its software.

The three hydraulic modelling packages were compared by running simulations in each package using three sewer system models of increasing complexity (Newton, 2012). It was concluded from the comparisons that SWMM 5 was the most suitable hydraulic modelling package for the flow control positioning method over InfoWorks CS and WinDes. Reasons for selecting SWMM 5 were:

1) It is an open source software package and can, therefore, interact with other external software packages, such as VBA and *MATLAB*;
2) SWMM 5 does not use the rational method as the rational method has disadvantages when simulating medium and large sewer system model runoff areas (Wisner *et al.*, 1980);
3) SWMM 5 can replicate the full hydraulic behaviour of the VFC unlike InfoWorks CS; and

*The SWMM 5 software package is freely available from http://www2.epa.gov/water-research/storm-water-management-model-swmm. SWMM version 5.0.022 was accessible prior to 15th May 2015.

4) The SWMM 5 hydraulic modelling package is freely available and downloadable from the internet.

4.3.4 Hyetograph generator

SWMM 5 was selected as the hydraulic modelling package for the assessment framework, Section 4.3.3. SWMM 5, however, does not contain a hyetograph generator like InfoWorks CS and WinDes. It was, therefore, decided to develop a critical input hyetograph (CIH) generator to reduce the computational and simulation requirements of the flow control positioning method. By opting to use a CIH, only one simulation for each return period is required. The CIH generator developed was based on the *Flood Studies Report* (FSR) hyetograph generator and Micro Drainage's *Super-Storm* methodology (Newton *et al*., 2013a). Hyetograph profiles for rainfall durations of every one minute from 15 to 1440 minutes are derived and then combined into a single 1440 minute profile, Figure 4.3-3. The derived single 1440 minute hyetograph profile is both critical in volume and intensity causing the whole system to be stressed to its critical hydraulic behaviour within one simulation. The differences of the developed method compared to Keifer and Chu's synthetic storm pattern (1957) are:

1) Duration of the rainfall event is set to 24 hours and not the sewer system's longest time of concentration;
2) Antecedent conditions are not considered; and
3) No relocation of the rainfall's peak intensity as antecedent conditions are not considered.

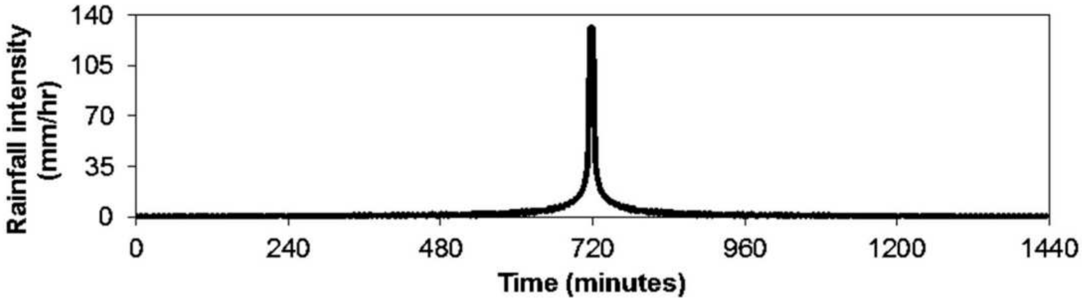


Figure 4.3-3: Example critical input hyetograph profile used in the flow control positioning method when hydraulically simulating the sewer system model.

To determine whether the CIH generator was suitable for this application, the results from simulations using the CIH (A) and Micro Drainage's *Super-Storm* (B) were compared to the simulation using the most critical FSR rainfall profile (C). The most critical FSR profile was determined as the rainfall profile that caused the greatest volume of flooding in a simulation. Comparisons from the simulations found that use of the CIH for simulating a sewer system model produced comparable results to Micro Drainage's *Super-Storm* as all of the Pearson Correlation Coefficient (r) and Coefficient of Determination (R^2) values are greater than 0.8453, Table 4.3-1. The CIH generator also requires less computational power and storage than the Micro Drainage's *Super-Storm* method and Kiefer and Chu's synthetic storm pattern as it does not require large quantities of stored data and requires less computational steps respectively (Kiefer & Chu, 1957).

Table 4.3-1: Table of r and R^2 values comparing the results from simulations A and B to simulation C (Newton et al, 2013a).

Two inputs used in the simulations compared	A & C		B & C	
Selected correlation coefficient	r	R^2	r	R^2
Head of water in nodes	0.9194	0.8453	0.9758	0.9521
Flow-rate in nodes	0.9845	0.9693	0.9955	0.9910
Proportion of conduit full	0.9997	0.9994	0.9996	0.9993
Flood volume at nodes	0.9970	0.9940	0.9992	0.9983

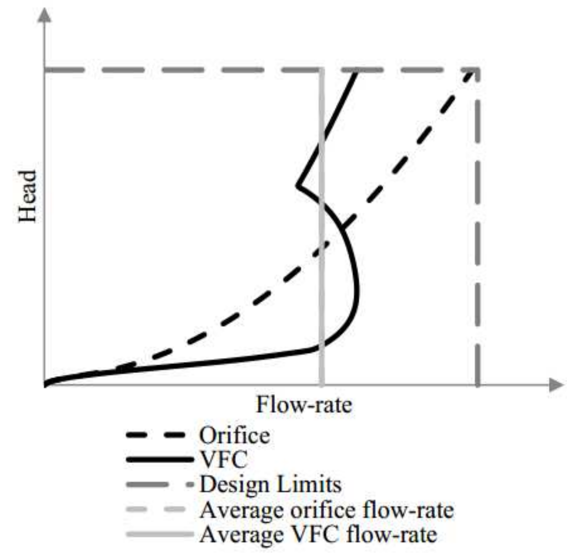
4.3.5 Design of vortex flow controls

The developed flow control positioning method selects the positions and design parameters for passive flow controls, Sections 3.4 and 3.5 respectively. Both orifice plates and VFCs are able to be designed into the sewer system models using the flow control positioning method. The orifice plates are designed from the storage routing procedure used for determining the average downstream flow-rate to maximise the use of the available attenuation volumes in the sewer system, Section 3.4. The orifice plates are easier to design as their hydraulic behaviour is only dependent on the outlet diameter variable, Equation 3.6.

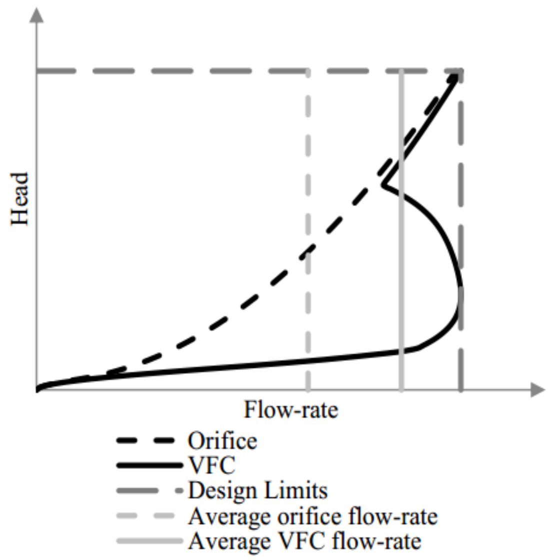
The VFCs, on the other hand, require an additional software package to design its geometry and hydraulic characteristic. In the assessment framework, a previously derived VFC design package is used (Jarman *et al*, 2014). The VFC's design have the same average flow-rate as the designed orifice plate from the flow control positioning method, Section 3.4.

The VFC is designed to have the same average flow-rate to prevent an excessive volume of water being conveyed downstream and causing flooding in the downstream sewer system sections. This design principle is based on the design comparisons by Newton *et al.* (2013b). Newton *et al.* demonstrated that the retrofit of orifice plates with VFCs, which were designed to have the same average flow-rate, increased the sewer system's FR level, Figure 4.3-4a. This is due to the volumes of water being conveyed through the sewer system are more balanced.

In contrast, retrofitting the orifice plates with VFCs that had the same maximum design flow-rate caused the downstream sections of the sewer system to flood and the FR level was reduced, Figure 4.3-4b. This is due to the greater volumes of water being conveyed downstream at the lower head values (i.e. before the post-initiation phase of the VFC's characteristic behaviour).



a) Hydrographs of two flow controls with different design flow-rates but equal average flow-rates.



b) Hydrographs of two flow controls with the same design point but different average flow-rates.

Figure 4.3-4: Plots comparing the hydrographs of an orifice plate and VFC in which a) the average flow-rates are equal and b) the design flow-rates are equal (Newton et al, 2013b).

4.3.6 Flood vulnerability scores

Within the flow control positioning method, flood vulnerability scores (FVSs) can be used to prioritise the flood protection of critical subcatchments within the sewer system model, Section 3.4. The user of the flow control positioning method can assign varying FVSs to the subcatchments within the model. The FVSs that can be assigned to the sewer system subcatchments are not pre-described for the flow control positioning method as long as the values range from a minimum value of -1 for subcatchments with the lowest priority for flood protection and a maximum value of 1 for subcatchments with the highest priority for flood protection. In this project, three different sets of FVSs have been used:

1) All subcatchments have an equal value of 1;
2) Initial flood consequence rating from *Designing for Exceedance* (2006); and

3) The flood risk rankings from either the EA *Risk of flooding from surface water* interactive map (2015a) or the SEPA *Flood Maps* (2015a) depending on the sewer system's location.

In the event that the user has either not assigned FVSs to the sewer system model or has assigned equal scores to all of the subcatchments, no subcatchment has a higher priority for flood protection. This option has been selected for the first section of presented outputs from the application of the flow control positioning method, Chapter 5. The second two options, values from *Designing for Exceedance* (hereby abbreviated to 'DfE') and the flood map rankings, have been applied on two of the case study sewer systems, Chapter 6. The initial flood consequence ratings, from DfE, were applied to two of sewer system models for analysis by the flow control positioning method. These ratings were assigned to the sewer system's subcatchments using the Ordnance Survey map for reference. Arbitrary flood vulnerability scores for the low, medium and high ratings were assigned as -0.75, 0 and 1 respectively depending on what infrastructure was observed in the subcatchment, Table 4.3-2. If multiple FVSs could be applied to a subcatchment, the highest of those values should be assigned.

In addition to the FVSs being assigned using the initial flood consequence ratings, Table 4.3-2, the scores have also been assigned using the respective risk of flooding from surface water maps (RFSWIM) from the Environment Agency and SEPA (2015a & 2015a). Examples of the respective interactive flood maps are shown in Figure 4.3-5 and Figure 4.3-6. To assign the scores to the sewer system models, the flood maps were set as a background to the sewer system model in SWMM 5 and the greatest level of risk seen in the subcatchment was assigned. Arbitrary FVSs for the very low, low, medium and high rankings from the Environment Agency's flood map were assigned as -0.75, 0, 0.5 and 1 respectively. Arbitrary FVSs for no ranking, low, medium and high rankings from SEPA's flood maps were assigned as -0.75, 0, 0.5 and 1 respectively.

Table 4.3-2: Initial flood consequence ratings for different potential impact zones and structures developed by Balmforth et al. (2006).

Initial consequence rating		
Low	**Medium**	**High**
− Open spaces	− Major transport routes	− Hospitals
− Minor transport routes	− Medium/low value manufacturing	− Junior/infant school and nurseries
− Car parks	− Permanent domestic buildings	− Any facilities located in a tunnel
− Minor sports facilities	− Other schools	− Emergency services
− Derelict buildings	− Commercial/business areas	− Telecommunication centres
− Brownfield sites	− Local shopping areas	− High value manufacturing
− Canals	− Major sports facilities	− Temporary domestic dwellings
		− Major shopping areas
		− Senior citizen housing
		− Major stormwater pumping stations
		− Power supplies
		− Water and wastewater treatment works
		− Road/railway cuttings
		− Underground car parks
		− Access for emergency services and to these areas

Figure 4.3-5: Screenshot of the Environment Agency's 'Risk of Flooding from Surface Water' interactive map for London City Centre. The varying blue colours show different risk levels from surface water flooding (2015b).

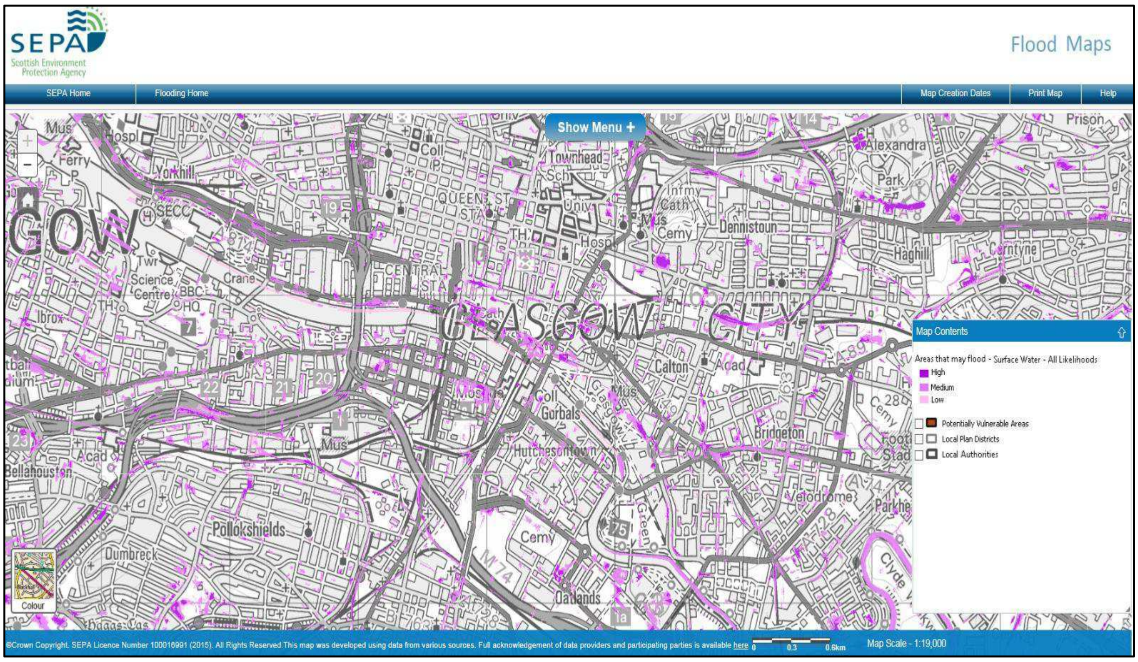


Figure 4.3-6: Screenshot of SEPA's 'Flood Maps' for Glasgow City where the varying pink colours indicate different likelihoods of surface water flooding (2015b).

4.4 Definition and calculation of costs

The aim of the assessment framework is to demonstrate the application and the benefits of the flow control positioning method. The outputs generated from the assessment framework are:

1) A list of flow control designs and positions within the sewer system; and
2) A plot showing the estimated cost and FR level achieved of each proposed design, Section 3.7.

Within the flow control positioning method, the user is able to select the costs of:

1) The percentage increase as a hypothetical consultancy fee;
2) Installing a flow control in an existing manhole chamber;
3) Installing a flow control by removing the manhole lid; and
4) Installing a new manhole chamber.

The cost of purchasing either a VFC or orifice plate, which is embedded within the VFC design package, cannot be changed by the user, Section 4.3.5.

The processes involved in the three methods for installing the flow controls into the chosen manhole chamber are described, Figure 4.4-1. Three methods have been derived based on the physical geometries of the flow controls that the flow control positioning method suggests to install. The first flow control installation method requires no removal of the manhole chamber lid as the flow control can be passed through the manhole cover. A flow control is deemed too large to be passed through the manhole cover if the physical flow control unit diameter is larger than 600mm (value taken from *Sewers for Adoption: 7th Edition*, 2012).

The cost of this method was estimated based on the steps proposed in Figure 4.4-1 and a worker operating within the manhole chamber. The benefits with this process is that it is cheap and could potentially be completed over night. The disadvantage of this process is that it requires the worker to operate in a confined space.

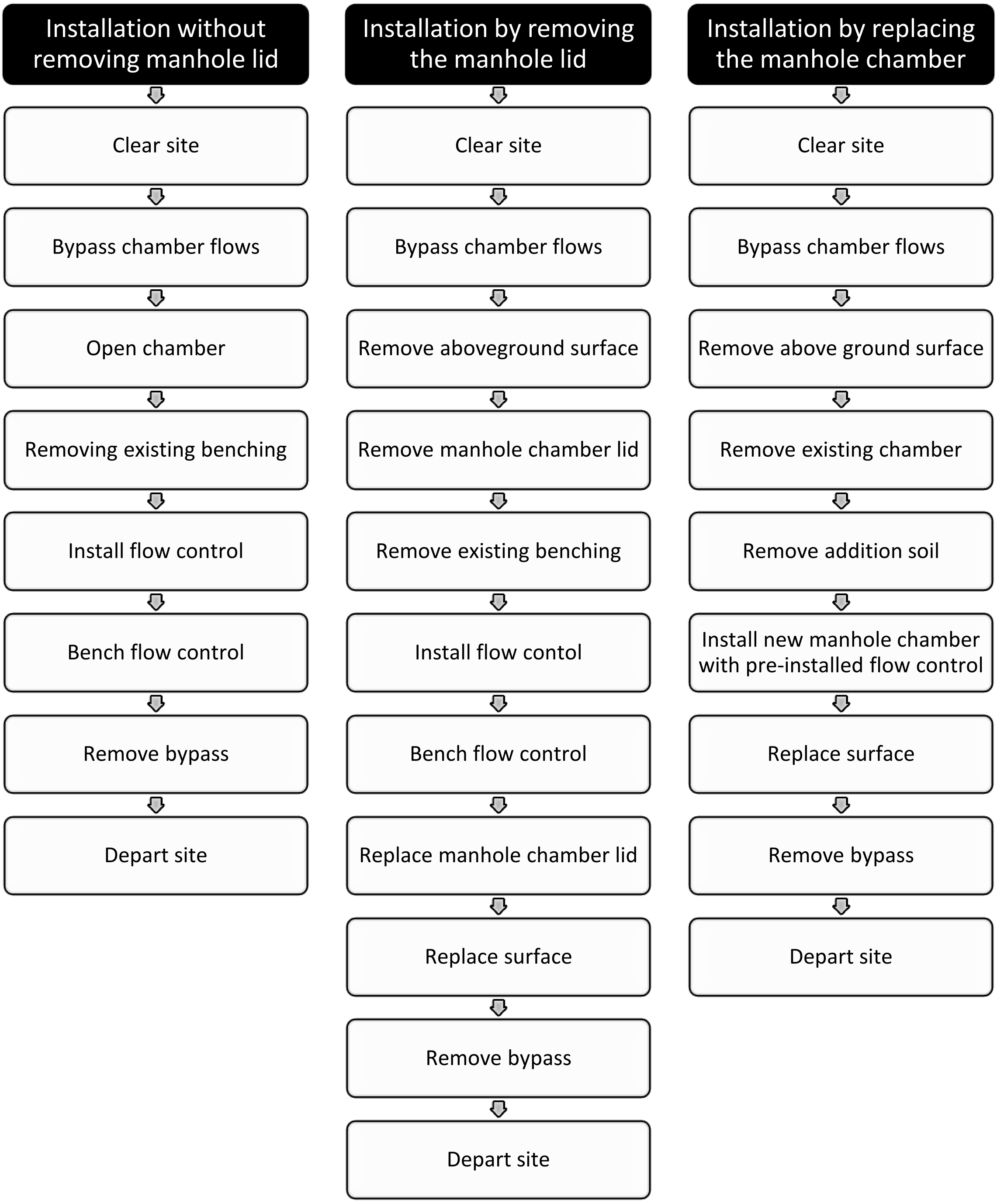


Figure 4.4-1: Flow diagram of the three methods of installing a flow control into an existing sewer system.

The second flow control installation method requires the removal of the manhole chamber lid, Figure 4.4-1. This method is selected when the flow control cannot pass through the manhole cover (physical flow control unit diameter is greater than 600mm) but is suitably small enough to be positioned within the manhole chamber (physical flow control unit diameter is less than the manhole chamber internal diameter). The process of installing the flow control additionally requires the removal of the aboveground surface to access the manhole chamber lid and the chamber lid's removal. The benefit of employing this method of installation is that it could reduce the risk to the worker's by removing the requirement to work in a confined space.

The third method of installing a flow control into the sewer system is to remove the existing manhole chamber and replace it with a manhole chamber that has a larger internal diameter, Figure 4.4-1. This method is selected if the physical flow control unit diameter is greater than the manhole chamber's diameter. This process requires excavation of the existing manhole chamber, further excavation of additional soil and earth for the new manhole chamber, positioning of the new manhole chamber and finally the resurfacing of the aboveground landscape. The benefit to this method is that it may be possible to not place a worker within a confined space or excavation as well as the flow control can be installed off site. The disadvantage of the method is that it is the most expensive and will require the greatest amount of time.

For the case study outputs presented in Chapter 5 and 6 of this thesis, the costs have been estimated for the three methods of installing the flow controls into the sewer system using *Spon's Civil Engineering and Highway Works Price Book* (2013) and discussions with chartered experienced consultants (Hydro Consultancy, 2015), Table 4.4-1.

Table 4.4-1: Summary of the estimated costs used in the flow control positioning method (Appendix A2 to Appendix A4).

Activity	Estimated cost
Consultancy fee.	20% of final cost
Installation of a flow control without removing the manhole lid.	£3,500
Installation of a flow control by removing the manhole chamber lid.	£13,000
Installation of a flow control and replacing the manhole chamber.	£22,750

4.5 Conclusion

This chapter has discussed the implementation of the flow control positioning method into an assessment framework with the aim of investigating and quantifying the benefits of positioning flow controls within sewer systems. The assessment framework have been developed in Microsoft Excel® and automated using *Visual Basic for Applications*. To complete the assessment framework, four additional components were required (hydraulic modelling package, VFC design package, a hyetograph generator and flood vulnerability scores), Section 4.3.3 to 4.3.6.

The automation of the flow control positioning method is not intended to be the development of a commercial assessment framework and, therefore, the quality of the coding is not of a high standard or follows expected coding practices. If this assessment framework was to be used commercially, it is suggested that the assessment framework is reconstructed in a more suitable code platform to eliminate observed issues:

1) Slow and restricted processor usage in Visual Basic for Applications;
2) System crashing during Microsoft Office updates;

3) Restricted use of Microsoft Office Suite when running the assessment framework;
4) Spreadsheets with Visual Basic for Applications can have issues when opening and running in different versions than the version it was constructed in; and
5) Method only operates with the SWMM version 5.0.022 dynamic-link library file and not the newest SWMM 5 version.

Adaptions, considerations and future improvements that are proposed for the tool are further discussed with the case studies and in the conclusion, Chapter 5, 6 and 8 respectively.

Chapter 5

Application of the assessment framework

5.1 Introduction

In the preceding chapters of this thesis, the development of the flow control positioning method and its implementation into an assessment framework has been described (Chapter 3 and 4). The assessment framework has been applied on four different sewer system models of varying sizes and complexities (Section 5.2). This chapter discusses:

1) The application of the assessment framework on the four systems;
2) Quantification of the benefits achieved from application of the assessment framework; and
3) Any possible improvements that can be made to the flow control positioning method and the assessment framework.

After this introduction to the chapter, this chapter secondly describes the four case studies used to investigate the benefits that can be achieved from the assessment framework (Section 5.2). Of the four case study sewer systems presented, one sewer system is hypothetical, the Artificial Network (Section 5.2.1), and the remaining three sewer systems have been anonymised (Section 5.2.2 to 5.2.4). The benefits achieved from the assessment framework are quantified using the achieved FR level from modelling the proposed solutions and the total estimated cost to implement the proposed retrofit solution (previously outlined in Section 3.7). Schematics of the sewer system models are displayed showing the selected positions for the flow controls for the greatest achieved FR level solutions. No overall definitive configuration of positioned flow controls for each sewer system model analysis is selected from the assessment framework as other considerations would need to be accounted for by the user.

Section 5.3 discusses the direct implementation of the assessment framework on the four case study sewer systems. The notation '$d_{o,min}$' is used in place of 'minimum flow control outlet diameter' throughout the remainder of the thesis. The following analyses using the assessment framework were completed for each sewer system model:

1) Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 100 mm.
2) Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm.
3) Positioning of only orifice plates with the $d_{o,min}$ set to 100 mm.
4) Positioning of only orifice plates with the $d_{o,min}$ set to 200 mm.

The positioning of only orifice plates was completed as a comparison to show whether there is additional hydraulic benefit that can be achieved by positioning more advanced flow controls (such as VFCs). This chapter is concluded with a summary of the findings from the completed assessment framework analyses.

5.2 Case study sewer system models

This section of the chapter presents the four sewer system models used to demonstrate the application of the assessment framework (Section 5.2.1 to 5.2.4). The models are located in varying regions of the UK. Each of the sewer system models have been analysed by the assessment framework with prescribed input parameters (Table 5.2-1). Unfortunately, none of the sewer systems based on existing sewer system models could be calibrated due to a lack of available flow monitoring data (the anonymised stormwater sewer system, the Langley combined sewer system and the anonymised combined sewer system). This means the cost benefit analyses (increase in FR level for the associated estimated cost) from the assessment framework presented in this research are all relative and possibly not actual achievable values. Validation of the sewer system models and further assessment of the cost benefit analyses would be required to determine validated, absolute values for FR levels in each sewer system configuration.

Table 5.2-1: Table of user input options entered into the assessment framework for the different sewer system case studies.

Constraint	Artificial Network	Anonymised stormwater sewer system	Langley combined sewer system	Anonymised combined sewer system
Sewer system type	Stormwater	Stormwater	Combined	Combined
M5-60 (mm)	20	18	18	15.5
Ratio-R	0.35	0.4	0.4	0.25
Area (km^2)	0.145	0.0152	0.469	0.3813
Climate Change (%)	0	0	0	0
Location ('1' - England & Wales, '2' - Scotland & Ireland)	1, South England	1, SW England	1, SE England	2, NE Scotland
Free board between top water level and cover (m)	0.3	0.3	0.3	0.3
Discharge consent (l/s)	200	13.2	30	22
Desired FR level	30	120	30	30
Desired FR level factor	1.5	1	1.5	1.5
Desired budget (£)	300,000	50,000	250,000	250,000
Cost of installing a flow control though manhole chamber lid (£)	3,500	3,500	3,500	3,500
Cost of installing a flow control by removing the manhole chamber lid (£)	13,000	13,000	13,000	13,000
Cost of increasing the size of a manhole (£)	22,000	22,000	22,000	22,000
Capacity before adding storage	0.9	0.9	0.5	0.5
Minimum outlet diameter, $d_{o,min}$ (mm)	100 / 200	100 / 200	100 / 200	100 / 200

A number of the input parameters for the assessment framework, previously described in Section 3.1, remain constant for all of the analyses of each case study (Table 5.2-1). Parameters that vary between the different analyses are indicated with multiple entries. Regarding the $d_{o,min}$ value, only 100 mm and 200 mm were considered for the sewer system models as: 100 mm is stated as a minimum in *'Sewers for Adoption - 7th Edition'* (2012); and 200 mm was selected as an arbitrary conservative alternative.

5.2.1 The Artificial Network

The hypothetical Artificial Network has been previously presented and discussed in academic literature (Sun, 2010, & Atkinson, 2013). The sewer system model contains 29 nodes and 29 pipes that convey collected stormwater to an outfall from the 14.5 hectare site (Figure 5.2-1). The subcatchment parameters assigned to each node were 0.5 hectares, 50% imperviousness and an average slope of 0.0004 m/m. The discharge consent for the Artificial Network was set as 200 l/s, which was controlled by an existing VFC at the last manhole chamber before the outfall.

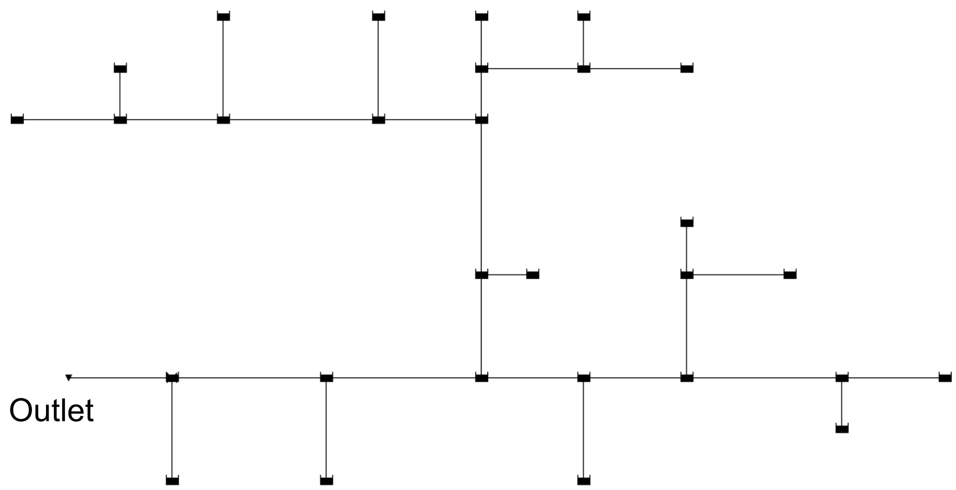


Figure 5.2-1: Schematic of the Artificial Network (Atkinson, 2013).

5.2.2 The anonymised stormwater sewer system

The anonymised stormwater sewer system conveys collected stormwater from a 1.5 hectare catchment to a single outlet at the eastern most point of the system (Figure 5.2-2). The subcatchments parameters set for each node are 100% imperviousness and a slope of 0.0002 m/m. The system contains 14 nodes and 14 circular conduits. The discharge consent for the anonymised stormwater sewer system is 13.2 l/s, which is controlled by an existing VFC at the last manhole chamber before the outfall. The sewer system is located in the South-West region of England.

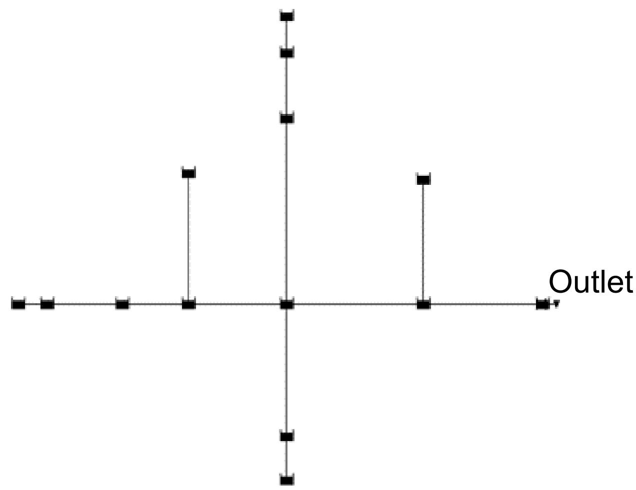


Figure 5.2-2: Schematic of the anonymised stormwater sewer system model.

5.2.3 The Langley combined sewer system

The Langley combined sewer system model is the largest of the four sewer system models that was analysed, Figure 5.2-3 (Innovyze, 2011a). The sewer system contains 281 nodes, 279 pipes, 1 pump and an orifice plate that conveys both stormwater and domestic wastewater to a single outlet. The discharge consent of the sewer system is 30 l/s and the outlet is immediately downstream of a 58.8 m^3 storage chamber, in which the outflow-rate is controlled by an orifice plate. The sewer system model contains 46.9 hectares of subcatchments, which have an average 29.7% imperviousness, and an average slope of 0.014 m/m. The model also contains a diurnal dry weather flow profile assuming a population of approximately 2,350 people using 160 l/capita/day. The Langley combined sewer system model is located in the South-East region of the UK.

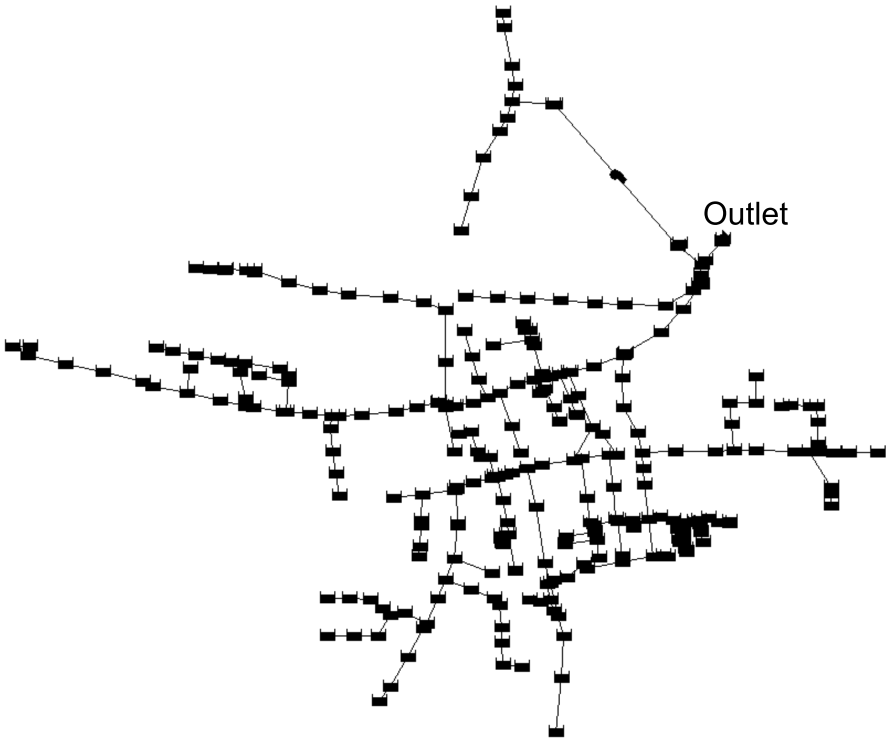


Figure 5.2-3: Schematic of the Langley combined sewer system model (Innovyze, 2011a).

