Physical characterisation and hydrograph response modelling of vortex flow controls

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ABSTRACT

Urban drainage networks require accurate, reliable flow control systems for their effective operation and minimisation of flood risk. Different types of flow control produce different hydraulic characteristics, having implications to system design in particular relating to upstream storage utilisation. Vortex flow controls (VFCs) present particular opportunities, producing desirable hydraulic characteristics while also having large clearances compared to other devices. This paper describes the implementation of advanced flow control characterisation procedures and techniques allowing VFCs in particular to be characterised within a period of a few hours. The results are shown to correspond with those collected using conventional methods. Work is also described relating to the development and application of a model to allow storm hydrograph response modelling of storage-flow control combinations. It is demonstrated how the use of a VFC can lead to significantly more efficient storage utilisation compared to when a simple orifice plate is used. Further to this, it is found that system recovery times can be significantly improved, with gains of in excess of 35% being obtained. Initial verification of the simulations shows a favourable correspondence with test outputs produced by others.

KEYWORDS

Urban drainage; flooding; storage; vortex flow controls; instrumentation; storm modelling.

INTRODUCTION

The serious flooding events that have been at the forefront of the news over the last few years have highlighted the requirement for more effective urban storm water management controls. In many spheres of activity, development has been shown to have an adverse effect on runoff hydrographs; paving over or compacting land can increase peak flows (Ziemer, 1981) and clearance of forest can increase runoff volumes (Hewlett and Helvey, 1970).

In order to mitigate the adverse impacts of development, the use of flow controls in conjunction with upstream storage facilities has become common practice. In new developments, flow controls and underground or surface storage are often applied to control stormwater discharge rates to no more than pre-development run-off rates (Faram and Kane, 2006). Opportunities are also presented through the strategic placement of flow controls in existing drainage networks to take advantage of in-pipe storage (Smisson, 1980). At a larger scale, advanced flow controls have been used in conjunction with dams to prevent flooding of downstream communities by allowing flow to back up onto agricultural land (Boakes *et al.*, 2004).

For any storage based stormwater management approach, there will be an associated cost of installation and potentially an opportunity cost (e.g. in the case of surface storage, there may be land-take implications). It can therefore be seen that techniques for maximising the efficiency of storage utilisation can lead to savings in terms of space requirement and cost, in addition to reduced risk of flooding (Andoh and Declerck, 1999).

Storage operation is governed by the incoming flow hydrograph and the hydraulic characteristics of the flow control device at the outlet. Ideally, a flow control should be designed to discharge at as close to consented flow rates as possible. As well as preventing downstream flooding, this also ensures that storage volumes are not consumed prematurely. For new developments this can enable a more efficient design, manifesting as reduced storage volume requirements, with implications to both installation and opportunity costs.

The ability to accurately and reliably control flows in drainage and sewerage systems is critical for the effective operation of such systems. Use of inaccurate or unreliable flow controls can lead to undesirable effects including flooding. This paper is concerned with methods for the accurate characterisation of flow controls, with a particular emphasis on vortex flow controls (VFCs). A mathematical model of storage and flow control operation is also presented, allowing comparisons to be made between the various different types.

FLOW CONTROL TYPES AND BEHAVIOUR

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

Table 1. Flow control types and attributes.

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

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 VFCs 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, VFCs use purely hydrodynamic means (Lamb, 1983). As a result of this these systems are more resilient to blockage.

Figure 1 provides typical comparisons between the characteristics of a VFC and an equivalent orifice plate, alongside that which might be aimed for in an ‘ideal’ (constant discharge) flow control. Each unit is specified to give a common ‘duty’ head-flow point, which in this case is the point where the curves for the VFC, equivalent orifice and ideal flow control cross. Also included is a large orifice plate with the same minimum clearance as the VFC, though this is unable to meet the constraints of the duty head-flow point, discharging significantly more flow at the duty head level. These characteristics were applied in the modelling component of the current study, presented later in the paper.

