Vortex flow controls: state of the art review and application (from the catchbasin to the dam)

Contrôle des flux par effet vortex : état de l'art et applications (du bassin versant au barrage)

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RÉSUMÉ

La gestion des événements pluviométriques intenses est un défi majeur pour la conception des systèmes d’assainissement. Leur localisation et leur intensité sont par nature difficiles à prédire avec précision, et le seront d’autant plus à l’aube du changement climatique. L’étalement et la densification de l’environnement urbain ainsi que les pratiques actuelles d’usages des sols rendent la situation d’autant plus délicate qu’ils contribuent à augmenter les ruissellements. Cela résulte en des inondations accrues et des surverses de réseaux unitaires dans le milieu naturel. Les solutions de gestion à la source sont alors considérées comme étant plus durables que les solutions traditionnelles « au bout du tuyau ». Un point essentiel motivant le recours à ces solutions est le besoin de contrôler les débits. Dans ce contexte, cet article présente une revue des systèmes de contrôle de débit par effet vortex. De tels systèmes ont un fonctionnement purement hydraulique, ce qui leur confère une capacité d’auto-curage plus grande que les systèmes linéaires conventionnels tels que les orifices calibrés. Ils présentent également un intérêt pour l’efficacité attendue des ouvrages de stockage amont grâce à leur caractéristique «hauteur de charge-débit » en forme de « S ». Cet article présente un certain nombre d’exemples dans lesquels des systèmes de contrôle par effet vortex ont été utilisés avec succès, incluant des usages en grand nombre pour le contrôle des débits en entrée de système d’assainissement et, à plus grande échelle, sur des barrages écrêteurs de débits.

ABSTRACT

Capacity considerations represent one of the primary challenges in drainage system design. Wet-weather location and intensity are inherently difficult to predict accurately and will become increasingly difficult with the onset of climate change. Expansion and densification of the urban environment and modern land management practices further complicate the position by increasing stormwater runoff rates. The result is increased flooding and the discharge of combined stormwater and foul sewage into the natural environment. Source control approaches to stormwater management are increasingly regarded as being more sustainable than traditional ‘end of pipe’ solutions. Fundamental to such approaches is the requirement for flow controls. This paper presents a review of the design, application and benefits of vortex flow controls as applied in this context. Such devices operate using purely fluidic means, which provides them with significantly larger clearance than conventional linear flow controls such as orifice plates, and also leads to benefits in terms of efficiency of use of upstream storage facilities, resulting from their unique S-shaped head-flow characteristic. The paper includes a number of case studies of where vortex flow controls have been successfully applied, including use in large numbers on sewer inlet control schemes and at large scale on flood alleviation dams.

KEYWORDS

Vortex flow control, vortex valve, source control, distributed storage, flood alleviation

1 INTRODUCTION

Stormwater management issues have become extremely topical in recent years, not only among industry professionals, but also among the general public. Public exposure to the challenges faced is increasingly first hand, with extreme flooding appearing to have become more frequent and accordingly high levels of attention being paid to this in the popular press. The causes of the flooding have been overwhelmingly linked to the activities of mankind. Surface water runoff has traditionally been regarded as an inconvenience; something to ‘get rid of’ as quickly as possible.