5.2.4 The anonymised combined sewer system

The anonymised combined sewer system is a model of an existing sewer system in the North-East of Scotland (Figure 5.2-4). The system conveys both stormwater and wastewater from a 38.1 hectare catchment. The subcatchments have an average imperviousness of 76.25% and average slope of 0.029 m/m. The sewer system model contains 206 nodes, 203 pipes, 1 pump, 4 orifice plates and 5 weirs. These convey the flow to an outlet in the North-East corner of the system. The outlet has a discharge consent of 22 l/s, which is controlled by a pump. There is also a CSO in the sewer system and its outflow is included in the discharge consent limit. The sewer system contains a number of domestic wastewater profiles and trade wastewater profiles. The domestic waste diurnal profile assumes a population of approximately 1,850 people using 150 l/capita/day.

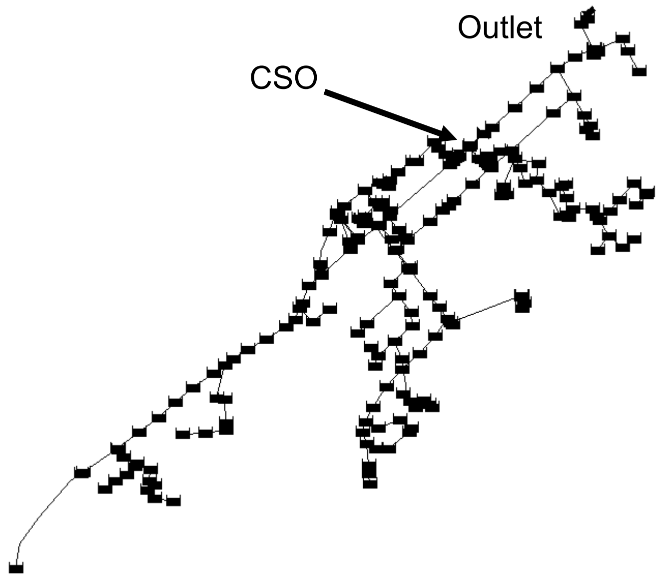


Figure 5.2-4: Schematic of the anonymised combined sewer system model.

5.3 Application of the assessment framework

The four case study sewer system models were analysed using the assessment framework. Each of the four sewer system models were analysed with the aim of increasing the FR level of the sewer system whilst limiting the sewer system outflow-rate to a specified discharge consent (Table 5.2-1). In these analyses, the flood vulnerability scores (FVSs) for all subcatchments in all sewer system models were equal. All four sewer system case studies were analysed for the following four scenarios:

1) Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 100 mm.
2) Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm.
3) Positioning of only orifice plates with the $d_{o,min}$ set to 100 mm.
4) Positioning of only orifice plates with the $d_{o,min}$ set to 200 mm.

5.3.1 Analysis of the Artificial Network

The assessment framework was first applied to the Artificial Network. The input parameters set for the analyses of the Artificial Network are shown in Table 5.2-1. For all of the analyses of the Artificial Network sewer system discussed in this chapter, the same starting sewer system model file was used.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 100 mm.

This analysis of the Artificial Network was when both VFCs and orifice plates were positioned with the $d_{o,min}$ set to 100 mm (Figure 5.3-1). Figure 5.3-1 is a cost benefit analysis for the assessment framework's proposed configurations with the cost for each configuration plotted against the achieved FR level. The plot shows the cost benefit analyses when the $d_{o,min}$ was set to 100 mm and 200 mm respectively. The initial assessment of the Artificial Network found that its initial FR level was a 1 in 4 year return period. When the $d_{o,min}$ was 100 mm, the greatest achieved FR level was a 1 in 28 year return period. This solution had an estimated cost of £204,500, which included the eight flow controls, their installation and a consultancy fee.

The cost benefit analyses show that relatively little increase in the FR level was achieved for an estimated cost below £183,250. For the same approximate cost of £183,250, however, four configurations with a FR level of a: 1 in 7; 1 in 9; 1 in 19; and 1 in 24 year return period were proposed. The increase in the FR level without the increase in cost is caused by the assessment framework redesigning the VFCs already positioned to attenuate a greater volume of water within the sewer system geometry. Beyond the 1 in 24 year return period, a further four more years increase in FR was achieved before the analysis exceeded the maximum desired budget of £300,000.

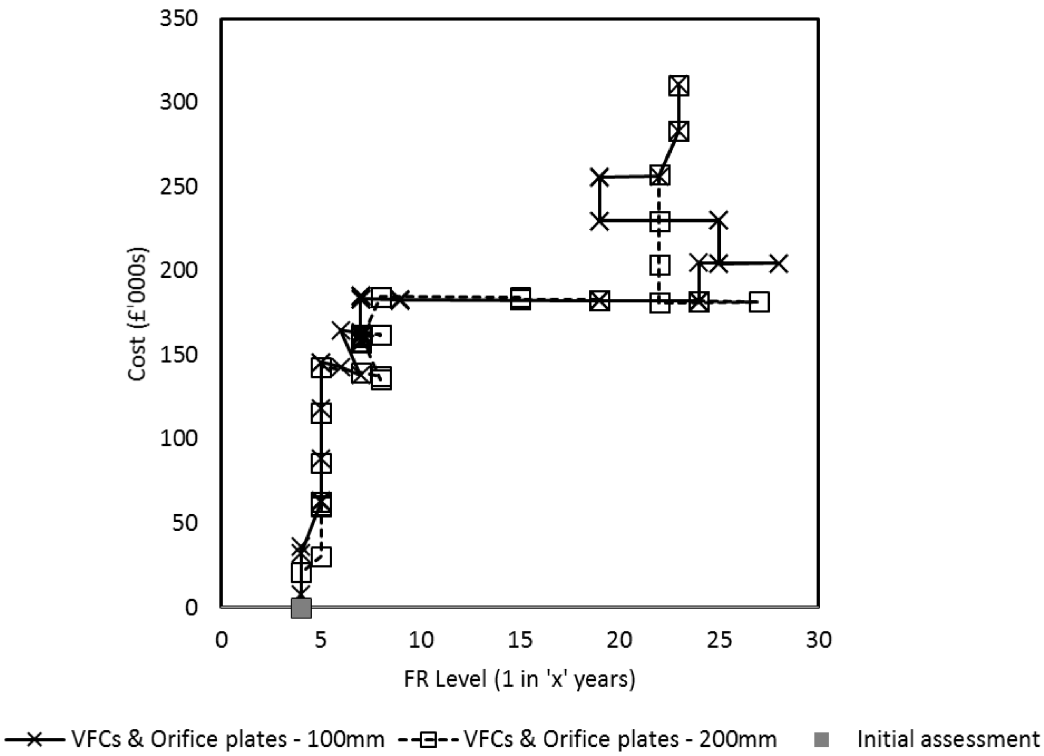


Figure 5.3-1: Plot comparing the assessment framework cost benefit analyses from the analysis of the Artificial Network when VFCs and orifice plates with the $d_{o,min}$ set to 100 mm and 200 mm were positioned, respectively.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm.

The Artificial Network was analysed when both VFCs and orifice plates were positioned with the $d_{o,min}$ set to 200 mm (Figure 5.3-1). The initial assessment of the Artificial Network achieved a FR level of a 1 in 4 year return period. The solution with the greatest FR level, which achieved a FR level of 1 in 27 year return period, required seven VFCs to be positioned. The proposed solution had an estimated cost of £181,750. Before the greatest FR level was achieved, little change in the FR level was observed below an estimated cost of £184,750 (1 in 4 year return period FR level to a FR level of 1 in 8 year return period). Once an estimated cost of £184,750 was exceeded, the FR level of the sewer system was increased from a 1 in 8 year return period to a 1 in 27 year return period without the positioning of an additional flow control. From a FR level of a 1 in 8 year return period to a 1 in 27 year return, the already positioned flow controls were redesigned improving the hydraulic behaviour of the sewer system, as well as, reducing the cost of the proposed solutions (saving £3,000). Beyond the greatest achieved FR level of a 1 in 27 year return period, no additional benefit was achieved before the maximum desired budget of £300,000 was exceeded.

Comparison of the two assessment framework cost benefit analyses show a visually similar trend in the increasing FR level and estimated cost. An explanation for the similar costs and increase in FR levels is that both analyses were proposing flow controls with an average outlet diameter of 458 mm and 468 mm, respectively, which greatly exceeds the assigned $d_{o,min}$ values set to 100 mm and 200 mm. Neither analysis achieved the desired 1 in 30 year return period target before the budget was exceeded.

The cost benefit analyses from the analysis of the Artificial Network, where both VFCs and orifice plates were placed, positioned eight and seven flow controls respectively (Figure 5.3-1). Figure 5.3-2 and 5.3-3 are schematics of the Artificial Network showing the locations of the VFCs positioned to achieve the respective greatest FR levels of a 1 in 28 and a 1 in 27 year return period. In all of the schematics of the sewer systems presented in this chapter showing the locations of the designed flow controls, the flow controls are represented as process diagram valve symbols. The Artificial Network already contained a flow control at the manhole immediately upstream of the outlet (SU1). Comparison of Figure 5.3-2 and 5.3-3 show that seven of the VFCs positioned were positioned by the flow control positioning method in the same locations. In Figure 5.3-2, where an additional VFC was positioned, this was positioned in ‘SU12’ in an upstream section of the sewer system. In both analyses, the first VFC was positioned in ‘SU5’. Selecting ‘SU5’ as the first manhole chamber is logical as it has the largest upstream volume available for attenuation. This highlights that the assessment framework attempts to propose the most cost beneficial solutions by using the fewest flow controls to attenuate the necessary volumes of water.

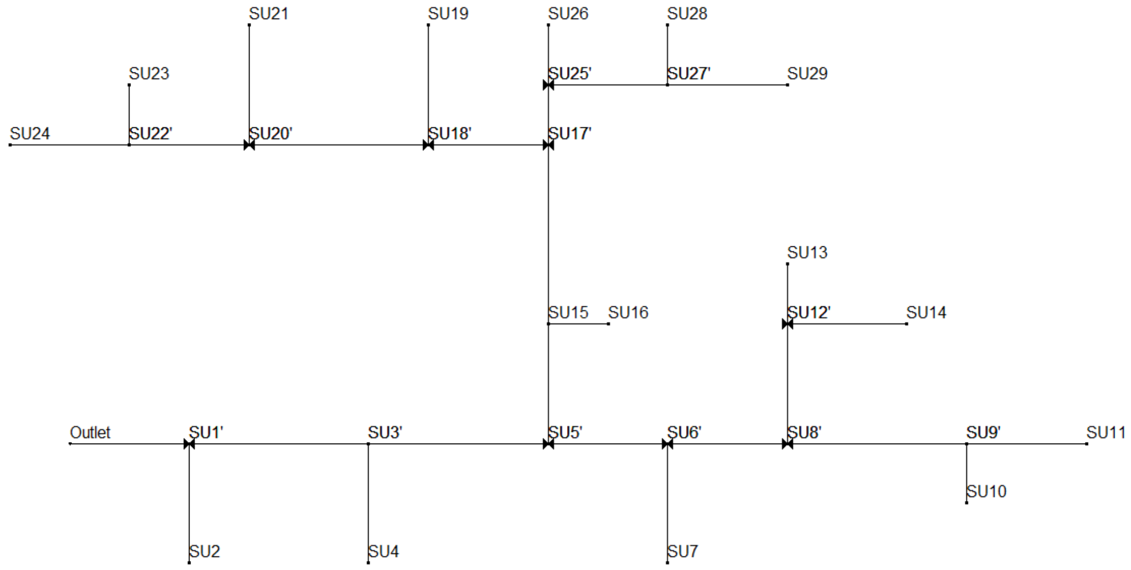


Figure 5.3-2: Schematic of the Artificial Network showing the positions of the VFCs, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 28 year return period.

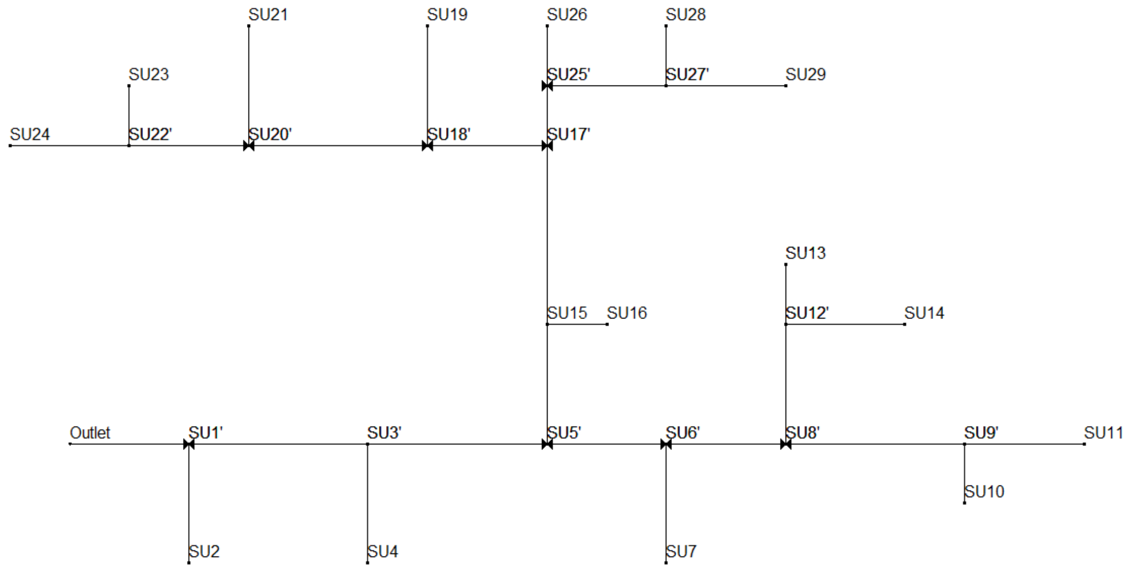


Figure 5.3-3: Schematic of the Artificial Network showing the positions of the VFCs, with the $d_{o,min}$ set to 200 mm, to achieve the greatest FR level of a 1 in 27 year return period.

Positioning of orifice plates with the $d_{o,min}$ set to 100 mm.

The Artificial Network was also analysed only positioning orifice plates with the $d_{o,min}$ set to 100 mm (Figure 5.3-4). In the analysis, the FR level was increased from an initial FR level of a 1 in 4 year return period to the greatest achieved FR level of a 1 in 49 year return period. The solution required the installation of 13 orifice plates and had an estimated cost of £248,750. Figure 5.3-4 shows a general progressive increase in the FR level of the sewer system as the number of iterations of the assessment framework also increases. This was not observed in the positioning of the VFCs and orifice plates in Figure 5.3-1. The analysis ended as the achieved FR level exceeded the user's greatest desired FR level of 1 in 30 years plus the FR level factor of 1.5 (Table 5.2-1).

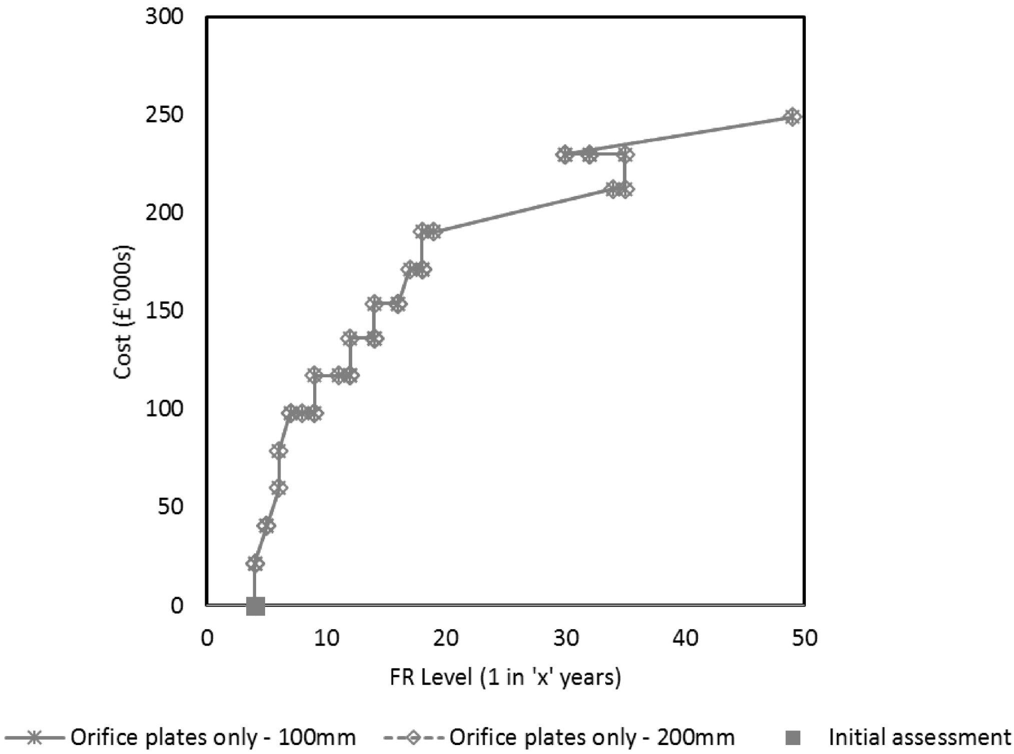


Figure 5.3-4: Cost benefit analyses from the assessment framework after the analysis of the Artificial Network when only orifice plates with the $d_{o,min}$ set to 100 mm and 200 mm were positioned, respectively.

Positioning of orifice plates with the $d_{o,min}$ set to 200 mm.

The analysis of the Artificial Network when only orifice plates with the $d_{o,min}$ set to 200 mm was identical to the cost benefit analysis presented when only orifice plates with the $d_{o,min}$ set to 100 mm were positioned. This cost benefit analysis shows that, in this case, the $d_{o,min}$ was not an influencing constraint due to the geometries of the flow controls being designed into the sewer system model. The smallest flow control outlet diameter designed in both analyses was 200 mm.

The analysis of the Artificial Network where only orifice plates were positioned achieved the greatest FR level of a 1 in 49 year return period. The identical solutions were achieved with the positioning of 13 orifice plates in the sewer system (Figure 5.3-5). Only 13 orifice plates could have been positioned into sewer system model as the flow control positioning method is only allowed to position flow controls into nodes downstream of a conduit (Section 3.4).

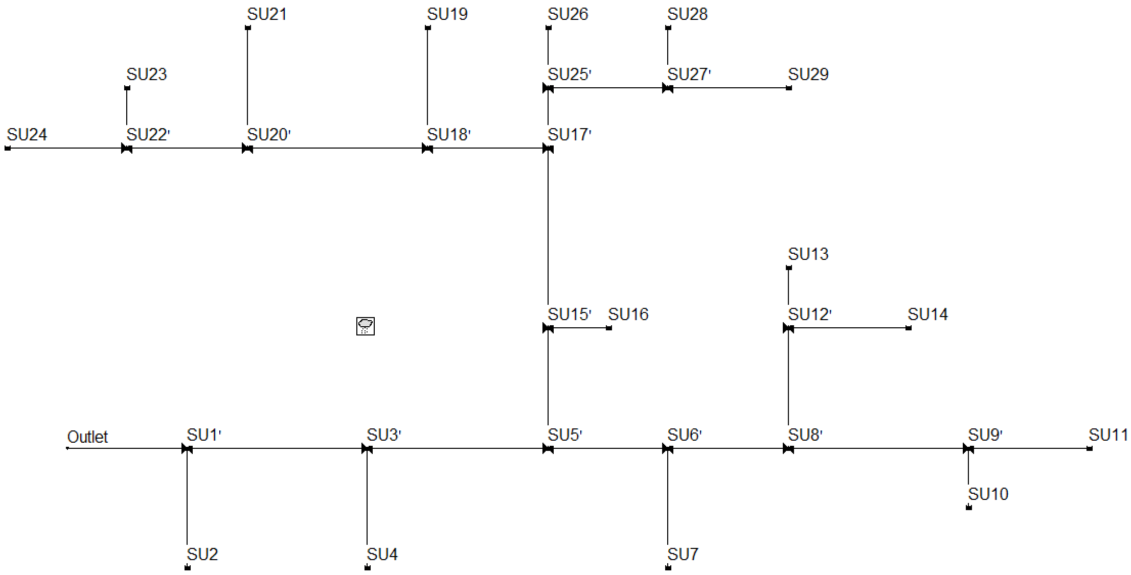


Figure 5.3-5: Schematic of the Artificial Network showing the positions of the orifice plates to achieve the greatest FR level of a 1 in 49 year return period when the $d_{o,min}$ was set to 100mm and 200 mm.

Comparison of all four sets of cost benefit analyses from the analyses of the Artificial Network (Figure 5.3-1 and Figure 5.3-4) are presented in Figure 5.3-6 and Table 5.3-1. Figure 5.3-6 shows that installing orifice plates into the Artificial Network sewer system achieves a greater FR level below the budget constraint of £300,000. Below a FR level of a 1 in 18 year return period, positioning orifice plates within the sewer system provided a cheaper solution than positioning VFCs. Between a FR level of a 1 in 19 and 1 in 28 year return period, installing VFCs was a cheaper option as no configurations positioning only orifice plates were proposed. Above a FR level of a 1 in 28 year return period, only configurations positioning orifice plates were proposed.

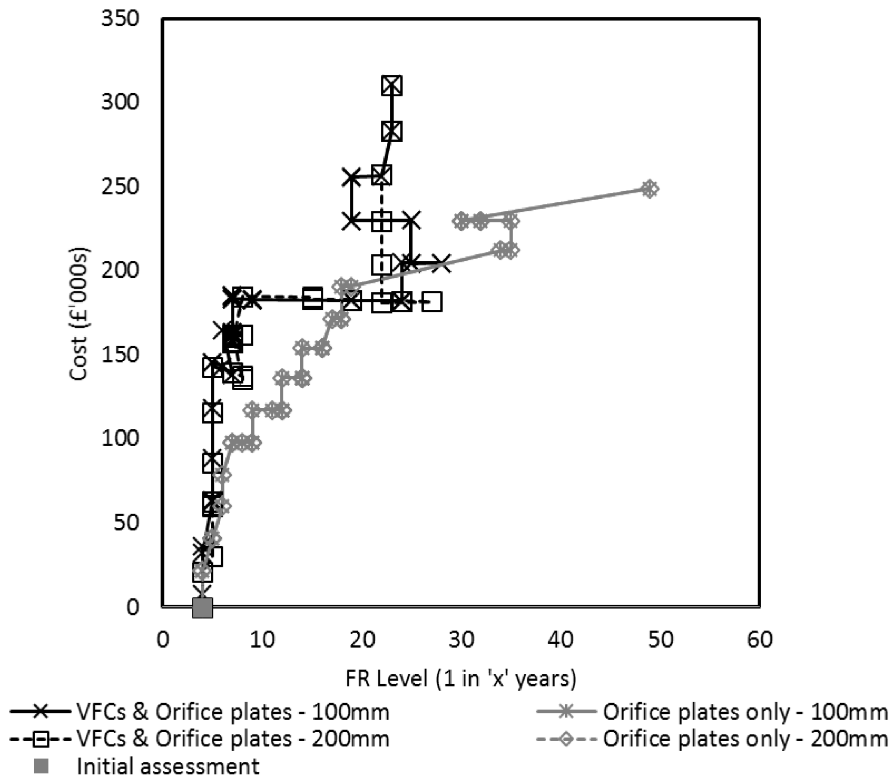


Figure 5.3-6: Plot comparing the cost benefit analyses when the Artificial Network was analysed when both VFCs and orifice plates could be installed and only when orifice plates could be installed.

Table 5.3-1: Summary of the flow controls installed in the Artificial Network when both VFCs and orifice plates were positioned and when only orifice plates were positioned.

	Baseline	VFCs & orifice plates		Orifice plates only	
$d_{o,min}$ (mm)	-	100	200	100	200
Greatest achieved FR level (1 in 'x' years)	4	28	27	49	49
Total estimated cost (£)	-	204,500	181,750	248,750	248,750
Number of flow controls installed	-	8	7	13	13
Minimum outlet diameter (mm)	-	364	354	200	200
Average design flow-rate (l/s)	-	155	162	199	199

5.3.2 Analysis of the anonymised stormwater sewer system

The anonymised stormwater sewer system model was previously described in Section 5.2.2. This sewer system is the smallest sewer system analysed in this project and only contains 14 manhole chambers. The analysis constraints applied to the anonymised stormwater sewer system are presented in Table 5.2-1. The desired FR level was a 1 in 120 year return period and the user's desired maximum budget was £50,000 (Table 5.2-1). For all of the analyses of the anonymised stormwater sewer system discussed in this chapter, the same starting sewer system model was used.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 100 mm

The assessment of the anonymised stormwater sewer system model positioned both VFCs and orifice plates with the $d_{o,min}$ set to 100 mm (Figure 5.3-7). Figure 5.3-7 shows the cost benefit analyses when the $d_{o,min}$ was set as 100 mm and 200 mm respectively. The application of the assessment framework on the sewer system achieved an increase in the FR level from an initial 1 in 3 year return period to a 1 in 108 year return period after three iterations of the assessment framework. The solution with the greatest achieved FR level required the installation of two VFCs and had an estimated cost of £16,000. The assessment framework redesigned an already positioned VFC during the analysis and this can be seen between the proposed solutions with a FR level of a 1 in 60 and 1 in 108 year return period as the cost reduces by £12,500 as the VFC was designed for a lower design flow-rate (11 l/s instead of 23 l/s). The assessment framework was unable to increase the FR level of the solution in the additional three designs that were further proposed. The analysis ended as the desired maximum budget of £50,000 was exceeded. The desired FR level of a 1 in 120 year return period was not achieved.

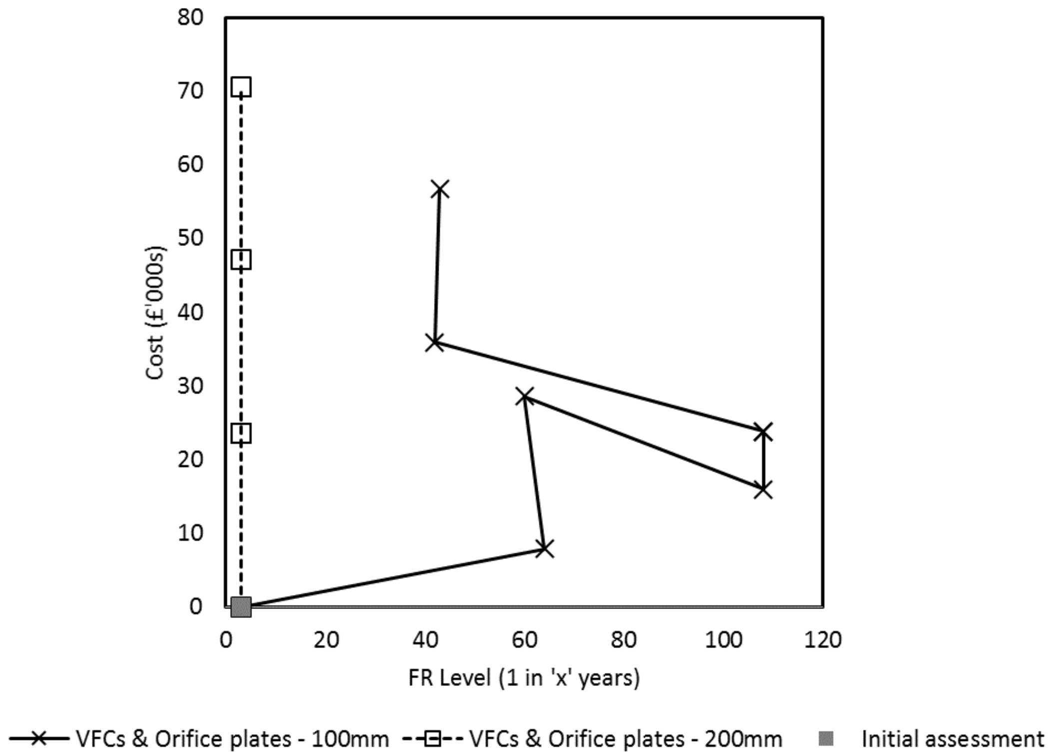


Figure 5.3-7: Cost benefit analysis from the assessment framework after the analysis of the anonymised stormwater sewer system when both VFCs and orifice plates, with the $d_{o,min}$ set to 100 mm and 200 mm, were positioned.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm

Analysis of the anonymised stormwater sewer system when both VFCs and orifice plates, with the $d_{o,min}$ set to 200 mm, were positioned was also completed (Figure 5.3-7). An initial FR level of a 1 in 3 year return period was found, but, the FR level of the sewer system was not able to be increased. In the analysis, three VFCs were positioned. The analysis ended when the cost of the proposed solution exceeded the maximum desired budget of £50,000 by £20,750. The cause of the assessment framework not being able to increase the FR level of the sewer system was that the designed VFCs were unable to attenuate the required volumes of water whilst maintaining the $d_{o,min}$ set to 200 mm.

To achieve the greatest FR level of a 1 in 108 year return period in the anonymised stormwater sewer system case study, only two VFCs were required to be positioned (Figure 5.3-8). Figure 5.3-8 shows the schematic of the sewer system model with the flow controls positioned in SU5 and SU11 to achieve a FR level of 1 in 108 year return period. The sewer system originally contained a VFC before the analysis in the manhole chamber labelled ‘SU14’. The first VFC positioned was located in the manhole chamber labelled ‘SU11’. The second VFC was positioned upstream of the first in ‘SU5’. The schematic of the sewer system where the VFCs and orifice plates with the $d_{o,min}$ set to 200 mm were positioned has not been presented as no increase in the FR level was achieved. In that scenario, however, VFCs were positioned at ‘SU11’, ‘SU5’ and ‘SU3’ before the maximum budget was exceeded. The selection of ‘SU11’ as the first position of the VFCs in both analyses again shows that the flow control positioning method aims to increase the FR level of the sewer system for the lowest cost, as ‘SU11' has the greatest number of upstream conduits and also volume.

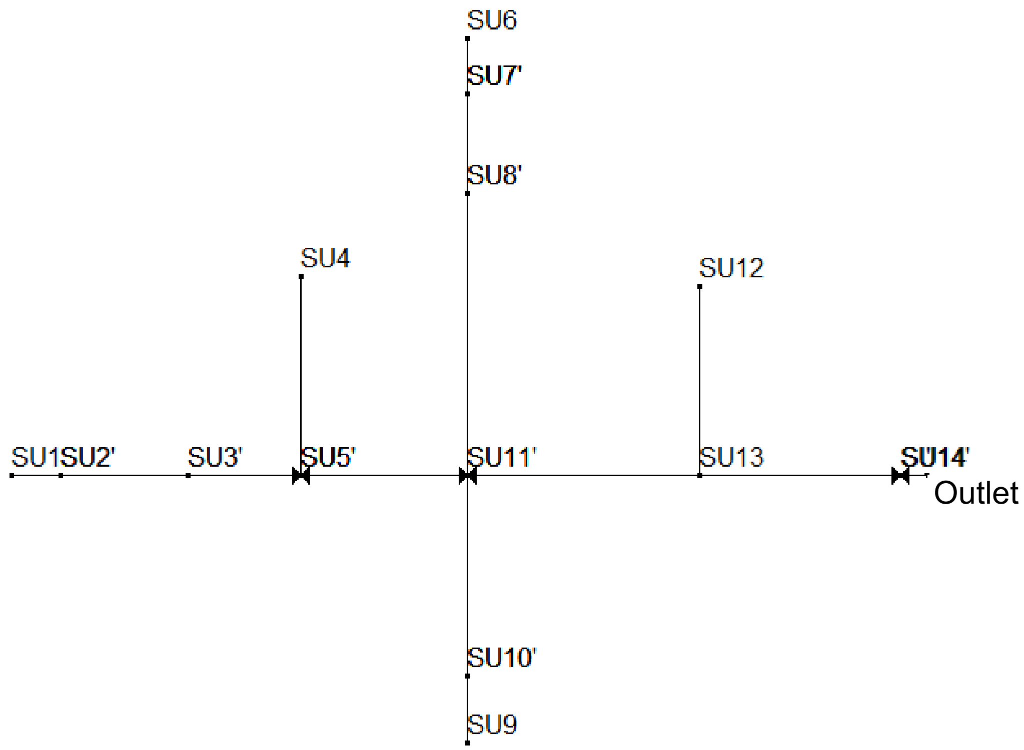


Figure 5.3-8: Schematic of the anonymised stormwater sewer system showing the positions of the VFCs, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 108 year return period.

Positioning of only orifice plates with the $d_{o,min}$ set to 100 mm

The anonymised stormwater sewer system model was also analysed when positioning only orifice plates with the $d_{o,min}$ set to 100 mm (Figure 5.3-9). The initial FR level of the sewer system was a 1 in 3 year return period. The assessment framework only managed to achieve an increase in the FR level to a 1 in 6 year return period. Only one orifice plate was required and this solution had an estimated purchase and installation cost of £5,000. After the installation of the first orifice plate, no additional orifice plates positioned achieved an increase in the sewer system's FR level. All of the additional seven orifice plates positioned had an outlet diameter set to 100 mm, which was the set as the minimum allowable clearance (Table 5.2-1). The orifice plates were, therefore, not restrictive enough to attenuate any further volume of water to enable the FR level to be increased. The analysis of the anonymised stormwater sewer system ended when the maximum desired budget of £50,000 was exceeded.