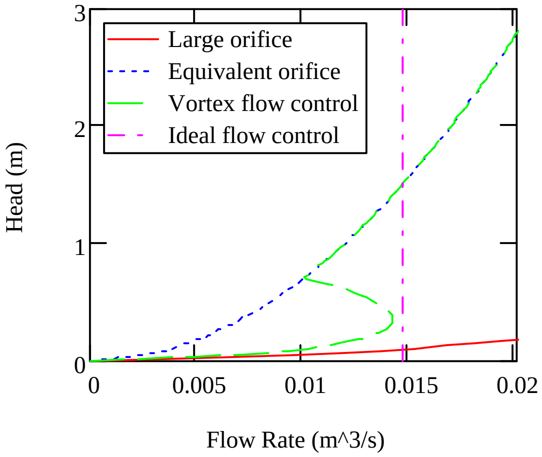


Figure 1. Comparison between the hydraulic characteristics of the flow control devices modelled.

The ideal flow control permits flow rates up to the duty flow to pass unimpeded and up to that point essentially performs as a large orifice. Once this duty flow rate is reached it restricts to this flow irrespective of the head applied. In many respects this can be likened to simple real time control (RTC) systems as described by Villeneuve *et al.* (1999) and Duong *et al.* (2005). The equivalent orifice can achieve the design head-flow point, but restricts to substantially lower flow rates at low heads. The VFC produces a 3-stage characteristic that falls between that for the orifice plate and the ideal flow control. At low heads, this device behaves as a large orifice. As the head increases, vortex motion develops within the device (‘vortex initiation’) producing the characteristic ‘kick-back’ effect. Once the vortex is fully established, the device behaves as a small orifice.

CHARACTERISATION OF FLOW CONTROLS

Conventional and advanced test methods

Accurate hydraulic characterisation of flow controls can be a complex and time consuming process, requiring the application of both expertise and the use of suitably accurate calibrated facilities. Devices are traditionally characterised through taking measurements of discharge at different steady state levels of upstream head. This method can provide accurate outputs for most types of device, but can be extremely time consuming; the allowance of a stabilisation time between readings is required (LeCornu and Faram, 2006). Furthermore, use of this method for VFC characterisation can present challenges as the vortex initiation phase of operation (corresponding to the ‘kick-back’) is an inherently dynamic process. Therefore accurate characterisation around this region calls for advanced test methods.

The authors have developed a methodology for dynamically testing flow controls. This involves real-time simultaneous monitoring and recording of the head acting on a flow control and the flow entering its mounting chamber, whilst the flow is gradually increased over time. Collected head data is processed and integrated with the depth-cross sectional area profile of the mounting chamber to give a chamber fill rate, which is then correlated with the chamber inflow rate to give a discharge rate. This leads to the generation of a relationship between discharge flow rate and head. Dynamic testing has potential to be more efficient than steady state testing as it does not require allowance of a stabilisation time between readings.

In order to perform dynamic flow control testing it is necessary to have suitably sophisticated test facilities. Whilst steady state testing can be carried out as a manual process dynamic testing can not, only becoming practical with the support of automated control and data logging facilities. This method provides additional opportunities, including scope to evaluate the response of a flow control to a time-varying flow profile, for example, a simulated storm hydrograph. A description of Hydro International’s advanced test facility, developed to allow dynamic as well as steady state testing, is described in the following section.

Hydro International’s flow control test facility

Figure 2 shows a schematic of Hydro International’s flow control test facility.

