Improvements in vortex flow control design to increase sewer network flood resistance

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Abstract Flow controls are used within the water industry to manage the flow through sewer networks by attenuating flows at convenient or critical locations. Many sewer networks, regardless whether the systems have a flow control installed, are predicted to become stressed in the future due to the effects of climate change, population growth and urbanisation. This issue is compounded by the age of the Britain's sewerage infrastructure as well as the cost and difficulty of replacing and upgrading the infrastructure. Statutory 'Catchment Flood Management Plans' have been introduced within the United Kingdom to tackle this issue by better understanding the flow path of flood water on a catchment scale. This paper discusses a method to maximise the use of the current sewerage infrastructure by installing flow controls, meaning a greater volume of the sewer network can be used for stormwater storage. This paper continues by describing a method of increasing a sewer network's flood resistance by using vortex flow controls with a lower design flow-rate compared to an orifice plate. This paper then concludes by describing three case studies demonstrating the use vortex flow controls when retrofitting sewer networks as well as the impact of implementing the retrofit design method.

Keywords Combined sewer networks; increased flood resistance; improved storage; retrofit design method; vortex flow controls

INTRODUCTION

Combined sewer networks within the United Kingdom are more frequently being tested by storm events and increasing volumes of surface runoff due to the effects of climate change, population growth and urbanisation (Pitt, 2008). The United Kingdom's Government have responded to this by introducing the Flood and Water Management Act 2010. This Act prioritises the implementation of arguably more sustainable solutions, such as sustainable drainage systems (SuDS), with the aim of managing surface runoff using structures that mimic natural water cycle processes rather than combined sewer networks. Drainage solutions, such as SuDS that are proposed to help reduce surface runoff volumes in existing urban areas, are often considered to be unfeasible for installation within dense urban catchments due to space restrictions and lack of permeable surfaces. It is also seen as unfeasible for a water company to replace its entire sewer system with larger pipes to address larger volumes of surface runoff. Therefore, water companies have to make the best use of their existing combined sewer networks in conjunction with the use of SuDS, rainwater harvesting and water re-use methods. One method of doing this is by installing flow controls to attenuate the water in otherwise unused volumes of the sewer network. Work by Andoh and Declerck (1997 and 1999) has shown that installing attenuation systems and flow controls in upstream sections of a combined sewer network can improve the network's behaviour and increase flood resistance. The work reported in this paper builds on Andoh's and Declerck's work by highlighting the benefits of using vortex flow controls to increase a combined sewer network's flood resistance as well as investigating a retrofit design method that shows potential to further increase the network's flood resistance. In this paper, flood resistance is defined and quantified as the return period of the most severe storm that does not cause water to flow back out of the modelled network or breach discharge conscents during the simulations. Within this paper, *HBFC* has been used to indicate Hydro-Brake® Flow Controls, *HBO* has been used to indicate Hydro-Brake Optimum® Flow Controls and *VFC* has been used to indicate vortex flow controls.

CURRENT FLOW CONTROLS AND THEIR DESIGN METHODS

Two common types of flow control are the orifice plate and the VFC. Orifice plates work on the principle of physically restricting the flow area within a pipe and can be considered a simple flow control solution as they are easier to design, manufacture and install. However, orifice plates have an increased risk of blockage compared to other flow controls due to their relatively smaller outlet areas. A second and more advanced type of flow control is the VFC. A VFC further restricts the flow of water compared to an orifice plate by creating a vortex at high head levels. Figure 1 shows the characteristic behaviour of an orifice plate and a VFC. A previous comparison of an orifice plate and VFC's behaviour found that a VFC can reduce upstream storage volume requirements by 13%, increase downstream velocities and enable the network to discharge the stormwater in a shorter time period after a significant rainfall event (Jarman et al, 2011).