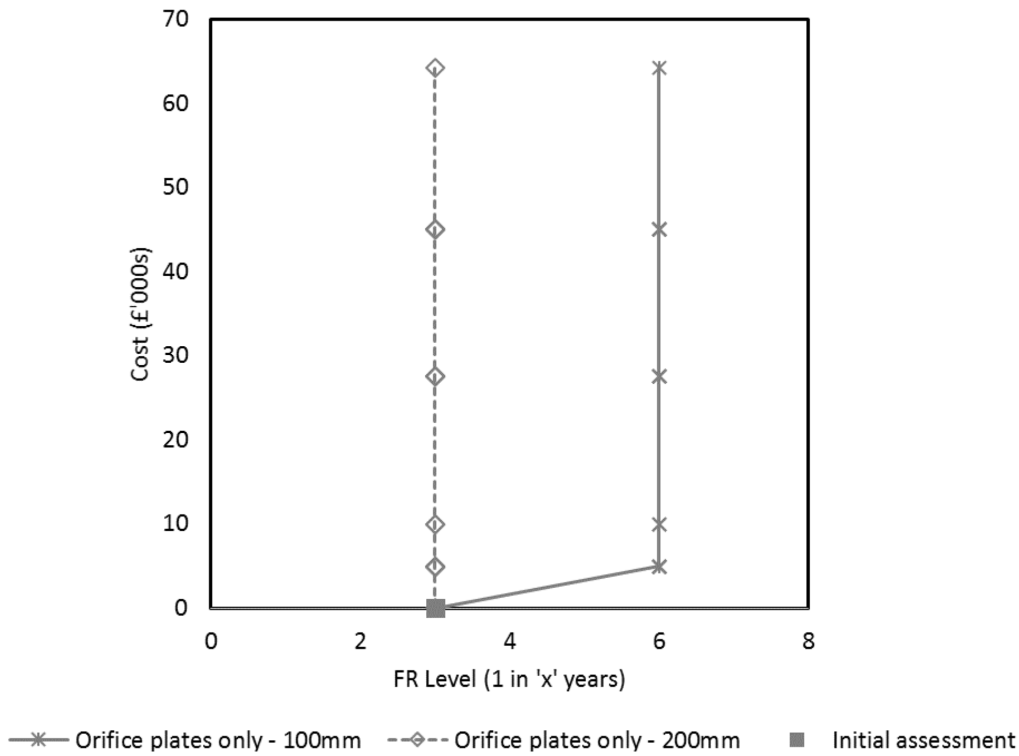


Figure 5.3-9: Cost benefit analysis from the assessment framework after the analysis of the anonymised stormwater sewer system when only orifice plates, with the $d_{o,min}$ set to 100 mm and 200 mm, were positioned.

Positioning of only orifice plates with the $d_{o,min}$ set to 200 mm

Figure 5.3-9 also shows the cost benefit analyses of the assessment framework when only orifice plates with the $d_{o,min}$ set to 200 mm were positioned. The assessment framework was unable to increase the FR level of the sewer system from an initial 1 in 3 year return period. In the analysis, five orifice plates with an outlet diameter set to 200 mm were positioned. The analysis of the sewer system ended as the maximum desired budget of £50,000 was exceeded. This, again, shows that the orifice plates were not restrictive enough to attenuate the required volumes to increase the FR level in the sewer system model.

For the analysis where only orifice plates were positioned, an increase in the FR Level was achieved with the positioning of one orifice plate. Figure 5.3-10 shows the schematic of the sewer system where the orifice plate was positioned in the above analysis. The single orifice plate was positioned in the manhole chamber labelled 'SU11'. The sewer system already contained a VFC positioned at the manhole chamber labelled 'SU14'. The schematic of the sewer system where only orifice plates with the $d_{o,min}$ set to 200 mm were positioned has not been presented, as no increase in the FR level was achieved. In that scenario, however, orifice plates were positioned in the manhole chambers labelled 'SU11', 'SU5', 'SU3', 'SU2' and 'SU8' before the maximum budget was exceeded. Similarly to the cost benefit analyses where both VFCs and orifice plates were positioned, the assessment framework selected the same manhole chamber as the first position for the flow control.

Comparison of all of the cost benefit analyses from the assessment framework after analysing the anonymised stormwater sewer system are compared in Figure 5.3-11 and Table 5.3-2. The comparison shows that the installation of VFCs instead of only orifice plates provides a retrofit sewer system solution that achieves a greater FR level (a 1 in 108 year return period compared to a 1 in 6 year return period). This is achieved because the VFCs are able to attenuate the required volumes whilst maintaining acceptable outlet diameters unlike the designed orifice plates.

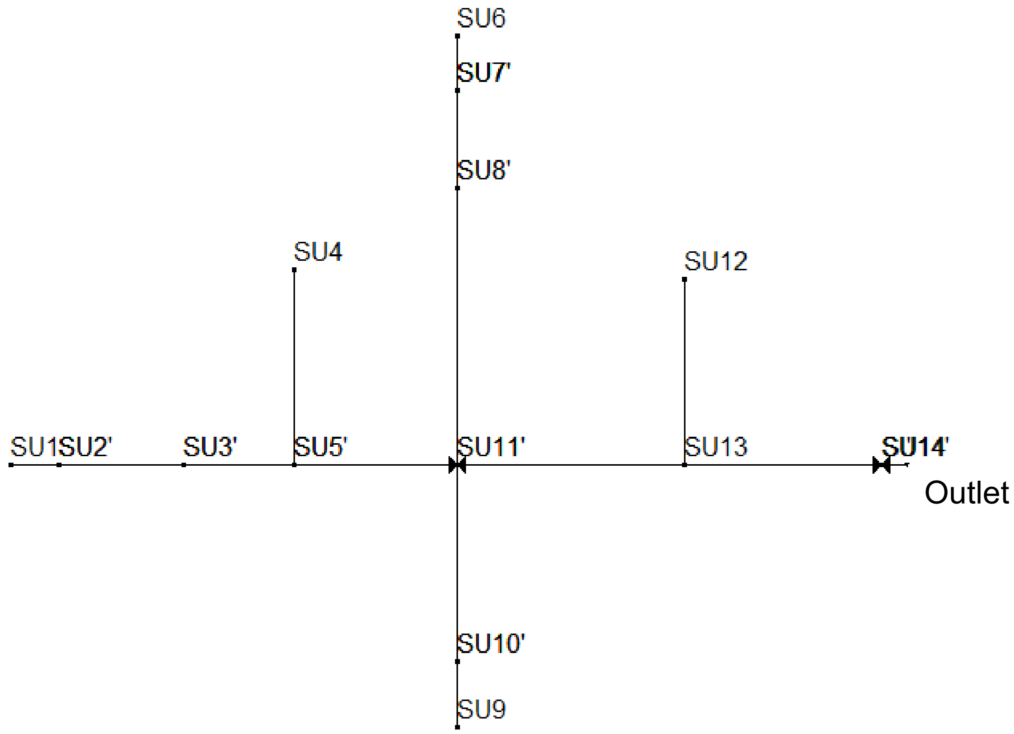


Figure 5.3-10: Schematic of the anonymised stormwater sewer system showing the positions of the orifice plates, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 6 year return period.

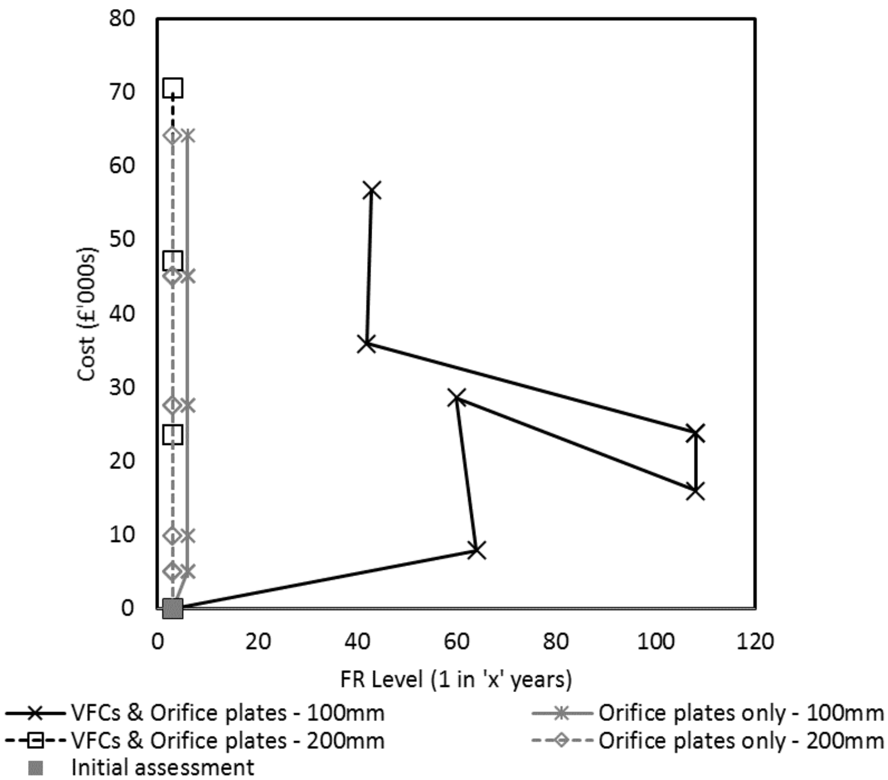


Figure 5.3-11: Cost benefit analyses when the anonymised stormwater sewer system was analysed when both VFCs and orifice plates were installed and only when orifice plates were installed.

Table 5.3-2: Comparison of the flow controls installed in the anonymised stormwater sewer system when both VFCs and orifice plates were positioned and when only orifice plates were positioned.

	Baseline	VFCs & orifice plates		Orifice plates only	
$d_{o,min}$ (mm)	-	100	200	100	200
Greatest achieved FR level (1 in 'x' years)	3	108	3	6	3
Total estimated cost (£)	-	16,000	-	5,000	-
Number of flow controls installed	-	2	0	1	0
Minimum outlet diameter (mm)	-	105	-	100	-
Average design flow-rate (l/s)	-	10	-	37	-

5.3.3 Analysis of the Langley combined sewer system

The Langley combined sewer system was also analysed using the assessment framework and the analysis parameters set in Table 5.2-1. The Langley combined sewer system is the largest sewer system analysed and was unfortunately not able to be calibrated. The same starting sewer system model was used for the four analyses of the Langley combined sewer system discussed in this section. The desired FR level for the sewer system was a 1 in 30 year return period plus the FR level factor of 1.5.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 100 mm

The cost benefit analyses from the analysis of the Langley combined sewer system are presented (Figure 5.3-12) and the parameter constraints were previously discussed (Table 5.2-1). The initial assessment of the sewer system model found the FR level to be a 1 in 1 year return period. In the analysis of the sewer system when the $d_{o,min}$ was set to 100 mm, 21 VFCs were positioned. The greatest achieved FR level was a 1 in 71 year return period and had an estimated cost of £240,500. The analysis was ended once the greatest FR level was achieved as it exceeded the user's desired FR level of a 1 in 45 year return period. During the analysis, only an increase in FR level to a 1 in 4 year return period was achieved below a cost of £169,000. Above a purchase and installation cost of £169,000, the FR level was increased through the redesign of VFCs that had already been positioned. Examples of this occurring are between the FR levels of a 1 in 3 and a 1 in 12 year return period and a between the FR levels of a 1 in 24 and 1 in 71 year return period.

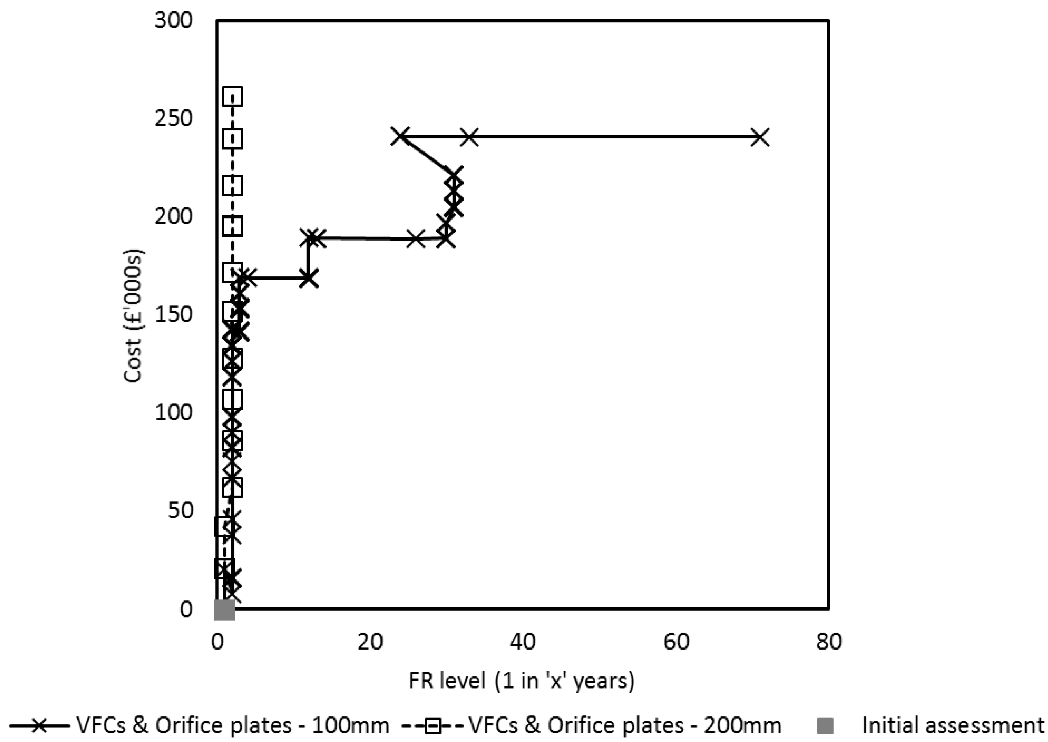


Figure 5.3-12: Cost benefit analysis of the Langley combined sewer system where both VFCs and orifice plates were positioned, the $d_{o,min}$ was set to 100 mm and 200 mm respectively.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm

In this analysis of the Langley combined sewer system, VFCs and orifice plates were positioned with the $d_{o,min}$ set to 200 mm. The analysis of the sewer system achieved an increase in the FR level from a 1 in 1 year return period to a 1 in 2 year return period. The proposed solution with the greatest achieved FR level, for the lowest estimated cost, required the positioning of three VFCs. The estimated cost of purchasing and installing the three flow controls was £62,500. Beyond the solution a further 12 VFCs were positioned before the maximum desired budget of £250,000 was exceeded.

Schematics of the proposed retrofit solutions with the greatest achieved FR levels for each analysis in Figure 5.3-12 are presented (Figure 5.3-13 and 5.3-14). The existing flow control within the Langley combined sewer system model is positioned at the outlet of the sewer system. In the analysis where VFCs and orifice plates with the $d_{o,min}$ set to 100 mm were positioned, 21 additional VFCs were placed (Figure 5.3-13). The schematic shows that the flow controls have been spread across the sewer system model, with six flow controls being positioned on the main pipe line through the centre of the model. There are, however, a number of flow controls that have been positioned in close proximity to one another in the lower half of the schematic. It could be questioned whether both of these flow controls were necessary to still achieve the FR level of a 1 in 71 year return period? If they are not needed, a cheaper solution for the 1 in 71 year return period could be achieved. The locations of the three VFCs positioned when the $d_{o,min}$ was 200 mm, Figure 5.3-14, were also locations selected in analysis where the $d_{o,min}$ was 100 mm.

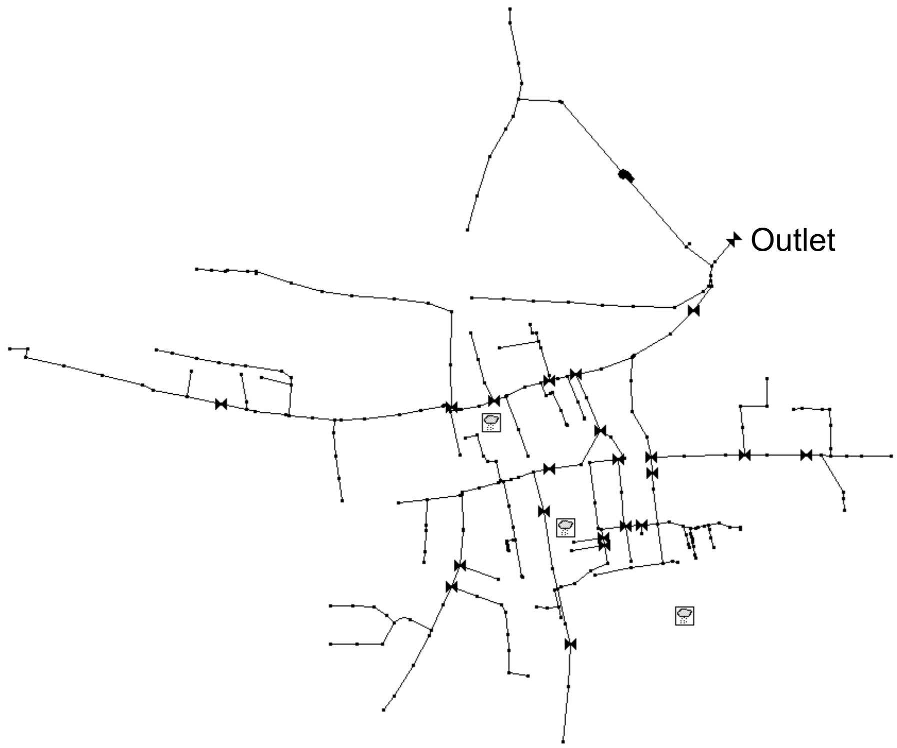


Figure 5.3-13: Schematic of the Langley combined sewer system showing the positions of the VFCs, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 71 year return period.

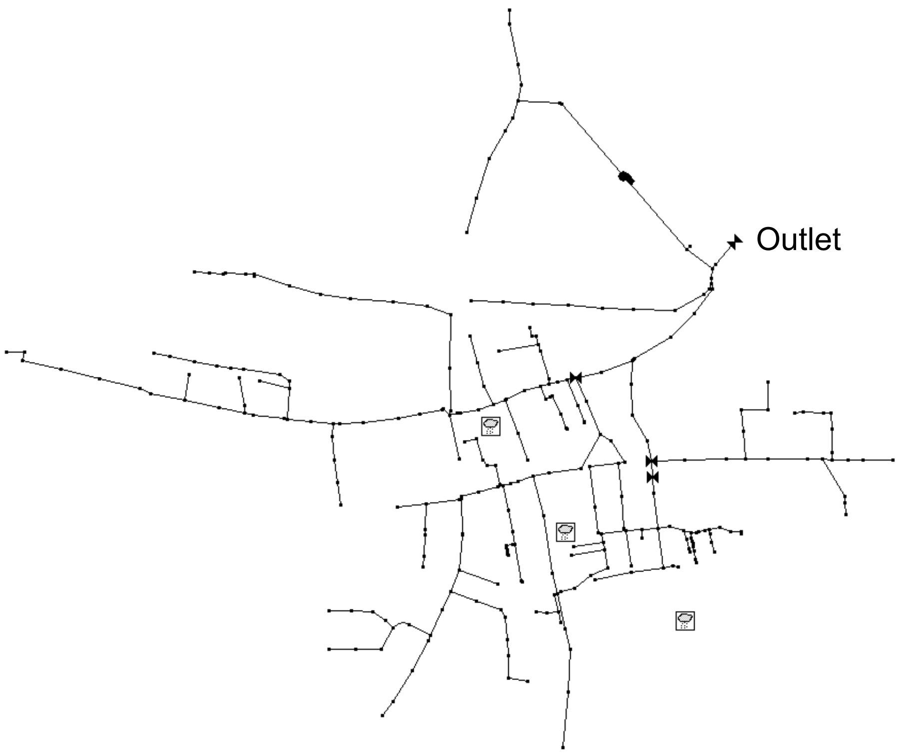


Figure 5.3-14: Schematic of the Langley combined sewer system showing the positions of the VFCs, with the $d_{o,min}$ set to 200 mm, to achieve the greatest FR level of a 1 in 2 year return period.

Positioning only orifice plates with the $d_{o,min}$ set to 100 mm

The assessment framework also analysed the Langley combined sewer system model when only orifice plates were positioned (Figure 5.3-15). In the analysis when only orifice plates with the $d_{o,min}$ set to 100 mm were positioned, the initial FR level for the sewer system was a 1 in 1 year return period. The analysis of the Langley combined sewer system showed a gradual increase in the FR level from the initial FR level of a 1 in 1 year return period to a greatest achieved FR level of a 1 in 9 year return period. The estimated cost to install the required 48 orifice plates was £247,000. The analysis of the Langley combined sewer system was completed as the maximum desired budget of £250,000 was exceeded.

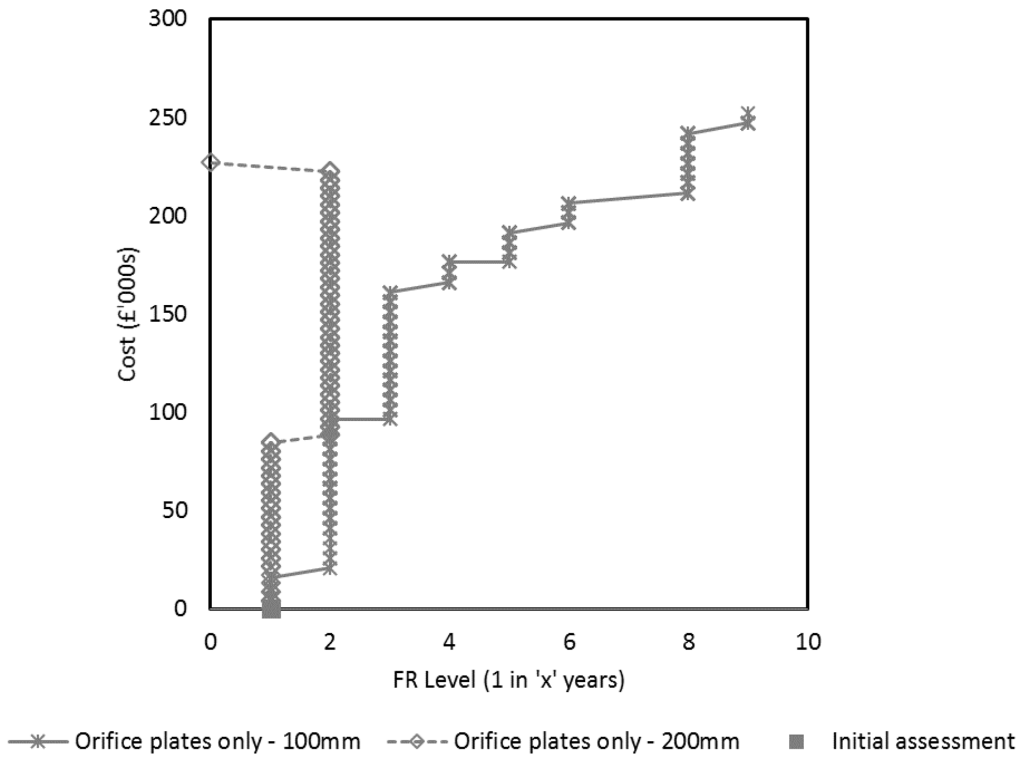


Figure 5.3-15: Cost benefit analysis of the Langley combined sewer system where only orifice plates were positioned and the $d_{o,min}$ was 100 mm and 200 mm, respectively.

Positioning only orifice plates with the $d_{o,min}$ set to 200 mm

Figure 5.3-15 also presents the cost benefit analyses from the analysis of the Langley combined sewer system when only orifice plates with the $d_{o,min}$ set to 200 mm were positioned. The initial assessment of the sewer system found that the starting FR level was a 1 in 1 year return period. The greatest achieved FR level was a 1 in 2 year return period. This was found after the assessment framework positioned 21 orifice plates. The estimated cost of the solution was £88,750. The analysis ended when the FR level reduced to a 1 in 0.000001 year return period, effectively flooding during dry weather flow.

In the analysis where orifice plates with the $d_{o,min}$ set to 100 mm and 200 mm were positioned in the Langley combined sewer system, 48 and 21 orifice plates were positioned respectively. They are presented in the schematics of the sewer system in Figure 5.3-16 and 5.3-17. Flow controls were installed in similar locations in both analyses, as well as similar positions to the 21 VFC positions shown in Figure 5.3-13. This shows that the flow control positioning method repeatedly selects the same manhole chambers in the sewer system to attenuate the volumes of water.

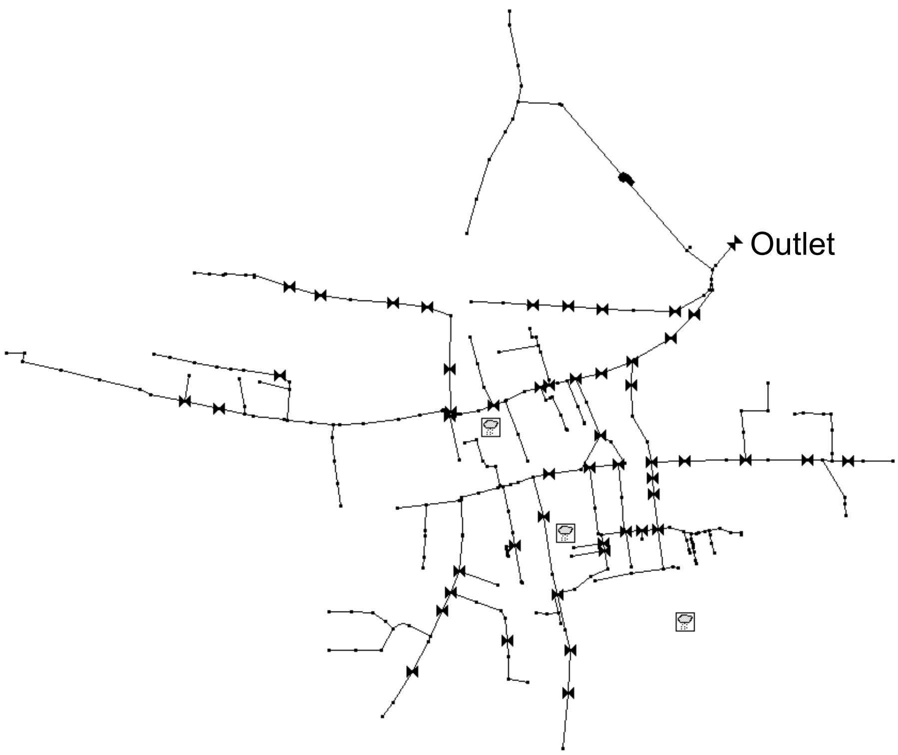


Figure 5.3-16: Schematic of the Langley combined sewer system showing the positions of the orifice plates, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 9 year return period.

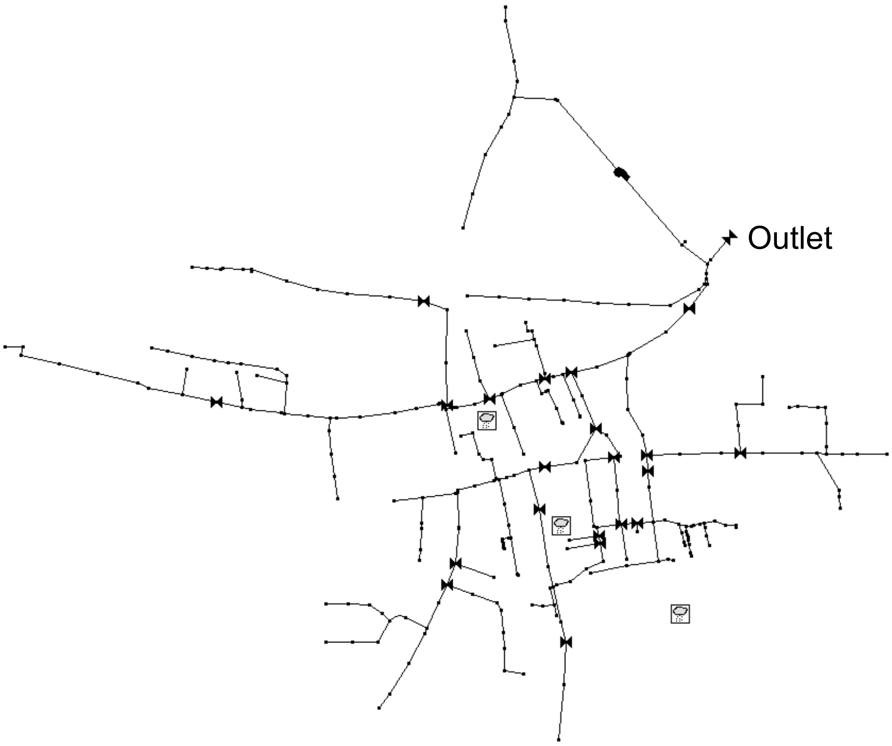


Figure 5.3-17: Schematic of the Langley combined sewer system showing the positions of the orifice plates, with the $d_{o,min}$ set to 200 mm, to achieve the greatest FR level of a 1 in 2 year return period.

All four of the cost benefit analyses from the analysis of the Langley combined sewer system model were compared (Figure 5.3-18 & Table 5.3-3). The graph shows that the greatest increase in the FR level of the sewer system was achieved when VFCs and orifice plates with the $d_{o,min}$ set to 100 mm were positioned. The configurations where VFCs and orifice plates were positioned, with the $d_{o,min}$ set to 100 mm, were also the cheapest solutions for all of the FR levels achieved, excluding the 1 in 3 and 1 in 4 year return periods. For the FR level of a 1 in 3 and 1 in 4 year return period, the cheapest proposed configurations required the installation of orifice plates with the $d_{o,min}$ set to 100 mm and not VFCs.

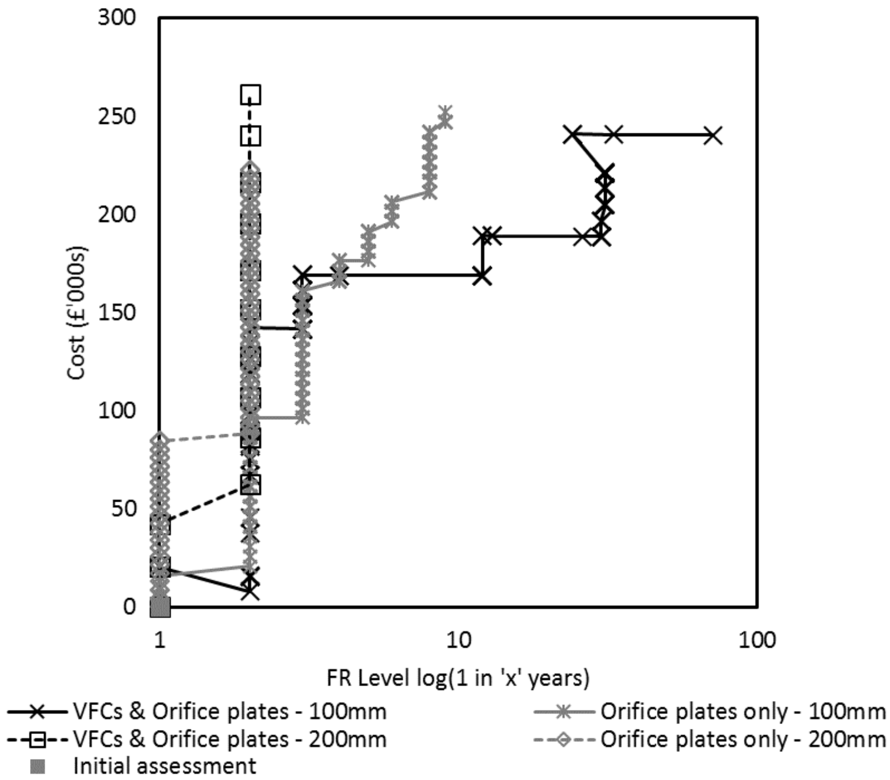


Figure 5.3-18: Cost benefit analyses when the Langley combined sewer system was analysed when both VFCs and orifice plates were installed and only when orifice plates were installed.

Table 5.3-3: Comparison of the flow controls installed in the Langley combined sewer system when both VFCs and orifice plates were positioned and when only orifice plates were positioned.

	Baseline	VFCs & orifice plates		Orifice plates only	
$d_{o,min}$ (mm)	-	100	200	100	200
Greatest achieved FR level (1 in ‘x’ years)	1	71	2	9	2
Total estimated cost (£)	-	240,500	62,500	247,000	88,750
Number of flow controls installed	-	21	3	48	21
Minimum outlet diameter (mm)	-	104	204	100	200
Average design flow-rate (l/s)	-	13	31	30	115

5.3.4 Analysis of the anonymised combined sewer system

The last sewer system that was analysed with the assessment framework was the anonymised combined sewer system (Section 5.2.4). The anonymised combined sewer system contains 206 nodes and is based in the North-East of Scotland. The desired FR level for the sewer system was a 1 in 30 year return period, plus a FR level factor of 1.5, and had a maximum budget of £250,000 for the solution (Table 5.2-1).

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 100 mm

The analysis of the anonymised combined sewer system where both VFCs and orifice plates were positioned in the sewer system and the selected input analysis constraints were applied (Table 5.2-1). The analysis of the anonymised combined sewer system, with the $d_{o,min}$ set to 100 mm, found that an improvement in the FR level could be achieved (Figure 5.3-19). The FR level was increased from a 1 in 1 year return period to a 1 in 3 year return period. The proposed solution required one VFC to be installed and the estimated cost for purchase and installation was £7,750. The analysis of the anonymised combined sewer system ended when the £250,000 maximum desired budget was exceeded. This is understood to be due to the assessment framework positioning an overly restrictive flow control in the first iteration of assessment framework, when the $d_{o,min}$ was set to 100 mm, causing over-discharge from the CSO in the middle of the sewer system (Figure 5.2-4).

