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## Developing a decision support tool for the positioning and sizing of vortex flow controls in existing sewer systems

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### Abstract

This paper describes the development of a decision support tool for the positioning and sizing of vortex flow controls in existing sewer systems. The tool aims to prioritise the placement of vortex flow controls primarily within subcatchments with the greatest flood consequence rating and maximise the use of unused inpipe volumes during critical rainfall events. The decision support tool is intended for use in catchments where opportunities to implement SuDS and rainwater harvesting to defend against flooding are limited. The decision support tool is envisaged to identify potential strategies which could enhance flood resistance of sewer systems in a cost effective manner.

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### 1. Introduction

The increase in the number of flood events in the United Kingdom is linked to the effects of climate change, population growth and urbanisation. For example, Murphy *et al.* (2009) predict a 33% increase in precipitation volumes in the west of England by 2080. The Office of National Statistics (2011) estimates that the population of the United Kingdom will reach 73.2 million by the year 2035, and in excess of 85 million by the year 2081, thus meaning there will be a significant increase in the amount of sewage to be collected in sewer systems. Additionally, Allitt and Tewkesbury (2009) have reported that the increase in impermeable area is occurring at a rate of 1.2 m<sup>2</sup> per

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property per annum in urban areas. The combination of these factors is estimated to result in a 50% plus increase in sewer flooding in the United Kingdom by the year 2040 (Mott MacDonald, 2011). Urbanised catchments can be adapted to tackle these hydraulic issues by: transporting; attenuating; evaporating and infiltrating the surface water runoff with the aim of reducing flood volumes and managing the conveyance of flows to within acceptable flow-rates. However, not all of these solutions are applicable to all catchments.

In addition to the environmental factors affecting an in-situ sewer system's performance, there are growing economic demands. Water service providers within the United Kingdom are under financial pressure to reduce their operational and maintenance costs. They are also under legislative and consumer pressure to improve the consumer experience and improve the quality of water treated in potable and wastewater treatment works. These political and environmental pressures highlight the necessity for water companies to improve the efficiency of their assets and operations.

This paper proposes the development of a decision support tool to position and design flow controls to attenuate sewer flows, and in turn aid in managing the economic and environmental challenges. The solutions are aimed at reducing sewer flooding by introducing flow controls to improve the hydraulic behaviour of existing sewer systems. This will assist water companies in meeting flood prevention targets at a reduced cost when compared to building additional sewer systems or increasing the capacity (upsizing) of the current sewer system.

## 2. Existing methods for increasing flood resistance

There are accepted methods for increasing a catchment's flood resistance level: transportation of flows away from high risk catchments; attenuation of flows in upstream catchments; evaporation and infiltration of flows from catchments. In this paper, the term 'flood resistance' is used to define the level of flood protection a sewer system can provide. It refers to the lowest return period *rainfall* event that results in the sewer system over discharging or surface flooding arising from excess sewer surcharge. Increasing flood resistance through transportation of flood flows involves diverting these volumes away from vulnerable catchments. An example of transporting potential flood volumes to protect catchments from flooding is the 'Stormwater Management and Road Tunnel' (SMART Motorway Tunnel) that has been built to carry potential flood volumes away from Kuala Lumpur, Malaysia. Above ground transportation measures require a suitable flow path, also known as a "blue path", through the catchment to allow the surface water to reach a natural watercourse. The second method of increasing flood resistance is to attenuate the potential flood volumes. The aim of attenuation is to retain excess flow volumes upstream of the subcatchment at risk of flooding. This volume can then be discharged over an extended period at an acceptable flow-rate. Systems, which are used for attenuation, consist of a storage volume and a flow control. Common structures which provide storage for attenuation systems are ponds, detention basins, tanks or subterranean cellular storage blocks. Devices used as flow controls are typically orifice plates, penstocks, vortex flow controls (VFCs) and weirs. Examples of large scale flood attenuation schemes include the White Cart Water Flood Prevention Scheme (Education Scotland) and the Wigan Flood Alleviation Scheme (Gemmell, 2010). Work by Andoh and Declerck (1997, 1999) also found that implementing attenuation systems throughout sewer systems can increase a sewer system's flood resistance and improve the system's hydraulic behaviour, compared to end-of-pipe solutions. The third method of increasing flood resistance is to exploit natural hydrological processes such as evaporation and infiltration. Flood prevention through the exploitation of natural hydrological processes is commonly described as sustainable drainage systems (SuDS). Examples of SuDS schemes using evaporation and infiltration are given in 'The SuDS Manual' (Woods-Ballard *et al.*, 2007). These examples show how SuDS can be developed into urban environments to provide protection from flooding as well as for surface water treatment and to improve local amenity. Draft guidance (Department for Environment, Food and Rural Affairs, 2011) on the subject of flood resistance encourages the use of SuDS. Where the use of SuDS is not possible the construction of additional sewer systems may be necessary.