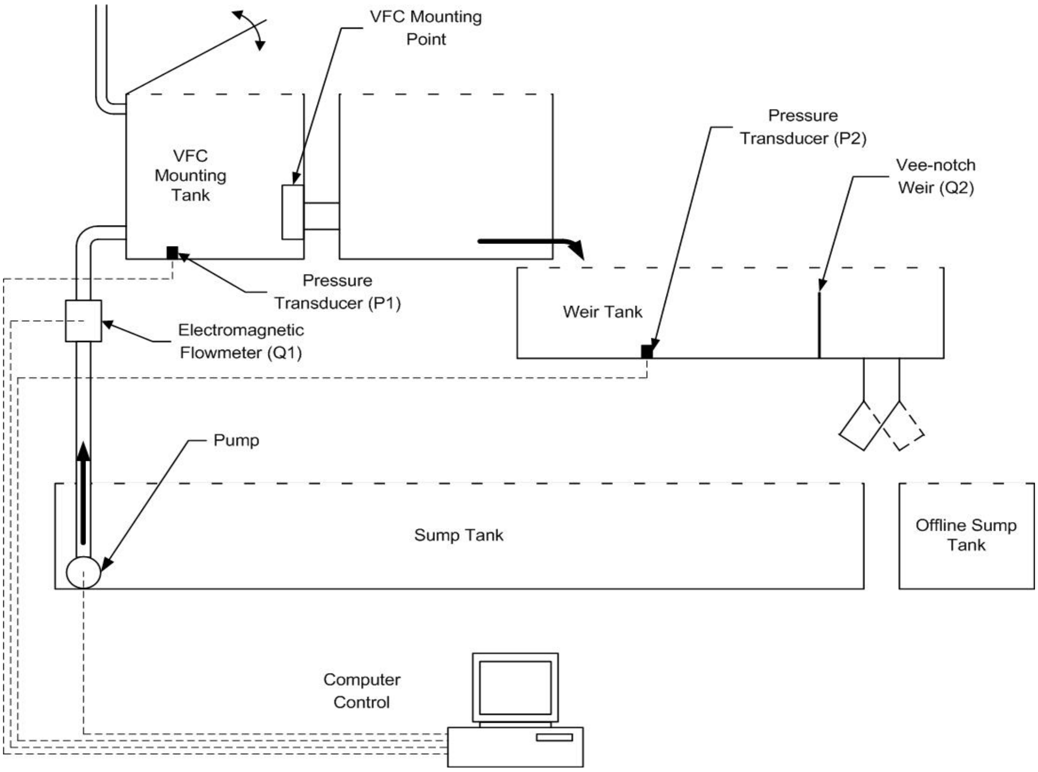


Figure 2. Schematic of Hydro International's test facility.

The flow control to be tested is installed in the mounting tank. Flow is fed to this tank from a submersible pump, located in a basement sump tank. The pump speed, and hence, flow rate is controlled using a LabVIEW program utilising the PROFIBUS communication protocol. In addition to controlling the pump speed this is able to log readings from instrumentation including; an Endress + Hauser Promag 50 electromagnetic flow meter immediately upstream of the VFC mounting tank (Q1), two Smar LD303D pressure transducers, one in the VFC mounting tank (P1) and another in the vee-notch weir tank (P2) into which flow from the VFC passes. Following passage through the weir tank, flow returns to the basement sump. An offline sump tank is available at this point for timed volumetric flow rate checking.

The instruments are factory calibrated and traceable to national and international standards. In the case of the electromagnetic flow meter this calibration is to ±0.16% of reading and the pressure transducers are calibrated to measure to ±0.04% of range. The calibration for the depth-cross sectional area of the mounting tank, required for dynamic testing, is also traceable to national and international standards.

Test method verification and comparisons

Test work has been carried out to demonstrate the accuracy of outputs produced from Hydro International's test facility using both steady state and dynamic test methods. For the steady state method both manual and automated testing approaches have been applied.

Figure 3 shows test outputs produced for a 100mm diameter orifice plate that has previously been tested using conventional manual steady state methods at an independent facility at the University of Bristol. Figure 4 shows outputs for a VFC, tested using both the steady state and dynamic methods at Hydro International's facility.