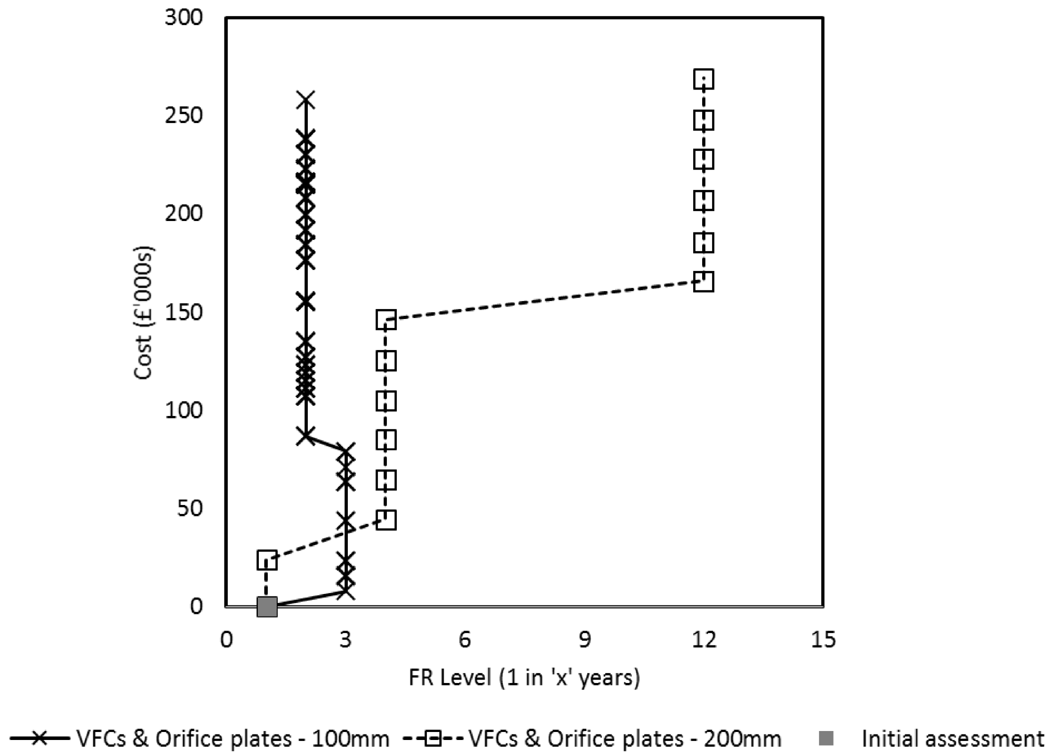


Figure 5.3-19: Cost benefit analysis from the assessment framework after the analysis of the anonymised combined sewer system when both VFCs and orifice plates were positioned. The $d_{o,min}$ was set as 100 mm and 200 mm respectively.

Positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm

The analysis of the anonymised combined sewer system positioned both VFCs and orifice plates with the $d_{o,min}$ set to 200 mm (Figure 5.3-19). The cost benefit analysis shows an improvement in the sewer system's FR level was achieved. The FR level was increased from a 1 in 1 year return period to a 1 in 12 year return period. The cheapest solution with the greatest achieved FR level had an estimated cost of £166,000 and required the installation of eight VFCs. The analysis of the sewer system ended when the proposed solution exceeded the maximum desired budget of £250,000. In this case, it has been found that a greater FR level has been achieved by positioning flow controls with a $d_{o,min}$ set to 200 mm rather than 100 mm. This, again, is understood to be due to the assessment framework positioning an overly restrictive flow control in the first iteration of assessment framework, when the $d_{o,min}$ was set to 100 mm, causing over-discharge from the CSO in the middle of the sewer system (Figure 5.2-4).

This has been noted as an improvement that should be made to the flow control positioning method (Section 5.4).

In the analyses of the anonymised combined sewer system, the assessment framework positioned one and eight VFCs when the $d_{o,min}$ was set to 100 mm and 200 mm respectively. Schematics showing the positions of the flow controls designed into the sewer system are presented (Figure 5.3-20 & 5.3-21). The five existing flow controls are shown by red crosses. Figure 5.3-20 shows the location of the single VFC positioned in the analysis to achieve a 1 in 3 year return period, when the $d_{o,min}$ was set to 100 mm. This location is close to the outlet and on a main junction of the sewer system. Figure 5.3-21 shows the location of the eight VFCs positioned in the analysis, to achieve a 1 in 12 year return period, when the $d_{o,min}$ was set to 200 mm.

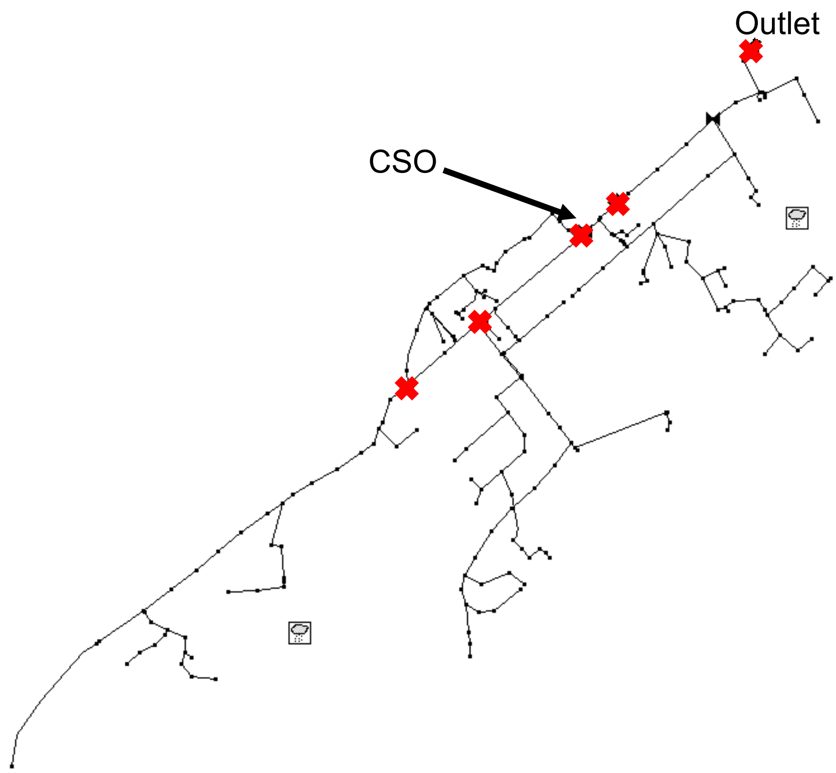


Figure 5.3-20: Schematic of the anonymised combined sewer system showing the positions of the VFCs, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 3 year return period.

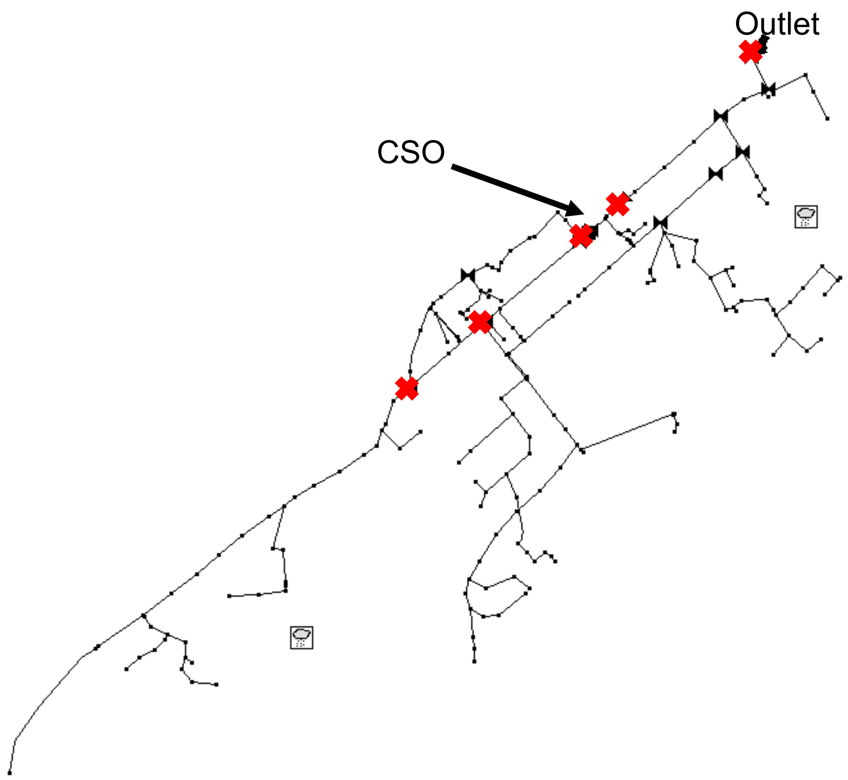


Figure 5.3-21: Schematic of the anonymised combined sewer system showing the positions of the VFCs, with the $d_{o,min}$ set to 200 mm, to achieve the greatest FR level of a 1 in 12 year return period.

Positioning only orifice plates with the $d_{o,min}$ set to 100 mm

The analysis of the anonymised combined sewer system, where the $d_{o,min}$ of the orifice plates was set to 100 mm, is presented (Figure 5.3-22). The initial FR level was found to be a 1 in 1 year return period. In the analysis of the sewer system the FR level was increased to a 1 in 11 year return period. This was achieved from the positioning of one 100 mm orifice plate in the first iteration of the assessment framework. The estimated cost of the solution was £14,000 for the purchase of the orifice plate and its installation. After the first iteration of the assessment framework, no further increase in the FR level or reduction of the solution's estimated cost was achieved. The analysis of the sewer system concluded when an error occurred in the assessment framework, explaining why neither the desired FR level nor the financial budget analysis constraints were reached.

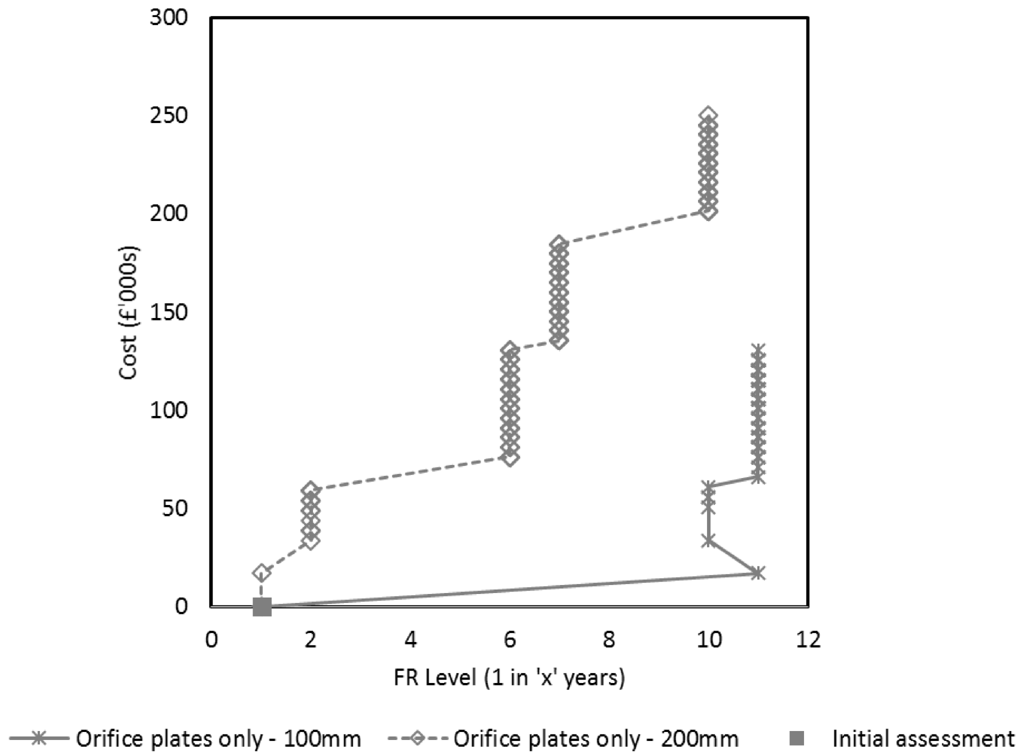


Figure 5.3-22: Cost benefit analysis from the assessment framework after the analysis of the anonymised combined sewer system when only orifice plates, with the $d_{o,min}$ set to 100 mm and 200 mm respectively, were positioned.

Positioning only orifice plates with the $d_{o,min}$ set to 200 mm

The analysis of the sewer system, also presented in Figure 5.3-22, shows the cost benefit analysis when only orifice plates with the $d_{o,min}$ set to 200 mm were positioned. The initial FR level of the sewer system was a 1 in 1 year return period and the analysis achieved a greatest FR level of a 1 in 10 year return period. This required the installation of 31 orifice plates and had an estimated cost of £168,000. The assessment framework also proposed solutions achieving FR levels of a: 1 in 2; 1 in 6; and 1 in 7 year return period. The analysis of the anonymised combined sewer system ended as the estimated cost of the solution exceeded the maximum desired budget of £250,000.

The locations of the orifice plates positioned in the analyses of the anonymised combined sewer system to achieve the greatest FR levels respectively are presented (Figure 5.3-23 & 5.3-24). Figure 5.3-23 shows the locations when the

$d_{o,min}$ was set to 100 mm and Figure 5.3-24 shows the locations when the $d_{o,min}$ was set to 200 mm. Figure 5.3-23 and Figure 5.3-20, when VFCs with the $d_{o,min}$ set to 100 mm, show the identical flow control position for both scenarios. In the analysis where both VFCs and orifice plates were positioned, a VFC with the $d_{o,min}$ set to 100 mm was positioned and achieved a FR level of a 1 in 3 year return period.

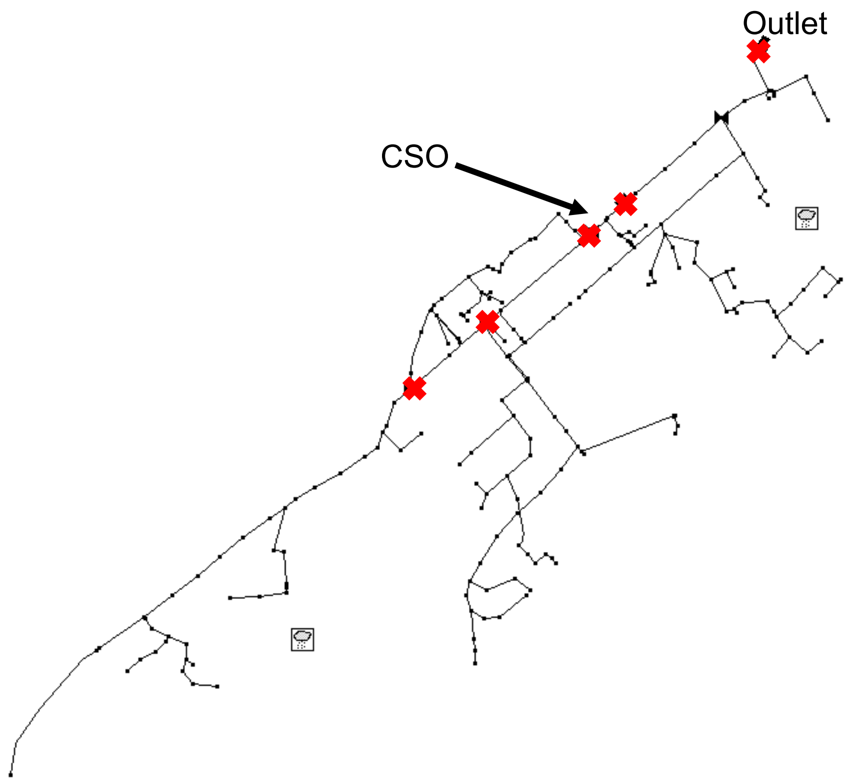


Figure 5.3-23: Schematic of the anonymised combined sewer system showing the positions of the orifice plates, with the $d_{o,min}$ set to 100 mm, to achieve the greatest FR level of a 1 in 11 year return period.

In the analysis where only orifice plates were positioned and the $d_{o,min}$ was set to 100 mm, a 100 mm orifice plate was positioned and achieved a FR level of a 1 in 11 year return period. The positioning of the orifice plate achieved a greater FR level as it allowed a greater volume of water to pass downstream than the VFC positioned in Figure 5.3-19. The VFC, which was overly restrictive, attenuated too great a volume of water in the upstream section of the sewer system causing the CSO in the middle of the sewer system model to overspill. Figure 5.3-24, on the other hand, shows the locations of 31 additional orifice plates positioned in the sewer system with the $d_{o,min}$ set to 200 mm. Comparison of Figure 5.3-23 and

5.3-24 shows that increasing the $d_{o,min}$ value, to reduce blockage risk in the sewer system, can greatly increase the cost necessary to increase FR levels when considering retrofit designs.

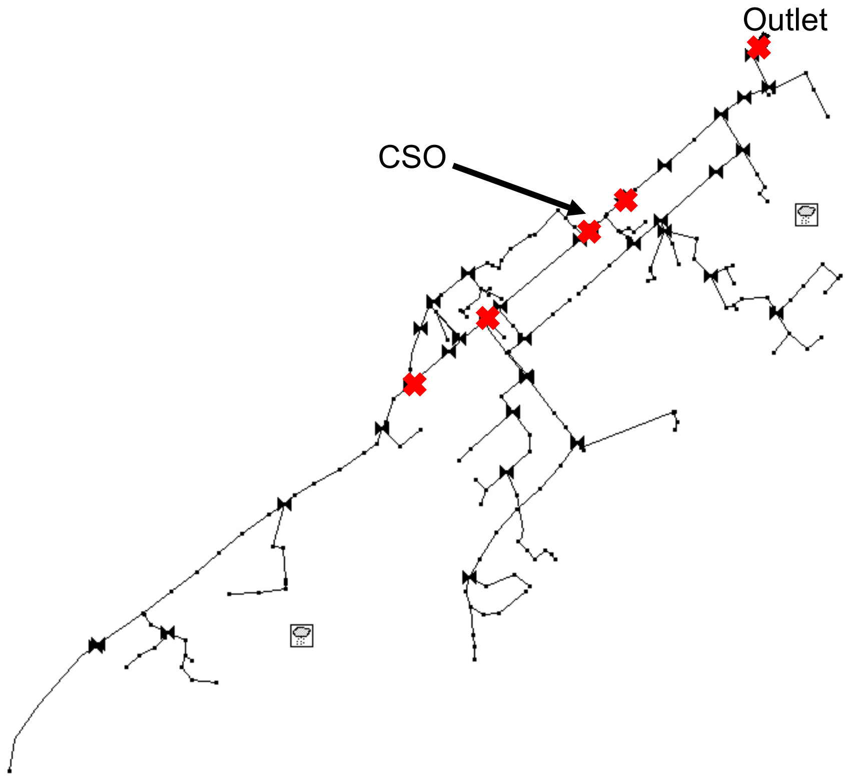


Figure 5.3-24: Schematic of the anonymised combined sewer system showing the positions of the orifice plates, with the $d_{o,min}$ set to 200 mm, to achieve the greatest FR level of a 1 in 10 year return period.

All of the cost benefit analyses for the anonymised combined sewer system have been presented and compared (Figure 5.3-25 & Table 5.3-4). The positioning of VFCs and orifice plates with the $d_{o,min}$ set to 200 mm achieved the highest FR level, a 1 in 12 year return period, compared to the other three analyses. The positioning of orifice plates with the $d_{o,min}$ set to 100 mm achieved a FR level of a 1 in 11 year return period, but its estimated cost was £150,250 cheaper than the solution for a FR level of a 1 in 12 year return period when VFCs and orifice plates were positioned. Positioning VFCs and orifice plates with the $d_{o,min}$ set to 100 mm provided the lowest greatest achieved FR level of all of the analyses, a 1 in 3 year return period. In this analysis, the first flow control was positioned in the same location as the first flow control placement for orifice plates alone. The difference being that the VFC positioned had a design flow-rate of 9 l/s compared to the orifice plate that had a design flow-rate of 37 l/s. In the solution where the VFC was positioned the VFC was overly restrictive causing over-discharge in the upstream CSO. This prevented the FR level from increasing further due to CSO spilling. This outcome demonstrates that there is a need for the flow control positioning method to select the design head of the flow control, not on the selected manhole chamber itself (Section 3.5), but also on the flood and spill levels of the upstream assets. This could also show that the flow control positioning method should review the flow controls positioned to prevent these flow controls ending the analysis.

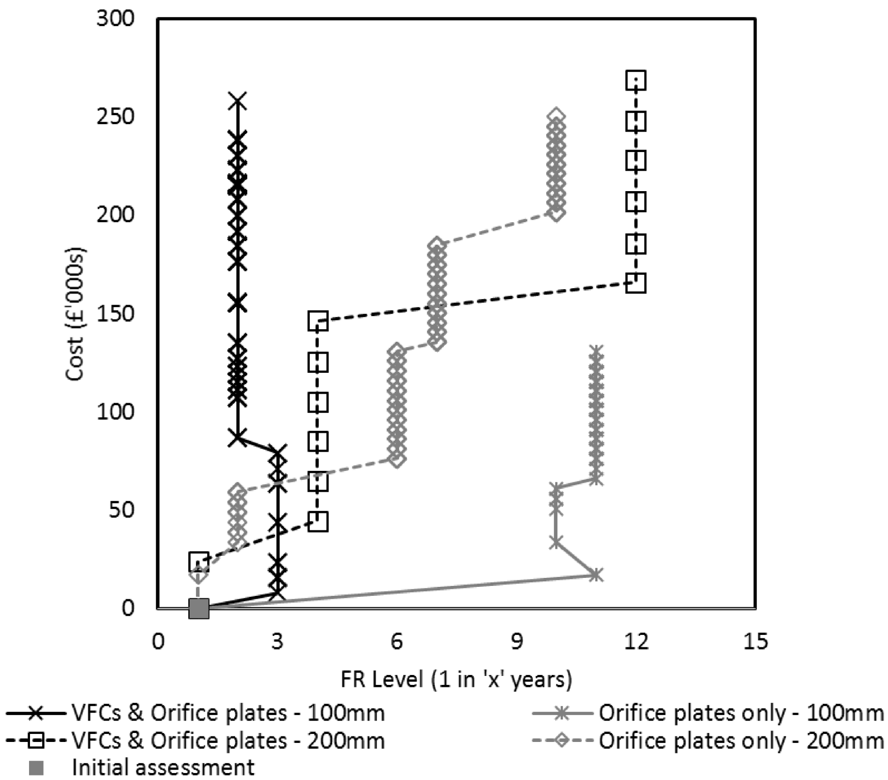


Figure 5.3-25: Cost benefit analysis from the assessment framework after the analysis of the anonymised combined sewer system when VFCs and orifice plates and only orifice plates, with the $d_{o,min}$ set to 100 mm and 200 mm, were positioned.

Table 5.3-4: Comparison of the flow controls installed in the anonymised combined sewer system when both VFCs and orifice plates were positioned and when only orifice plates were positioned.

	Baseline	VFCs & orifice plates		Orifice plates only	
$d_{o,min}$ (mm)	-	100	200	100	200
Greatest achieved FR level (1 in 'x' years)	1	3	12	11	10
Total estimated cost (£)	-	7,750	166,00	17,000	201,500
Number of flow controls installed	-	1	8	1	31
Minimum outlet diameter (mm)	-	105	204	100	200
Average design flow-rate (l/s)	-	9	26	37	103

5.4 Summary and conclusions from the application of the assessment framework

Section 5.3 has presented the application of the assessment framework on four sewer system models. The case studies have shown that the strategic positioning of flow controls within sewer systems can have a beneficial effect increasing the flood resistance level of the sewer system (Table 5.4-1). Table 5.4-1 shows the greatest increase in the FR level was from a 1 in 3 year return period to a 1 in 108 year return period seen in the analysis of the anonymised stormwater sewer system. In the sewer system that had the greatest outlet discharge limits and greatest diameter pipes, the Artificial Network, the installation of orifice plates only was shown to provide a greater increase in the FR level. In the sewer system that had the smallest outlet discharge limit and the fewest number of pipes, the anonymised stormwater sewer system, the installation of VFCs was shown to provide a greater increase in the FR level.

Table 5.4-1: Comparison of the proposed sewer system solutions from the flow control positioning method that achieved the greatest increase in the FR level.

	Artificial Network	Anonymised stormwater sewer system	Langley combined sewer system	Anonymised combined sewer system
Flow controls installed	Orifice plates only	VFCs & orifice plates	VFCs & orifice plates	VFCs & orifice plates
$d_{o,min}$ (mm)	100	100	100	200
Initial FR level (1 in ‘x’ years)	4	3	1	1
Greatest achieved FR level (1 in ‘x’ years)	49	108	71	12
Total estimated cost (£)	248,750	16,000	240,500	166,000
Number of flow controls installed	13	2	21	8
Minimum outlet diameter (mm)	200	105	104	204
Average design flow-rate (l/s)	199	10	13	26

The analysis outputs have also enabled the benefits to be quantified. The conclusions for the analysis and comparisons completed in this chapter show:

1) The application of the assessment framework has increased the FR level of the sewer system through the strategic positioning of passive flow controls where the greatest increase in the FR level was from a 1 in 3 year return period to a 1 in 108 year return period;
2) The assessment framework identified and selected manhole chambers in which to position flow controls. The assessment framework consistently repeated the same manhole chambers regardless of how the input parameters of the method were varied;
3) The assessment framework proposed a range of solutions for the end user to select for possible implementation into their sewer system; and

4) By demonstrating an increase in the sewer system's FR level, the number of pollution incidents from the sewer system are reduced as FR level is determined by a flow-rate from CSOs and over-discharges at the outlet of the sewer system.

As discussed in Section 4.2, the predicted benefits from the application of the assessment framework on sewer system models, and whether the benefit has been demonstrated, were:

1) Proposed designs that improve the FR level of existing sewer systems - demonstrated;
2) A strategic positioning method to locate suitable manhole chambers for flow attenuation - demonstrated;
3) A range of solutions to improve FR levels of the sewer system considering estimated costs and flood vulnerability of subcatchments – not yet investigated;
4) Solutions that only require minimal construction within existing sewer assets – not yet investigated; and
5) Attenuate potential flood volumes in the sewer system to reduce the number of CSO spills and pollution incidents - demonstrated.

Even though benefit was achieved from the application of the assessment framework, there are still a number of activities that can be completed to improve the assessment framework. These activities are:

1) Select the design head of the flow control also from the available levels on upstream assets to prevent CSO spillages (Section 5.3.4)
2) Improved pattern matching algorithm to prevent method becoming stuck in repeating loop (Section 5.4.1).

Chapter 6

Application of subcatchment vulnerability scores and comparison to other flood alleviation solutions

6.1 Introduction

Chapter 5 showed that the application of the assessment framework was able to increase the FR level of the sewer systems through the strategic positioning of flow controls. Those analyses presented configurations from the assessment framework when the flood vulnerability scores (FVSs) of the subcatchments were all set to be equal. The effect of assigning various FVSs to various subcatchments of the sewer system is presented and discussed in this chapter. Application of the FVSs is used to protect high priority areas for flood protection, such as a hospital, as previously discussed in Section 4.3.4. In this chapter, two different mechanisms for determining the FVSs are explored. These mechanisms are:

1) Initial hierarchy of the consequences of flooding of different properties and locations (Balmforth *et al*, 2006); and
2) Flood risk maps for England and Scotland (Environment Agency, 2015, & SEPA, 2015).

The latter section of this chapter summarises all of the outputs from the assessment framework when analysing the Langley and anonymised combined sewer systems (Section 6.3) and compares the proposed configurations from the assessment framework to other traditional flood alleviation solutions for all of the sewer system analyses (Section 6.4). This comparison of sewer system flood alleviation solutions aims to state whether the solutions proposed by the assessment framework are economically competitive with other FR level increasing solutions. The solutions proposed by the assessment framework are compared to:

1) A deep shaft solution (method explained in Appendix 5), and
2) Alternative solutions used in the UK water industry (Newton *et al*, 2015) including:
    a) Isolate from the system (installation of non-return valves and pumping stations);
    b) Manage flow (upgrading a pumping station or installing a new CSO);
    c) Sewer upsizing (installation of pumping stations, new storage chambers or sewers); and
    d) Flow attenuation (installation of detention tanks, pumping stations and surface flow attenuation).

The solutions proposed by the assessment framework were not compared to any SuDS solutions as the costs of installing these solutions are not comprehensively documented with multiple case studies.

6.2 Effect of changing subcatchment flood vulnerability scores

In the previous analyses (Chapter 5), the assessment framework considered sewer system models in which the subcatchments were assigned equal FVSs. This sub-section of the chapter moves on to investigate the effect of assigning varying FVSs to the sewer system's subcatchments and how this impacts the FR level achieved.

As discussed in Section 4.3.4, there are two different sets of the FVSs that will be assigned to the sewer system's subcatchments in this project. These are the initial flood consequence ratings from '*Designing for exceedance*' (2006) and the Environment Agency's and SEPA's flood map scores (2015 & 2015). The difference between the two sets of scores are:

1) The initial flood consequence ratings are assigned based on the aboveground infrastructure; and

2) The flood map outputs are based on the simulation outputs of aboveground 2D surface water flood mapping.

In this chapter, the abbreviation '*DfE*' indicates the sewer system model has had the initial flood consequence ratings assigned to the subcatchments from '*Designing for exceedance*' (2006). The abbreviation '*RFSWIM*' indicates the sewer system model has had the flood map scores assigned to the subcatchments.

In this assessment framework analysis, both sets of the FVSs, DfE and RFSWIM, were applied to the anonymised and Langley combined sewer system model subcatchments. For the DfE set of values, the subcatchment was assigned the greatest FVS of the infrastructure that was located in the subcatchment. An example being: if a subcatchment contained a hospital and a brownfield site, the higher of the two FVSs would be assigned to the subcatchment. For the RFSWIM set of values, the surface water flood maps were projected onto the sewer system model and the greatest flood risk score that appeared in the subcatchment was assigned as the subcatchment's FVS. The distribution of the FVSs assigned to the anonymised and Langley combined sewer system subcatchments are presented in Table 6.2-1. It was found that, for both sewer system models, the RFSWIM values generated 19 and 21 additional high priority subcatchments (FVSs equal to 0.5 or 1), respectively, compared to the DfE values. The RFSWIM values also generated more low priority subcatchments for flood protection (FVS equal to -0.75) compared to the DfE values (58 versus 6 in total). The DfE values in comparison, 77% and 92% of the subcatchments were assigned as medium priority subcatchments (FVS of 0).

For the analyses of the two sewer system models, the same analysis method was applied in this chapter as Chapter 5. The Langley combined sewer system model was analysed first, then the anonymised combined sewer system. The same input parameters were also used, Table 5.2-1.

6.2.1 The Langley combined sewer system

The Langley combined sewer system was first analysed with all of the FVSs equal. The FR level was then increased from a 1 in 1 year return period to a 1 in 71 year return period (Section 5.3.3). The DfE FVSs were assigned to the Langley combined sewer system model subcatchments and analysed by the assessment framework.

Table 6.2-1: Number of subcatchments in the anonymised and Langley combined case studies assigned with the various FVS values (DfE and RFSWIM).

Flood vulnerability	FVS	Langley combined sewer system DfE	Langley combined sewer system RFSWIM	Anonymised combined sewer system DfE	Anonymised combined sewer system RFSWIM
High	1	28	28	3	12
	0.5	-	19	-	12
Medium	0	105	55	59	17
Low	-0.75	4	35	2	23
TOTAL:		137	137	64	64

Analysis with the DfE FVSs assigned and the $d_{o,min}$ set to 100 mm

In the analysis where the $d_{o,min}$ was set to 100 mm and the DfE FVSs were assigned, an improvement in the FR level was achieved from a 1 in 1 year return period to a 1 in 2 year return period (Figure 6.2-1). This was achieved after the positioning and redesign a single VFC with an estimated cost of £8,000. Further iterations of the assessment framework achieved a FR level of a 1 in 5 year return period with an estimated cost of £84,750. This solution required the positioning of nine VFCs and 52 iterations of the assessment framework. Further iterations of the assessment framework did not further increase the FR level of the sewer system and the analysis was ended when the algorithm became stuck in a repeating loop of the same flow controls being positioned and designed. It was later discovered that the algorithm was becoming stuck as there were two smaller patterns of flow controls being designed producing a larger pattern, which was not noticed or prevented from repeating. An improvement of the flow control positioning method would be to continue the pattern matching algorithm throughout the entire list of flow controls previously designed.

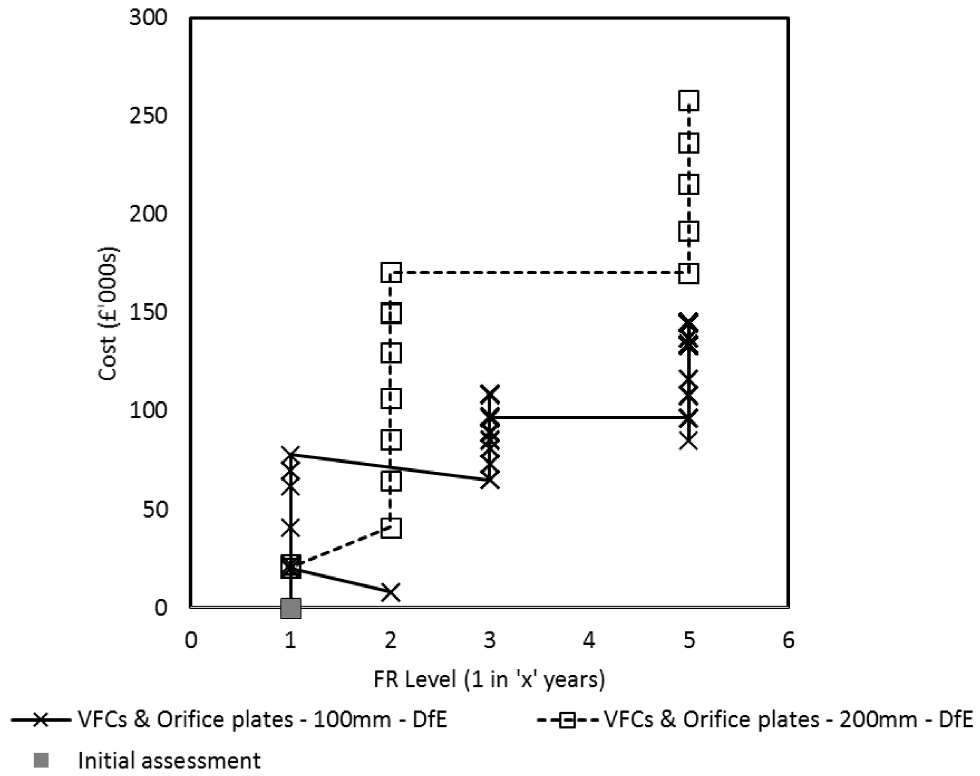


Figure 6.2-1: Cost benefit analyses from the assessment framework after the analysis the Langley combined sewer system with DfE FVSs assigned to the subcatchments and the $d_{o,min}$ set to 100 mm and 200 mm respectively.