The use of SuDS to prevent flooding in catchments is preferred to the transportation and attenuation of flood volumes as SuDS mimic the natural hydrological cycle (Department for Environment, Food and Rural Affairs, 2011). The implementation of SuDS, however, firstly depends on the catchment's available area to enable evaporation and infiltration. To implement infiltration SuDS, the available ground surface has to have an adequate permeability. The 'Infiltration SuDS Map' developed by the British Geographical Survey (2013) shows that only 11.8% of the United Kingdom is "compatible for infiltration SuDS", 24.6% of the United Kingdom is "probably compatible for infiltration SuDS" and 25.9% of the United Kingdom is effectively unsuitable for the implementation

of infiltration SuDS. The 'Infiltration SuDS Map' therefore indicates that the surface water runoff from potentially 88.2% of the United Kingdom cannot be managed through SuDS methods alone. SuDS are also used for transporting flood volumes from catchments, in structures such as swales, due to their high amenity rating. This also encourages evaporation as the flow volumes are kept above ground. Low soil infiltration rates and already urbanised catchments, containing existing structures that impede the flow path of surface water, make it challenging to follow current guidance on protecting catchments from flooding. If an acceptable flood resistance level cannot be achieved through the implementation of SuDS then alternative methods of increasing a catchment's level of flood resistance must be found. SuDS are sometimes implemented with flow attenuation measures to achieve desired flood resistance levels when the soil's infiltration rate is inadequate. Due to the difficulty of implementing SuDS solutions in existing urban catchments, this paper discusses the option of increasing a catchment's flood resistance level by improving the hydraulic behaviour of existing sewer systems.

The United Kingdom already has an extensive sewer system for the transportation of stormwater and wastewater, however, the adaptation or re-development of the existing infrastructure is not discussed in current stormwater management guidance (Digman *et al.*, 2012). Digman *et al.* suggest solutions such as green roofs, rainwater harvesting, rain gardens and designated floodable public spaces to manage surface water.

Adaptation of the existing sewer infrastructure to attenuate flood flows has the potential to reduce flood risk where the opportunities for SuDS are limited. Deciding where to install attenuation systems within large sewer systems is a complex and time consuming task. This is due to the many possible locations an attenuation system could be installed in an existing sewer system as positioning and design may negatively affect the efficiency of the sewer system. Assessing the effect of the attenuation system's behaviour on the flood resistance of the sewer system is also computationally expensive as multiple configurations and return period rainfall events must be modelled in order to determine the most beneficial sewer system design.

Considering the complexities involved, this paper proposes the development of a decision support tool to automate and complete the task of positioning, sizing and evaluating the performance of attenuation systems in existing sewer systems. The attenuation measures proposed for the decision support tool will involve using vortex flow controls as the flow control and the existing volume of the sewer system as the storage volume.

### 3. Function and benefits of vortex flow controls

#### 3.1. Function of vortex flow controls

The proposed decision support tool will size and position vortex flow controls (VFCs) in existing sewer systems to enable the use of previously unused storage volumes to attenuate excess flows. VFCs are commonly used to manage the flow-rate of the water within both combined and surface water sewer systems. VFCs are a more advanced flow control compared to traditional flow control options, such as orifice plates, as they exhibit a self-activating throttling behaviour (Jarman *et al.* 2011). The self-activating behaviour can be tailored to give a number of hydraulic and operational advantages for a sewer system compared to a sewer system without flow controls. Figure 1 represents the hydraulic characteristics of an equivalent orifice plate and VFC. In this paper, the term 'equivalent' is used to describe any two flow controls that have the same maximum design head and design flow-rate, but not necessarily the same characteristic behaviour. Figure 1 shows that over the specified design head range the VFC will deliver, on average, a greater flow-rate than an equivalent orifice plate.