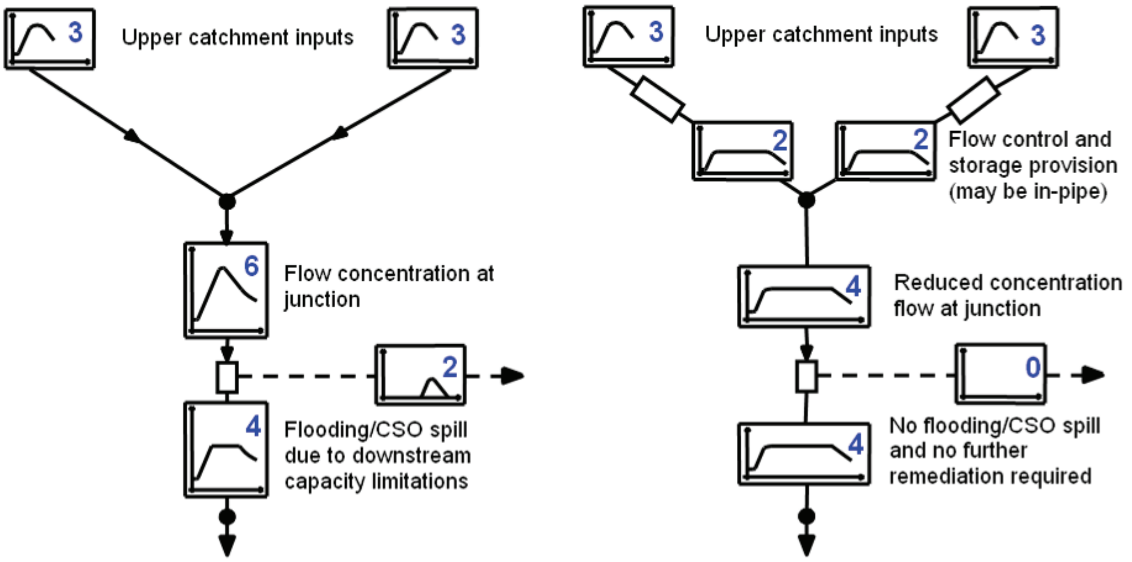
The early sewer systems of Europe evolved along an essentially reactive course, originating as simple channels designed to collect and transport surface water to the nearest watercourse (Stanbridge, 1976). In many cases, these were also used as conduits for the disposal of human waste and were ultimately covered over, along with the watercourses that they fed into. Eventually, these evolved into the combined sewer systems that remain in service today, coupled with wastewater treatment facilities to treat the effluent prior to discharge to the natural environment. The advent of the engineered sewerage system and accompanying treatment facilities has no doubt had major implications to the status of public health in the developed world, playing an important role in the subsequent prosperity of these regions. However, some fundamental challenges remain. While climate change is expected to lead to less frequent, more intense rainfall (DEFRA, 2009), the effects have been accentuated by inappropriate urban development and also changes in agricultural land management practice. Over-working of agricultural land can lead to ground compaction and increased run-off rates (Boardman *et al.*, 1994). Expansion or densification of the built environment, during which previously permeable ground is replaced with impermeable surfaces, can also lead to increased run-off (Butler and Davies, 2000). A traditional response has been to implement remedies “at the point of the problem”. For example, in a situation where a settlement suffers from flooding due to watercourse breaches, a popular option has often been to simply heighten the breach level, using either permanent or temporary facilities. At a more localised level, sewer flooding issues have been resolved through either implementing higher capacity pipework (also denoting a need for higher capacity treatment plant) or instating emergency relief facilities - “combined sewer overflows” (CSOs).

A long held aspiration of the drainage manager has been to replace combined sewers with separate foul and surface water sewers, one leading to treatment, the other to a watercourse. Indeed, in many developments of the modern world, this approach has been taken from the outset. Such approaches have, however, failed to address stormwater quantity issues. They have also lead to unexpected water quality issues, due to the fact that stormwater often contains pollutants such as heavy metals, hydrocarbons and nutrients, entrained from the surfaces over which it flows (Campbell *et al.*, 2005). The reactive approach of “getting rid of stormwater as quickly as possible” and dealing with resulting difficulties “at the point of the problem” is now generally understood to be unsustainable (though is often still implemented perhaps due to short-term convenience (Faram *et al.*, 2010)). In the context of this paper, the concept of source control is advocated, with particular attention paid to how vortex flow controls can be applied as part of effective and economical stormwater management solutions.

2 SOURCE CONTROL MANAGEMENT OF STORMWATER

In the UK and elsewhere, it is now standard practice for new developments that increases in surface water runoff must be compensated for through the provision of infiltration or storage and flow control facilities, designed to control discharge rates to no more than pre-development rates (CIRIA, 2007). Flow control is therefore an important element in source control. Further opportunities are to be gained through implementing such approaches into existing drainage infrastructure.

Andoh and Declerck (1999) present a useful study comparing the relative economics of implementing a source control solution compared to a downstream solution into existing drainage infrastructure, with the objective of reducing CSO spills. Figure 1 provides an illustration of the concept of this approach, with Figure 1(a) presenting a scenario in which the downstream system capacity is exceeded, leading to flooding. Conventional remediation of this might involve either the implementation of higher capacity pipework or the provision of a CSO facility at the point of undercapacity. The first of these options may ultimately denote the requirement for upgraded downstream treatment facilities, while the second will result in polluted effluent being discharged to a watercourse. Figure 1(b) illustrates the effect of implementing source control facilities into the upper catchment. This could involve the provision of flow control and storage facilities, or where spare capacity in upstream pipework allows, only flow controls. The illustration demonstrates that through this approach, it may be possible that the flooding or CSO spill could be eliminated.



