Assessment of the Effectiveness of Stormwater Treatment Chambers using Computational Fluid Dynamics

Michael G. Faram* and Robert Harwood**

*Technical Development Manager, Hydro International, Shearwater House, Clevedon Hall Estate, Victoria Road, Clevedon, North Somerset, BS21 7RD, UK; PH +44(0)1275 878371; mike.faram@hydro-international.co.uk
**Principal Engineer, Fluent Europe Ltd, Sheffield Airport Business Park, Europa Link, Sheffield, S9 1XU, UK; PH +44(0)114 2818888; rh@fluent.co.uk

Abstract

Modern day pressures to find solutions to the problems of stormwater run-off from impermeable surfaces have resulted in the development of various proprietary "flow-through" treatment technologies. Such devices are typically installed immediately downstream of stormwater intake points, where their purpose is to intercept and store pollutants such as sediments and oils for later manual removal and safe disposal. There is currently little data in the public domain that would enable meaningful comparisons to be made between different proprietary chamber types. Such comparisons would require that systems were tested side by side under controlled conditions and using identical protocols. Presently, whether for technical or commercial reasons, such a study has not taken place.

In the paper, the results of a Computational Fluid Dynamics (CFD) simulation study of four generic chamber types are presented. In particular, the importance of the ability of a chamber to retain stored pollutants following capture is highlighted. It is concluded that chambers in which the storage region is isolated from the main treatment region are likely to be far more effective than those chambers in which this is not the case.

Introduction

With increasing urbanization, the problems of stormwater run-off from impermeable surfaces have become increasingly apparent (Novotny & Olem, 1994). Run-off often carries a high sediment load, and this, along with other associated pollutants, can have a detrimental impact on receiving watercourses.

Recognizing urban run-off, and in particular, sediments, as one of the main sources of pollution in the USA (US EPA, 1998), Phases I and II of the US stormwater program, promulgated by the EPA in 1990 and 2000 under the 1972 Clean Water Act, are leading to significant improvements in the quality of US waters. The regulations largely target non-point source pollution in run-off from urbanized areas where land is often scarce and expensive.

In response to the technical need for compact and effective stormwater treatment chambers, various configurations of proprietary "flow-through" treatment device have emerged. The most popular of these utilize hydrodynamic principles for the removal of sediments and other pollutants from stormwater (US EPA, 1999). These can be categorized into the following three generic groupings;

- ***Gravity Sedimentation Devices.*** These devices rely on simple gravitational settlement to perform their function.

- ***Simple Vortex Separators***. These devices rely on enhanced gravitational settlement to perform their function, through the use of a rotating flow field. Flow rotation results in extended particle residence times, and increased opportunity for settlement to take place.

- ***Advanced Vortex Separators***. These devices operate in a similar manner to Simple Vortex Separators, but utilize specially designed internal components to control and enhance the quality of performance.

Such devices are typically installed immediately downstream of a stormwater intake point, where they operate by removing and storing pollutants for later manual removal.

Historically, simple catchbasins have been used as entry points to storm drainage systems. A detailed study of catchbasins is presented by Lager *et al.* (1977), many of the findings of which are still relevant today. Historically, one of the main purposes of catchbasins was to remove debris from stormwater, preventing clogging in the receiving pipework. However, testing of such systems has identified the limitations of their effectiveness. In particular, such systems can be prone to the phenomenon of wash-out, whereby collected material is remobilized and discharged during intense storm events. In this context, catchbasins can actually represent a source of pollution.

The paper presents the results of a study in which Computational Fluid Dynamics (CFD) simulation was applied for the comparative assessment of a number of different configurations of stormwater treatment chamber. The configurations considered included designs falling into each of the categories described above. The authors are unaware of any previous studies, either experimental or numerical, involving the direct side by side evaluation of such systems. In this sense, the results of the study presented in the paper are of particular significance.

Computational Fluid Dynamics (CFD) Simulation Studies

In recent years, CFD fluid flow simulation codes have become increasingly applied for the study of sewer and drainage systems and processes (Faram & Andoh, 1999, 2000; Faram & Harwood, 2000, 2002; Harwood, 1998, 1999, 2002; Okamoto *et al.*, 2002). Such techniques are invaluable for the study of systems and processes that would otherwise be difficult to study using traditional experimental methods. In particular, the experience of the authors has been that CFD approaches are particularly useful for identifying relative effects that result from changes in either operating conditions or geometry of a system. Positive validations of such techniques have been presented on many occasions (included in the above references).