#### 3.2. Benefits of vortex flow controls

The geometry and behavioural characteristic of a VFC provides a number of benefits compared to an orifice plate. A VFC has a greater average flow-rate over a specified head range compared to an equivalent orifice plate, meaning a smaller attenuation storage volume is needed to prevent surcharging and flooding (Jarman *et al.*, 2011). Jarman *et al.* (2011) also found that the benefits of installing a VFC in a surface water attenuation system compared to an equivalent orifice plate were that: a 13% attenuation volume saving was made in response to the critical 1 in 30 year rainfall event; a 22% attenuation volume saving was made in response to a rainfall series with an estimated return period of between 30 and 60 years; and that the flow-rates exiting the VFC were generally greater than an orifice plate. The increased exiting flow-rates of the VFC mean that there is a reduced probability of sedimentation

and therefore a lower chance of sewer system blockage. Newton *et al.* (2013) have shown that VFCs can provide benefits when retrofitted into existing sewer systems. Replacing existing old generation VFCs with new generation VFCs can further increase the flood resistance of a sewer system. It was also determined that replacing upstream orifice plates with VFCs that have the same average flow-rate can further increase the sewer system's flood resistance, compared to replacing orifice plates with equivalent VFCs. Figure 2 is a plot of a hydraulic characteristic of an orifice plate and a hydraulic characteristic of a VFC with the same average flow-rate over the design head range. The difference between the VFCs in Figure 1 and Figure 2 is that the VFC in Figure 2 has been made physically smaller to increase the throttling behaviour and hence have the same average flow-rate as the orifice plate. This approach (the retrofit design method) can reduce the cost of delivering a greater level of flood resistance compared to simply replacing existing flow controls with the equivalent VFCs.

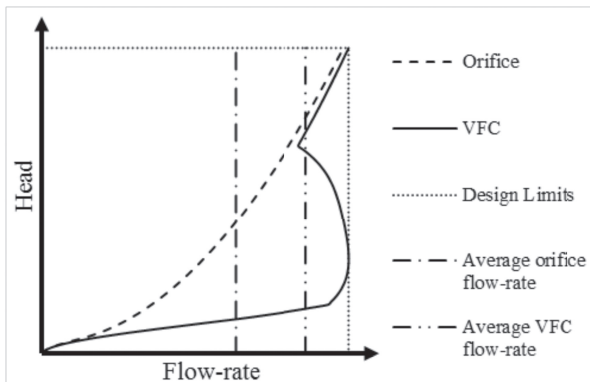


Figure 1: Hydraulic characteristics of an equivalent orifice plate and a VFC.

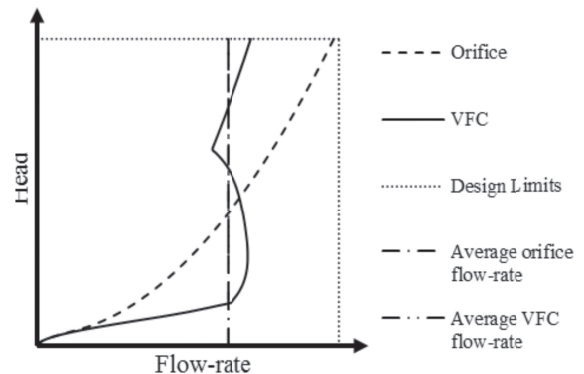


Figure 2: Hydraulic characteristics of an orifice plate as well as a VFC designed using the 'retrofit design method'.

New analysis has been conducted to compare the volume of additional attenuation storage that would be required when using a single VFC at the outflow of the sewer system or using multiple VFCs that are positioned throughout the sewer system. In this new analysis, cellular storage was used to provide the storage volume as it is a commonly used system and is easier to calculate its cost compared to a natural storage system, such as a pond. Figure 3 shows a schematic of the sewer system used for this comparison. The total pipe length in the sewer system is 500 metres and the catchment area is 1.5 hectares. The outlet of the sewer system is the junction at the end of conduit number 1.006.

To assess the benefits of using multiple VFCs distributed throughout the sewer system (Figure 3) compared to using a single control at the outlet of the system, two design scenarios were analysed. The first scenario used one VFC at the outlet of the sewer system, junction seven, and the second scenario used three VFCs installed at junctions four, five and seven. The two scenarios were subjected to a series of 1 in 100 year rainfall events (M5-60 of 18mm and a Ratio-R value of 0.4) with an additional 30% intensity to account for future climate change. These rainfall events had durations ranging from 15 minutes to 7 days. The capital cost of cellular storage and VFCs required to prevent flooding and over discharge from the sewer system was used as a metric to evaluate the cost effectiveness of the design. The VFCs' characteristics were supplied by Hydro International plc, as were the costs of the cellular storage and the VFCs were supplied by Hydro International (2013) as were the VFC characteristics. The results from the analysis are shown in Table 1. In the first scenario, which only used a single VFC, 671 m<sup>3</sup> of cellular storage was required to protect the catchment from the critical 1 in 100 year rainfall event. The cost of the VFC and the cellular storage totalled £88,250. In the second scenario, three VFCs were installed to control the flow-rate of water throughout the sewer system as well as the outlet flow-rate. For this case 308 m<sup>3</sup> of cellular storage was required to protect the catchment from the critical 1 in 100 year rainfall event. The cost of the three VFCs and the cellular storage totalled £45,750. This shows that, for the sewer system, a £42,250 (48%) saving in capital cost can be achieved by using multiple VFCs compared to using a single VFC and cellular storage.