Analysis with the DfE FVSs assigned and the $d_{o,min}$ set to 200 mm

In the analysis where the $d_{o,min}$ was set to 200 mm, the FR level increased from the initial assessment level of a 1 in 1 year return period to a 1 in 5 year return period (Figure 6.2-1). The estimated cost of the cheapest solution with the greatest FR level was £170,250 and required the installation of eight VFCs. Further iterations of the assessment framework did not increase the FR level and the analysis ended when the maximum budget of £250,000 was reached. The analysis also achieved a FR level of a 1 in 2 year return period with the solutions costing between £50,000 and £172,250.

Comparison of the two plots show that installing flow controls with the $d_{o,min}$ set to 100 mm achieves a similar greatest FR level as when flow controls with the $d_{o,min}$ set to 200 mm were installed. The proposed solutions with the greatest achieved FR level, however, have different estimated costs and the solution containing flow controls with the $d_{o,min}$ of 100 mm was £85,500 cheaper than the configuration where the $d_{o,min}$ was set to 200 mm. This solution was cheaper than the configuration where the $d_{o,min}$ was set to 200 mm, even though it positioned one more flow control, as the VFCs had smaller geometries and were cheaper to manufacture and install.

Analysis with the RFSWIM FVSs assigned and the $d_{o,min}$ set to 100 mm

The Langley combined sewer system was also analysed when the FVSs were assigned from the RFSWIM method in Figure 6.2-2. The range of the FVSs assigned are presented in Table 6.2-1. Figure 6.2-2 shows the outputs when the $d_{o,min}$ was set to 100 mm and 200 mm. When the $d_{o,min}$ was set to 100 mm, the outputs generated were identical to the outputs generated when the DfE FVSs were assigned (Figure 6.2-1). The greatest achieved FR level was a 1 in 5 year return period with an estimated cost of £84,750. The analysis was manually ended as, like the previous analysis in Figure 6.2-1, the algorithm became stuck in a repeating loop. This plot shows that the change in the range of FVSs of the sewer system did not have an effect on the configurations proposed by the assessment framework.

Analysis with the RFSWIM FVSs assigned and the $d_{o,min}$ set to 200 mm

The analysis of the Langley combined sewer system when the $d_{o,min}$ was set to 200 mm achieved a greatest FR level of a 1 in 2 year return period from an initial FR level of a 1 in 1 year return period. No increase in the FR level was achieved below an estimated cost of £172,250. The solution with the 1 in 2 year return period required the positioning and redesign of eight flow controls and 30 iterations of the flow control positioning method. The analysis of the sewer system ended when the maximum financial budget of £250,000 was exceeded.

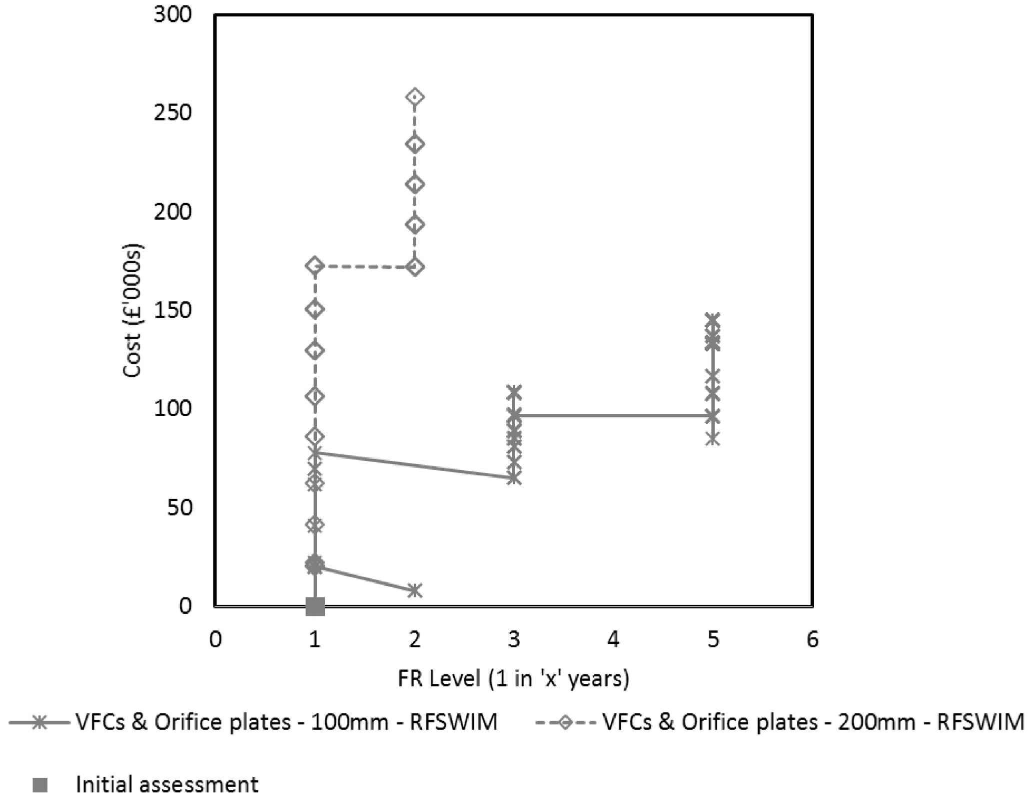
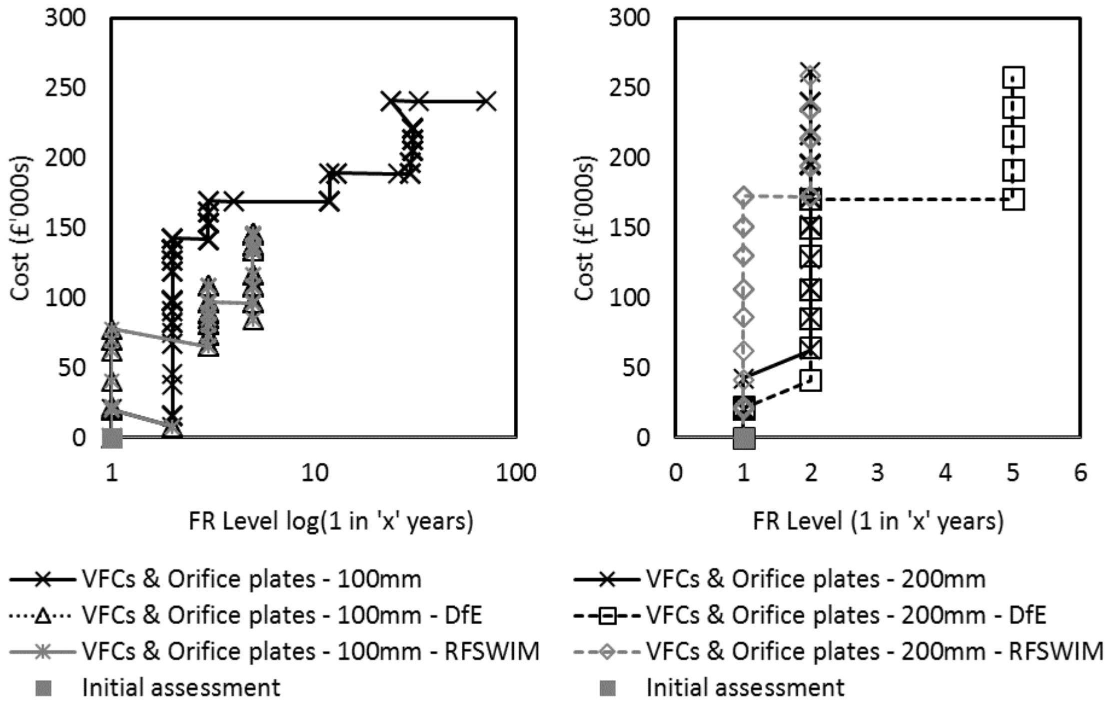


Figure 6.2-2: Cost benefit analyses from the assessment framework after the analysis the Langley combined sewer system with RFSWIM FVSs assigned to the subcatchments and the $d_{o,min}$ set to 100 mm and 200 mm respectively.

The outputs of the analyses of the Langley combined sewer system with the DfE and RFSWIM FVSs were compared to the analyses that had equal FVSs for all subcatchments in Section 5.3 (Figure 6.2-3). Figure 6.2-3a compares the outputs when the $d_{o,min}$ was set to 100 mm and Figure 6.2-3b compares the outputs when the $d_{o,min}$ was set to 200 mm. When the $d_{o,min}$ of the flow controls was set to 100 mm, Figure 6.2-3a shows that the analysis where the FVS's were all equal proposes a configuration with the greatest FR level (a 1 in 71 year return period compared to a 1 in 5 year return period). For a FR level of a 1 in 5 year return period and below, however, the analyses where the DfE and RFSWIM FVSs were assigned proposed cheaper solutions for the same FR level. For the solutions with a FR level of a 1 in 3 year return period, the outputs that included the DfE and RFSWIM FVSs were £76,250 (-54%) cheaper compared to the configuration the FVSs were equal.



a) Comparison of the three analyses outputs when the $d_{o,min}$ was 100 mm.

b) Comparison of the three analyses outputs when the $d_{o,min}$ was 200 mm.

Figure 6.2-3: Comparison of all of the Langley combined sewer system analyses with different FVSs (no scores, DfE and RFSWIM) and different set $d_{o,min}$ values (100 mm and 200 mm).

Figure 6.2-3b shows the plots of the analyses were the flow control's $d_{o,min}$ was set to 200 mm. The comparison shows that for the analyses where the FVSs assigned were equal or selected from the RFSWIM method, the greatest achieved FR level was a 1 in 2 year return period. The respective estimated costs of the proposed solutions with the greatest achieved FR levels were £62,500 and £172,250. In contrast, the analyses where the FVSs were selected from the DfE method, the greatest achieved FR level was a 1 in 5 year return period. The estimated cost of the proposed solution was £170,250. In this case, assigning the DfE FVSs has had a beneficial impact by increasing the achieved FR level and provided cheaper solutions at the FR level of a 1 in 2 year return period.

6.2.2 The anonymised combined sewer system

The anonymised case study was last presented in Section 5.3.4 where all of the FVSs assigned to the subcatchments were equal. In this section, the FVSs were varied to investigate the difference in the flow control configurations presented by the assessment framework. It was found that flow controls could be positioned and designed into the sewer system and achieve an improvement in the FR level compared to where the FVS values were equal. An improvement in the FR level was seen in both cases when the $d_{o,min}$ was either 100 mm or 200 mm. The greatest achieved FR level was a 1 in 12 year return period when VFCs and orifice plates were positioned with a set $d_{o,min}$ of 200 mm.

In this sub-section, the DfE FVSs were assigned to the anonymised combined sewer system subcatchments and the analyses completed. The sewer system was analysed with the $d_{o,min}$ values set to 100 mm and 200 mm respectively. The initial assessment of the anonymised combined sewer system found the initial FR level was a 1 in 1 year return period.

Analysis with the DfE FVSs assigned and the $d_{o,min}$ set to 100 mm

The plot when the $d_{o,min}$ was set to 100 mm showed that an improvement in the FR level could be achieved (Figure 6.2-4). An improvement in the FR level was achieved from a 1 in 1 year return period to a 1 in 2 year return period. The estimated cost of the solution was £7,750. The FR level was not increased any further than the 1 in 2 year return period. The analysis of the sewer system was manually ended as the assessment framework became stuck in a repeating loop of flow control designs. This repeating loop had occurred for 165 iterations of the assessment framework and was not stopped as expected by the FAST pattern recognition algorithm encoded in the flow control positioning method (Section 3.4).

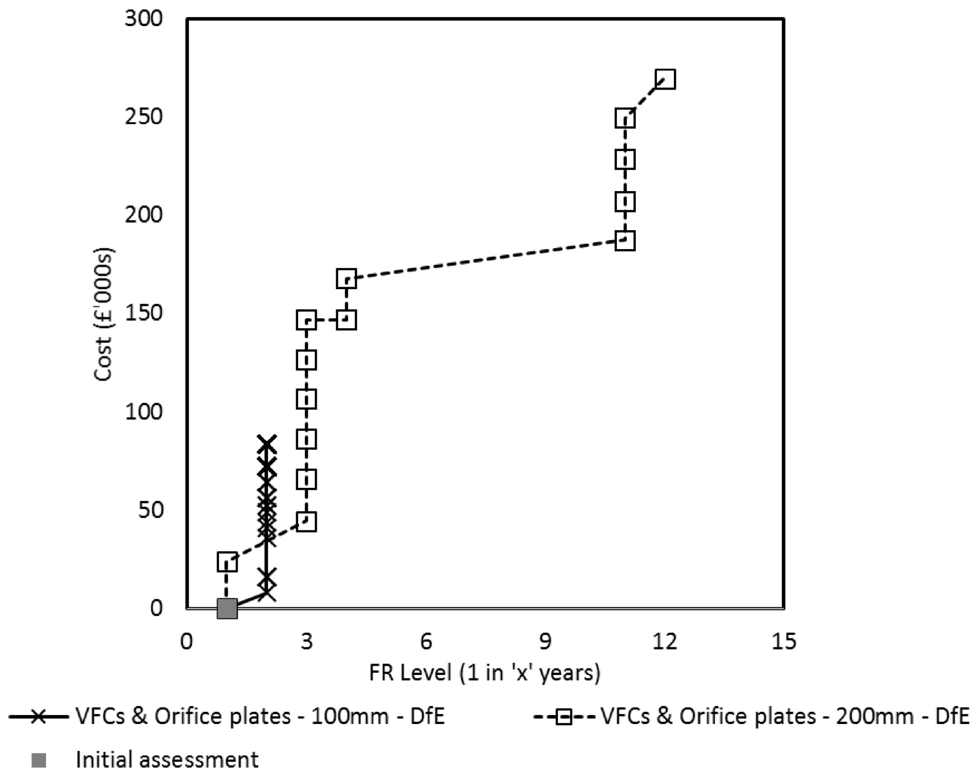


Figure 6.2-4: Cost benefit analyses from the assessment framework after the analysis the anonymised combined sewer system with DfE FVSs assigned to the subcatchments and the $d_{o,min}$ set to 100 mm and 200 mm respectively.

Analysis with the DfE FVSs assigned and the $d_{o,min}$ set to 200 mm

The plot from the analysis when the $d_{o,min}$ was set to 200 mm shows a greater improvement in the FR level of the sewer system compared to the outputs where the $d_{o,min}$ was set to 100 mm. In this analysis, the FR level was increased from a 1 in 1 year return period to 1 in 11 year return period before the maximum budget of £250,000 was exceeded. The greatest FR level of a 1 in 11 year return period was achieved for an estimated cost of £187,500.

The analysis where the anonymised combined sewer system had the RFSWIM FVSs assigned to the sewer system subcatchments was also completed. The plots with the two different set $d_{o,min}$ values are shown in Figure 6.2-5. The initial FR level was found to be a 1 in 1 year return period.

Analysis with the RFSWIM FVSs assigned and the $d_{o,min}$ set to 100 mm

The analysis when the $d_{o,min}$ was set to 100 mm showed an improvement in the FR level of the sewer system from a 1 in 1 year return period to a 1 in 5 year return period (Figure 6.2-5). The greatest improvement in the FR level to a 1 in 5 year return period, had an estimated cost of £7,750. This proposed solution was found after the first iteration of the assessment framework. The analysis continued for another 290 iterations before the algorithm entered a repeating loop of flow control designs and positions. The analysis of the sewer system was manually ended.

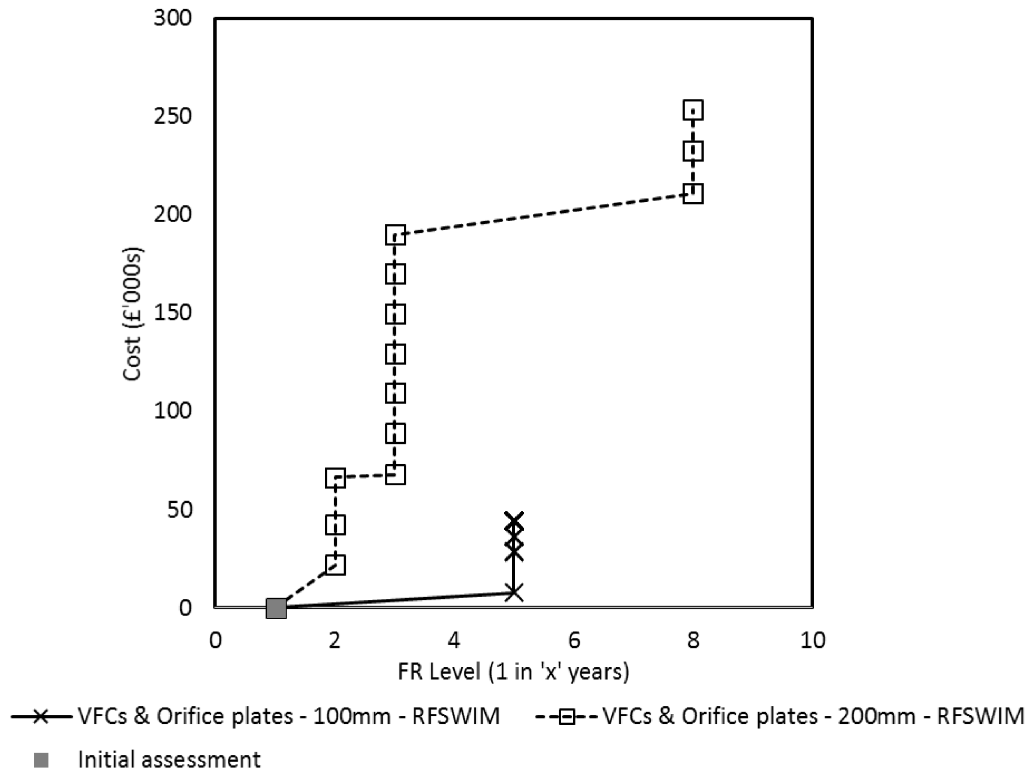


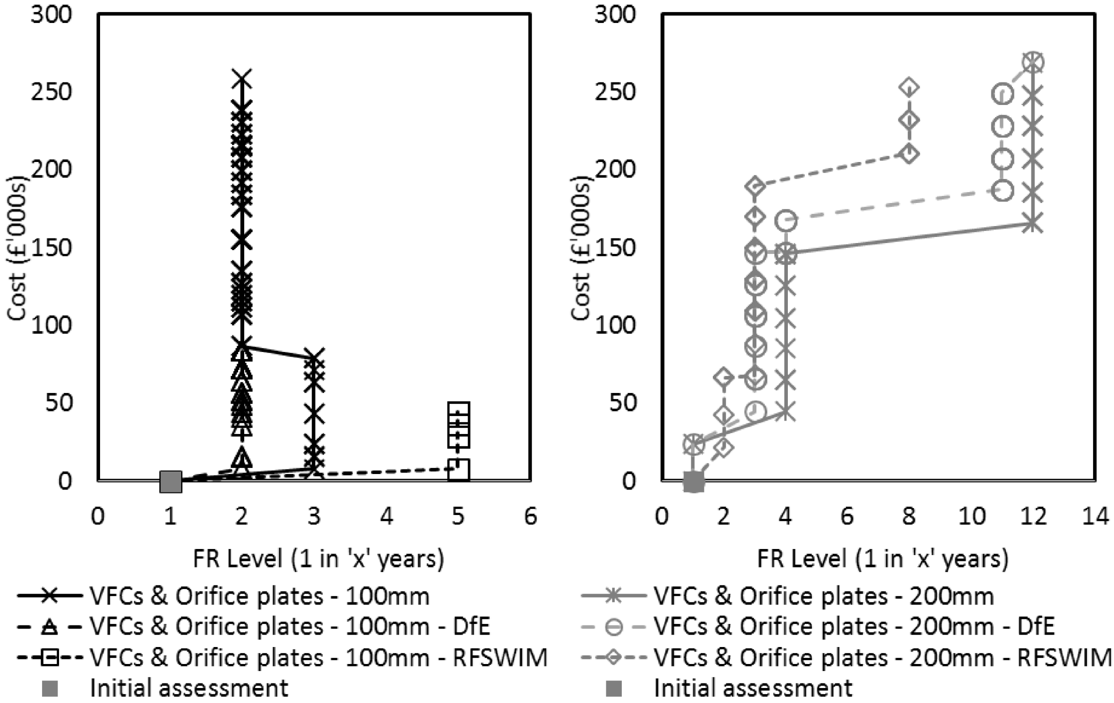
Figure 6.2-5: Cost benefit analyses from the assessment framework after the analysis the anonymised combined sewer system with RFSWIM FVSs assigned to the subcatchments and the $d_{o,min}$ set to 100 mm and 200 mm respectively.

Analysis with the RFSWIM FVSs assigned and the $d_{o,min}$ set to 200 mm

The plot from the analysis where the $d_{o,min}$ was set to 200 mm also showed an improvement in the FR level of the sewer system through the positioning of VFCs and orifice plates. A greatest achieved FR level of a 1 in 8 year return period was achieved from an initial 1 in 1 year return period. This retrofit design had an estimated cost of £210,750 and required the positioning of 10 VFCs. The analysis also proposed designs for FR levels of a 1 in 2 year return period and 1 in 3 year return period. The analysis ended when the maximum budget of £250,000 was exceeded.

A comparison of the proposed solutions from the analyses of the anonymised combined sewer system, using varying FVSs, is shown in Figure 6.2-6. Figure 6.2-6a shows the configurations from the analyses where the $d_{o,min}$ was set to 100 mm. Out of the three analyses presented, it was only possible to complete the analysis where the FVSs were equal due to the algorithm becoming stuck in a repeating loop. The plot shows that the greatest achieved FR level was a 1 in 5 year return period. This was achieved when the RFSWIM FVSs were applied to the sewer system model. All of the analyses also achieved their greatest FR level after the first iteration of the assessment framework. The analysis where the RFSWIM FVSs were assigned selected a different first position for the flow control, however, this was the next downstream manhole from the positions selected by the other two analyses. Overall in this comparison, it was shown that assigning varying FVSs increases the achieved FR level of the sewer system.

Figure 6.2-6b compares the plots from the anonymised combined sewer system analyses with various FVSs assigned and the $d_{o,min}$ set to 200 mm. The comparison shows that the greatest achieved FR level was found when all of the FVSs in the model were equal. The greatest achieved FR level was a 1 in 12 year return period with an estimated cost of £166,000. All of the analyses were completed without user interaction and when the maximum budget was exceeded.



a) Comparison of the three analyses plots when the $d_{o,min}$ was 100 mm.

b) Comparison of the three analyses plots when the $d_{o,min}$ was 200 mm.

Figure 6.2-6: Comparison of all of the anonymised combined sewer systems with different FVSs (no scores, DfE and RFSWIM) and different set $d_{o,min}$ values (100 mm and 200 mm).

6.2.3 Summary of applying different flood vulnerability scores

Section 6.2 investigated the effect of varying FVSs on the sewer system subcatchments when analysed by the assessment framework. Changing the subcatchment FVSs changes the calculated weighted available upstream volume used to select which manhole chamber to position the next flow control (Equation 3.4). By altering the subcatchment FVSs, the user can prioritise areas requiring flood protection and attenuate the flows in the upstream section of the sewer system. The following conclusions were drawn from this analysis:

1) Varying the FVSs can increase the FR level of the sewer system through the analysis of the sewer system (occurred in two of the four analyses).
2) Varying the FVSs can propose cheaper retrofit solutions through the analysis of the sewer system (occurred in three of the four analyses).

3) Issues were highlighted with the FAST pattern matching algorithm as two of the analyses became stuck in a repeating loop and were only stopped through user interaction.

6.3 Summary of outputs from the assessment framework

Section 5.3 and 6.2 have presented and discussed the outputs from the analyses of the Langley and anonymised combined sewer systems. The sewer systems have been analysed in a four different ways:

1) The positioning of VFCs and orifice plates with equal subcatchment FVSs (Section 5.3);
2) The positioning of orifice plates only with equal subcatchment FVSs (Section 5.3);
3) The positioning of VFCs and orifice plates with FVSs assigned from DfE (Section 6.2); and
4) The positioning of VFCs and orifice plates with FVSs assigned from RFSWIM (Section 6.2).

Section 6.3 summarises all of the outputs from the analyses of the two sewer systems and draws conclusions and observations regarding the application of the assessment framework.

6.3.1 The Langley combined sewer system summary

The solutions from the Langley combined sewer system have been compared in Table 6.3-1. These are compared to show which analysis completed by the assessment framework achieved the greatest improvement in the sewer system's FR level. Table 6.3-1 shows that the positioning of flow controls with a $d_{o,min}$ set to 200 mm is not as beneficial as positioning flow controls with a $d_{o,min}$ set to 100 mm as the greatest achieved FR level only reached a 1 in 5 year return period. Only the analysis of the Langley combined sewer system where the FVSs were equal and the $d_{o,min}$ was set to 100 mm exceeded the desired FR level of a 1 in 30 year return period. This solution was only one of two solutions from all of the analyses performed in this research that exceeded the targeted FR level. Applying varied FVSs did not further increase the FR level of the sewer system beyond the 1 in 71 year return period.

6.3.2 The anonymised combined sewer system summary

The outputs from the anonymised combined sewer system analyses are summarised in Table 6.3-2. Table 6.3-2 shows that the greatest achieved FR level was a 1 in 12 year return period, which had a proposed cost of £166,000. The positioning of orifice plates only with a $d_{o,min}$ of 100 mm, however, achieved a FR level of a 1 in 11 year return period with an estimated cost of £17,000. This is £149,000 cheaper than the VFC and orifice plate solution with the FR level of a 1 in 12 year return period. The analyses of the anonymised combined sewer system with varied FVSs did propose a configuration of orifice plates that achieved a 1 in 11 year return period. This configuration, however, was not cheaper than the configurations proposed when the FVSs were equal.

Even though the application of the varied FVSs did not show an increase in the FR level of the sewer systems once the flow controls were positioned, the analysis of the anonymised combined sewer system with varied FVSs, and the $d_{0,min}$ equal to 200mm, did achieved a 1 in 11 year return period compared the 1 in 12 year return period with equal FVSs. The output with the varied FVSs may be a more resilient solution as the high priority areas in the catchment were specifically targeted to reduce flood risk. Further analysis and quantification of the increased resilience would need to be completed. This further analysis was not completed in this research due to time constraints.

Table 6.3-1: Comparison of the flow controls installed in the Langley combined sewer system when.

	Baseline	VFCs & OPs		OPs		VFCs & OPs – DfE		VFCs & OPs - RFSWIM	
$d_{o,min}$ (mm)	-	100	200	100	200	100	200	100	200
Greatest achieved FR level (1 in 'x' years)	1	71	2	9	2	5	5	5	2
Total estimated cost (£)	-	240,500	62,500	247,000	88,750	84,750	170,250	84,750	172,250
Number of flow controls installed	-	21	3	48	21	9	8	9	8
Minimum outlet diameter (mm)	-	104	204	100	200	105	204	105	204
Average design flow-rate (l/s)	-	13	31	30	115	12	31	12	30

Table 6.3-2: Comparison of the flow controls installed in the anonymised combined sewer system.

	Baseline	VFCs & OPs		OPs		VFCs & OPs – DfE		VFCs & OPs - RFSWIM	
$d_{o,min}$ (mm)	-	100	200	100	200	100	200	100	200
Greatest achieved FR level (1 in ‘x’ years)	1	3	12	11	10	2	11	5	8
Total estimated cost (£)	-	7,750	166,000	17,000	201,500	7,750	187,500	7,750	210,750
Number of flow controls installed	-	1	8	1	31	1	9	1	10
Minimum outlet diameter (mm)	-	105	204	100	200	105	204	105	200
Average design flow-rate (l/s)	-	9	26	37	103	9	26	9	26

6.4 Comparison to other flood alleviation solutions

Section 6.3 has summarised the outputs from the analyses of the Langley and anonymised combined sewer systems by the assessment framework. The summarised analyses outputs from the Artificial Network and anonymised stormwater sewer system were previously shown in Table 5.3-1 and Table 5.3-2 respectively. The summaries have highlighted that an increase in the FR level can be achieved through the strategic positioning and design of flow controls. To theoretically assess the competitiveness of the assessment framework's outputs to other industry flood alleviation solutions for increasing the FR level the proposed configurations are benchmarked. In this comparison, the cost to install the retrofit solutions with the greatest achieved FR level are compared for each sewer system models in turn (Figure 6.4-1 to 6.4-4). The different applications of the assessment framework and the alternative flood alleviation solutions compared were:

1) Application of the assessment framework where VFCs and orifice plates were positioned;
2) Application of the assessment framework where only orifice plates were positioned;
3) Application of the assessment framework where VFCs and orifice plates were positioned and alternative FVSs were assigned;
4) A deep shaft solution (method explained in Appendix 5); and
5) The alternative flood alleviation solutions used in the UK water industry (Newton *et al*, 2015):
    a) Isolate from the system (installation of non-return valves and pumping stations);
    b) Manage flow (upgrading pumping station or installing a new CSO);
    c) Sewer upsizing (installation of pumping stations, new storage chambers or sewers); and
    d) Flow attenuation (installation of detention tanks, pumping stations and surface flow attenuation).

In Newton *et al*'s work (2015), the estimated costs of implementing proposed solutions from the assessment framework were compared to the estimated costs of alternative flood alleviation solutions from Babtie Ltd and Ofwat (2003). The alternative flood alleviation solutions were designed to achieve the same greatest FR level as achieved by the assessment framework. The estimated costs of solely installing pumping stations was not used following the Babtie Ltd and Ofwat reports' authors advice due to the lack of available data.

The estimated costs for the installation of the flood alleviation options were calculated from the total flooded area for each FR level CIH simulated. The total flooded area was divided by the average plot area to estimate the number of properties flooded. This was then multiplied by the average cost for installing each flood alleviation solutions.

The outputs, in this section of the chapter, are presented as spider diagrams. On each diagram, the series indicates estimated cost of implementing the solution with greatest achieved FR level from each flood alleviation solution. The alternative flood alleviation methods solutions, from the Babtie Ltd & Ofwat report, were designed to have the same FR level as the outputs from the assessment framework. The flood alleviation methods are sorted clockwise around the diagram by greatest FR level and then lowest estimated cost. These diagrams enable the comparison of the estimated cost for each of the modelled flood alleviation methods.

6.4.1 Comparison of the Artificial Network solutions

The Artificial Network has only been analysed by the assessment framework for the scenarios where either both VFCs and orifice plates were positioned and only orifice plates were positioned, Sections 5.3.1. The FVSs were all equal for each analysis. The solution where only orifice plates were positioned required an additional £8,500 for a 1 in 21 year increase in the return period. These outputs were compared to alternative flood alleviation methods (Figure 6.4-1). The positioning of VFCs & orifice plates was the cheapest of the remaining methods and installing a deep shaft was the most expensive. The estimated costs of the flood alleviation methods ranged from £204,500 to £2,048,000.

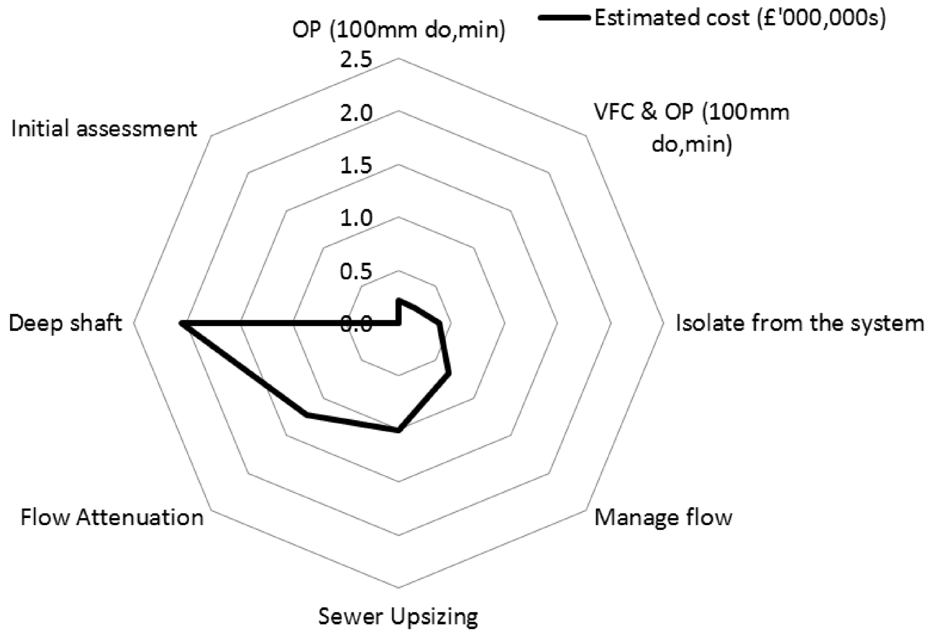


Figure 6.4-1: Comparison of the associated estimated costs for implementing the different flood alleviation methods for the Artificial Network. The raw data is presented in Appendix 6-1.