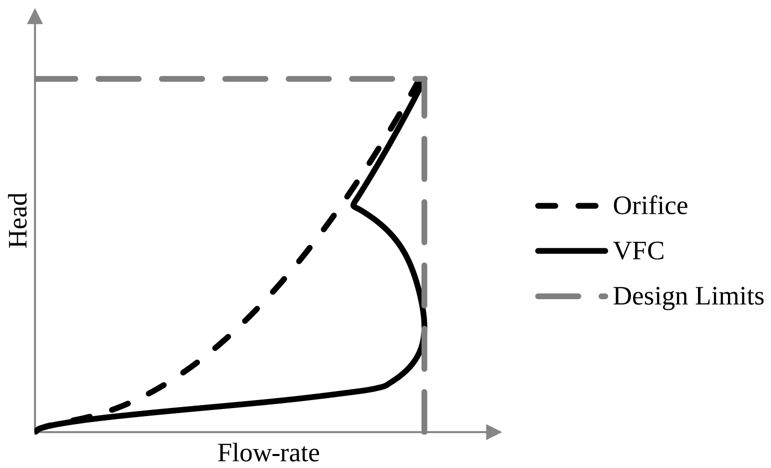
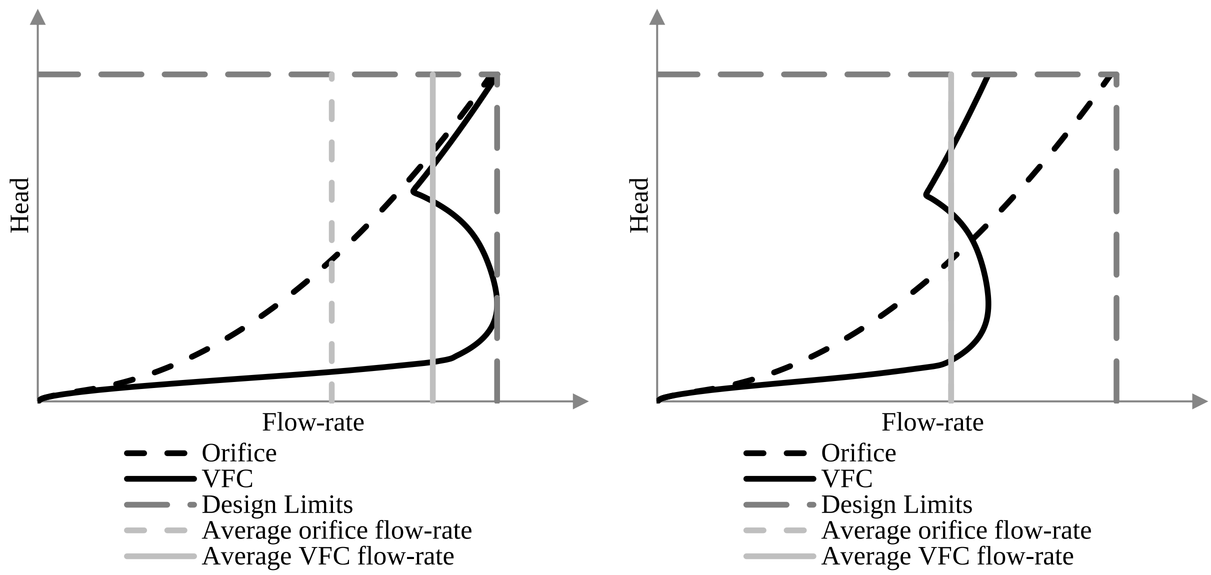


Figure 1: Head against discharge curves of an orifice plate and a VFC as well as their head and discharge design limits.

The Hydro-Brake® Flow Control (HBFC) and the Hydro-Brake Optimum® Flow Control (HBO) are both VFCs that designed by Hydro International. The HBO is an optimised version of the HBFC. The differences in performance between the two VFCs are that the HBO provides: greater reductions in storage volumes; higher average flow-rates; greater physical strength and an adjustable inlet to adjust the design flow-rate post installation (Hydro International plc, 2012). Flow controls are designed using the maximum allowable upstream head and maximum allowable downstream flow-rate. In this paper, flow controls with the same design head and flow-rate are known as equivalent flow controls. This design point of the flow control is typically decided by the geometry of the network's infrastructure in which it will be installed. This design method is simple to understand and apply, however, is flawed with regard to defining the flow control's behaviour at lower flow-rates than the design flow-rate and hence how the flow control will impact upstream and downstream conditions.