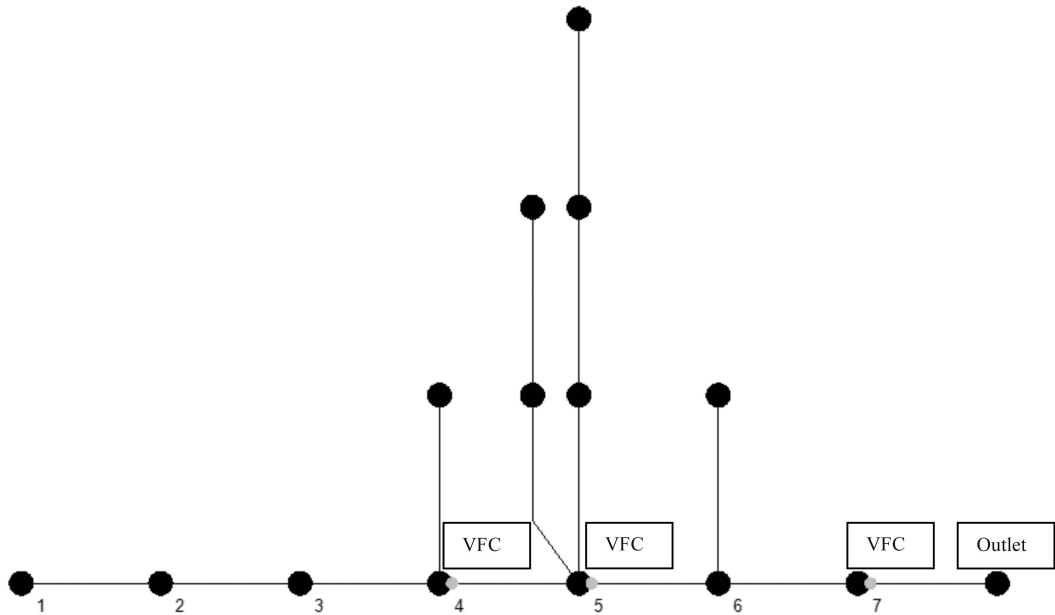


Figure 3: Schematic of the sewer system used in the case study showing the location of the three VFCs and the outlet of the system (Newton *et al.*, 2013).

Table 1: Comparison of cost and volume requirements to prevent flooding when using single or multiple VFCs in a sewer system.

	Scenario one	Scenario two
Critical rainfall event duration	120 minutes	120 minutes
Location and type of VFCs	Junction 7 – 153 S-Type HBO	Junction 4 – 108 S-Type HBO Junction 5 – 129 S-Type HBO Junction 7 – 153 S-Type HBO
Total cost of VFCs	£2,250	£6,250
Volume of required cellular storage	671 m <sup>3</sup>	308 m <sup>3</sup>
Cost of cellular storage	£86,000	£39,500
Total cost of attenuation	£88,250	£45,750

### 3.3. Implementation of the benefits of vortex flow controls

The decision support tool proposed in this paper incorporates the work by Andoh and Declerck (1997, 1999), Jarman *et al.* (2011) and Newton *et al.* (2013). As discussed in Section 2, the decision support tool will suggest attenuation measures to improve the flood resistance of existing sewer systems. This will be achieved by the positioning and sizing of VFCs with the aim of attenuating flows to maximise the flood resistance, whilst minimising capital expenditure. The locations, at which the decision support tool will install VFCs, will be prioritised to exploit the maximum unused volumes of the sewer system during severe rainfall events in order to attenuate the flow. The ‘retrofit design method’, discussed in Section 3 & 4, will also be incorporated into the decision support tool to determine the appropriate design flow-rate of the VFCs. The envisaged benefits that this decision support tool will provide are:

- An increase in a sewer system’s flood resistance level.
- An increase in a catchment’s flood resistance level at a reduced cost compared to constructing a new surface water sewer system or upsizing the existing system.

- An increase in the self-cleansing frequency within the sewer system compared to using other types of flow controls.
- Development of cheaper flooding prevention schemes through using multiple flow controls rather than purely online storage.