6.4.2 Comparison of the anonymised stormwater sewer system solutions

The anonymised stormwater sewer system was only analysed when both VFCs and orifice plates were positioned and when only orifice plates were positioned, Section 5.3.2. The FVSs were all equal for each analysis. The initial assessment of the anonymised stormwater sewer system found that the FR level was a 1 in 4 year return period. All of the flood alleviation methods, except when the only orifice plates were positioned, achieved a greatest FR level of a 1 in 108 year return period (Figure 6.4-2). The cheapest of these solutions was the solution where both VFCs and orifice plates were positioned in the sewer system, where the estimated cost was £16,000. The next cheapest solution had an estimated cost of £126,000 and was the 'isolate from the system' solution. The most expensive solution was the deep shaft solution with an estimated cost of

£1,071,250. The solution where only orifice plates were positioned only achieved a greatest FR level of a 1 in 6 year return period at an estimated cost of £5,000.

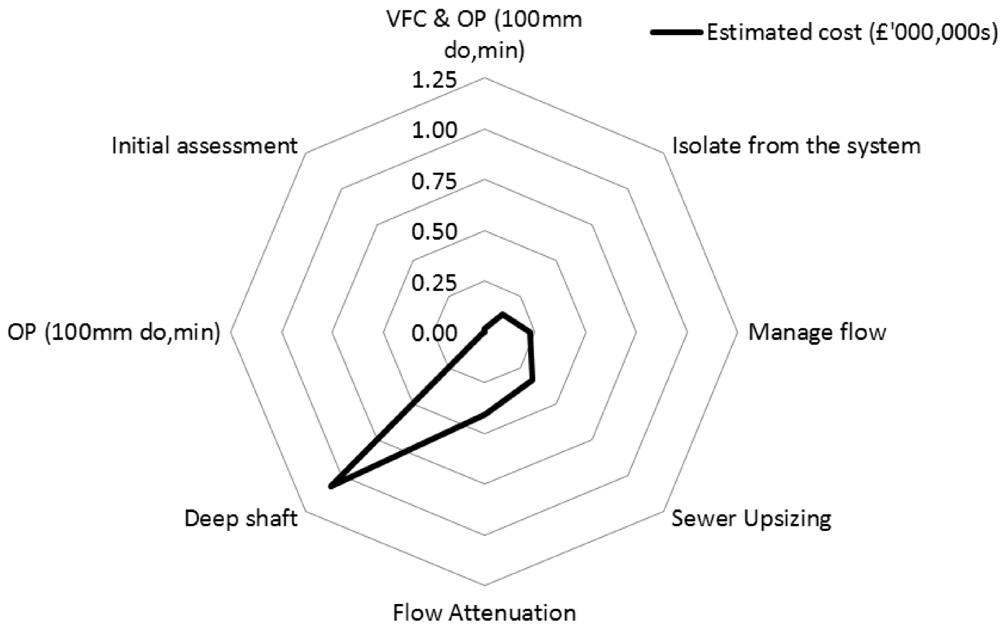


Figure 6.4-2: Comparison of the associated estimated costs for implementing the different flood alleviation methods for the anonymised stormwater sewer system. The raw data is presented in Appendix 6-2.

6.4.3 Comparison of the Langley combined sewer system solutions

The Langley combined sewer system was analysed in three different ways by the assessment framework:

1) Positioning VFCs and orifice plates;
2) Only positioning orifice plates; and
3) Positioning VFCs and orifice plates with varying FVSs.

The initial assessment of the Langley combined sewer system found the FR level was a 1 in 1 year return period. Comparing all of the flood alleviation solutions, the greatest FR level achieved was a 1 in 71 year return period by applying the Babtie Ltd and Ofwat flood alleviation methods, the deep shaft method and the positioning of VFCs and orifice plates (Figure 6.4-3). The cheapest solution was the ‘isolate from the system’ method that had an estimated cost of £180,000. The second cheapest flood alleviation method was the positioning of VFCs and orifice plates, which had an estimated cost of £240,500. The most expensive flood alleviation method was the deep shaft solution that had an estimated cost of £1,821,000. The remaining analyses completed by the assessment framework (positioning orifice plates only and positioning VFCs and orifice plates with varying FVSs) had estimated costs of £247,000 and £84,750 repectively.

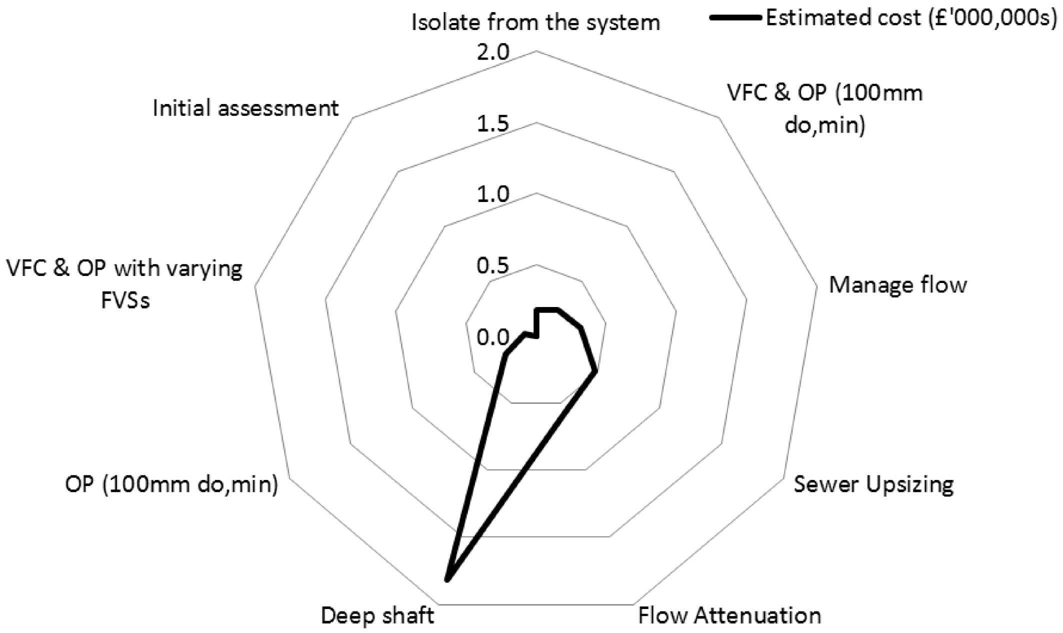


Figure 6.4-3: Comparison of the associated estimated costs for implementing the different flood alleviation methods for the Langley combined sewer system. The raw data is presented in Appendix 6-3.

6.4.4 Comparison of the anonymised combined sewer system solutions

The anonymised combined sewer system was analysed for the same scenarios as the Langley combined sewer system above. The initial assessment of the anonymised combined sewer system found the FR level to be a 1 in 1 year return period. The cheapest solution that was found, with a FR level of a 1 in 12 year return period, was the 'isolate from the system' solution costing £72,000 (Figure 6.4-4). The solution that was the most expensive solution from all nine flood alleviation methods was the deep shaft solution with an estimated cost of

£236,500. The remaining solutions had a ranging estimated cost from £17,000 (when only positioning orifice plates) to £232,000 (installing a deep shaft solution).

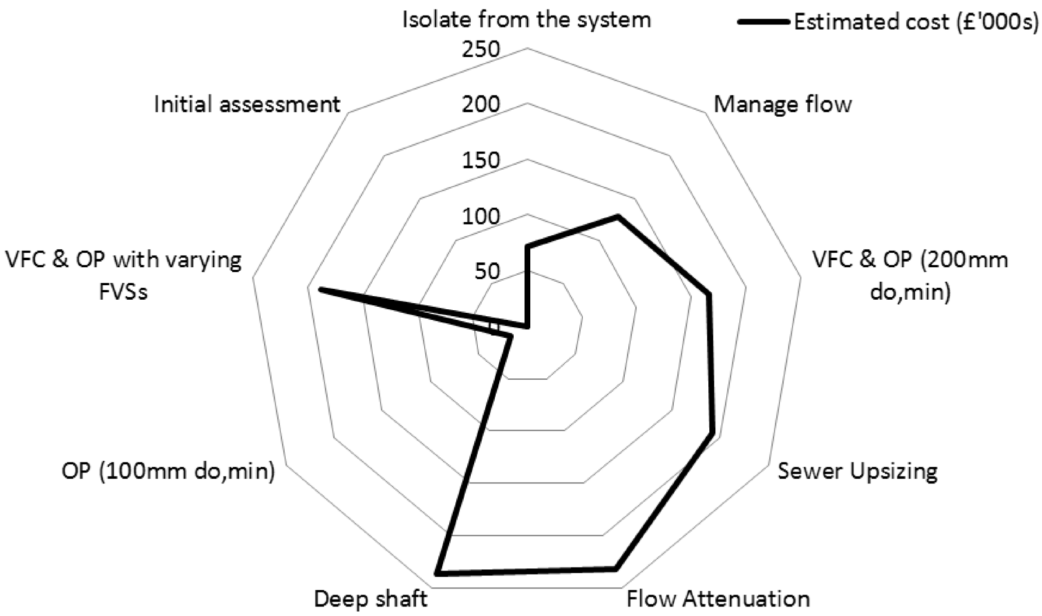


Figure 6.4-4: Comparison of the associated estimated costs for implementing the different flood alleviation methods for the anonymised combined sewer system. The raw data is presented in Appendix 6-4.

The proposed solutions from the different flood alleviation methods for each case study sewer system have been compared (Figure 6.4-1 to 6.4-4). Summarising the comparisons, it has been shown that:

1) Solutions provided by the assessment framework were the cheapest for the greatest achieved FR level for the Artificial Network and anonymised stormwater sewer system;
2) For the Langley combined sewer system and anonymised combined sewer system, the proposed retrofit solutions from the assessment framework were the second and third cheapest solutions respectively. The cheaper solutions, however, require a power supply so may become more expensive over the life of the solution; and
3) The deep shaft solution was consistently the most expensive flood alleviation method compared to the other solutions.

6.5 Conclusion

The conclusions for the analysis and comparisons completed in Chapter 6 show that varying the FVSs did not increase the FR level of the sewer system through the analysis of the sewer system. The proposed solutions from the assessment framework with the varied FVSs, however, may have a greater flood resilience as the high priority areas of the catchment are designed to be protected from flooding. This would require additional analysis to determine if it is the case.

Comparison of the costs of the solutions provided by the assessment framework to alternative flood alleviation methods were found to be the cheapest for the greatest achieved FR level for the Artificial Network and anonymised stormwater sewer system. In the other two sewer systems analysed, the positioning of flow controls was found to be the second and third cheapest solution. This shows that positioning flow controls in sewer systems to reduce flood risk is a viable solution compared to current alternative flood alleviation methods.

Chapter 7

Validation & parameter analysis of the assessment framework

7.1 Introduction

Chapters 5 and 6 discuss the different flow control configurations determined by the assessment framework for the four sewer systems analysed. This chapter, Chapter 7, is separated into two sections to discuss the validation and parameter analysis of the assessment framework respectively. For the validation of the simulations completed in the assessment framework, the results are compared to hydraulic simulations from InfoWorks CS (Section 7.2). The hydraulic simulations are compared, as well as, the effect of the different VFC characteristic curves assessed. The chapter then discusses the one-factor-at-a-time parameter (OAT) analysis conducted (Section 7.3). The OAT analysis is used to investigate the differences in the cost benefit analyses from the assessment framework based on the variation of the assessment framework's input values as listed in Table 5.2-1.

7.2 Validation of the assessment framework

The validation of the sewer system models from the assessment framework was completed to investigate and quantify the differences between the sewer system's hydraulic behaviour when simulated in the SWMM 5 based assessment framework and InfoWorks CS. InfoWorks CS is reportedly commonly used by sewerage companies and designers, within the UK, to model the hydraulic behaviour of the existing sewer systems they manage. The comparison evaluates the correlation between flow-rates and flow depths from the sewer system conduits in both the SWMM 5 and InfoWorks CS models. The flow depth and flow-rate outputs from the sewer system model simulations will then be analysed using the:

1) Pearson correlation coefficient;
2) Coefficient of determination;
3) Nash Sutcliffe efficiency;
4) Index of agreement correlation indicators; and
5) The normalised root square mean deviation (RMSD).

Reasons for the selection of these correlation coefficients, and their weaknesses, are discussed in Section 7.2.2. In this section of the chapter, the sewer system models used for the validation are described (Section 7.2.1) as well as a comparison of the hydraulic behaviours from each of the simulations in SWMM 5 and InfoWorks CS (Section 7.2.2). For the comparison, SWMM Version 5.00.21 and InfoWorks CS Version 12.1 was used.

7.2.1 Sewer system models used for validation

The sewer system models used in the validation of the assessment framework were the Langley combined sewer system and the anonymised combined sewer system (Section 5.2.3 and 5.2.4 respectively). The sewer system models are of anonymised existing sewer systems and are un-validated. The sewer system models were transferred from a SWMM 5 format into an InfoWorks CS format following InfoWorks CS guidelines for importing SWMM 5 models (2011b). Suggested corrections were made to the sewer system models, once they were transferred into InfoWorks CS, so that they could be successfully simulated. The VFC characteristic curves were also adapted so that the flow-rate does not decrease whilst the head level increases as this scenario creates an error within InfoWorks CS due to the occurrence of multiple head levels for a given flow-rate (Orman, 2009). The sewer system models chosen for this validation exercise were:

1) The Langley combined sewer system that has not been analysed by the assessment framework and contains no additional flow controls;

2) The Langley combined sewer system, which was analysed by the assessment framework achieving a FR level of a 1 in 71 year return period, and contains 21 additional VFCs (Section 5.3.3);
3) The anonymised combined sewer system that has not been analysed by the assessment framework and contains no additional flow controls; and
4) The anonymised combined sewer system, which was analysed by the assessment framework achieving a FR level of a 1 in 12 year return period, and contains eight additional VFCs (Section 5.3.4).

7.2.2 Hydraulic validation

The four sewer system models listed in Section 7.2.1 were simulated in both InfoWorks CS and SWMM 5. Both of the sewer system models were simulated with a series of input hyetographs ranging up to the greatest achieved FR level for the respective sewer system. The Langley combined sewer system models were simulated for dry-weather flow (DWF) and with the critical input hyetographs (CIHs) with a: 1 in 1; 1in 5; 1 in 10; 1 in 30; and a 1 in 71 year return period. The anonymised combined sewer system models were simulated for DWF and with the CIHs with a: 1 in 1; 1 in 2; 1 in 5; 1 in 10; and 1 in 12 year return period. For the purposes of the simulation comparison plots displayed later in this section, the DWF simulations are presented to have a 1 in 0 year return period.

The flow-rates and flow depths from the two hydraulic simulation packages were compared (Figure 7.2-1 and 7.2-2 respectively). The flow-rates and flow depths were taken from pipes immediately upstream of the outlets of the respective sewer system models. Figure 7.2-1 compares the flow-rates from the SWMM 5 and InfoWorks CS simulations of both the anonymised and Langley combined sewer systems. The solid black line displayed on the plot represents equal values (i.e. exact correlation of values). The plot shows an approximate equal split of InfoWorks CS predicting greater and lower flow-rates compared to SWMM 5. The looping effect on the plots is caused by the offset in the predicted peak flow-rates in the simulation. On average, InfoWorks CS predicted a 22% greater peak flow-rate compared to the SWMM 5 model. The plot also shows that the InfoWorks

CS simulations did not predict a flow-rate lower than 4.31 l/s. This minimum predicted flow-rate is due to the base and trade flow-rate patterns entered in the model.

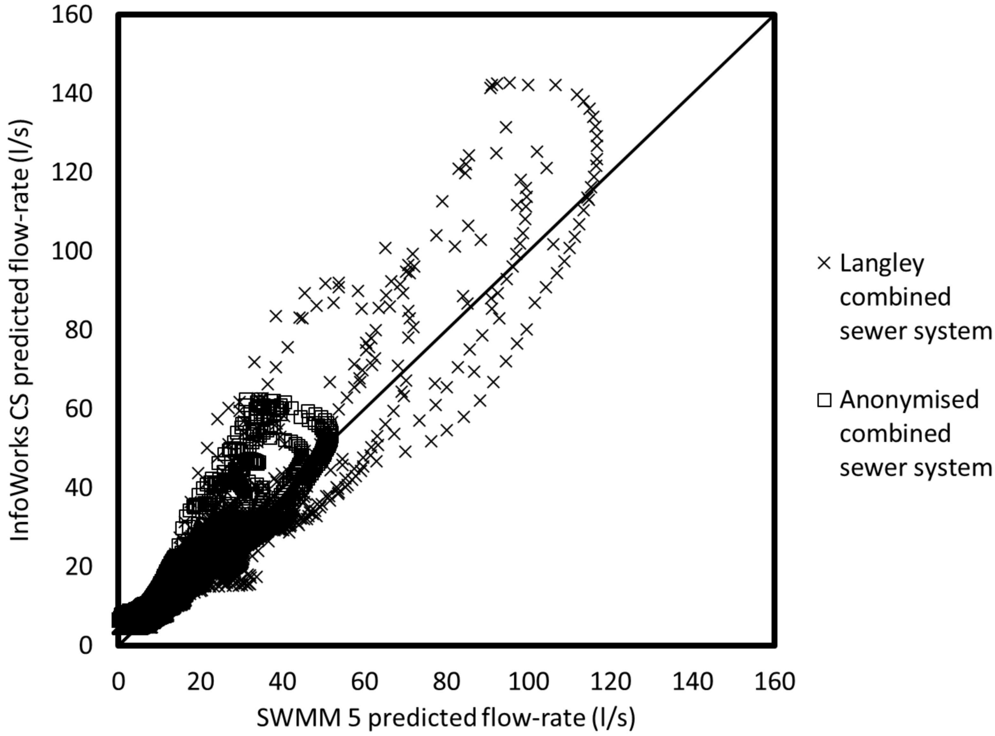


Figure 7.2-1: Plot of flow-rates from the SWMM 5 simulations compared to their respective InfoWorks CS simulations.

Figure 7.2-2 compares the flow depths from the SWMM 5 and InfoWorks CS simulations of both the anonymised and Langley combined sewer systems. As with Figure 7.2-1, the solid black line on the plot represents exact correlation of the flow depth values between the modelling programmes. The plot shows that 99.3% of the flow depth predictions from InfoWorks CS were greater than the SWMM 5 values. For all of the flow depths, the InfoWorks CS values have a positive error bias as none of the simulations begin from a zero head level. This is more apparent in the anonymised combined sewer system results when SWMM 5 predicts a flow depth of 0 m and InfoWorks CS predicts 0.51 m and 0.61 m for both sewer system simulations. This predicted flow depth is due to the trade flow added to the model. As with the flow-rate plot (Figure 7.2-1), the looping nature of the outputs is caused by the offset in the peak flow depth predictions from the hydraulic model simulations. InfoWorks CS gave a 230%

greater peak flow depth compared to the SWMM 5 model. Overall, it can be said that the InfoWorks CS model will provide a more conservative drainage solution as it predicts greater flow depths for similar flow-rates compared to the SWMM 5 simulations.

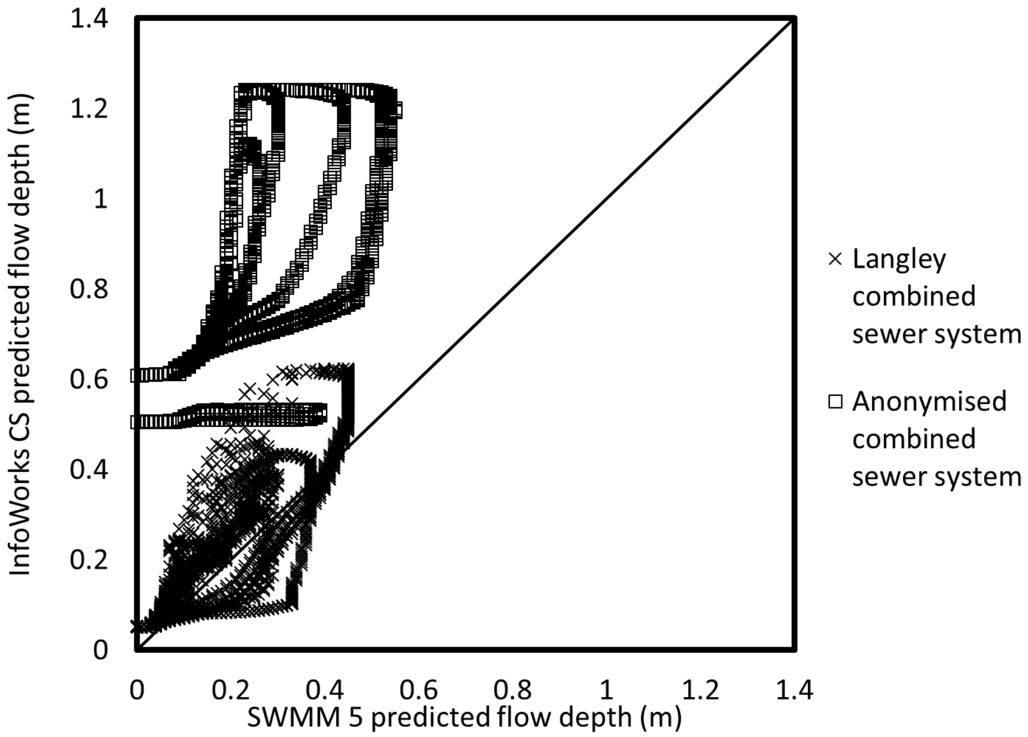


Figure 7.2-2: Plot of flow depths from the SWMM 5 simulations compared to their respective InfoWorks CS simulations.

The flow depths and flow-rates from the sewer system model simulations were compared using the:

1) Pearson correlation coefficient;
2) Coefficient of determination;
3) Nash Sutcliffe efficiency;
4) Index of agreement correlation indicators; and
5) The normalised RMSD.

The RMSD is normalised by dividing the RMSD value by the range of dependent variables (in this case, the values from the InfoWorks CS simulations). These correlation indicators are used to allow a broad comparison of the outputs as all of the correlation indicators have their representative weaknesses (Krause *et al*, 2005). The drawbacks of the five respective correlation indicators are:

1) The Pearson correlation coefficient, and the other three correlation indicators used, are insensitive to systematic over or under-predictions;
2) The Coefficient of determination only quantifies the dispersion of the data;
3) The Nash Sutcliffe efficiency calculates the differences in the time series as squared values and, therefore, overestimates larger differences compared to smaller values; and
4) The Index of agreement can achieve high values with poor model fits.

The correlation indicators have been plotted against the FR level of the CIHs applied in the simulation. As a reminder, the DWF simulations were assigned a 1 in 0 year return period so they could also be plotted on the graphs. The calculated correlation values from the simulation flow-rates and flow depths are presented (Figure 7.2-3 to 7.2-4) and the legend labelling system for this section of the thesis explained in Table 7.2-1.

Table 7.2-1: Explanation and description of legend labels used in Figures 7.2-3 to 7.2-4.

Flow-rate outputs compared		Flow depth outputs compared	
1Q	The unanalysed Langley combined sewer system	1H	The unanalysed Langley combined sewer system
2Q	The analysed Langley combined sewer system	2H	The analysed Langley combined sewer system
3Q	The unanalysed anonymised combined sewer system	3H	The unanalysed anonymised combined sewer system
4Q	The analysed anonymised combined sewer system	4H	The analysed anonymised combined sewer system

The Pearson correlation coefficient, Coefficient of determination, Nash-Sutcliffe efficiency and Index of agreement values calculated from the simulations of the four sewer system models are presented (Figure 7.2-3a-d). The markers from the analyses of the Langley combined sewer system are hollow and the markers from the analyses of the anonymised combined sewer system are solid black. The values are presented against the FR level of the CIHs applied in the simulations. The flow-rates and flow-depths from the analyses generally show an increasing correlation value is achieved as the FR level of the CIH increases. This is, however, not observed for the 2H, 2Q, 4H and 4Q sets of outputs that decrease after the 1 in 10 year return period, 1 in 10 year return period, 1 in 5 year return period and 1 in 5 year return period simulations respectively. The lowest correlation values were seen during the DWF simulations in each of the figure plots (Figure 7.2-3a-d). This indicates that the base, dry weather and trade flow-rates input into the models do not correlate well. In Figure 7.2-3a, b and d, the series labelled 3H was the complete series with the lowest scores. Approximately 49.5% of all of the correlation coefficient values presented in Figure 7.2-3a-d are greater than 0.8 indicating that there is a strong correlation between the simulation outputs.

With regard to the Nash-Sutcliffe efficiency values, not all of the values were presented in Figure 7.2-3c to better display the majority of the values calculated. The remainder are presented in Table 7.2-2. Approximately 48% of the values were below zero, which indicates that the mean value of the observed time series would be a better predictive value than the use of the model itself (Krause *et al*, 2005).

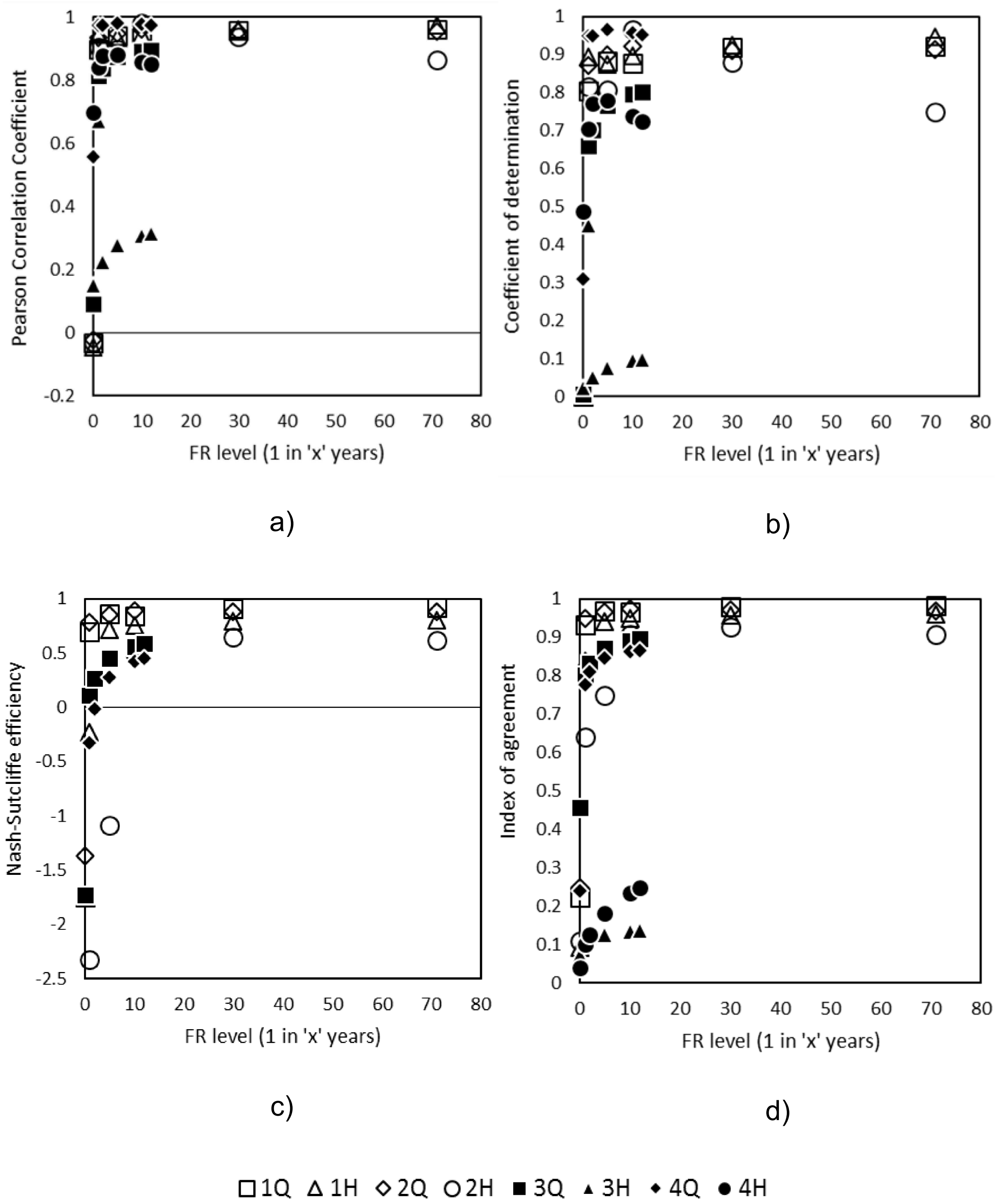


Figure 7.2-3: Plots showing a) the Pearson correlation coefficient values, b) Coefficient of determination, c) Nash-Sutcliffe efficiency and d) Index of agreement for each of the simulations completed for each of the FR levels simulated.

Table 7.2-2: Table of missing Nash-Sutcliffe efficiency scores from Figure 7.2-3c.

Legend label	FR level (1 in 'x' years)	Nash-Sutcliffe efficiency score	Legend label	FR level (1 in 'x' years)	Nash-Sutcliffe efficiency score
1H	0 (DWF)	-31.989	4Q	0 (DWF)	-30.222
2H	0 (DWF)	-27.666	4H	0 (DWF)	-1,626.52
3H	0 (DWF)	-492.147	4H	1	-215.544
3H	1	-83.897	4H	2	-156.295
3H	2	-64.486	4H	5	-65.720
3H	5	-52.081	4H	10	-34.288
3H	10	-45.766	4H	12	-29.420
3H	12	-44.429			

The four correlation indicators presented in Figure 7.2-3 have shown a wide range in correlation with 73%, 52%, 17% and 56% of the indicator scores being greater than 0.8 (Pearson Correlation Coefficient, Coefficient of determination, Nash-Sutcliffe efficiency and Index of agreement, respectively). This was most seen in the flow-rate outputs with greater CIH return periods applied to the simulations. All four of the correlation indictors used can be insensitive to over and under-predictions. To investigate whether a systematic over or under-prediction has occurred, the normalised RMSD was calculated and presented (Figure 7.2-4 and Table 7.2-3). Similarly to the Nash-Sutcliffe efficiency outputs, an additional table has been inserted to list the outputs with a value greater than 1.2 not presented in the plot (Table 7.2-3).

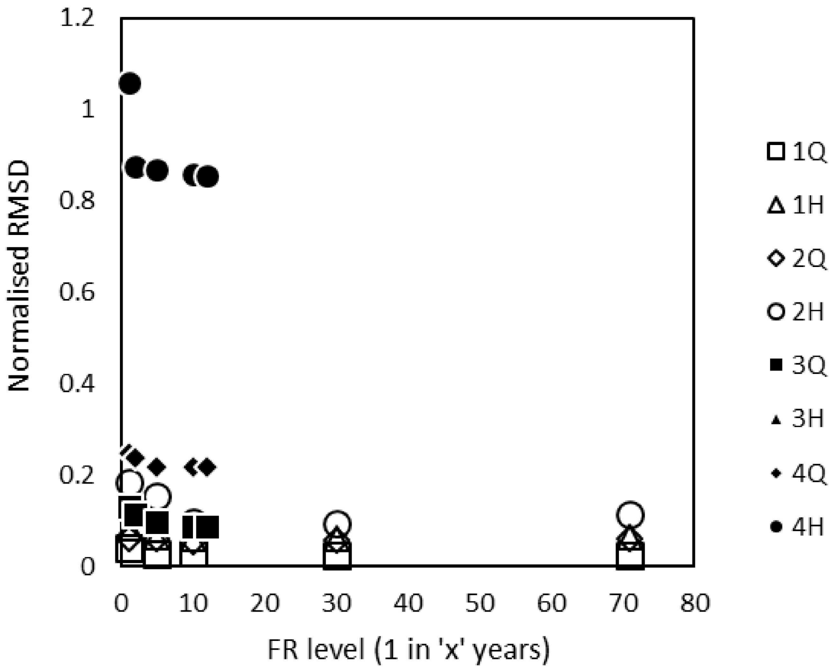


Figure 7.2-4: Plot showing the normalised RMSD between the SWMM 5 and InfoWorks CS flow-rate and flow depth outputs from the analyses of the Langley and anonymised combined sewer system.

Figure 7.2-4 shows a general trend of the normalised RMSD values reducing as the FR level of the CIH increases. The largest values were seen in all series for the DWF simulations. The plot also shows that the normalised RMSD from the analysis of the anonymised combined sewer system are greater than the Langley combined sewer system values. The lowest normalised RMSD value was 0.025 for the 1 in 30 year return period simulation in 1Q (flow-rate outputs from the unanalysed Langley combined sewer system). It was found that 52% of the normalised RMSD values are below 0.2. Table 7.2-3 presents the normalised RMSD scores not shown in Figure 7.2-4. Eight of the 13 scores presented are from the DWF simulations of both the combined sewer system models. The remaining five scores are from the analysis of the flow depth outputs from the assessment framework analysed anonymised combined sewer system.

Table 7.2-3: Table of normalised RSMD values not presented in Figure 7.2-4.

Legend label	FR level (1 in 'x' years)	Normalised RSMD	Legend label	FR level (1 in 'x' years)	Normalised RSMD (%)
1Q	0 (DWF)	3.113	3H	0 (DWF)	51,086.06
1H	0 (DWF)	42.896	3H	1	25.577
2Q	0 (DWF)	3.164	3H	2	22.147
2H	0 (DWF)	43.074	3H	5	18.394
3Q	0 (DWF)	618.266	3H	10	16.547
4Q	0 (DWF)	11.326	3H	12	16.088
4H	0 (DWF)	137.92			

7.2.3 Discussion of the obtained hydraulic validation correlation indicator values

From the correlation indicator analyses completed in Section 7.2.2, a number of conclusions can be drawn from averaging the indicator scores for each sewer system model (Table 7.2-4). Table 7.2-4 shows the averages indicator scores when the DWF simulations were included and excluded, as well as before and after the sewer system had been analysed by the assessment framework. An improved correlation indicator score was seen when the DWF simulations were excluded for the Pearson correlation coefficient, Coefficient of determination, Nash-Sutcliffe efficiency and the Index of agreement. In the case of the normalised RSMD, including the DWF simulations provided an improved score. This highlights that there are potential base, dry weather and trade flow profile errors when the models are transferred from SWMM 5 to InfoWorks CS. Improvements were not made to the sewer system models to try and improve the correlation as the project ran out of time.