PROPOSED RETROFIT DESIGN METHOD

The proposed retrofit design method aims to increase the volume of water that can be stored in a sewer network during storm events by balancing the volumes of water that are transferred throughout the network. As discussed in the previous section, flow controls are designed based on the maximum allowable upstream head of water and the maximum allowable downstream flow-rate from the flow control. However, difficulties designing retrofit solutions for sewer networks can occur when comparing and understanding the variable behaviour of flow controls over their entire operating head. This difficulty is highlighted in Figure 2a, which shows two equivalent flow control characteristics and their respective average flow-rates. It can therefore be hypothesised that if the orifice plate characteristic in Figure 2a was replaced in a sewer network by the VFC characteristic in Figure 2a, the downstream sewer network would have to accommodate a greater volume of water during storm events due to the increase in average flow-rate. This increase in average flow-rate is not accounted for in the design and selection of a flow control. Therefore, to gain the added benefits of installing VFCs compared to orifice plates, it has been found that designing upstream VFCs to have the same average flow-rate as an orifice plate with the same operating head range can increase a sewer network's flood resistance. Figure 2b illustrates this method as the flow controls have different respective design points but the same average flow-rate. The overall benefit of using this retrofit design method is that the sewer network should have a greater flood resistance for a lower financial cost. This retrofit design method has been applied in the second and third case studies in the latter sections of this report.



a) Graph of two flow control characteristics with the same design point and different average flow-rates.

b) Graph of two flow control characteristics with the same average flow-rate and unequal design flow-rates.

Figure 2: Graphs of orifice plate and VFC characteristics demonstrating two different design approaches to obtain comparable behaviour.

RETROFIT CASE STUDIES

This paper reports on three case studies to investigate the effects of the retrofit design method. The first case study investigates the benefits of retrofitting surface water sewers with modern VFCs and the second and third case studies investigates the benefits when the retrofit design method was used to design the upstream flow controls.

Each sewer network was analysed using WinDes® (Micro Drainage, 2012). This software was selected due to its speed of computation and ability to accurately model the transition phase of a VFC's behaviour. The transition phase of the VFC's behaviour is when the vortex is developing and stabilising within the device. This phase is shown as the section of the characteristic curve with a negative gradient. The analysis was carried out by only replacing existing flow controls within each of the sewer networks. The behavioural characteristics and costs of the VFCs were supplied by Hydro International (2012). All other features of the sewer network, for example: pipe lengths; pipe diameters; manhole positions, manhole depths; surface runoff coefficients; etc, are as specified for the original installation. Each sewer network was then subjected to hydrographs derived from the Flood Studies Report (Centre for Ecology and Hydrology, 1979) and these hydrographs ranged from fifteen minutes to seven days in duration. Both summer and winter synthetic hydrographs were used to find each network's critical storm event and the return periods of storms used were varied for each case study. The performance of the network was quantified by recording the highest return period of the hydrograph that did not cause the flow-rate at the outlet to exceed the discharge consent or the maximum head of water at any manhole to exceed the cover level. This method of assessing the network's flood resistance was applied on each case study.

Case Study One

The first case study analysed a surface water sewer in Newquay, United Kingdom (Hydro International plc, 1986). The 100 metre surface water sewer was designed to transport runoff from an impervious car park to a local stream. The surface water sewer was also designed to dissipate the kinetic energy of the runoff as it travelled to the stream that has a water level 24 metres below the car park and hence protect the hillside from erosion and scouring. The surface water sewer uses three stormwater HBFCs and in pipe storage to dissipate the kinetic energy and limit the discharge to 103 l/s. A long section of the surface water sewer is given in Figure 3 and shows the locations of the three flow controls.

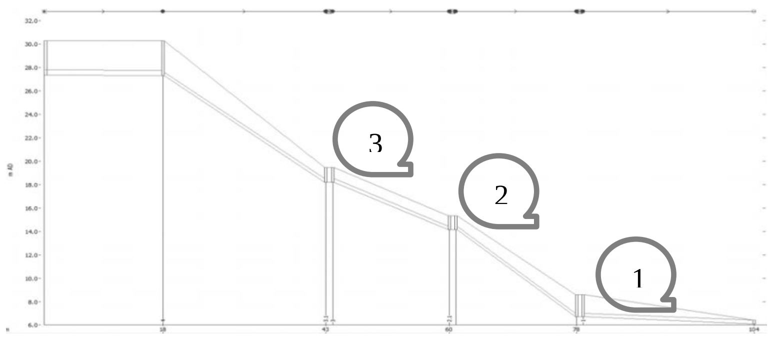


Figure 3: Long section of the Newquay surface water sewer.