(a) Overloaded system with CSO requirement

(b) System with source control implemented

Figure 1 Hydrograph response (with peak flow rates) at different points in a drainage system before and after remediation – 'conventional' and 'source control' approaches (adapted from Andoh and Declerck (1999))

Andoh and Declerk's (1999) study found that the source control option was significantly more cost effective than the conventional approach. At a practical scale, there are now a number of examples, particularly in the USA, of where source control approaches have been applied extensively as a means of reducing CSO spills and flooding. A well documented example is that of Skokie, near Chicago (Carr and Walesh, 2008). Further examples are provided later in the paper.

With flow control being an important element in source control, the following section reviews flow control types, leading to an introduction to vortex flow controls.

3 FLOW CONTROL TYPES AND BEHAVIOUR

Various types of flow control are used in practice, ranging from simple orifice plates and float controlled valves to vortex flow controls and real time controlled (RTC) penstocks. These operate in different ways, some employing mechanical or electro-mechanical principles in their operation, others employing purely hydrodynamic means. This has implications to their performance as well as cost. Table 1 provides a summary of the key attributes of these devices.

Device	Operating mechanism	Clearances	Hydraulic performance	Cost
Orifice plate	Hydraulic /hydrodynamic	Constant/small	Least optimum	Low
Float controlled valve	Mechanical	Variable – reduce with increasing head	Tending towards optimum	Moderate
Vortex flow control (VFC)	Hydraulic /hydrodynamic	Constant/large	Tending towards optimum	Moderate
RTC penstock	Electro-mechanical	Variable – adapt to suit requirements	Potentially optimum	High

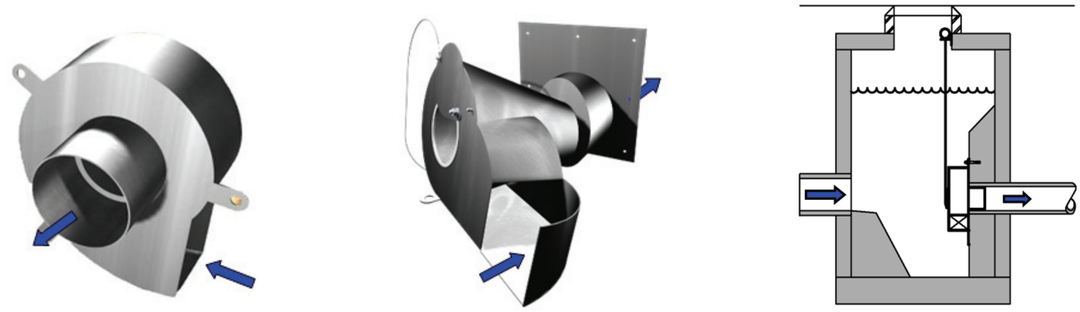
Table 1 Flow control types and attributes

One important parameter, the device clearances, affects the ability of a device to transfer debris and hence avoid blocking. Another is the ability to transfer flows at low heads, avoiding premature consumption of storage volumes, for example, during the early stages of a storm. The simplest and cheapest form of flow control is the orifice plate. Orifice plates can provide effective flow control but have some practical limitations. They tend to over-restrict flows at low heads when it is not required, resulting in inefficient use of upstream storage and increased liability to blockage. Float controlled valves, RTC penstocks and vortex flow controls provide the opportunity for adaptable flow regulation during the course of a storm, allowing more efficient use of storage compared to orifice plates. While float valve and penstock systems employ physical restriction in their operation, vortex flow controls use purely hydrodynamic means (Lamb, 1983). As a result of this these systems are more resilient to blockage. Vortex flow controls are described in more detail in the following section.

4 VORTEX FLOW CONTROLS – STATE OF THE ART REVIEW

4.1 Overview and benefits

The idea of applying vortex flow controls in the field of stormwater management is believed to have originated in the 1970's (Brombach, 1972; 1981; Smisson, 1980) becoming increasingly popular from the 1980's through to the present day (Lamb, 1984; Faram and Kane, 2006; Andoh *et al.*, 2009). Figure 2 provides illustrations of typical proprietary devices, along with a typical installation layout for a sump-style unit. Sump-style units tend to be more efficient than conical units, but do not allow complete draindown of upstream facilities, so are typically preferred for surface runoff applications.