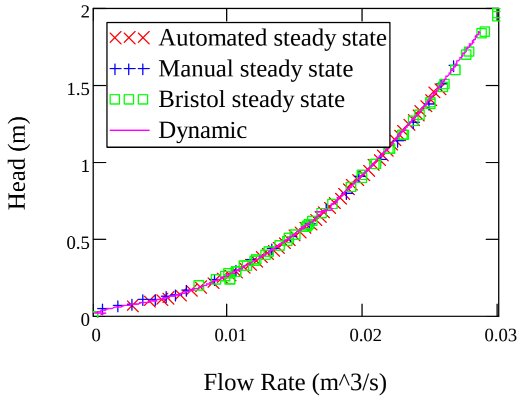


Figure 3. Orifice plate verification results.

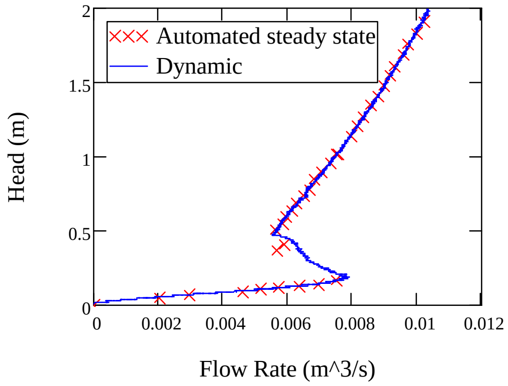


Figure 4. Vortex flow control verification results.

There are about 2500 data points plotted for each dynamic test, compared to around 50 for the automated and manual steady state tests. The dynamic data is smoothed using a five point moving average at the time of calculating the discharge flow rates in a spreadsheet. This is necessary to reduce the effect of ripples on the water surface, picked up during the monitoring process.

The correlations between the different data sets collected for the orifice plate are remarkably close. Similarly close correspondence is found for the VFC tests, the only discrepancy being around the vortex initiation region, where the flow rate reduces with increasing head. In this region, the steady state test fails to provide much data population. This is attributed to the inherently dynamic nature of this part of the characteristic; the head and flow essentially 'migrate' to the stable point at which the flow starts to increase again even though the chamber inlet flow rate has not been changed. When dynamic testing is applied, this part of the characteristic is recorded.

Overall, the high levels of correspondence observed between the different data sets confirm the validity of both the facility and the test methods.

STORM HYDROGRAPH RESPONSE MODELLING

Model objectives, construction and parameters

Modelling work has been carried out to evaluate the effects of using different types of flow control on the performance and hence design of a stormwater storage system subject to hydrographs of different duration and intensity. A longer term aspiration is to validate this simulation with experimental work, to be conducted using Hydro International's flow control test facilities.

The simulations assumed that a storage chamber with a flow control attached to its outlet would be presented with a storm hydrograph. The maximum storage depth (duty head) and the maximum discharge flow rate (duty flow) were fixed for each scenario considered. Several different flow rate and head level combinations were modelled; flow rates ranged between 0.01 and 0.021 m^3/s and head levels between 0.7 and 3 m. These two parameters define the 'duty point' of the flow control. This allowed appropriate flow controls and associated design head-flow characteristics to be defined. The model then calculated the required storage plan area required to accommodate the input hydrographs such that the duty head was always reached but never exceeded i.e. ensuring full use of the available storage. The output hydrograph was calculated as part of this process, having direct implications to the storage volume required, allowing determination of the storage savings dictated by the use of one flow control compared to another.

The model was produced as a MathCAD spreadsheet. Systems such as these may be modelled as a partial differential equation, however they are difficult to solve. Computing power makes it possible to use an iterative approach whereby outputs from one time step are input as boundary conditions for the next. This method is further simplified by choosing a time step of one second as this removes a layer of calculation and is expressed simply in Equation 1 below. The model receives inputs in the form of storm type, volume and duration and required duty flow rate and head level. The model then performs an iterative calculation using a built in function of the MathCAD software to find the storage area required and the associated recovery time of the storage for the duty conditions and outputs the discharge hydrograph for the flow control analysed.