Table 7.2-4: correlation indicator scores for all of the analyses discussed for when DWF simulations are accounted for or not and before and after the sewer system had been analysed by the assessment framework.

	Including DWF simulations	Excluding DWF simulations	Before analysis by the assessment framework	After analysis by the assessment framework
Pearson correlation coefficient	0.739	0.853	0.655	0.822
Coefficient of determination	0.656	0.767	0.562	0.751
Nash-Sutcliffe efficiency	-62.351	-19.486	-33.719	-90.983
Index of determination	0.622	0.709	0.634	0.610
Normalised RMSD	1,084.42	2.659	2,160.42	8.420

Table 7.2-4 also presents the average correlation indicator scores for the simulations before and after the sewer system model was analysed by the assessment framework. Before the analysis by the assessment framework, the two models in total contained four orifice plates and one VFC. After the analysis by the assessment framework, the two models in total contained four orifice plates and 30 VFCs. Average correlation indicator scores increased when there were more flow controls in the sewer system model for the Pearson correlation coefficient, Coefficient of determination and normalised RMSD. The Nash-Sutcliffe efficiency and Index of agreement scores, however, reduced when comparing the simulations containing the greater number of flow controls.

7.3 Parameter analysis

The assessment framework requires the user to specify a number of input parameters (Section 3.1). These parameters are required:

1) For the hyetograph generator;
2) To constrain the analysis of the sewer system; and
3) Select the costings used in the cost benefit analyses.

Applying different values for the input parameters, especially when the confidence in the value's accuracy is low, could provide a range of outputs from the assessment framework that could then be reviewed to conclude whether more accurate data was required. The aim of the parameter analysis is to quantify which parameters have the greatest impact on the proposed configurations from the assessment framework. The analysis looks at the impact on both the change in the FR level and the change in estimated purchase and installation costs.

The method applied to analyse the impact the parameters have on the outputs was a 'one-factor-at-a-time' (OAT) approach taken from literature (Sweetapple *et al*, 2013). The reasons for selecting this approach were:

1) Limited to only investigating one parameter at a time due to length of time running the assessment framework;
2) Clear identification of which parameter causes what impact in the model outputs; and
3) Structured method for varying the input parameter values based on the value's perceived confidence.

7.3.1 Application of the 'One-factor-at-a-time' approach on the assessment framework

The OAT approach was applied to the sewer system following the procedure outlined by Sweetapple *et al*. (2013). The first step of the approach is to decide the level of uncertainty there is for each of the 10 input parameters selected.

These are presented in Section 7.3.2. Three levels of uncertainty were assigned and an uncertainty range was applied to the input parameter (Table 7.3-1). The uncertainty classes provide the upper and lower bounds for the values to be entered in the analysis. The same uncertainty percentage values were used from Sweetapple *et al*. and the classes were applied to each input parameter based on the author's judgement. The 10 input parameters were selected based on the arguments presented in Section 7.3.2.

The OAT analysis assessed the effect when the extreme values of the input parameters were used for the assessment framework. The base case was developed from user selected input parameters. The OAT analysis then changed the input parameter values to upper and lower bounds one at a time to see the effect on the proposed configurations. For the analysis, 21 combinations of inputs were entered into the assessment framework. One of the combinations was the base case, the remaining 20 input parameter combinations only differed from the base case by one value being entered as the upper or lower bound. Apart from the base case input values, any other input parameter values between the upper and lower bounds were not analysed due to time pressures on the project.

Once the user has input the analysis parameters, the OAT analysis repeats the following steps:

1) Input the first/next set of parameters into the assessment framework.
2) Begin the analysis of the sewer system using the assessment framework.
3) If the analysis constraints of the assessment framework (Section 3.3) are exceeded, move onto Step 7.
4) If the analysis constraints are not exceeded (Section 3.3), allow the assessment framework to continue until 11 flow controls had been positioned in the sewer system†. If the 11th flow control has been positioned, end the assessment framework and move onto Step 6.
5) The assessment framework positions another flow control in the system.

† The analysis was ended after the positioning of the 11th flow control due to the length of the simulations required and the time restrictions on the project.

6) Record the cost benefit analysis from the assessment framework as well as the input parameters used in the analysis of the sewer system,
7) Check if all of the required sewer system analyses have been completed. If so, end the loop to save all of the outputs from the OAT analysis. If not, return back to Step 1 to run the next analysis.

Finally, all of the outputs from the analysis are saved for the user to analyse.

Table 7.3-1: Selected parameter uncertainty classes (Sweetapple et al. 2013).

Class	Description	Uncertainty (%)
1	Accurately known parameters	5
2	Intermediate	20
3	Very poorly known parameters	50

7.3.2 Case study sewer system

The parameter analysis was conducted on was the anonymised stormwater sewer system (Section 5.2.2). The sewer system is the smallest of the case study models considered in this project and, for that reason, was used in the analysis to reduce the computational time. From the 16 input parameters (Section 3.1), only ten parameters were input and varied for the analysis (Table 7.3-2). The remaining parameters that were excluded from the analysis, with reasons for their exclusion, were:

1) **Sewer system model physical dimensions and properties.** Similarly to Sweetapple *et al*'s work (2013), the physical dimensions and properties of the sewer system have been excluded as it is presumed the sewer system model has already been created and verified.
2) Location of the sewer system model. Same reason as point 1.
3) **Desired FR level factor, budget, budget factor & maximum desired capacity full value.** These values do not impact the outputs from the flow control positioning method except to reduce the available solution space.

4) **Minimum outlet diameter of the flow controls.** Values for the minimum flow control outlet diameter are commonly set by industry guidance (e.g. *Sewers for Adoption*, 2012, which states a minimum of 100mm) or individual company policy (e.g. *Thames Water – addendum to sewers for adoption - 7th edition*, 2012, which states a minimum of 150mm).
5) **Manhole cover dimensions.** Minimum dimension is set by *Sewers for adoption* (2012) and same reason as point 1.
6) **Design of orifice plates and VFCs.** The parameters used for the design of both the orifice plates and VFCs have been excluded. The design methods of the flow controls have not been discussed in this project and are not in this section.

The multiplier applied to the rainfall series, Parameter number 6 in Table 7.3-2, was an additional parameter considered in this analysis. The reason for its inclusion was to further investigate whether the rainfall series used in stressing the sewer system to position and design the flow controls had an impact on the outputs generated from the assessment framework. All of the other parameters not presented in this section remain consistent with the method presented in Chapter 3.

7.3.3 Identification of the assessed parameters.

The parameter analysis was conducted for two scenarios: with VFCs and orifice plates set to be positioned and sized; and with only orifice plates set to be positioned and sized. The cost benefit analysis presented in Section 5.3.2 showed that VFCs provided a more beneficial retrofit solution as the solution achieved a FR level with a return period of 1 in 108 years, compared to the orifice plate solution that achieve a greatest achieved FR level with a 1 in 6 year return period. The input parameters from the cost benefit analysis were varied according to Table 7.3-2, resulting in a total of 21 simulations.

Table 7.3-2: Input parameters for the anonymised stormwater sewer system model considered by the OAT approach.

Parameter Number	Parameter	Base case	Uncertainty Class	Upper Bound Value	Lower Bound Value
1	M5-60 (mm)	18	1	18.9	17.1
2	Ratio-R	0.4	1	0.42	0.38
3	Climate Change (%)	30	3	45	15
4	Freeboard (m)	0.2	3	0.3	0.1
5	Discharge Consent (l/s)	13.2	2	15.84	10.56
6	Multiplier applied to the rainfall series	1	1	1.05	0.95
7	Desired FR Level (1 in 'x' years)	110	3	165	55
8	Cost of installing a flow control (£)	3,500	2	4,200	2,800
9	Cost of removing the lid of the manhole chamber (£)	10,000	2	12,000	8,000
10	When to add storage	0.6	3	0.9	0.3

In the parameter analysis, the base case analysis must first be completed for each scenario to be able to show the impact of changing the input parameters. The cost benefit analysis from the base case analysis is displayed in the same manner as the results in Chapter 5. The outputs from the parameter analysis are displayed as horizontal bar charts. For each scenario, the difference in the greatest achieved FR value and difference in cost for that solution is presented.

Parameter analysis when positioning VFCs and orifice plates

Analysis of the base case with the assessment framework increased the anonymised stormwater sewer systems' FR level from a 1 in 1 year return period to a 1 in 22 year return period (Figure 7.3-1). This retrofit solution with the greatest achieved FR level required the installation of three VFCs and had an estimated cost of £24,500. The flow control positioning method required six iterations to find the solution. After the solution with the greatest achieved FR level was found, a VFC was redesigned causing a reduction in the FR level to a 1 in 1 year return period. No further benefit was achieved in the analysis before the parameter analysis ended the simulation. Figure 7.3-1 shows the assessment framework caused oscillations in the costs of the proposed solutions. This occurs when a new flow control is placed and then reduced in size to attenuate a greater flow volume.

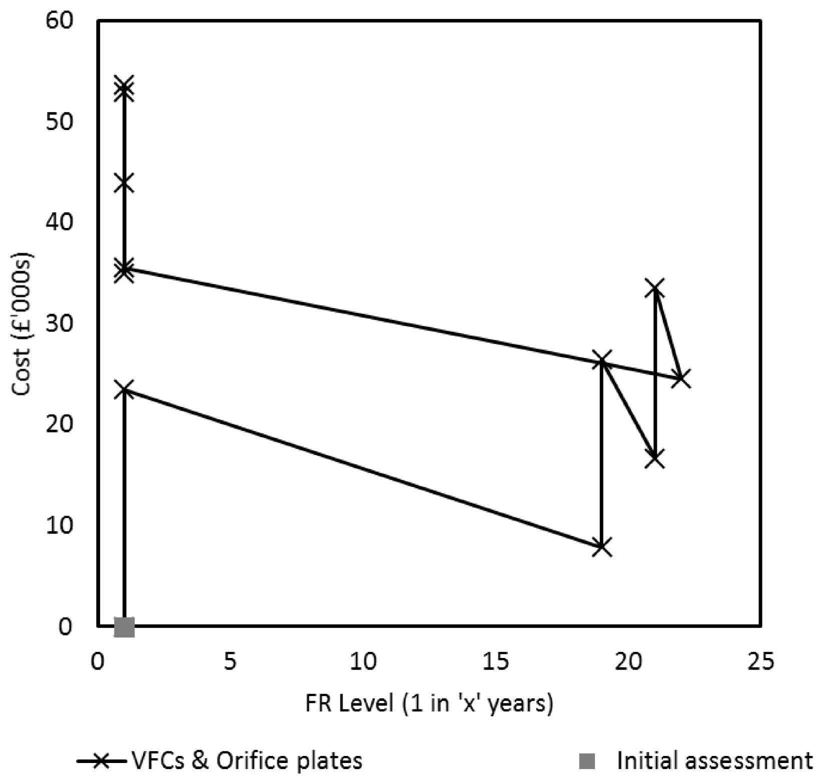
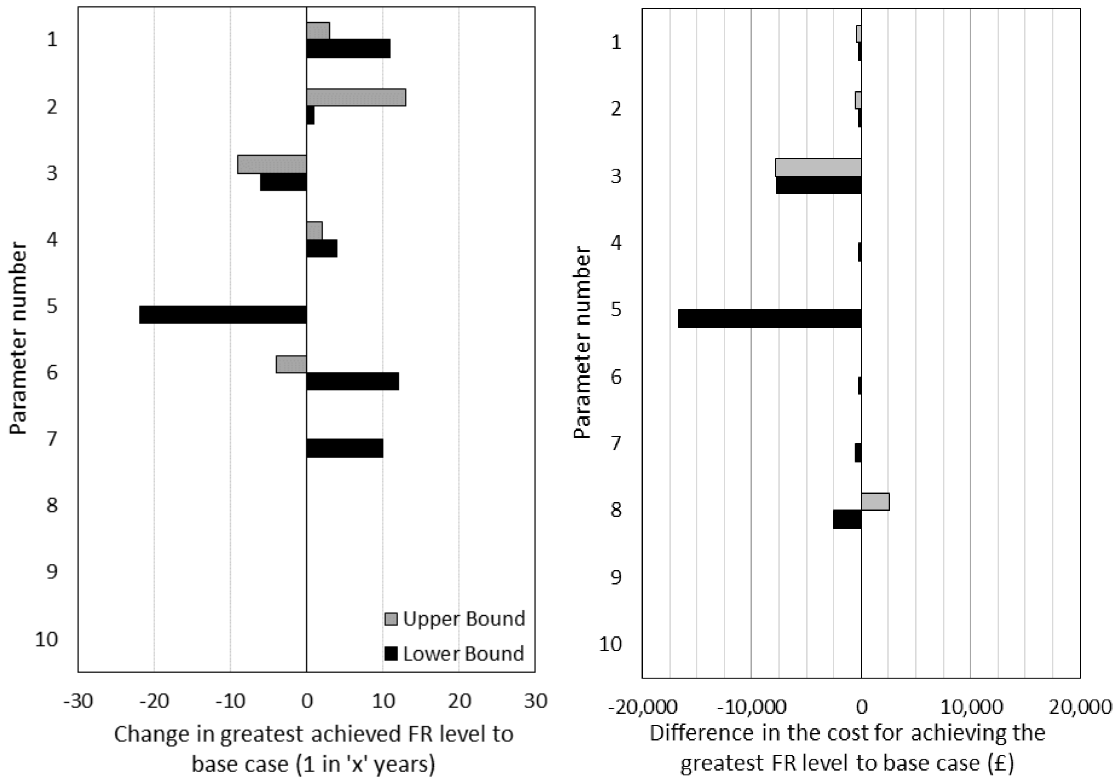


Figure 7.3-1: Base case cost benefit analysis when both VFCs and orifice plates could be positioned in the anonymised stormwater sewer system.

The cost benefit analysis when VFCs and orifice plates were set to be positioned and sized is present in Figure 7.3-2. The parameter analysis shows the change in the greatest achieved FR level relative to the base case and difference in cost of achieving the greatest FR level relative to the base case (Figure 7.3-2a and Figure 7.3-2b respectively). In all of the parameter analysis comparison plots in this section, the solid grey bars show the change in the FR level when the upper bound values were entered, and the solid black bars show the change in the FR level when the lower bound values were entered.



Key			
	1: M5-60 (mm)	2: Ratio-R	3: Climate change (%)
	4: Freeboard (m)	5: Discharge consent (l/s)	6: Rainfall series multiplier
	7: Desired FR level (1 in ‘x’ years)	8 Cost of installing a flow controls (£)	9: Cost of removing a manhole chamber lid (£)
	10: When to add storage		

a) *Plot showing change in the greatest achieved FR level compared to the base case.*

b) *Plot showing change in estimated cost for the greatest achieved FR level compared to the base case.*

Figure 7.3-2: Parameter analysis comparison plots when both VFCs and orifice plates were set to be positioned in the anonymised stormwater sewer system where a) shows the difference in the greatest achieved FR level and b) shows the difference in estimated cost.

Figure 7.3-2a shows that variations in the input parameters does have an impact on the configurations from the assessment framework in seven of the ten parameters. No differences in the greatest achieved FR level were observed when the cost of installing a flow control, cost of installing a flow control by removing the manhole chamber lid and when to add storage values were varied (parameter numbers 8, 9 and 10). With regard to the changes in the greatest achieved FR level, the greatest achieved increase in the achieved FR level was observed when the Ratio-R value was increased to its upper bound (parameter number 2). In the case of the Ratio-R value, increasing the input Ratio-R value by 5% caused the largest change in the greatest achieved FR level; and increase in the FR level from a 1 in 22 year return period to a 1 in 35 year return period.

Varying the value of the M5-60 and freeboard parameters (parameter numbers 1 and 4) also caused an increase in the greatest achieved FR level. In the case of the M5-60 value, decreasing the input M5-60 value by 5% caused the second largest change in the greatest achieved FR level; this was an increase in the FR level from a 1 in 22 year return period to a 1 in 33 year return period. In the case of the freeboard value, decreasing the input freeboard value by 50% caused the third largest change in the greatest achieved FR level; an increase in the FR level from a 1 in 22 year return period to a 1 in 26 year return period. It should also be noted that varying the M5-60, Ratio-R, climate change and freeboard values to the upper or lower bound caused either both an increase or decrease in the greatest achieved FR level.

With regard to the change in the cost for achieving the greatest flood FR level to the base case, only one parameter change resulted in an increase in the cost from the base case value of £24,500 (Figure 7.3-2b). The increase in the estimated cost was only observed when the cost of installing a flow control into a manhole chamber was increased. The increase in the estimated cost was £2,500. Changing the climate change and discharge consent input values caused the largest reductions in the estimated cost of the solution with the greatest achieved FR level were seen. This was due to the solutions not achieving as high a FR level as the base case and fewer flow controls were positioned. Varying the remaining input parameters caused little or no impact on the cost of achieving the greatest FR level (less than £565), even though, for the greatest achieved FR level was increased in five of the analyses.

Parameter analysis when positioning orifice plates

In this section, the parameter analysis was completed where only orifice plates were set to be positioned. Firstly, the base case analysis was completed (Figure 7.3-3). The number of iterations when only orifice plates were positioned was increased from 11 to 26 as, initially, no significant change in the FR level and cost outputs were observed over the whole analysis when only 11 iterations of the assessment framework was completed. At the end of this analysis it was found that this step was irrelevant as all of the changes to the FR level in each simulation happened in the first two iterations of the flow control positioning method. The base case analysis shows that the anonymised stormwater sewer system's FR level was not able to be increased from a 1 in 1 year return period. Orifice plates were positioned in all seven of the possible manhole chambers that could have been selected. The greatest estimated cost was £73,750.

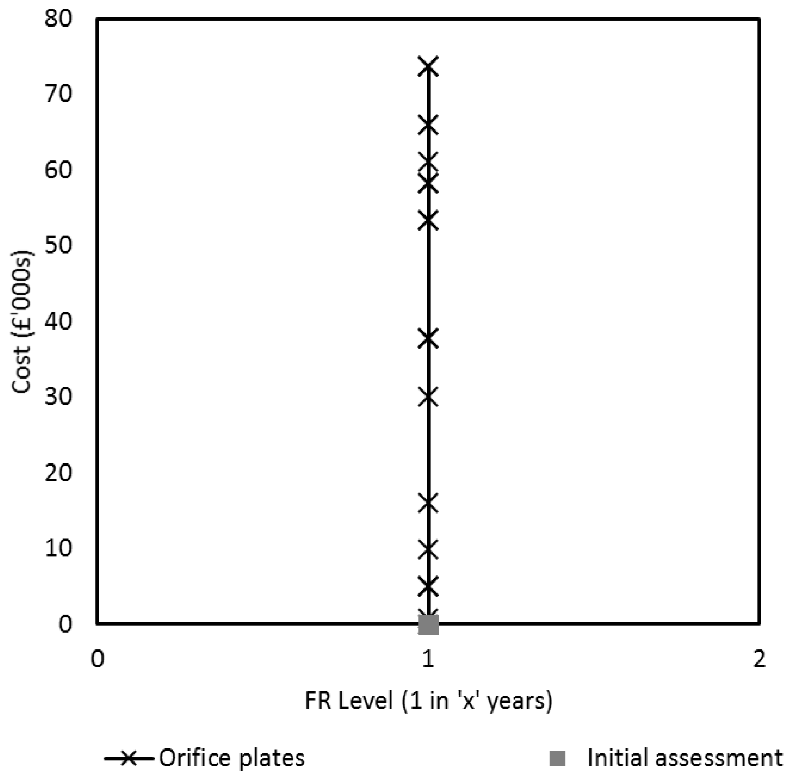


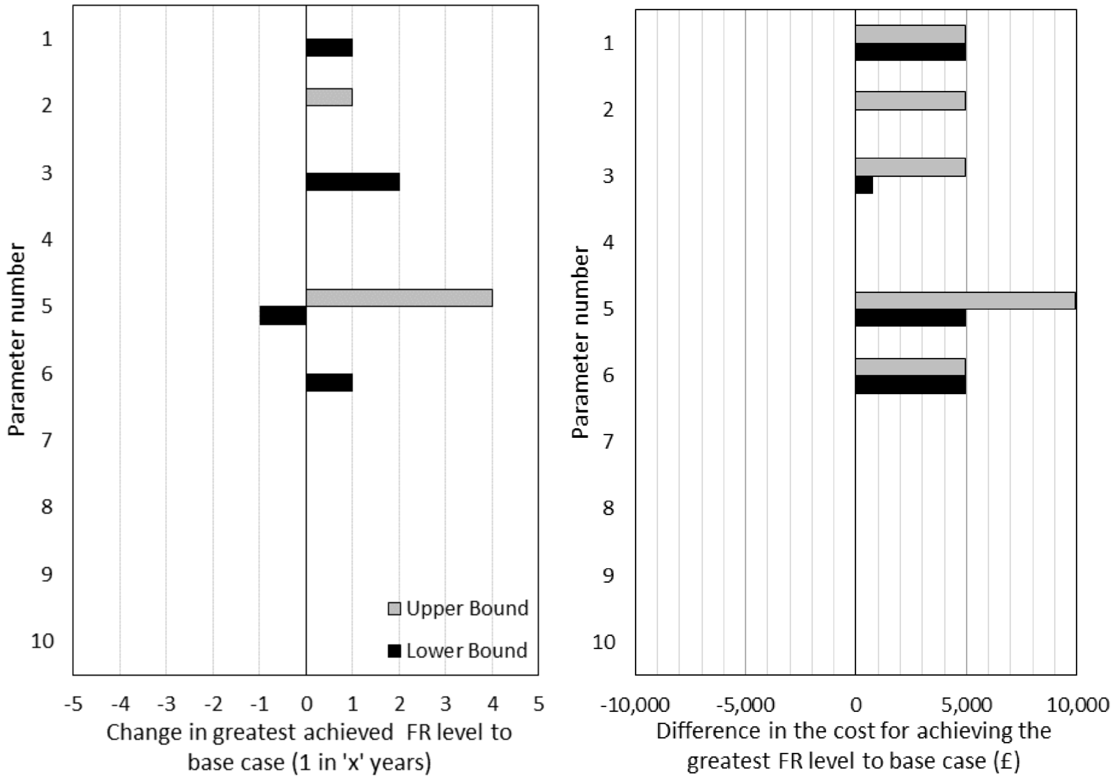
Figure 7.3-3: Base case cost benefit analysis when only orifice plates were set to be positioned in the anonymised stormwater sewer system.

The parameter analysis, which followed on from the assessment framework configurations above (Figure 7.3-3), is presented in Figure 7.3-4. Figure 7.3-4a shows the change in the achieved greatest achieved FR level compared to the base case simulation. Figure 7.3-4b shows the difference in estimated cost for the proposed solutions with the greatest achieved FR levels. As with the analysis where both VFCs and orifice plates were set to be positioned, the grey series represents when the upper bounds were input and the black series represents when the lower bounds were input. With regard to the changes in the greatest achieved FR level, the greatest achieved increase in the achieved FR level was observed when the discharge consent was increased to its upper bound (parameter number 5). Varying the discharge consent to its lower bound also caused the only decrease in the change in the achieved FR level compared to when all the other input parameters were varied.

An increase in the FR level was observed when the upper bound value of the Ratio-R was entered and the lower bound values of the M5-60, climate change and the multiplier applied to the rainfall series values. No observed change in the greatest achieved FR level was observed when:

1) The freeboard;
2) The desired FR level;
3) The costs of installing a flow control;
4) The cost of installing a flow control by removing the manhole chamber lid; and
5) When to add storage values were varied (parameter numbers 4, 7, 8, 9 and 10 respectively).

Figure 7.3-4b shows the change in the estimated cost of implementing the solution with the greatest achieved FR level compared to the base case. For all of the changes in the FR presented in Figure 7.3-4a, a change in the estimated cost is also seen in Figure 7.3-4b. Additional increases in the estimated costs are also seen when the: M5-60 upper bound value; climate change upper bound value; and multiplier applied to the rainfall series upper bound was input.



Key

1:	M5-60 (mm)	2:	Ratio-R	3:	Climate change (%)
4:	Freeboard (m)	5:	Discharge consent (l/s)	6:	Rainfall series multiplier
7:	Desired FR level (1 in 'x' years)	8	Cost of installing a flow controls (£)	9:	Cost of removing a manhole chamber lid (£)
10:	When to add storage				

a) *Plot showing change in the greatest achieved FR level compared to the base case.*

b) *Plot showing change in the estimated cost with the greatest achieved FR level compared to the base case.*

Figure 7.3-4: Parameter analysis comparisons when only orifice plates were set to be positioned in the anonymised stormwater sewer system where a) shows the difference in the greatest achieved FR level and b) shows the difference in estimated cost.

It was observed that a number of the simulations completed, where only orifice plates were positioned, did not show any differences to the base case scenario as the analysis progressed. The majority of the solutions with the cheapest greatest FR level were found in the initial iteration of the assessment framework. This was attributed to the designed orifice plates not being able to attenuate the required flows, rather than a change caused by the variation in the parameter value. If more time and computational power was available, the analysis should be run of a larger sewer system until the assessment framework completes its analysis for more comprehensive outcomes.

7.3.4 Discussion of how these parameters effect and could improve the operation of the tool

The results from the parameter analysis are presented for comparison (Table 7.3-4). The analysis has shown that an over-predicted increase in the achieved FR level of the sewer system could be achieved by varying the inputs values of:

1) The M5-60 value (parameter number 1);
2) The Ratio-R value (parameter number 2);
3) The freeboard value (parameter number 4);
4) The multiplier applied to the rainfall series (parameter number 6); and
5) The desired FR level value.

This means that an error in selecting the parameter values for either of the parameters listed above, would mean the solution proposed does not provide the desired reduction in flood risk when actually installed into the real-life sewer system. The results have also shown that varying the climate change value and discharge consent value (parameter numbers 3 and 5) may potentially underestimate solutions. In both of these cases, decreases in the greatest achieved FR levels were observed. Selecting these incorrect parameter values could result in conservative drainage solutions being installed and the user not achieving the most cost effective solution. Table 7.3-4 also shows that parameter numbers 1, 2 3 and 5 (the M5-60, Ratio-R, climate change and discharge consent values) had the greatest effect on the solutions from the assessment framework.

Table 7.3-4: Summary of parameter analysis showing changes in the greatest achieved FR level and cost of the solution.

Input parameter	VFCs and orifice plates				Orifice plates only			
	Upper bound		Lower bound		Upper bound		Lower bound	
	Change in FR level (1 in 'x' years)	Change in cost (£)	Change in FR level (1 in 'x' years)	Change in cost (£)	Change in FR level (1 in 'x' years)	Change in cost (£)	Change in FR level (1 in 'x' years)	Change in cost (£)
M5-60	+3	-455	+11	-236	0	+4,966	+1	+4,966
Ratio-R	+13	-563	+1	-236	+1	+4,966	0	0
Climate change	-9	-7,871	-6	-7,691	0	+4,966	+2	+766
Freeboard	+2	0	+4	-236	0	0	0	0
Discharge consent	0	0	-21.9	-16,681	+4	+9,931	-0.9	+4,966
Rainfall series multiplier	-4	0	+12	-236	0	+4,966	+1	+4,966
Desired FR level	0	0	+10	-563	0	0	0	0
Cost of installing a flow control	0	+2,520	0	-2,520	0	0	0	0
Cost of removing the manhole chamber lid	0	0	0	0	0	0	0	0
When to add storage	0	0	0	0	0	0	0	0

7.4 Conclusion

This chapter has discussed the validation and parameter analysis of the flow control positioning method and subsequent assessment framework (Sections 7.2 and 7.3). The results have shown that the InfoWorks CS model will over-predict the depth of water in the sewer system compared to the SWMM 5 model. It has also shown there is very little correlation between the two models when there is little or no rainfall applied in the simulation.

A quantitative comparison of the flow-rate outputs and flow depth outputs was also completed (Table 7.2-4). The comparison showed that a greater correlation between the InfoWorks CS and SWMM 5 model outputs was achieved when the DWF scenarios were not considered and after the framework analysis had been completed. The Pearson correlation coefficient, coefficient of determination and index of determination showed a moderate to strong correlation with values between 0.61 and 0.853. The Nash Sutcliffe efficiency and normalised RMSD values (worst case values of -91 and 216,042 respectively), however, showed that the models require further adaptation to gain greater correlation.

The parameter analysis using the OAT method showed, that out of the ten parameters, varying the M5-60, Ratio-R, climate change and discharge consent and rainfall series multiplier values within the assessment framework had the greatest impact on the framework's outcomes. The greatest increase in the FR level was observed when the upper bound of the Ratio-R value was an input into the analysis (+13 years onto the return period). The greatest decrease in the FR level was observed when the lower bound of the discharge consent value was input into the analysis (-21.9 years off of the return period.

Chapter 8

Conclusion

8.1 Introduction

As initially presented in the Introduction of this thesis, the primary aim of the project was to establish a protocol for increasing the flood resistance (FR) level of catchments where typical runoff reducing measures, such as sustainable drainage systems, are impractical or applying powered in-sewer real-time control strategies are unfeasible. The protocol will enable decision makers to increase the FR level of the catchment and reduce detrimental effects on the environment due to the accumulation of pollutants or increased combined sewer overflow spills. The aim will be achieved by developing an assessment framework decision support tool that will advise decision makers on retrofit solutions that will improve the behaviour of their sewer systems. The decision makers can then use a cost against FR level increase relationship output to support their decisions.

The objectives of the research are also listed. They have also been cross-referenced to the chapters in which they were discussed. The objectives of the research were to:

1) Conduct a literature review of current knowledge regarding the use of flow attenuation devices and current retrofit strategies of sewer systems (Chapter 2).
2) Develop an algorithm which can be used to analyse potential retrofitting opportunities and produce outputs for a decision maker (Chapter 3).
3) Automate the developed algorithm to then demonstrate the potential benefits of positioning flow controls into the sewer system (Chapter 4).

4) Use new case study data to demonstrate the application of the method (Chapter 5 & 6).
5) Compare the outputs from the algorithm to other flood alleviation methods to determine the benefits the can be achieved by implementing flow attenuation devices into the sewer system (Chapter 6).

This chapter concludes the main findings from this research as well as demonstrate that the above aim and objectives have been met. The chapter is separated into the main elements of the thesis. Recommendations of improvements that could be made to the flow control positioning method and associated assessment framework are also made in hindsight of the completed analyses. Further work that can be prepared from this research is presented at the end of this chapter.

8.2 Literature review

The literature review for this project covered the relevant literature regarding the current methods used to design sewer systems. The conclusions drawn from the literature review were that there was a gap in knowledge regarding:

1) A method incorporating the concept of flood vulnerability in the decision making process; and
2) A methodology designing a VFC for installation into an existing sewer system with the aim of reducing flood risk.

The body of work within this thesis, therefore, aimed to make the following contribution to knowledge:

1) A new method for increasing the flood resistance level of sewer systems by increasing the total capacity utilised during rainfall events by positioning flow controls in strategic locations;
2) The outputs of the method include quantified changes in flood resistance level of the sewer system and the estimated cost of installing the solution,

therefore, allowing users of the method to select appropriate designs based on their required design target and financial constraints; and

3) Decision based retrofit designs based on the available volume within the sewer system and assigned flood vulnerability scores.

8.3 Description of the method

The method discussed in Chapter 3 is used to strategically position and design flow controls into an existing sewer system model with the aim of improving flood resistance levels.

The contributions to knowledge made by the development of the flow control positioning method are:

1) The method of designing the appropriate VFC for the sewer system by equating its average flow-rate with that of an equivalent orifice plate's (Newton *et al.*, 2013b);
2) Incorporating subcatchment flood vulnerability scores into the selection process of which manhole chamber to install the flow control; and
3) Application of a simplified CIH method and applying the CIHs as the rainfall inputs when simulating the sewer system, thereby, reducing the required number of simulations per return period (Newton *et al.*, 2013a).

8.4 Development of the assessment framework

The flow control positioning method was developed into an assessment framework to demonstrate the application of the method on a sewer system model. Conclusions from the development of the assessment framework were that, if the framework were to be used for commercial reasons, the following issues need to be addressed:

1) Slow and restricted processor usage in Visual Basic for Applications;
2) System crashing during Microsoft Office updates;

3) Restricted use of Microsoft Office Suite when running the assessment framework;
4) Spreadsheets with Visual Basic for Applications can have issues when opening and running in different versions than the version it was constructed in; and
5) Method only operates with the SWMM version 5.0.022 dynamic-link library file and not the newest SWMM 5 version.

8.5 Application of the assessment framework

The application of the assessment framework on the four analysed sewer systems have demonstrated that an increase in a sewer system's flood resistance level can be achieved through the strategic positioning of flow controls. The varied size and structure of the sewer systems has demonstrated that the framework is applicable to a range of sewer systems. The greatest increase in the FR level of a sewer system was seen in the analysis of the anonymised stormwater sewer system in which the FR level was increased from a 1 in 3 year return period to a 1 in 108 year return period. Out of the 20 analyses completed by the framework, only three analyses achieved to exceed the desired FR level set by the user, which were:

1) Analysis of the Artificial Network where only orifice plates, with a $d_{o,min}$ set to 100 mm, were selected to be installed. The analysis had a target FR level of a 1 in 30 year return period, but achieved a 1 in 49 year return period;
2) Analysis of the Artificial Network where only orifice plates, with a $d_{o,min}$ set to 200 mm, were selected to be installed. The analysis had a target FR level of a 1 in 30 year return period, but achieved a 1 in 49 year return period; and
3) Analysis of the Langley combined sewer system where both VFCs and orifice plates, with a $d_{o,min}$ set to 100 mm, were selected to be installed. The analysis had a target FR level of a 1 in 30 year return period, but achieved a 1 in 71 year return period.