(a) Sump-style unit (b) Conical-style unit (c) Installation detail (sump-style)

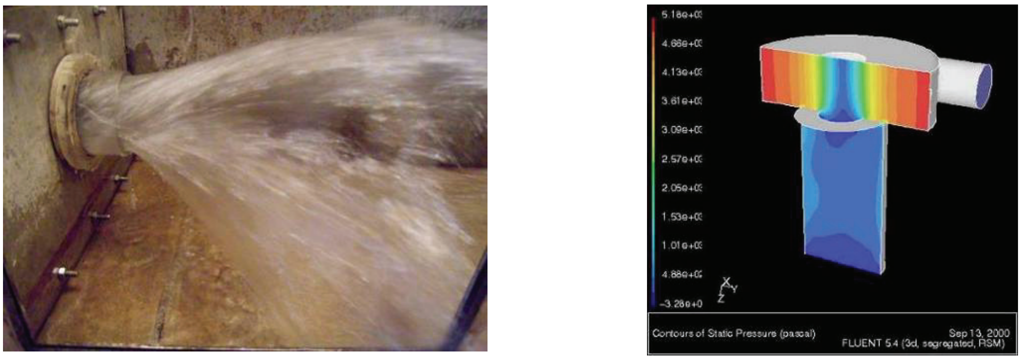
Figure 2 Sump and conical style vortex flow controls and installation detail

Vortex flow controls operate according to the principle that a pressure drop is generated when a flow is accelerated into a swirling motion. This generally results in the formation of an air core along the device axis, resulting in an annular discharge of flow at the outlet in the form of a spiral fan.

Practical benefits of using vortex flow controls include:

- Physical clearances for a given head-flow duty point can be up to five times larger than for conventional linear flow control devices (e.g. orifice plates) – this is a very important feature, as it significantly reduces the likelihood of blockage, thereby reducing maintenance.
- At low heads, vortex flow controls behave like a large orifice – this means that early-storm flows are not unnecessarily held back, which allows enhanced utilisation of upstream storage facilities. This is explained in more detail later in the paper.
- The fanning of the discharge flows reduces the likelihood of scour that can occur with linear flow control devices, where energy can be directed towards outlet structures.

Figure 3 shows the fanned spiral discharge of a small vortex flow control unit, alongside a prediction from computational fluid dynamics showing gradients of pressure across the vortex.



(a) Fan-shaped flow at the discharge of a vortex flow control (b) CFD prediction of pressure loss

Figure 3 Flow and pressure effects at the outlet of and inside a vortex flow control during operation

It has been suggested (Lamb, 1983) that the flow fanning will also increase the level of dissolved oxygen in the water, which has a bearing on water quality improvement. This may also reduce its temperature (i.e. due to evaporative cooling) which could have relevance in situations where surface water is being received from man-made surfaces in warmer climates.

4.2 Hydraulic characteristics and opportunities in practice

Vortex flow controls have a unique hydraulic characteristic. At low heads, they behave like a large orifice plate. At higher heads, as the vortex initiates, their behaviour transitions to equivalent to a small orifice plate. This results in an S-shaped head-flow characteristic, illustrated in Figure 4. As indicated previously, this presents storage, space and ultimately costs saving opportunities (in addition to increasing clearances) when compared to use of conventional flow controls such as orifice plates.

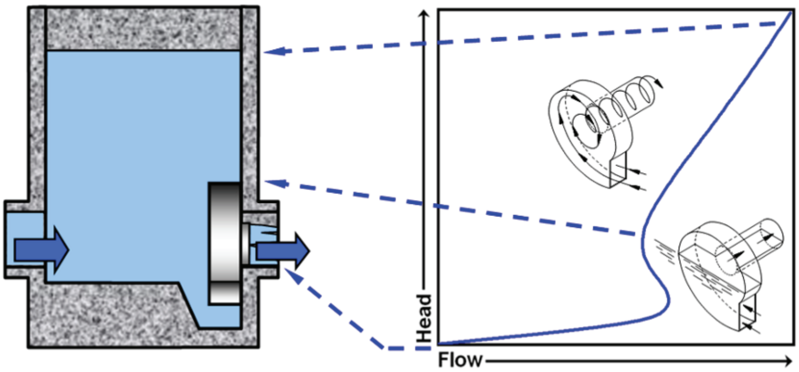


Figure 4 Vortex flow control hydraulic characteristic

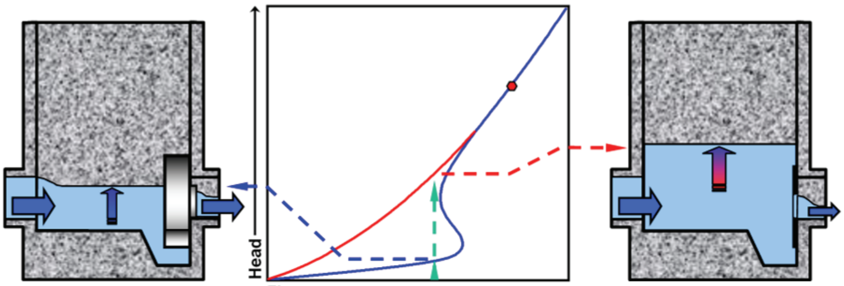
The benefits compared to an orifice plate can be illustrated through comparing the operation of the two devices under different conditions. Figure 5 shows orifice and vortex flow control chambers and respective hydraulic characteristics.