In the current study, CFD was applied for the comparative assessment of different configurations of stormwater treatment chamber, including a simple catchbasin **(SCB)**, a gravity sedimentation device **(GSD)**, a simple vortex separator **(SVS)** and an advanced vortex separator **(AVS)**. Performance was quantified in terms of both sediment particle removal, and sediment particle retention efficiency for each chamber.

With the exception of the AVS, which was based on a Hydro International Downstream Defender® (Deahl & Faram, 2002), proprietary designs were not simulated as part of the current study. To ensure the meaningfulness of the comparisons, chambers with identical overall dimensions were considered. The main physical parameter differences between the chambers included the inlet orientation, and the presence or absence of internal components.

Graphical representations of each of the configurations considered are presented in Figure 1, (a) to (d). The AVS and SVS each had a 200 mm diameter tangential inlet, while the GSD had a 200 mm perpendicular inlet. The inlet to the SCB was based on a calculated approximation of a falling fluid stream, defined based on the assumption of a lateral kerb, rather than overhead grating style intake. Each chamber had a 300 mm diameter overflow, the invert of which was located approximately 1.2 m above the base of the sediment storage region. Differentiating itself from the other chambers considered, the AVS contained a number of flow modifying members.

CFD Assessment Methodology

Throughout the studies, the Fluent CFD software (Version 5.5) was used in conjunction with the associated Gambit preprocessor (Fluent, 1998). Each chamber was simulated at inlet flowrates of 20, 40, 60 and 80 l/s, corresponding to multiples of 1, 2, 3 and 4 times typical design flowrates for an AVS (Hydro International, 1998).

The following simulation methodology was adopted;

- ***Computational Mesh***. 3-dimensional models of each chamber were constructed using tetrahedral meshes comprising of between 100,000 and 150,000 computational cells. Previous sensitivity studies indicated that hexahedral meshes did not give sufficiently different outputs to warrant the extra time involved in producing such a mesh (Faram & Harwood, 2002).

- ***Boundary Conditions***. Inlet flowrates were defined by uniform velocities across the inlet plane of each system. System outlets were defined with a pressure corresponding to atmospheric pressure, representing a free discharge. The fluid free surfaces in each chamber were approximated by fixed frictionless wall boundaries, the locations of which were derived experimentally. For the SCB, the falling fluid stream profile was approximated based on projectile theory.

- ***Flowfield Predictions***. Steady state flowfield predictions were obtained using the Reynolds Stress Model of turbulence (RSM). Solutions were converged to an iterative residual level of $1x10^{-3}$.

- ***Particle Trajectory Predictions***. Using the Lagrangian particle tracking routine, discrete, non-interacting spherical particles with a density of 2650 kg/m^3, corresponding to that of sand, and with sizes ranging from 10 to 1000 microns, were injected into the flow domain. These were injected in the plane of the inlet for particle removal efficiency studies, and in a plane 100 mm above the base of the sediment storage region for particle retention efficiency studies. For each particle size, around 500 injections were made, based on the findings of studies presented elsewhere (Harwood, 1998). Also based on the findings of a validation study, the spatial interval at which individual particle trajectories were recalculated was set at 0.5 mm (Faram & Harwood, 2002). The total number of calculation intervals was set at 2.5 million, to ensure that particles were tracked for a sufficient length of time to facilitate the objectives of the study. The transit times of particles that exited through the overflow were recorded in a data file.

- ***Efficiency Derivation***. Using data logs of particle exit times, device particle removal and retention efficiencies were calculated using Equation 1;

$$\text{Efficiency (\%) at t(e)} = \frac{\text{(Tot. no. particles injected at t(0)) - (No. exits at t(e))}}{\text{Tot. no. particles injected at t(0)}} \times 100 \qquad \text{Equation 1}$$

where t(e) = particle transit time at exit and t(0) = particle injection time

To optimise upon the efficiency with which repetitive aspects of the study were performed, pre-constructed 'command' files were used in conjunction with the Fluent software. Such files contain strings of commands that are fed into the software interface automatically, thereby removing the necessity for manual intervention from the operator. In addition, a 'user defined function' (UDF) was utilised such that particle trajectory calculations were terminated after a pre-defined tracking time had been exceeded. A UDF is a 'bolt-on' that extends software functionality to suit specific project requirements.

A validation study performed as part of the current study yielded good comparisons between predictions and experimental data for particle removal efficiency. Details of this study, along with further details of the simulation procedure, have been presented previously and are not repeated here (Faram & Harwood, 2002). Due to the difficulties associated with the experimental assessment of particle retention efficiencies, it was not possible to perform a validation on this parameter.