#### 4. VFC positioning and sizing methodology

The fundamental process in this decision support tool is the positioning and sizing of the VFCs. The positioning and sizing of VFCs are dependent on a number of different factors which will vary at every sewer system junction. These factors are: the available upstream storage volume; the probability of the downstream subcatchment flooding; and the potential hydraulic head. An iterative approach will be taken to systematically design VFCs. Figure 4 shows the schematic of a simplified iterative method to: simulate; position; size; then calculate costs. The start of the process is to simulate the behaviour of the sewer system during critical rainfall events to locate conduits that contain the greatest unused storage volumes. Locations at which to install VFCs within the sewer system will be prioritised to increase the flood resistance, whilst reducing the negative socioeconomic impacts of flooding. This prioritisation process will rank the possible VFC locations based on the available upstream storage volumes, the subcatchment's area, the subcatchment's consequence of flooding and the subcatchment's current flood resistance level. The consequence of flooding for a subcatchment will be derived using CIRIA C635, 'Designing for exceedance in urban drainage - good practice' (Balmforth *et al.*, 2006). Within CIRIA C635, consequences of flooding are evaluated based on the existing structures on the subcatchment and use of the subcatchment. This will enable the user to minimise the negative socioeconomic affects from flooding for the least amount of expenditure. A VFC will be designed and installed in a location that is both downstream of a conduit with an unused storage volume and upstream of the subcatchment with the highest consequence rating. The design of the VFC will make use of the VFC design package from Hydro International plc (2013) and the 'retrofit design method', as shown in Figure 2. This will ensure that the mean flow-rate of the flow control, over the design head range, does not change and the downstream flow-rate capacity of the system is not exceeded. The capital cost of the VFCs and the lowest return period of any flood event will then be calculated and reported as an output for the user. The capital costs will include the cost of the VFC and, where the physical dimensions of the VFC mean it will not fit in the existing manhole chamber, the cost of a larger manhole chamber. These capital costs have also been supplied by Hydro International plc (2012). The iterative approach (Figure 4) would then be repeated. This cyclic method will be continued until all of the unused volumes within the sewer system are utilised or until it is not financially beneficial to continue.

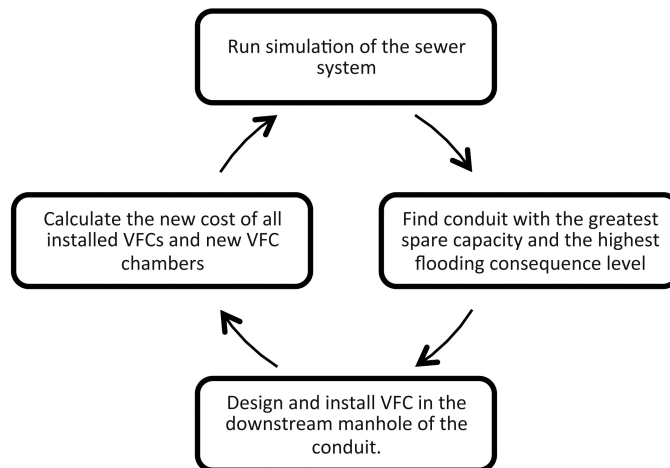


Figure 4: Flow chart of the iterative algorithmic approach proposed for the decision support tool.

## 5. Structure and components of the decision support tool

The overall structure of the decision support tool is illustrated in Figure 5. The decision support tool will be constructed using different programs to complete different tasks shown in Figure 4. The framework of the decision support tool will be constructed using Microsoft Excel. The other components that will be part of the decision support tool are: a sewer system simulator; a rainfall hyetograph generator; a VFC design tool and a flooding consequence estimator. All of these components are described and discussed in the following subsections.

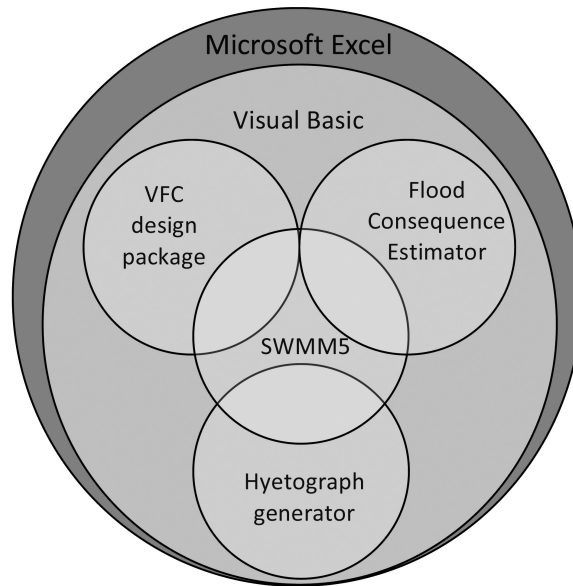


Figure 5: Illustration of the different components proposed for the decision support tool.