- At low flowrates (for example at the start of a storm) the headloss through the orifice plate will be significantly larger than that through the vortex flow control, due to the orifice plate having smaller clearances. The result of this is that the orifice plate chamber will operate with a higher head than the vortex flow control chamber (Figure 5(a)).
- As the flowrate increases, the orifice plate chamber will continue to operate at a higher head until such a point as the vortex flow control is fully submerged. From this point, the flow controls will converge to a similar hydraulic characteristic, though since the vortex flow control will have discharged more flow earlier in the storm, the available storage volume will have been used more economically (Figure 5(b)).

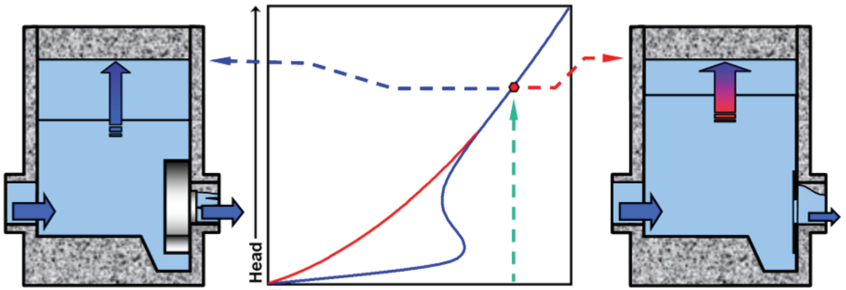
The result of the above in practice is that upstream storage will be better utilised. In the retrofit context, this can either eliminate or reduce the capacity requirement for added storage (e.g. in the context of an overstressed network and assuming some in-pipe storage is possible) or in the context of new development, reduce volume requirements for new storage. This can lead to significant cost savings.

Recently, LeCornu *et al.* (2008) have undertaken simple model studies to predict the hydrograph response of a vortex flow control, an orifice plate and an ‘ideal’ flow control, each with the same duty head-flow point (an ideal flow control discharges flow below the duty flowrate immediately and then at the duty flow for flowrates exceeding this). Graphical outputs from the study are shown in Figure 6. The profiles were found to correspond generally in appearance with those determined from experimentation by Parsian and Butler (1993). Analysis to look at opportunities for storage savings when devices were modelled in this context found that a vortex flow control could allow volume reductions of over 20% compared to when an orifice plate was used, extending to over 50% in special circumstances. Notably, the study also found that recovery times were significantly faster i.e. the time for the storage volume to return to an empty state. Vortex flow controls are now incorporated into many hydraulic modelling packages, allowing these opportunities to be exploited in practical design.

In some situations, land area under which to construct storage facilities can be a constraining factor, for example, in densely urbanised areas. In these situations a vortex flow control can be used to facilitate the use of deeper/lower footprint storage, but without compromising on clearances. Figure 7 illustrates this, showing how the same duty point can be achieved using a vortex flow control and an orifice plate with the same clearances but different zero head datums.

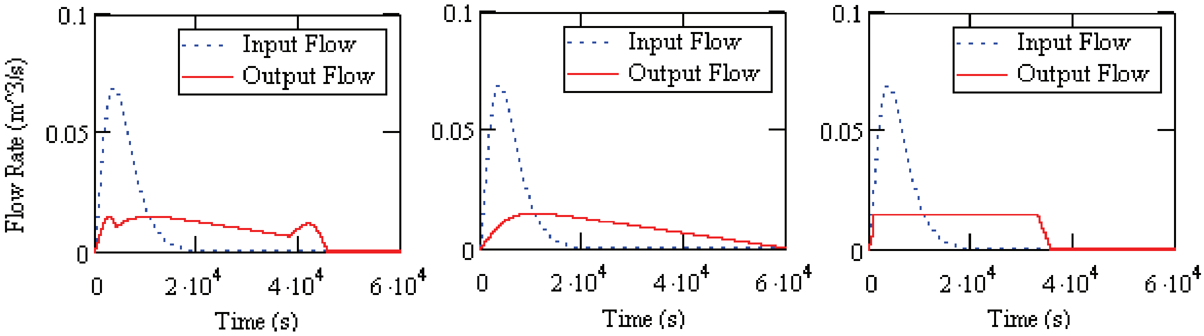


Vortex flow control (a) Low inlet flowrate Orifice plate



Vortex flow control (b) Higher inlet flowrate leading to duty point Orifice plate