Equation 1.

$$Qi_n := Qo_{n-1} + A \cdot h_{n-1}$$

Where: Qi is the input flow rate (a function of time)
Qo is the output flow rate (a function of h)
A is the storage area
h is the water level in the storage
n is the time increment number

The inflow hydrograph was simulated with a gamma distribution. This was chosen because it has variability that allows the curve to become more or less symmetrical by changing two variables (θ and k in Equation 2). This symmetry is useful for the modelling of winter frontal storms where rainfall is more often due to the passing of a front across the catchment. Summer convective storms however tend to have a quick rise in intensity to an early peak. These correlations between summer and winter storm types can be found in Butler and Davies (2004) and CIRIA (1993).

Equation 2. Gamma distribution used in the model.

$$\mathrm{gamma}(x) := x^{k-1} \cdot \frac{e^{\frac{-x}{\theta}}}{\theta^{k} \cdot \Gamma(k)}$$

The gamma distribution has a unit volume when integrated with respect to x, and this allowed the curve to be scaled simply to fit the storm volume and duration required. The variables θ and k in Equation 2 were set to 2 and 3 for summer (convective) storms and 0.5 and 9 for winter (frontal) storms. The storm volume was varied from 200m^3 to 500m^3 and duration from 2 to 6 hours. This gave rise to storm hydrographs with a wide variety of durations and peak intensities.

Flow controls and hydrographs considered

Hydrographs of the storms simulated as part of the study are shown in Figure 5.

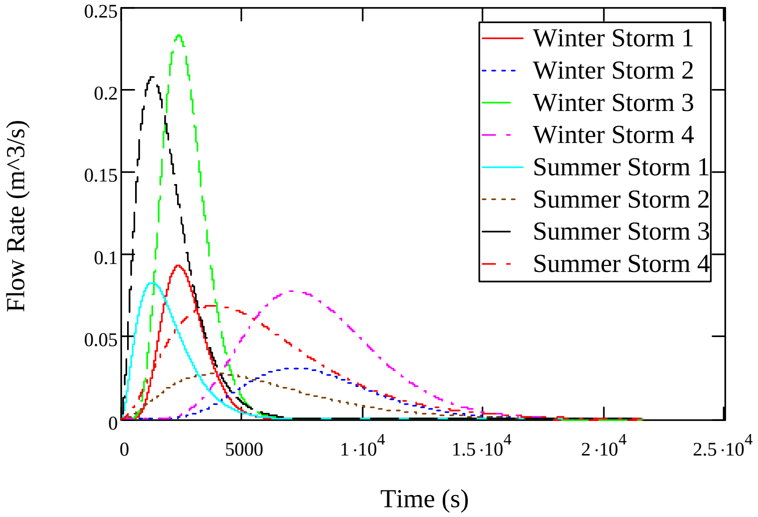


Figure 5. Storm hydrographs used in the model.

Three different flow control types were considered, selected to satisfy the predefined duty head-flow condition. These were a VFC with a 150mm diameter outlet, an equivalent orifice, and an ideal flow control as described previously. A 150mm diameter orifice plate was also included for comparison purposes, though being unable to fulfil the duty head-flow conditions. Design characteristics for these were presented in Figure 1, where the duty head-flow condition is identified as being the point at which the characteristic curves for the ideal flow control, equivalent orifice and VFC intercept. In total, 132 combinations of duty head, flow, storm hydrograph and flow control (excluding the large orifice) were considered.

Outputs and verification

For each flow control and storm profile considered, three outputs were obtained including the minimum storage volume required to accommodate the storm, the outflow hydrograph and the recovery time of the storage. The recovery time is defined as the time taken from the beginning of the storm for the chamber to return to an empty state. This parameter is potentially very important, for example, when a drainage system is presented with a series of consecutive storms. This is not accounted for in the storage requirement calculations presented in this paper.

Figures 6 to 9 show the outflow hydrographs for each of the flow controls when Summer storm 4 is applied with a duty flow of 0.015 m^3/s and duty head of 1.5 m.