Flowfield Predictions

Figures 2 and 3 (a) to (d) show vertical mid-sectional plane velocity vector and fluid pathline predictions for each system at an inlet flowrate of 40 l/s. The velocity vectors are scaled by their length and colour, with longer lengths denoting higher velocities, and with deep blue denoting lowest velocities, passing through green, yellow, and orange, and finally to red, with this denoting peak velocities. It should be noted that these do not contain components to represent flows passing perpendicular to the plane. The fluid pathlines, which can be understood to be equivalent to neutrally buoyant experimental dye tracers, originate from the inlet and sediment storage region of each system. These are coloured depending on residence time, again, going from blue through to red, with red denoting a residence time of 20 seconds. Best appreciation of overall flow characteristics is gained by viewing the velocity vectors and fluid pathlines in conjunction with one another.

For the SCB (Figures 2 and 3 (a)), the perpendicular entry of flows from above is predicted to result in a rolling motion in the chamber. Similar flow phenomena have been observed and documented in the experimental studies of others (Lager *et al.*, 1977). The initial entry velocity is relatively high (Figure 2(a)) due to the flow area narrowing dictated by gravitational acceleration (as theoretically approximated), resulting in relatively high velocities in the sediment storage region. Little differentiation is observed between fluid pathlines originating from the inlet, and those originating from the sediment storage region. In practice, these characteristics would be unlikely to be conducive to the removal or retention of sediment particles.

For the GSD, rolling motion is also predicted in the vertical plane (Figure 2(b)), but with lower velocities than were predicted for the SCB. However, the fluid pathline predictions indicate that overall flow behaviour is relatively unstructured (Figure 3(b)). For this configuration, the fluid pathlines show evidence of flows passing directly from the inlet to the outlet of the chamber, which, in practice, would represent an opportunity for pollutants to bypass treatment.

The flowfields predicted for the SVS and AVS (Figure 2 and 3 (c) and (d)) exhibit swirling behaviour, as dictated by the tangential orientation of the inlets in each case. The fluid pathline predictions for the SVS (Figure 3(c)) suggest that flows initially entering the vessel either pass directly to the overflow, or spiral down the outer wall towards the sediment storage region. Subsequently, the flow spirals back up the centre before leaving the vessel. The rolling motion indicated from the velocity vector predictions for this system would suggest skewing of the vortex.

The presence of internal baffles in the AVS results in a significantly different flowfield to that predicted for the SVS (Figures 2 and 3 (d)). For this device, the flowfield is divided into a distinct upper swirling region, and lower, relatively quiescent region, corresponding to the sediment storage region. The pathline predictions in this region (Figure 3(d)) indicate limited mixing with the upper region, with their predominantly red coloration denoting a long residence time. Additionally, there is no evidence of flow short-circuiting for this system, due to the fact that there is no direct path from the device inlet to the overflow. In practice, such characteristics are likely to be conducive to positive performance attributes.

In the following sections, the predictions for particle removal and retention efficiency are given consideration.

Time-Dependent Particle Removal and Retention Predictions

Figures 4 (a) and (b) illustrate how, during the period following initial injection of 10 micron 'sediment' particles into the inlet and sediment storage region of each simulated chamber, both particle removal and particle retention efficiency is predicted to decay with time. This data, which corresponds to an inlet flowrate of 40 l/s, highlights the importance of taking time factors into account when performing such a study, whether numerical or experimental.

The initial steep fall of removal efficiencies from 100 % (Figure 4 (a)) is believed to reflect the initial stages of particle entry to the chamber during which particles are often most vulnerable to being discharged. For the AVS, there is short delay before this occurs, and this can be explained by the fact that no direct path exists between the inlet and the overflow for this system. The SVS efficiency is predicted to plateau twice during its descent, which can be explained by considering the rotary flow path in the chamber; the duration of each plateau point is considered to reflect the time that it takes for particles to pass around the chamber perimeter wall. While for the SCB, GSD and SVS, removal efficiencies are predicted to ultimately tend towards zero, they are predicted to plateau for the AVS, implying that a proportion have become trapped in the sediment storage region.

For the GSD, SVS and AVS configurations, the predicted rates of particle retention efficiency decay are not as high as those predicted for particle removal efficiency (Figure 4(b)). In particular, the rate of decay is notably lower for the AVS compared to the other configurations, suggesting significantly better particle retention capabilities. For the SCB, however, decay rates are marginally higher. This can be explained by considering the physical location of the sediment storage region relative to the overflow for each chamber, and the way in which the flowfields impinge on this area.