Figure 5 Vortex flow control and orifice plate hydraulic characteristic comparisons for different inlet flowrates for units designed to give the same duty head-flow point (but with different clearances)



(a) Vortex flow control (b) Orifice plate (c) Ideal flow control

Figure 6 Hydrograph response characteristics of a vortex flow control, an orifice plate and an 'ideal' flow control, designed to meet the same duty head-flow point (LeCornu *et al.*, 2008)

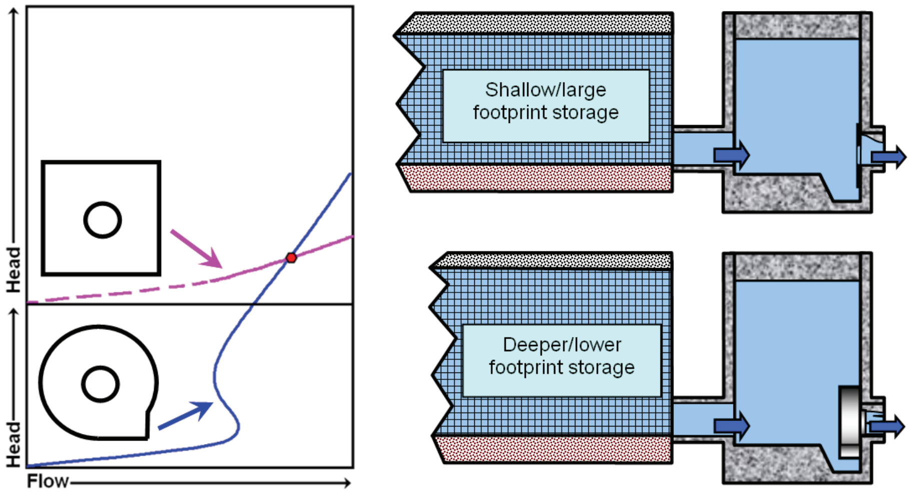


Figure 7 Vortex flow control and orifice plate characteristics for units with the same clearances, but designed with a different zero head datum to give the same duty head-flow point

5 APPLICATION CASE EXAMPLES

5.1 Evanston, Illinois, USA – inlet control scheme to prevent sewer flooding

The City of Evanston had a sewer flooding problem, leading to flooding of hundreds of basements up to six times a year. With the problem becoming progressively worse, city officials decided to embark on a major overhaul of the city's sewers (Hides, 1994). Working with consultants, the technical options summarised in Table 2 were identified, providing different levels of protection at different costs.

Option	Est'd cost ($million)	Level of protection	
		Basements	**Streets**
(1) No action	-	2 m	6 m - 1 yr
(2) Total sewer separation	320	100 yr	100 yr
(3) Combined sewer relief	290	10 yr	10 yr
(4) Inlet flow controls & partial sewer separation with overland flow	125	100 yr	5-10 yr
(5) Partial sewer separation without overland flow	210	100 yr	5-10 yr

Table 2 Options considered for addressing the sewer flooding problem in Evanston (adapted from Hides (1994))

The traditional solutions of installing relief sewers or replacing existing sewers with larger ones were not found to be acceptable, further to which 90% of Evanston's streets would be affected. Ultimately, the consultant recommended option (4) (see Table) involving rehabilitating portions of the existing combined sewers, installing stormwater relief sewers in downstream areas, and implementing an inlet control system in upstream catchment areas, designed to reduce the rate of flow into the combined sewer and create overland flow routes, diverting stormwater to the new relief system. Implementation commenced in 1991, continuing over a period of 12 years, during which time around 2800 vortex flow control units were installed. The scheme was very successful, virtually eliminating the sewer flooding problem at a cost that was acceptable to the city.

A similar approach is currently being implemented in Ottawa, Canada. Phases I and II of the $25 million (CAN) plan will involve the installation of approximately 1,000 vortex flow controls in catch basins during 2009 and 2010 (Andoh *et al.*, 2009).

5.2 Wadley Road, London – early inlet control scheme in the UK

One of the first examples of an inlet control based approach to addressing sewer capacity issues is that of Wadley Road in the Waltham Forest area of London (Lamb, 1983). Wadley Road was prone to flooding, caused by overflowing of the sewer system. The conventional solution of installing a bypass system was not appropriate, due to the cost and the fact that it would possibility transfer the problem to another street further downstream. To solve the problem, in 1983, nine vortex flow controls were installed at strategic points in the upstream system, coupled with diversion of excess flows to an existing ditch, with additional underground storage being considered longer term. Figure 8 shows the upstream pipe layout, identifying the area that had been prone to flooding, and the locations at which the vortex flow controls were installed.