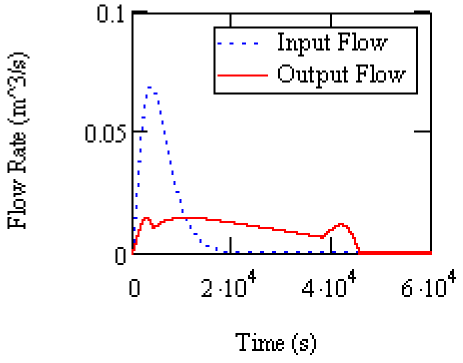


Figure 6. Vortex flow control with summer storm 4 applied.

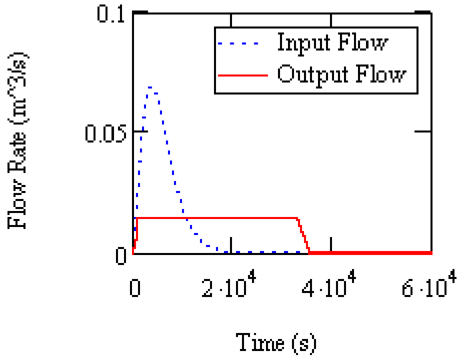


Figure 7. Ideal flow control with summer storm 4 applied.

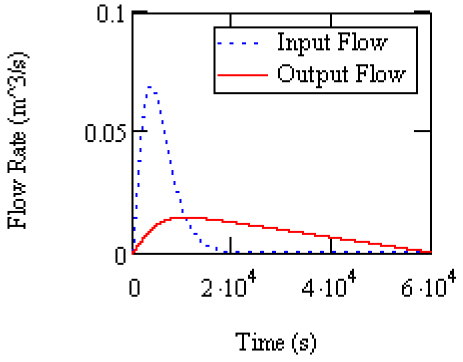


Figure 8. Equivalent orifice with summer storm 4 applied.

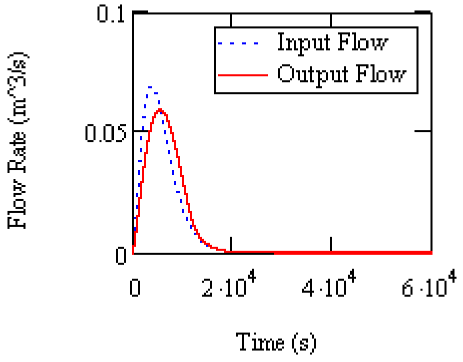
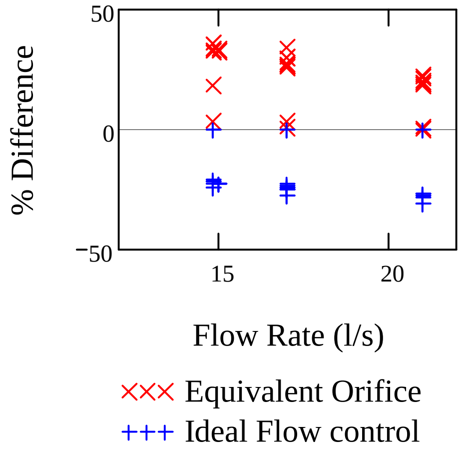


Figure 9. Large 150mm orifice with summer storm 4 applied.

An initial verification of the simulation was carried out by comparing the outflow hydrograph obtained for the VFC to that obtained by Parsian and Butler (1993) in their experimental study. This showed a similar shaped outflow hydrograph suggesting that the simulation was valid.

The equivalent orifice (Figure 8) performs in line with the defined duty head-flow criteria but produces a storage recovery time that significantly exceeds that of the other systems. The storage volume required to accommodate the storm is also significantly higher. The VFC and the ideal flow control (Figures 6 and 7) also perform to requirements but produce lower storage recovery times and storage volumes compared to those of the equivalent orifice plate. The large orifice (Figure 9) does not perform in line with the duty head-flow criteria, as indicated previously, and as such provides minimal controlling effect on the flows.