### 5.1. Data Management Portal (Microsoft Excel)

The primary function of the data management portal is to facilitate an interaction between the four tasks outlined in Figure 4 and achieve data transfer between the different components of the decision support tool. The portal will be built using Microsoft Excel, since most of the tool sub-components (e.g. VFC design package) exist in Microsoft Excel. The data transfer to and from sewer network simulation packages (e.g. SWMM5) can be achieved through programming in visual basic which is compatible with Microsoft Excel environment.

### 5.2. Sewer System Simulator

In order to prioritise the optimal location and size of a VFC for a sewer network under consideration, it is important to determine the unused capacity of the pipes, upstream of potential locations for VFC installation. To do this, a hydraulic simulation of a sewer network, subjected to a range of storm events, is required. In the proposed decision support tool, network simulations will be performed using the open source code of the Stormwater Management Model Version 5 (SWMM5). SWMM5 will evaluate a sewer conduits' used capacity for a given rainfall return period and locate unused volumes within the sewer system. SWMM5 provides the ratio of the filled capacity of a conduit as an output from a simulation. This output will be used in conjunction with the flood consequence estimation (described below) results to select the locations in the sewer system model at which to install VFCs. SWMM5 itself will not determine the location of new VFCs. The decision making process for VFC positioning will be written into the decision support tool programming using Visual Basic.

For the proposed tool, the selection of SWMM5 as the preferred sewer network simulator is based on several

factors. SWMM5 has inherent advantages in flexibility and usability as it is open source unlike InfoWorks CS and WinDes. Newton *et al.* (2012) found a number of benefits for using SWMM5 for this decision support tool over other commercial packages. One important benefit is that SWMM5 can accurately duplicate the transition phase of a VFC's behaviour, which is when a negative gradient in the head-flow characteristic occurs (Figure 1). SWMM5 has the additional benefit that the calculation functions can be operated directly from Microsoft Excel. This will be accomplished by writing function hooks in Visual Basic for the SWMM5 dynamic link library file. By using the SWMM5 dynamic link library file from Microsoft Excel, rather than opening the SWMM5 program itself, the decision support tool's computational time will be reduced and structure significantly simplified. Interaction of the decision support tool with commercial sewer system modelling packages (for example, InfoWorks CS), commonly used by several water services providers in the UK, will not be a restriction since sewer system model files of commercial packages can be converted into a format compatible with SWMM5 sewer model files.

### 5.3. Rainfall hyetograph generator

SWMM5 does not contain a rainfall hyetograph generator, unlike other hydraulic modelling packages such as InfoWorks CS and WinDes, and therefore a separate rainfall hyetograph generator will be required. The rainfall hyetograph generator will be developed using the method discussed in 'The revitalised FSR/FEH rainfall-runoff method' (Kjeldsen, 2007). One drawback of SWMM5 compared to InfoWorks CS and WinDes is that SWMM5 is computationally slower. In addition to this, SWMM5 is unable to perform sequential simulations without additional user interaction. To minimise the effect of these drawbacks, the superstorm methodology developed by Micro Drainage Ltd (2012) will be used. This methodology creates a single rainfall hyetograph for a given return period that is critical in both intensity and volume for that sewer system's geographic location. This single rainfall hyetograph is developed from a number of other rainfall hyetographs of the varying duration. ARUP (2012) developed the surface water management plans for Bristol City Council that used the superstorm methodology and found similar sewer system behaviours compared to real life events. The computational demand of the decision support tool will be reduced by applying the superstorm methodology as only one simulation per return period will need to be simulated.

### 5.4. VFC design package

The SWMM simulation results will also inform the VFC design process and investigate the impact the new designs on the extent of flooding. The VFC design package that will be used within the decision support tool was developed by Hydro International plc (2013). The VFC design package has also been supplied in a Microsoft Excel format, meaning it can be integrated within the decision support tool. The VFC design package uses the design equations derived by Jarman *et al.* (2011), as well as a genetic algorithm to optimise the geometry of VFCs for a user specified hydraulic behaviour (Jarman *et al.*, 2012). The VFC design package will design devices based on the allowable maximum head, determined by the geometry of the sewer system, and the flow-rate determined by the 'retrofit design method' (Newton *et al.*, 2013). The VFC design package provides the following information for the decision support tool and hence the final output for the user:

- The VFC's hydraulic behaviour
- The physical dimensions of the VFC
- Capital cost of the VFC
- Construction drawings