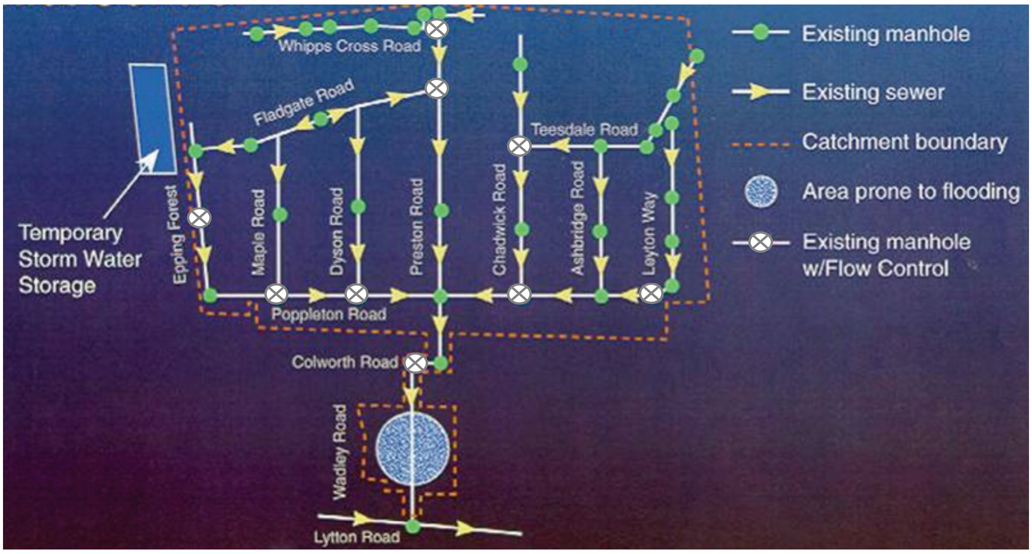


Figure 8 Layout of pipework upstream of the flood-prone Wadley Road, with locations of vortex flow controls

5.3 Chesapeake Bay, USA – regulation of discharges for watershed protection

To alleviate stormwater quality and thermal pollution of Chesapeake Bay estuary in Maryland, regulations require that in certain circumstances, a predetermined ‘water quality volume’ of stormwater runoff must be stored on a developed site. In a particular project for Chevy Chase bank in a town within Montgomery County, engineers had to comply with the above regulations, in addition to local ‘channel (erosion) protection storage volume’ and 2 inch (50mm) flow control minimum clearance requirements. Initially, they proposed to use shallow, arched media for storage, but hydraulic modelling showed that a 2 inch orifice plate would overdischarge even at the low head provided, while site constraints were such that the storage system would not fit within the available area. As an alternative, they considered using deeper, concrete chambers that would operate at only a proportion of total capacity. This resulted in an 826m^3 volume that was around 40% oversized and that might still exceed consents if operated above design capacity.

To address the problem, a 3.375 inch (86mm) outlet vortex flow control was used, which could achieve the required discharge rate at much higher heads, significantly reducing the need for excess storage. This approach provided footprint and storage volume savings of around 40%, along with cost savings. Figure 9 illustrates this (vortex flow control option labelled “Hydro solution”).

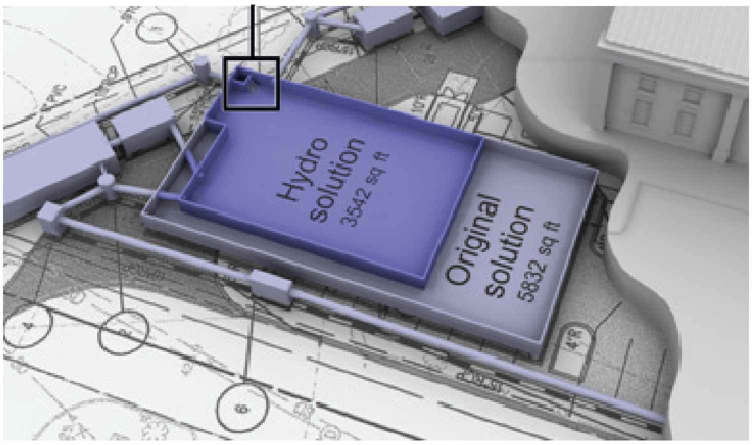

Location of vortex flow control

Figure 9 Storage area required for the original and final design options for Chevy Chase bank

5.4 Weedon Bec, UK – use of vortex flow controls on a flood alleviation dam

Weedon Bec, a small village in the East Midlands of England, had no formal flood defences. The village had suffered serious flooding from the River Nene during the Easter of 1998 and was at risk of flooding during a 1 in 3 year storm event with some 95 properties at risk. The main cause of flooding was the limited capacity of culverts under a railway embankment downstream of the village and at a road bridge within the village.