The behaviour of the surface water sewer was analysed twice with each analysis using different versions of VFCs. The outputs from the analysis are shown in Table 1. In simulation A, HBFCs were used and the flood resistance of the network was found to be 48 years where the flood resistance is quantified as the return period of the network's critical storm. In simulation B, HBOs were used and the flood resistance of the network was not found as no flooding or over discharge was predicted in a 1 in 200 year storm event. The network was not simulated with a storm event with a greater return period as the Flood Studies Report generated storm events do not exceed a 1 in 200 year return period (Centre for Ecology and Hydrology, 1979). These outputs show that replacing previous generation VFCs with newer VFCs is beneficial and increases a sewer's flood resistance.

Table 1: Outputs from the simulations of case study one.

Simulation	Type of flow control	Flood resistance (years)	Percentage increase (%)
A	HBFC	48	-
B	HBO	200+	310+

Case Study Two

The second case study is a hypothetical surface water sewer containing two flow controls and in pipe storage. The 170 metre surface water sewer has a discharge limit of 5.9 l/s and transports runoff from a fully impervious 0.53 hectare catchment to a stream at the outflow. Figure 4 shows the long section of the surface water sewer with the positions of the two flow controls.

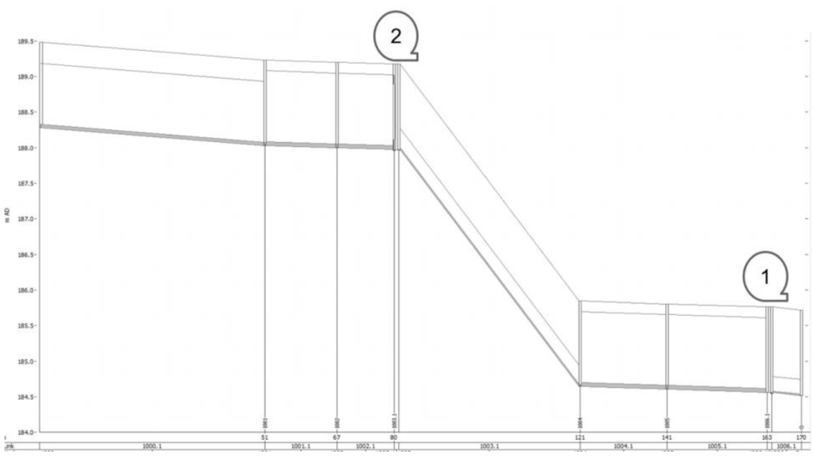


Figure 4: Long section of the hypothetical storm water sewer network used in case study two.

In the initial analysis, the surface water sewer was subjected to a series of 1 in 30 year storm events. Table 2 shows the outputs from the analysis of the surface water sewer containing the three different types of flow controls. Simulations A to C compare the three different types of flow control. The retrofit design method was implemented in simulation D. As shown in

Table 2, the only simulation out of simulation A to C that did not flood when subjected to the 1 in 30 year storm events was simulation B. The reason for the cause of flooding in simulation A was that there was not enough storage upstream of the orifice plate as the orifice plate retained a greater volume of stormwater compared to the VFCs. The reason for simulation C flooding was that the upstream flow control did not restrict the flow sufficiently meaning the volume of water being transported downstream was too great. This is demonstrated when comparing the characteristic curves of different flow controls as shown in Figure 2a.

In simulation D, the retrofit design method was implemented and the flow-rate of the upstream VFC was decreased. Table 2 shows the overall flood resistance for each solution with their respective flow controls. Overall the sewer's resistance to flooding was increased by nine years by implementing the retrofit design method compared to simply replacing the original orifice plates with equivalent VFCs. This increase in flood resistance is also achieved at a lower cost than simply retrofitting with equivalent VFCs

Table 2: Outputs from the simulations of case study two along with the total cost of the flow controls.