### 5.5. Flooding consequence estimator

The socioeconomic impacts of flooding will be assessed using a flood consequence estimator (FCE). The development of FCE is based on a methodology described Balmforth *et al.* (2006). The FCE results will allow the prioritisation of subcatchments for positioning VFCs to minimise the overall impact of flooding. For example, if two subcatchments had the same flood resistance level but one subcatchment contained a hospital compared to the other subcatchment containing a playing field, the decision support tool would prioritise to protect the subcatchment containing the hospital as it has a higher consequence of flooding (Balmforth *et al.*, 2006). The FCE component of



the decision support tool will require users to input details of the types of buildings and structures in the subcatchments into the sewer system model. This will enable the decision support tool to focus on priority areas so the tool user gains a greater benefit for a given capital expenditure.

## 6. Decision support tool outputs

The basic outputs from the decision support tool will be a plot of the capital cost for the proposed VFCs (and the cost of new sewer system chambers, if applicable) against the increase in the level of flood resistance provided by each additional VFC. This will produce a graph similar to that shown in Figure 6a, where each point on the graph is the addition of a VFC to the sewer system and hence a new cost and flood resistance level is found. The outputs will inform the user of the cost associated with increasing the level of flood resistance. The data shown in Figure 6a is only for illustration purposes, providing an example of the decision support tool output format.

The results of the decision support tool may also be weighted by the user to rescale the results for their different corporate, health and safety and operational policies that may be important to consider during the design phase. An example of the outputs from the decision support tool influenced by a notional weighting factor is shown in Figure 6b. An example of a notional weighting factor could be the predicted capital costs of installing the new VFCs (manhole access, manhole cleaning, etc.) and installing larger sewer system chambers (removal of old manhole, sewer diversion, delivery of new manhole, installation of new manhole, relay of the road, etc.) as provided by Langdon (2013).

The final output from the decision support tool will be a log of the different VFCs installation options for the sewer system model detailing their design points and their intended location(s) within the sewer system.

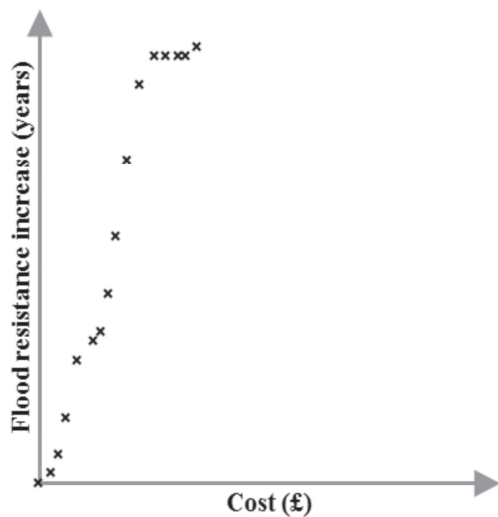


Figure 6a: Graph demonstrating example outputs from the decision support system.

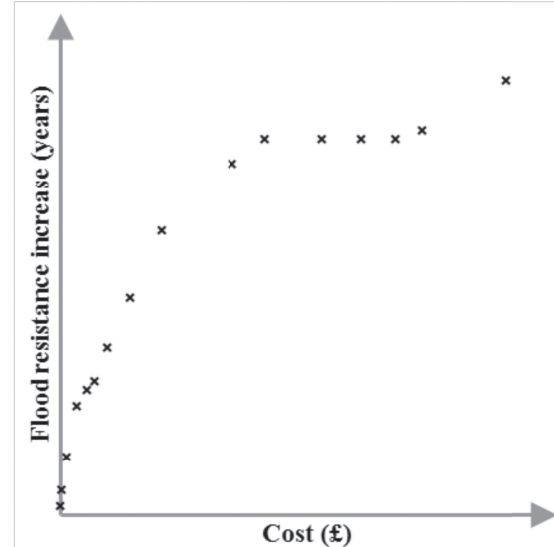


Figure 6b: Graph demonstrating example outputs from the decision support system where the costs have also been influenced by a notional weighting factor.

## 7. Conclusion

This paper has discussed the benefits and the methods of increasing the flood resistance of existing sewer systems in response to current economic and environmental drivers. A decision support tool has been proposed that will assist in the design and strategic placement of vortex flow controls within existing sewer systems to make use of previously unused volumes for flow attenuation. The vortex flow controls will enable effective attenuation of the potential flood volumes during severe rainfall events with the aim of increasing flood resistance. This paper discusses the structure of the decision support tool including its components, their development and how they will

be applied. This paper has also proposed that the results of the decision support tool will be able to be weighted to enable users to take into account company health and safety and operational policies in the decision making process.