Consultants seeking a solution considered a range of options (Boakes *et al*., 2004) but quickly settled on the concept of constructing a dam upstream of the village. One alternative of increasing the channel capacity would involve doubling the existing river size and enlarging the road bridge and railway culverts. This would be costly, lead to land loss and disruption and might also create flooding problems further downstream. A further option was to contain the flows by constructing a flood wall. However, this would need to pass through 30 private gardens and would also be costly and disruptive. There would also be access issues for future inspection and maintenance.

In 2002, an earth filled dam with a maximum height of 6.8m and crest length of around 450m was constructed at a site within a kilometre upstream of the village, where the river flowed through a valley. This is shown in Figure 10. The consultants considered three alternative flow control options, including a fixed orifice, an automatic penstock and a vortex flow control. These were modelled to establish water levels and extent of upstream flooding during different return period storm events. The outputs of this are included in Table 3, also including approximate return periods at which storage would begin.

The option of using an orifice plate was eliminated due to the fact that it would result in frequent and significant flooding of the land upstream of the dam, which would impact its agricultural value. This would be unacceptable to the affected landowners. Use of an automatic penstock was also not deemed appropriate, as this would require power to be provided to the site. There was also concern about possible power failure during storm events or failure of mechanical/electrical components due to intermittent use.

The preferred option, a vortex flow control with an outlet size of 1.75m was installed on the upstream side of the dam. This was fitted at the inlet of a box culvert, shown in Figure 11(a). The unit was designed to control the peak flow through Weedon Bec from 26 m^3/s to an acceptable level of 10 m^3/s during a 1 in 50 year storm event. A diagrammatic comparison of the stored flood levels and storage areas for the control options is shown in Figure 11(b) demonstrating that use of a vortex flow control (referred to as a “Hydro-Brake”) significantly reduces the extent of flooding that will occur during operation compared to when an orifice plate is used as the flow control.

Figure 10 Photographs of the Weedon flood alleviation dam (aerial view from Boakes *et al.*, 2004)

Flow control option	**1 in 3**		**1 in 50**		**Return period when storage begins**
	Level (mAOD)	**Flooded area (m^2)**	**Level (mAOD)**	**Flooded area (m^2)**	
Fixed orifice	89.6	146,145	91.7	417,890	1 in 1 year
Automatic penstock	88.2	21,660	91.5	379,610	1 in 3 year
Vortex flow control	88.6	49,635	91.4	369,370	1 in 1 year

Table 3 Storage areas and levels and approximate storm return periods at which flooding will commence for the different flow control types considered

(a) Vortex flow control being installed

(b) Flooding areas for different flow controls and storm events (adapted from Boakes *et al.*, 2004)

Figure 11 Weedon dam vortex flow control and flood area for 1 in 3 and 1 in 50 year storm events

With flooding presenting major challenges in the UK, there are now numerous schemes similar to that described above, either completed, or being prepared for implementation. One such scheme is Glasgow’s £50 million White Cart Water Flood Prevention Scheme (www.whitecartwaterproject.org) which was approved for progression in 2006. For many decades, residents and businesses in the south side of Glasgow had been under the threat of flooding from the White Cart Water (river). Levels can rise by up to 6 meters following 12 hours of rainfall, which in 1984 resulted in the flooding of 500 homes. The solution, which is currently being implemented, involves the creation of three flood storage areas upstream of the city, along with flood walls and embankments at certain points along the river corridor. The storage areas are being fitted with a total of five large vortex flow controls, with outlet sizes ranging from 1.7 to 1.9 meters, and individual unit design flowrates exceeding 10 m^3/s with design heads of up to 12.5m. This will ensure economical use is made of the available storage.

6 CONCLUSIONS

Vortex flow controls are versatile structures that help to provide a high degree of flexibility in the design of new drainage systems and the adaptation of existing drainage systems. They have large clearances compared to conventional flow controls and have a unique S-shaped head-flow characteristic that presents opportunities in enabling economical use of upstream storage facilities. The presented case studies demonstrate how vortex flow controls have been applied in a range of situations, ranging from controlling flows from catchbasins into collector sewers to controlling flows on flood alleviation dams.

To address future water issues in the most economical and effective manner, society will need to adopt integrated water management plans that prevent problems before they occur. Vortex flow controls are found to present opportunities in this context, enabling better solutions to be delivered with significant cost savings compared to conventional approaches.

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