Simulation	Type of flow control	Flood resistance (years)	Percentage increase (%)	Cost of flow controls (£)
A	Orifice	17	-	1500
B	HBFC	30	76	3750
C	HBO	27	59	3750
D	HBO	36	112	3500

Case Study Three

The third case study in this report analyses a larger, hypothetical sewer that contains three flow controls in series. A schematic of the sewer is shown in Figure 5. The sewer consists of over 500m of pipe and drains an area of over 1.5 hectares. In Figure 5, the locations of the flow controls are represented by the dots at the outlets of the manholes numbered four, five and seven. The outlet is represented by the lighter coloured circle at the end of the pipe numbered 1.006. Two scenarios have been considered using this case study. The first scenario is when the sewer network contained wastewater suitable variants of the VFC. The flood resistance and cost from this analysis is shown in Table 3. The second scenario considered the sewer network when the network contained stormwater suitable variants of the VFC. The flood resistance and cost from this analysis is shown in Table 4. This meant that different versions of flow control were used in each of the scenarios.

Table 3 shows the flood resistance of the network for wastewater suitable flow controls. The flow controls used in simulation A, B and C are all equivalent flow controls and are in the same locations. The outputs from the simulations show that the HBO provides the greatest level of flood resistance, 45 years, for the network and provides eight years more flood resistance compared to the original orifice plates.

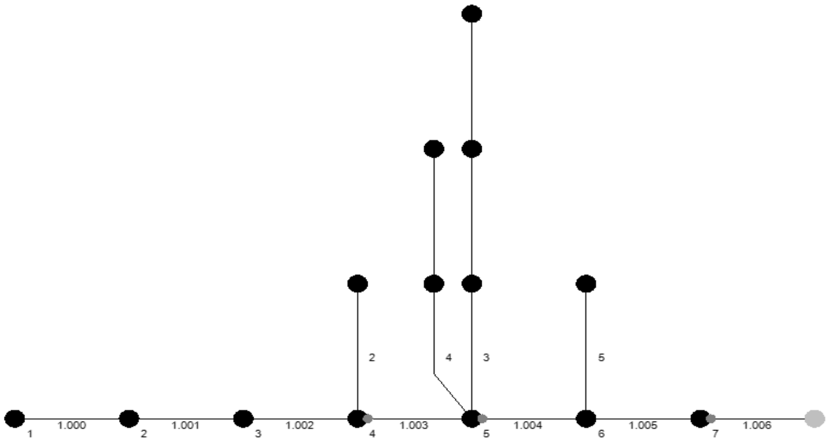


Figure 5: Schematic of the sewer network used in case study three.

Table 3: Outputs from the wastewater simulations of case study three along with the total cost of the flow controls.

Simulation	Type of flow control	Flood resistance (years)	Percentage increase (%)	Cost of flow controls (£)
A	Orifice	37	-	2250
B	HBFC	38	3	6500
C	HBO	45	22	10000
D	HBO	53	43	10000

For simulation D, the retrofit design method was implemented. By implementing the retrofit design method an additional eight years of flood resistance can be achieved by installing VFCs with a lower maximum design flow-rate compared to the equivalent VFCs used in simulation C. The VFCs used in simulation C and D were also of a similar cost showing that simulation D is a better value solution.

The sewer network, shown in Figure 5, was again analysed when stormwater suitable flow controls were installed in the sewer network. Table 4 shows the cost and flood resistance when the stormwater suitable VFCs were used. The flow controls used in simulation E, F and G are all equivalent and kept in the same location. The flood resistance levels from simulation E, F and G show that the more modern VFCs, used in simulation G, provide the greatest amount of flood resistance, 56 years. The retrofit design method that considers the design as a volume transfer problem was applied to the two upstream flow controls in simulation H. The flood resistance levels from simulation H show an increase of 17 years in flood resistance compared to using equivalent VFCs and at a similar cost to simulations F and G.

Table 4: Outputs from the stormwater simulations of case study three along with the total cost of the flow controls.

Simulation	Flow control	Flood resistance (years)	Percentage increase (%)	Cost of flow controls (£)
E	Orifice	37	-	2250
F	HBFC	42	14	6500
G	HBO	56	51	6500
H	HBO	73	97	6250

CONCLUSION

The overall conclusion of this investigation is that there is significant benefit to retrofitting sewer networks with modern VFCs. The three case studies presented in this paper show that replacing existing flow controls with equivalent modern flow controls does not always provide the most benefit. The case studies show that an additional eight to seventeen years of flood resistance can be achieved by using smaller upstream flow controls to manage the volume transferred downstream. This demonstrates that the average flow-rate over the operating head is a more influential parameter in achieving the maximum level of flood resistance. This also meant the overall financial cost of the flow controls was reduced.

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