This decision support tool is envisaged to offer considerable benefits to urbanised catchments with existing sewer systems where the introduction of SuDS or rainwater harvesting measures to increase flood resistance are unfeasible or impractical. The expected benefits of the decision support tool are that the solutions could provide additional options to increase the flood resistance of a catchment at a lower cost compared to constructing new additional sewer systems.

## References

- Allitt, M., & Tewkesbury, A. (2009). Investigation into Urban Creep at 5 Cities. *WaPUG Autumn Conference*.
- Andoh, R. Y., & Declerck, C. (1997). A cost effective approach to stormwater management? Source control and distributed storage. *Water Science and Technology* 36, 307-311.
- Andoh, R. Y., & Declerck, D. (1999). Source control and distributed storage - a cost effective approach to urban drainage for the new millennium? *8th International Conference on Urban Storm Drainage*, pp. 1997-2005. Sydney, Australia.
- Balmforth, D., Digman, C., Kellagher, R., & Butler, D. (2006). *Designing for exceedance in urban drainage - good practice*. London: CIRIA.
- British Geographical Survey. (2013). *Suitability of the subsurface for infiltration SuDS in Great Britain*. NERC.
- Department for Environment, Food and Rural Affairs. (2011). *National standards for sustainable drainage systems*.
- Digman, C., Ashley, R., Balmforth, D., Balmforth, D., Stovin, V., & Glerum, J. (2012). *Retrofitting to manage surface water*. London: CIRIA.
- Education Scotland. (n.d.). *White Cart Water Flood Prevention Scheme*. Retrieved January 25, 2013, from [http://www.educationscotland.gov.uk/Images/WhiteCartWaterFloodPreventionScheme2\\_tcm4-716465.pdf](http://www.educationscotland.gov.uk/Images/WhiteCartWaterFloodPreventionScheme2_tcm4-716465.pdf)
- Gemmell, I. (2010). Wigan Flood Alleviation Scheme. *Current Magazine*.
- Hydro International plc. (2012, November). Personal communication.
- Hydro International plc. (2013). Personal communication.
- Jarman, D. S., LeCornu, P., & Andoh, R. Y. (2012, August 02). *Patent No. GB1213721.2*. Great Britain.
- Jarman, D. S., LeCornu, P., Tabor, G., & Butler, D. (2011). Vortex flow control performance in response to single and time-series rainfall events. *CCWI 2011, 5-7 September*. Exeter, UK.
- Jarman, D. S., Tabor, G., Butler, D., & Andoh, R. Y. (2011). The use of CFD coupled with physical testing to develop a new range of vortex flow control with attributes approaching the ideal flow control device. *World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability*. Palm Springs, California, US.
- Kjeldsen, T. R. (2007). *Flood Estimation Handbook: The revitalised FSR/FEH rainfall-runoff method*. Wallingford, UK: Centre for Ecology & Hydrology.
- Langdon, D. (2013). *Spon's Civil Engineering and Highway Works Price Book*. London: Spon Press.
- Micro Drainage Ltd. (2012). *Super-Storm*. Newbury, UK.
- Mott MacDonald. (2011). *Future Impacts on Sewer Systems in England and Wales*. OFWAT.
- Murphy, J. M., Sexton, D. M., Jenkins, G. J., Boorman, P. M., Booth, B. B., Brown, C. C., et al. (2009). *UK Climate Projections Science Report: Climate change projections*. Exeter: MET Office Hadley Centre.
- Newton, C. J., Jarman, D. S., Memon, F. A., Andoh, R. Y., & Butler, D. (2012). *Comparison and selection of a hydraulic modelling package*.
- Newton, C. J., Jarman, D. S., Memon, F. A., Andoh, R. Y., & Butler, D. (2013). Improvements in vortex flow control design to increase sewer network flood resistance. *IWA Sewer Processes and Networks*. Sheffield, UK (in press): IWA.
- Office of National Statistics. (2011). *2010 - Based National Population Projections*.
- Ove Arup & Partners Ltd. (2012). *Bristol Surface Water Management Plan: Phase 1*. Bristol.
- Rossman, L. A. (2012). *Storm Water Management Model Version 5.0.22*. United States Environmental Protection Agency.
- SMART Motorway Tunnel. *Stormwater Management and Road Tunnel (SMART)*. Retrieved July 1, 2013, from <http://smarttunnel.com.my/>
- US Environmental Protection Agency. *SWMM5 Interfacing Guide*.
- Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SuDS Manual*. London: CIRIA.