8.6 Application of subcatchment vulnerability scores and comparison to other flood alleviation solutions

With regard to the application of the flood vulnerability scores within the application framework, it was found that their inclusion did not further increase the sewer system's flood resistance level. In the analyses run with the flood vulnerability scores applied, cheaper configurations of flow controls at the lower value flood resistance levels were found.

Comparing the proposed solutions from the assessment framework to alternative flood alleviation methods, it was found that the strategic positioning of VFCs was, at worst, the third cheapest solution. This has shown that the positioning of flow controls is a competitive and viable solution to increasing FR levels.

8.7 Validation and parameter analysis

In the validation and parameter analysis of the assessment framework it was found that the comparison of the InfoWorks CS and SWMM 5 sewer systems models produced variable results depending on the volume of rainfall applied in the simulation (Table 7.2-4). When no rainfall was applied to the simulation of the sewer system models, the dry weather flow simulations found a poorer correlation between the models (Pearson correlation coefficient of 0.739, Coefficient of determination of 0.656 and Index of determination of 0.622). When volumes of rainfall that potentially caused flooding within the sewer system model are simulated, and greater degree of correlation is observed (Pearson correlation coefficient of 0.853, Coefficient of determination of 0.767 and Index of determination of 0.709). It was also found that including VFCs in the model increased the correlation between the modelling packages.

The parameter analysis of the assessment framework analysed what effect would be observed by changing the input parameters of an analysis of the assessment framework. Of the ten variable parameters assessed, it was found that the parameters that had the greatest effect on the assessment framework proposed solutions were the M5-60, Ratio-R, climate change, discharge consent and rainfall series multiplier values. This analysis also showed that users need to understand the values they put in as inaccurate values could cause both over and under estimated drainage designs.

8.8 Proposed further work

The conclusions of the research found that, from the case studies presented, benefit could be achieved in all of the sewer system models analysed, Chapters 5 & 6. There is, however, still scope to continue and expand this research into new areas. This section contains a list of ideas and proposals for future further work building on the outputs in this thesis. The new research ideas and proposals have been summarised and presented in a mind map, Figure 8.1-1. The ideas have been grouped into their similar primary research areas (water quantity, water quality, flood resilience, and integration). In the figure, the specific ideas are colour coded to indicate expected timescales of the project and whether they are seen as short, medium, or long term projects in the author's opinion (green, yellow and red respectively). The ideas are also labelled with reference to the sub-section they are discussed in the paragraph (for example, '(8.8.1)' refers to sub section 8.8.1). A brief description of each idea is given with bullet points outlining the idea's novelty. The proposed ideas are discussed in numerical order as shown in Figure 8.1-1.

8.8.1 Water quantity

Five future project ideas have been proposed from this research that focus primarily on water quantity management, Section 8.8.1.1 to 8.8.1.5. The projects investigate the positioning of additional flow control ranges (Section 8.8.1.1 and Section 8.8.1.3), implementing multiple discharge limits (Section 8.8.1.2) and increasing the sewer system's storage capacity (Section 8.8.1.4 and Section

8.8.1.5).

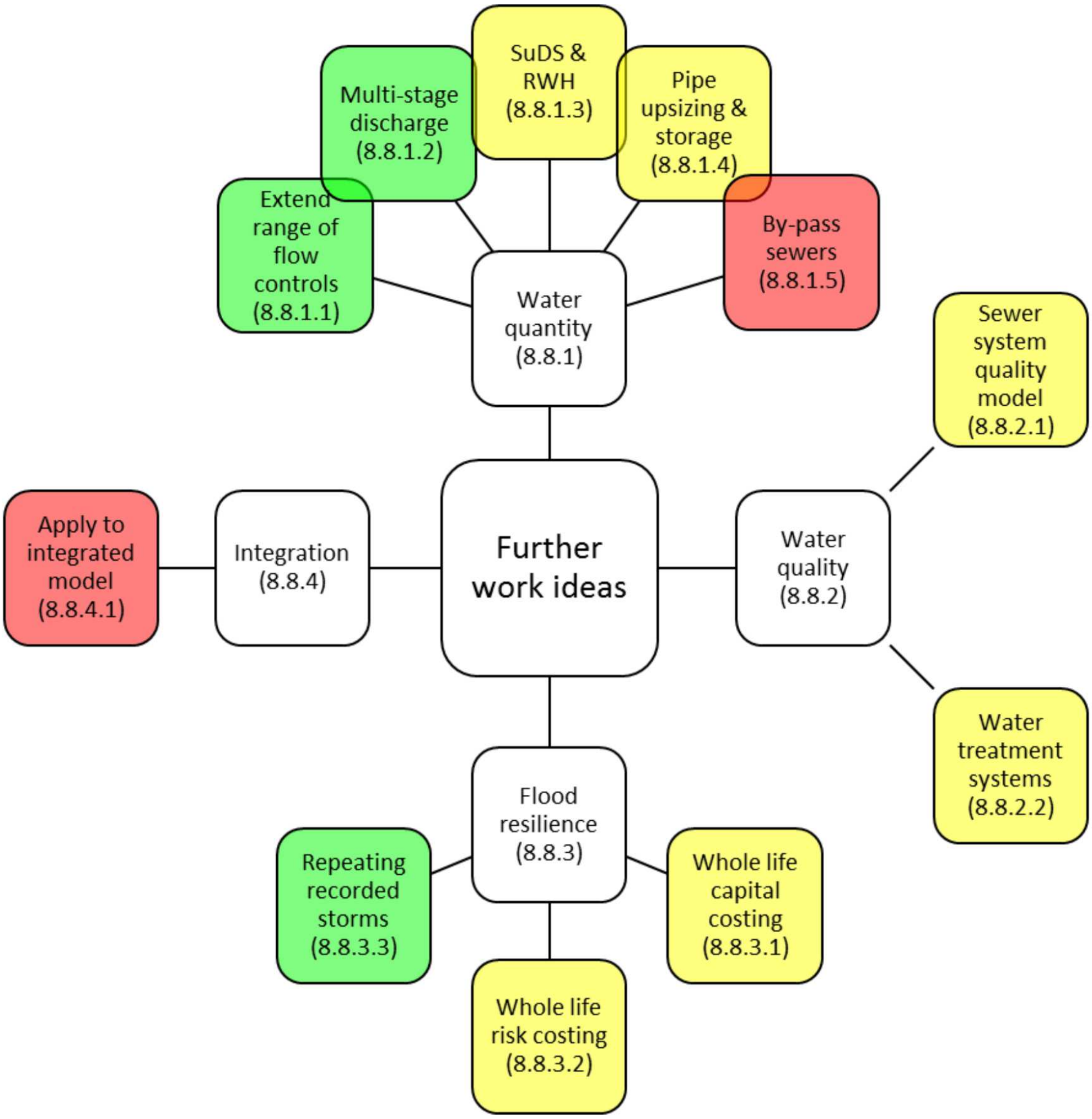


Figure 8.1-1: Mind map of proposed future further work ideas where the green, yellow and red colours indicate expected short, medium and long term project timescales.

8.8.1.1 Extend the range of flow controls positioned and designed

Within the current flow control positioning method only two types of flow controls are positioned, orifice plates and vortex flow controls, Chapter 3. The range of flow controls considered by the flow control positioning method could be extended to incorporate alternative solutions. Examples of alternative flow controls are: electro-mechanical penstocks, float activated penstocks, pumps, real-time controls and weirs. The challenge of this work, when applying it to the flow control positioning method, would be to develop a decision framework to select the most cost beneficial and hydraulically beneficial flow control for that position. Benefits that could be achieved from this project would be:

1) Greater interest from industry as different water companies prefer different flow controls;
2) Potentially cheaper sewer system solutions; and
3) More beneficial hydraulic behaviour of the sewer system.

The novelty of the idea is:

1) Decision framework for selecting the most appropriate flow control to be positioned and designed into the sewer system;
2) A method for selecting the flow control's position and investigating whether the position changes depending of the type of flow control; and
3) A method for selecting the flow control's hydraulic behaviour based on outputs from the hydraulic modelling of the sewer system.

8.8.1.2 Multistage discharge at the outlet

The total discharge flow-rate of the sewer system is a design constraint within the flow control positioning method. At present, only one value is entered for the constraint regardless of the flood resistance level achieved. Within the UK, and since the beginning of this project, there is now draft legislation in which surface water drainage designers must meet different discharge consents for the different rainfall return periods experienced (Kellagher, 2013). The aim behind this draft legislation is to reduce surface run-off back to previous greenfield run-off flow-rates before the catchment was developed. By enforcing staged discharge consents, additional run-off must be attenuated and managed at source rather than simply conveying it further downstream and increasing flood risk elsewhere. This, therefore, reduces the requirements for large scale sewer system enlargements in the downstream sections of the sewer system. Benefits that could be achieved from this project would be:

1) Conformation to upcoming legislation;
2) Reduced need to increase geometries of downstream assets through source control; and
3) Opportunities for treatment and removal of attenuated volumes in the upstream sections of the sewer system.

The novelty of the idea is:

1) Selection of the multiple design targets for the complex flow controls and the sewer system;
2) Method for designing and positioning of complex flow controls throughout the sewer system; and
3) Method for assessing the sewer system's hydraulic behaviour and quantifying achieved benefits of conforming to the multistage discharge consents.

8.8.1.3 Implementing aboveground sustainable drainage systems (SuDS) and rainwater harvesting (RWH) technologies

There are wide ranging benefits to installing and retrofitting SuDS and RWH technologies in catchments (Ashley *et al*., 2011, Digman *et al.*, 2012, & *Woods*-Ballard *et al*., 2007). The flow control positioning method only considers attenuating potential flood volumes within the sewer system, Chapter 3. An adaptation and extension of the flow control positioning method would be to position above ground SuDS and RWH features in the sewer system model subcatchments along with the flow controls. The positioning of the SuDS and RWH features could either be completed by calculating a potential storage volume in the subcatchment, or positioned when the sewer system becomes surcharged. There has already been a significant contribution of knowledge regarding SuDS positioning (Chow *et al*., 2013, Stovin *et al.*, 2013, & Warwick *et al*, 2013). However, applying the process applied in the flow control positioning method and combining both above and belowground solutions (flow controls, SuDS and RWH) may achieve a greater number of benefits, both amenity and hydraulic. The benefits that could be achieved from this project would be:

1) Combination of solutions designed in one process;
2) Improved hydraulic behaviour of the sewer system and catchment;
3) Reduced inflow into the sewer system;
4) Wider amenity benefits from the installation of SuDS/RWH features; and
5) Treatment and removal of solid particles from surface water runoff before entering the sewer system.

The novelty of the idea is:

1) Combination of solutions being designed into the sewer system through one method;
2) A flow control, SuDS and RWH selection framework; and
3) A method for assessing the combined benefits to the catchment.

8.8.1.4 Pipe upsizing to increase system storage capacity

When the flow control positioning method can no longer install flow controls due to a lack of sewer system capacity, additional storage volumes are installed in the sewer system, Chapter 3. The additional storage volumes are input into the sewer system model by increasing the diameter of the existing manhole chambers within the model. With the increasing developments in trenchless technologies, an alternative solution could be increasing the diameter of existing pipes to provide the additional storage required. Benefits that could be achieved from this project would be:

1) Increase in the hydraulic capacity of the sewer system and, therefore, increase in the flood resistance level of the sewer system; and
2) Solution requiring minimal disturbance of the urban infrastructure and traffic.

The novelty of the idea is:

1) Combination of retrofit design solutions;
2) Selection framework of where to place additional storage; and
3) Selection framework whether to place additional storage.

8.8.1.5 By-pass sewer placement to transfer potential flood volumes

By-pass sewers can be used to reduce the flood risk on downstream sewer system sections by transferring potential flood volumes to other less stressed sections of sewer systems. By-pass sewers are new constructed lengths of sewers and can be an unfeasible solution to reduce flood risk compared to positioning flow controls (Andoh, 1994). It may be necessary, however, to install by-pass sewers, or similar additional storage volume solutions, if there are no available spare storage capacities within the sewer system. The positioning of by-pass sewers does depend on other existing belowground infrastructure (electrical, gas, transport and water networks), as well as geology, and the available space within the soil to construct the by-pass sewer. Benefits that could be achieved from this project would be:

1) Reduce flood risk through the automated positioning and design of integrated solutions; and
2) Increase in the hydraulic capacity of the sewer system and, therefore, increase in the flood resistance level of the sewer system.

The novelty of the idea is:

1) Combination of retrofit design solutions;
2) Selection framework of where to position by-pass sewer in the system; and
3) Decision framework to quantify benefits and costs of where the by-pass sewer has been positioned.

8.8.2 Water quality

Implementing water quality modelling would enable the method users to take account of additional considerations regarding: receiving water quality; water quality fed to treatment works; sediment deposition in sewer system; and other water quality related concerns. Two further project ideas have been proposed that look at implementing a water quality model and positioning sewer treatment technologies respectively, Section 8.8.2.1 and Section 8.8.2.2.

8.8.2.1 Sewer system quality model

At present, the flow control positioning method simulates and proposes retrofit designs for the sewer system based on water quantity. SWMM 5 also contains a water quality model that could be used to consider other design targets and constraints. An example of an alternative design target would be to allow only a certain range of predicted water qualities to spill into a water course. Flow controls could be positioned to attenuate and dilute the concentration of contaminants in the water to an acceptable level. The benefits that could be achieved from this project would be:

1) Additional method of assessment and re-design of sewer systems based on water quality;
2) An automated method for retrofit design of the sewer system; and
3) Enables water companies to meet bathing water targets.

The novelty of the idea is:

1) Combination of targets being used to design the sewer system;
2) Novel design framework for the positioning of flow controls; and
3) Decision framework assessing the predicted benefit to the sewer system and wider catchment.

8.8.2.2 Implement in sewer treatment train systems

Following on from the inclusion of the sewer system water quality model discussed in Section 8.8.2.1, in-sewer treatment systems and technologies could be positioned in the sewer system to meet a user’s defined water quality target. The positioning of hydrodynamic separators and other treatment technologies within the sewer system would enable in-pipe treatment of the collected water.

This would, therefore, reduce the amount of pollution leaving the sewer system during spill events and potentially impacting natural habitats and human health. This type of application would be most appropriate for a separated storm-water sewer system. The positioning of the treatment technologies could be completed in a number of ways knowing the treatment efficiency of the technologies and the selected water quality targets. This project could also be combined with the positioning of SuDS and RWH technologies, Section 8.8.1.3. Modelling water run-off quality into the sewer system, combined with dry weather flows, would also enable the user to predict the quality of the water entering the sewerage treatment works and predict sections of the sewer system with the worst water quality. Benefits that could be achieved from this project would be:

1) Reduced pollution to natural habitats and effecting human health; and
2) At source treatment of collected stormwater reducing potential blockage risk of the sewer system.

The novelty of the idea is:

1) First storm train positioning methodology;
2) Design framework for the selection and positioning of the treatment technologies; and
3) Combination of storm flow attenuation and treatment.

8.8.3 Flood resilience

The flow control positioning method assesses a sewer system model by quantifying whether the sewer system ‘floods or does not flood?’ or ‘over-discharges or does not over-discharge?’. These are both binary questions and do not assess what happens if flooding or over-discharge occurs. This type of assessment of a sewer system does not account for risk, consequence or vulnerability of the infrastructure surrounding the sewer system and, therefore, may lead to excessive infrastructure designs and costs to reduce the risk of flooding. The three proposed projects concerned with flood resilience aim to incorporate whole life analysis of cost, risk and resilience. Incorporating resilience into the decision making process aims for only essential drainage infrastructure be built with the aim of defending critical infrastructure and human health from the impact of flooding.

8.8.3.1 Whole life cost analysis of designs

One of the three parameters of the flow control positioning method is the total estimated cost to install the proposed design solution. The estimated costs include: the cost of the flow controls, the costs to install the flow controls, the cost to include storage volumes and an estimated consultancy fee. This estimated cost only considers the costs of implementing the design. An extension of the flow control positioning method could be to consider the whole life costs of the design, for example: maintenance; inspection; replacement; recycling; cleaning unpreventable spill volumes; etc. This approach could be used to enable asset managers to compare the long-term effects of installing the proposed design into the sewer system. Benefits that could be achieved from this project would be:

1) Proposed solutions that also consider whole life costs;
2) Solutions that account for remediation costs when design fails; and
3) Allow decision makers and asset managers to plan for future expenditure.

The novelty of the idea is:

1) Assessment of flow control positioning solutions whole life costs; and.
2) Quantification of the whole life costs of flow controls, their maintenance, their inspection and costs of cleaning CSO spills.

8.8.3.2 Whole life risk analysis of designs

Decisions regarding urban water management are now being made based on the risk and consequence of an unwanted event happening, rather than solely prevention. An example would be to design sacrificial basins in the catchment to prevent property flooding. In this case with the sacrificial basin, even though the sewer system has flooded, the consequence of the flooding is negligible to critical infrastructure and human health. The flow control positioning method already considers the estimated cost of a proposed solution so that flooding or over-discharge does not occur. An extension of the flow control positioning method could be to design retrofit solutions so that a monetised estimated consequence of flooding or over-discharge was not exceeded. This could be achieved by assigning consequence of flooding depth/damage cost relationships to the sewer system model subcatchments in accordance with their flood vulnerability scores. Benefits that could be achieved from this project would be:

1) Increased cost/beneficial solutions considering cost of installation and consequence of flooding.

The novelty of the idea is:

1) Development of generic flood depth damage curves depending on assigned flood vulnerability scores;
2) Including a whole-life risk analysis metric would add an additional design constraint for consideration in the flow control positioning method; and
3) Decision framework considering consequence of flooding rather than flood prevention.

8.8.3.3 Recorded storms to be used for the design

The use of design storms to design sewer systems have been questioned regarding their suitability, especially when considering future predicted weather patterns. Design storms, like the FEH method used in the UK, are not representative of observed rainfall events. New research suggests using long term series of rainfall data delivers more resilient sewer system designs. Part of the issue with design storms is accurately representing antecedent conditions of the catchment. Using a long series of recorded rainfall data to design sewer systems allows the design to consider repeat storms that, therefore, reduces the importance for accurately estimating antecedent conditions. The benefits that could be achieved from this project would be:

1) More resilient sewer system designs as the designs are based on recorded rainfall; and
2) Designs would be easier to communicate to as the sewer system designs can be demonstrated against recorded rainfall.

The novelty of the idea is:

1) Developing a scoring method to quantify the benefit of proposed retrofit sewer system solutions with respect to the rainfall time-series used when simulating the behaviour of the sewer system; and
2) Comparison of the retrofit sewer system solutions when either design storms or recorded rainfall are used in the simulations.

8.8.4 Integration of the method with other urban water systems

Section 8.8.4 of this chapter presents one further project idea to increase the flow control method's integration with other urban water systems. As discussed in the literature review, Chapter 2, integrated modelling has been a large area of interest as it considers the whole water system (Bach *et al*., 2015 and Hammond *et al*., 2015). The proposed project discusses applying the flow control positioning method in an integrated model, such as SYNOPSIS (Butler & Schutze, 2005).

8.8.4.1 Apply method to an integrated model

The application of the flow control positioning method was designed to be used for 1D sewer system models and does not consider overland flow or any other interconnecting urban water systems. Urban water systems, however, can have a significant hydraulic and water quality impact on each other. Considering all of these systems in the same model, and their interactions, can deliver improved and more beneficial solutions. This type of analysis would, therefore, consider the 1D sewer systems, wastewater treatment works, 2D overland flows, and the natural watercourses. Applying the flow control positioning method on an integrated model could provide benefit regarding flood resistance levels and receiving water quality. The possible benefits that could be achieved from this project would be:

1) More holistic solutions for the catchments of concern,
2) Improved water quality for the whole catchment as all of the systems are considered, and
3) Potentially cheaper retrofit solutions proposed by the method.

The novelty of the idea is:

1) New approach for improving the flood resistance of sewer system and natural water courses.
2) New design framework for the positioning of flow controls within several water systems (combined sewer system, surface water system and river network).

Concluding remarks

This thesis has investigated a new method for positioning and designing flow controls into a sewer system with the aim of reducing the flood risk level by attenuating potential flood volumes within spare capacities of the system. The method was programed to select the positions of the flow controls based on the largest available spare capacities within the sewer system. The proposed flow control positioning method was subsequently developed into an assessment framework to automate the method and demonstrate its application on four case study sewer system models. Of the four sewer systems, the first assessed was hypothetical and the remaining three were existing anonymised systems.

From the analysis of the assessment framework, it was found that the FR level of a sewer system could be increased from an initial FR level of a 1 in 3 year return period to a 1 in 108 year return period. Comparison to alternative flood alleviation methods, such as installing additional storage or pumping stations, it was found that installing strategically positioned flow controls was the cheapest solution in two of the four sewer system analyses.

This new method for increasing the flood risk level of sewer systems would be beneficial in existing, urbanised areas where the application of preferred flood risk reduction measures, such as SuDS and rainwater harvesting, are infeasible or unpractical. This work also has the potential to extend its application and take account of additional decision making criteria used when designing sewer systems.

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Appendix

Appendix A1: The assessment framework's *Visual Basic for Applications* code for automating the flow control positioning method.

Appendix A2: Estimated cost to install a flow control without removing the manhole chamber lid.

	Activity	Quantity	Langdon (2013) page reference	Unit	£ Unit Rate	£ Calculated rate
Arrival at site	Delivery of flow control	1			30.00	30.00
	Site clearance ~ urban area/live carriageway	0.03	363	ha	4,146.35	111.95
	Traffic management	0.3	143	week	1,360.00	408.00
	Transport - 4WD long wheelbase	1 day	141	week	556.00	79.43
	Trailor	1 day	143	week	13.86	1.98
	Gang to do work	12	223	hr	62.50	750.00
	Information boards	2	362	nr	78.55	157.10
	Barriers round manholes	*Included in the gang rate*				
Bypass chamber flows	Access chamber ~ US chamber	*Included in the gang rate*				
	Access chamber ~ DS chamber	*Included in the gang rate*				
	Clean chamber for access ~ US manhole	0.25	337	hr	393.50	98.38
	Plug chamber outlet	1	336	nr	126.40	126.40
	Pump flow two chambers down ~ 200m	1	178	day	533.39	533.39
	Set up fresh air pump	1	178	day	533.39	533.39
Open chamber	Access chamber	*Included in the gang rate*				
	Clean chamber	0.25	337	hr	393.50	98.38
Remove exisitng benching	Enter chamber	*Included in the gang rate*				
	Break benching	1	177	m^3	54.84	54.84
	Remove rubble by hand	*Included in the above costs*				
	Unbolt existing flow control	*Included in the gang rate*				
	Remove existing flow control	0.5	177	m^3	54.84	27.42
	Disposal of removed rubble - Removal from site	1	165	m^3	19.48	19.48
	Disposal of removed rubble - Tipping charges	1	165	m^3	121.50	121.50
	Disposal of removed rubble - Landfill Tax	1	165	m^3	96.00	96.00
Install flow control	Re-clean chamber	0.5	337	hr	393.50	196.75
	Clean first section of pipe	2	336	m	17.00	34.00
	Drill bolt holes for VFC	*Included in the gang rate*				
	Install flow control	*Included in the gang rate*				
Bench flow control	Make concrete for benching	1	229		38.15	38.15
	Lower conrete into chamber	*Included in the above costs*				
	Bench chamber	*Included in the above costs*				
Depart site	Close chamber	*Included in the gang rate*				
	Remove bypass	*Included in the gang rate*				
	Depart site	*Included in the gang rate*				
				TOTAL:		£3,516.53

Appendix A3: Estimated cost to install a flow control with the need to remove the manhole chamber lid.

	Activity	Quantity	Langdon (2013) page reference	Unit	£ Unit Rate	£ Calculated rate
Arrival at site	Delivery of flow control	1			30.00	30.00
	Site clearance ~ urban area/live carriageway	0.03	363	ha	4,146.35	111.95
	Traffic diversion	1	67	nr	6,500.00	6,500.00
	Transport - 4WD long wheelbase	2 days	141	week	556.00	158.86
	Trailor	2 days	143	week	13.86	3.96
	Gang to do work	24	223	hr	62.50	1,500.00
	Site toilet	2 days	65	week	180.00	51.43
	Information boards	10	362	nr	78.55	785.50
	Barriers round manholes	*Included in the gang rate*				
Bypass chamber flows	Access chamber ~ US chamber	*Included in the gang rate*				
	Access chamber ~ DS chamber	*Included in the gang rate*				
	Clean chamber for access ~ US manhole	0.25	337	hr	393.50	98.38
	Plug chamber outlet	1	336	nr	126.40	126.40
	Pump flow two chambers down ~ 200m	1	178	day	533.39	533.39
	Set up fresh air pump	1	178	day	533.39	533.39
Open chamber	Remove aboveground tarmac	6.25	163	m^3	26.65	166.56
	Access chamber by removing the lid	0.34	156	m^3	850.00	288.40
	Clean chamber	0.25	337	hr	393.50	98.38
Remove exisitng benching	Enter chamber	*Included in the gang rate*				
	Break benching	1	177	m^3	54.84	54.84
	Remove rubble by hand	*Included in the above costs*				
	Unbolt existing flow control	*Included in the gang rate*				
	Remove existing flow control	0.5	177	m^3	54.84	27.42
	Disposal of removed rubble - Removal from site	1.57	165	m^3	19.48	30.50
	Disposal of removed rubble - Tipping charges	1.57	165	m^3	121.50	190.21
	Disposal of removed rubble - Landfill Tax	1.57	165	m^3	96.00	150.29
Install flow control	Re-clean chamber	0.5	337	hr	393.50	196.75
	Clean first section of pipe	2	336	m	17.00	34.00
	Drill bolt holes for VFC	*Included in the gang rate*				
	Install flow control	*Included in the gang rate*				
Bench flow control	Make concrete for benching	1	229	nr	38.15	38.15
	Lower conrete into chamber	*Included in the above costs*				
	Bench chamber	*Included in the above costs*				
Close chamber and depart site	Replace chamber lid	1		nr	78.00	115.00
	Delivery of chamber lid	1			200.00	220.00
	Crane to place chamber	0.5 days	143	week	2,366.00	169.00
	Resurface the above road - Base - 100mm	25.00	424	m^2	13.12	328.00
	Resurface the above road - Binder Course - 100mm	25.00	424	m^2	12.36	309.00
	Resurface the above road - Surface - 50mm	25.00	424	m^2	9.07	226.75
	Remove bypass	*Included in the gang rate*				
	Depart site	*Included in the gang rate*				
					TOTAL:	£13,076.48

Appendix A4: Estimated cost to install a flow control and a new manhole chamber.

	Activity	Quantity	Langdon (2013) page reference	Unit	Unit Rate £	Calculated rate £
Arrival on site	Site clearance ~ urban area/live carriageway	0.04	363	ha	4,146.35	178.29
	Traffic diversion	1.00	67	nr	6,500.00	6,500.00
	Transport - 4WD long wheelbase	4 days	141	week	556.00	317.71
	Trailor	4 days	143	week	13.86	7.92
	Resources - Plant - Drainage	36.00	336	hr	75.96	2,734.56
	Gang to do work	48.00	223	hr	62.50	3,000.00
	Site toilet	4 days	65	week	180.00	102.86
	Information boards	2.00	362	nr	78.55	157.10
	Barriers round manholes	*Included in the gang rate*				
Bypass chamber flows	Access chamber ~ US chamber	*Included in the gang rate*				
	Access chamber ~ DS chamber	*Included in the gang rate*				
	Clean chamber for access ~ US manhole	0.25	337	hr	393.50	98.38
	Plug chamber outlet	1.00	336	nr	126.40	126.40
	Pump flow two chambers down ~ 200m	1.00	178	day	533.39	533.39
Open cham ber	Access chamber	*Included in the gang rate*				
	Clean chamber	0.25	337	hr	393.50	98.38
Remove exisitng chamber	Remove aboveground tarmac	6.25	163	m^3	26.65	166.56
	Enter chamber	*Included in the gang rate*				
	Break benching	1.00	177	m^3	54.84	54.84
	Remove rubble by hand	*Included in the above costs*				
	Unbolt existing flow control	*Included in the gang rate*				
	Remove existing flow control	0.50	177	m^3	54.84	27.42
	Remove exisitng chamber	2.26	156	m^3	850.00	1,922.65
	Excavate for new chamber	6.59	163	m^3	8.57	56.49
	Disposal of removed rubble - Removal from site	6.59	165	m^3	19.48	128.41
	Disposal of removed rubble - Tipping charges	6.59	165	m^3	121.50	800.93
	Disposal of removed rubble - Landfill Tax	6.59	165	m^3	96.00	632.84
Install new chamber	Install new chamber	1.00	230	nr	2,690.85	2,690.85
	Crane to place chamber	3 days	143	week	2,366.00	1,014.00
	Delivery of chamber	2.00		nr	220.00	440.00
	Flush chamber of building debris	*Included in the gang rate*				
	Resurface the above road - Base - 100mm	25.00	424	m^2	13.12	328.00
	Resurface the above road - Binder Course - 100mm	25.00	424	m^2	12.36	309.00
	Resurface the above road - Surface - 50mm	25.00	424	m^2	9.07	226.75
Depart site	Close chamber	*Included in the gang rate*				
	Remove bypass	*Included in the gang rate*				
	Depart site	*Included in the gang rate*				
				TOTAL:		22,653.73

Appendix A5: Design and costing of deep shaft solution

The deep shaft solution adopted in this project mimics solutions currently being constructed in the UK (Cooper *et al.*, 2014). The drainage solution consists of the construction of a strategically placed man-made storage chamber below the ground surface. These structures were designed into the case study sewer system models following the below method:

1) Select FR level to be achieved,
2) Generate hyetograph to be used in the simulation of the sewer system model,
3) Run simulation of the sewer system model,
4) Install deep storage chambers at the locations of flooding,
5) Run simulation and re-size storage chamber until the sewer system does not over-discharge or flood.

An estimate of their cost for construction from industry was:

$$Construction\ cost\ of\ deep\ shaft = (1000V) + 25\%$$

where *V* is the total volume of the deep shaft structure (m^3), Hydro International (2014). This estimate was validated against the reported costs of the *Maida Vale Flood Alleviation Scheme*, Table A5. Other cost structures in the project are accounted for in Table A5. The sum of the cost estimates undertaken in this research were within 0.1% of the original quoted cost. The estimate cost rule was, therefore, deemed suitable to be used as a credible comparison.

Table A5: Estimate costs of the Maida Vale Flood Alleviation Scheme using the estimate cost rule and comparison to the actual quoted cost (Cooper et al., 2014).

Task	**Unit**	**Rate (£ per unit)**	**Cost (£)**
Temple Mews Gardens			
Storage	2,650 m^3	1,000	2,650,000
Pump and extras	-	25% of storage	662,500
Deep sewer*	500 m^3	240	120,000
Westbourne Green			
Storage	8,170 m^3	1,000	8,170,000
Pump & extras	-	25% of storage	2,042,500
Deep sewer*	1,870 m^3	350	654,500
Drop Shaft design work**	-	-	150,000
Drop Shaft**	-	-	60,000
Profits**	-	20.5% additional	2,974,500
TOTAL			17,484,000
MWH TOTAL			17,500,000
DIFFERENCE			-0.09%

* Langdon (2013)

** Hydro International (2012)

Appendix A6-1: Comparison of the greatest FR level's achieved for the Artificial Network through the application of the different flood alleviation methods.

Flood alleviation method	Greatest FR level (1 in 'x' years)	Estimated cost (£)	Percentage difference to 'VFC & OP' solution (%)
Initial assessment	3	0	-
VFC & OP (100mm)	28	204,500	-
OP (100mm)	35	212,000	+4
Deep shaft	28	2,048,000	+901
Flow Attenuation*	28	1,218,000	+496
Sewer Upsizing*	28	1,008,000	+393
Manage flow*	28	672,000	+229
Isolate from the system*	28	378,000	+85

Appendix A6-2: Comparison of the greatest FR level's achieved for the small anonymised sewer system through the application of the different flood alleviation methods.

Flood alleviation method	Greatest FR level (1 in 'x' years)	Estimated cost (£)	Percentage difference to 'VFC & OP' solution (%)
Initial assessment	4	0	-
VFC & OP (100mm)	108	16,000	-
OP (100mm)	6	5,000	-69
Deep shaft	108	1,071,250	+6,595
Flow Attenuation*	108	406,000	+2,438
Sewer Upsizing*	108	336,000	+2,000
Manage flow*	108	224,000	+1,300
Isolate from the system*	108	126,000	+688

Appendix A6-3: Comparison of the greatest FR level's achieved for the Langley sewer system through the application of the different flood alleviation methods.

Flood alleviation method	Greatest FR level (1 in 'x' years)	Estimated cost (£)	Percentage difference to 'VFC & OP' solution (%)
Initial assessment	1	0	-
VFC & OP (100mm)	71	240,500	-
OP (100mm)	9	247,000	+3
VFC & OP with FVS	5	84,750	-65
VFC & OP SSS	53	126,000	-48
Deep shaft	71	1,821,000	+657
Flow Attenuation*	71	580,000	+141
Sewer Upsizing*	71	480,000	+100
Manage flow*	71	320,000	+33
Isolate from the system*	71	180,000	-25

Appendix A6-4: Comparison of the greatest FR level's achieved for the anonymised sewer system through the application of the different flood alleviation methods.

Flood alleviation method	Greatest FR level (1 in 'x' years)	Estimated cost (£)	Percentage difference to 'VFC & OP' solution (%)
Initial assessment	1	0	-
VFC & OP (200mm)	12	166,000	-
OP (100mm)	11	17,000	-90
VFC & OP with FVS	11	187,500	+13
VFC & OP SSS	19	374,000	+125
Deep shaft	12	236,500	+42
Flow Attenuation*	12	232,000	+40
Sewer Upsizing*	12	192,000	+16
Manage flow*	12	128,000	-23
Isolate from the system*	12	72,000	-57