Figures 10 and 11 present analysis outputs for the full range of storm profiles and various duty criteria (excluding cases where the flow control discharge was allowed to exceed the duty flow below the duty head, considered later). This provides comparisons of storage volume requirement and recovery time for each set of conditions. The data is presented as percentage difference from the effect of using a VFC, with negative values denoting relatively smaller volumes or shorter recovery times, against the duty conditions of flow rate or head. Thus a positive value in Figures 10 or 11 for one flow control configuration shows that a larger storage tank, or a longer recovery time, would be required when compared to a VFC.



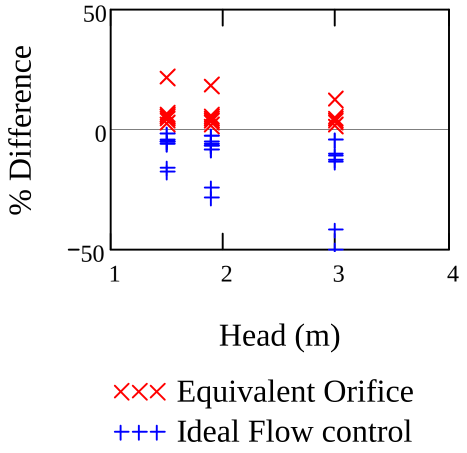


Figure 10. Recovery time-flow relationship.

Figure 11. Storage volume-head relationship.

In all cases the VFC was found to perform better than the equivalent orifice. A storage volume of up to 21% smaller and a recovery time of up to 36% shorter was required. High intensity storms, where the peak flow of the input hydrograph was around ten times that of the duty discharge flow rate, produced the lower differences. The Figures also show that, under the conditions for which data is presented, the ideal flow control required less storage volume and had shorter storage recovery times than the VFC.

Simulations carried out in which the flow control discharge was allowed to exceed the duty flow at heads below the duty head, while still meeting the duty point, resulted in the VFC requiring significantly less storage (up to 54%) and lower recovery times (up to 55%) than the equivalent orifice plate. Under these conditions, the VFC was also found to require a storage volume of up to 14% less than that required for the ideal flow control. The recovery time however was not improved upon by the VFC as it is impossible to discharge a volume greater than that presented by the storm up to that time. While not often considered as an option in practice, there may be cases where such a scenario may actually be hydraulically acceptable.

The characteristics of the ideal flow control are, to the authors' knowledge, unobtainable without a power source or the constriction of clearances, or both, within the device.

FURTHER WORK

Two areas of further work are planned. Firstly, it is planned to undertake experimental testing to establish the response of the different flow control types to an input hydrograph. This will provide information to enable validation of the mathematical model. Secondly, in order to further investigate the effect of the recovery time on storage volumes, the mathematical model will be extended to model series of consecutive storms. This may show the recovery time to be as important as storage volume when systems are presented with real conditions.

CONCLUSIONS

A number of conclusions can be drawn from the study;

- The hydraulic characteristics of flow controls used in urban drainage systems have important implications to system design, in particular relating to storage utilisation.
- Vortex flow controls (VFCs) present opportunities compared to other types flow control types, producing desirable hydraulic characteristics while also having large clearances.
- The application of advanced methods for VFC characterisation has been shown to produce accurate results that are consistent with those obtained using conventional methods, yet can be obtained within a fraction of the time.
- A simple model developed to allow storage and flow control storm response modelling has been shown to produce similar shaped output hydrographs to those found in the literature.
- A VFC is shown to present opportunities for storage volume savings and recovery time reductions of up to 21% and 36% respectively compared to when an equivalent orifice is used, with scope to extend these up to 55% under special circumstances.
- The simulation work finds that storage recovery time reductions resulting from the use of a VFC tend to be relatively larger than storage volume savings. This factor should therefore be given greater attention in drainage system design, presenting further optimisation scope.

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