While the time-dependent nature of efficiencies is an important attribute to be aware of, instantaneous efficiencies are those most commonly used to express a chambers performance. In the following section, instantaneous efficiency predictions are presented at a ‘test time’ of 20 minutes.

Instantaneous Particle Removal and Retention Predictions

Particle removal and retention efficiency predictions at a ‘test time’ of 20 minutes are presented in Figures 5 and 6 (a) to (d), including outputs at 20, 40, 60 and 80 l/s for each system. Overall, a deterioration of particle removal and retention efficiencies with increasing flowrate is predicted. This is expected for the types of device considered.

The SCB is predicted to be the least efficient chamber overall, with removal efficiencies of zero predicted for particles finer than 256 microns at 20 l/s, and 513 microns at 80 l/s (Figure 5 (a)). The retention efficiencies predicted for this system (Figure 6 (a)) are very similar to removals at each flowrate, suggesting that material collected at low flowrates is likely to be prone to washing out at higher flowrates. The GSD is predicted to be superior to the SCB, with positive removals predicted for particles larger than 90 microns at 20 l/s, and 256 microns at 80 l/s. Retention efficiencies are predicted to be marginally higher than removals at each flowrate, particularly for larger particles, suggesting some ability to retain material collected at lower flowrates. However, retention efficiencies at 80 l/s are significantly lower than removal efficiencies at 20 l/s, suggesting that with this flowrate increase, some degree of wash-out could occur.

The AVS is predicted to be superior at removing particles than the SVS at 20 l/s, in particular, for the smaller particle sizes considered. This performance differentiation becomes significantly larger as the inlet flowrate is progressively increased. Positive removals are predicted for all particles at flowrates from 20 l/s to 60 l/s for the AVS, and for particles larger than 75 microns at 80 l/s. For the SVS, however, positive removals are predicted for particles larger than 38 microns at 20 l/s and 128 microns at 80 l/s. Both systems are predicted to have higher particle retention efficiencies than removal efficiencies at each flowrate. However, the retention efficiency of the SVS at 60 l/s and 80 l/s is lower than its removal efficiency at 20 l/s, suggesting that wash-out could occur with this flowrate increase. For the AVS, retention efficiencies at 80 l/s are predicted to be similar to removal efficiencies at 20 l/s, corresponding to 100 % retention with this flowrate increase. Notably for the AVS, positive retention efficiencies are predicted for all particle sizes at flowrates of 20, 40 and 60 l/s, and for particles larger than 38 microns at 80 l/s.

An insight into the reasons for the different performance characteristics predicted for the chambers can be gained by considering these alongside the flowfield predictions presented previously. On the whole, particle removal and retention efficiency characteristics are shown to be dominated by the degree of structure in the flowfields, the degree to which flows are able to pass directly from the inlet to the outlet, and the degree of isolation of the sediment storage region from the main flow regions. In the case of the SVS and the AVS, a swirling flowfield would tend to dictate longer particle residence times, and therefore more opportunity for particles to be removed. In particular, for the AVS, the superior performance characteristics predicted for this system can be related to the highly structured swirling flowfield, the relative isolation of the sediment storage region, and the fact that direct short-circuiting of particles from the inlet to the outlet can not occur.

Conclusions

The need to remove sediments and other pollutants from stormwater prior to discharge has lead to the development of various configurations of “flow through” stormwater treatment device. The work of others has suggested that simple catchbasin technology can be prone to the phenomenon of wash-out, whereby previously collected pollutants are re-entrained and subsequently discharged to watercourses in high concentrations. This phenomenon has commonly been ignored in experimental studies of proprietary devices. In the current study, CFD simulation has been applied for the comparative assessment of four different generic types of stormwater treatment chamber. The conclusions of the study can be summarised by the following points;

- The geometry and configuration of stormwater treatment chambers has a major impact on predicted sediment particle removal and retention efficiencies.

- Simple catchbasin technology is predicted to have poor performance characteristics compared to other systems considered. Particle retention rates are predicted to be no better than particle removal rates. Vortex separators are predicted to have superior performance compared to linear separators, in terms of both particle removal and retention efficiencies.

- Isolation of the sediment storage region from the main treatment region is predicted to have a significant impact on the resulting ability of a chamber to retain collected particles at high flowrates. In particular, for one type of chamber considered, particle retention efficiencies at an inlet flowrate of 80 l/s were predicted to be superior to removal efficiencies at 20 l/s, implying 100 % retention with this flowrate increase.

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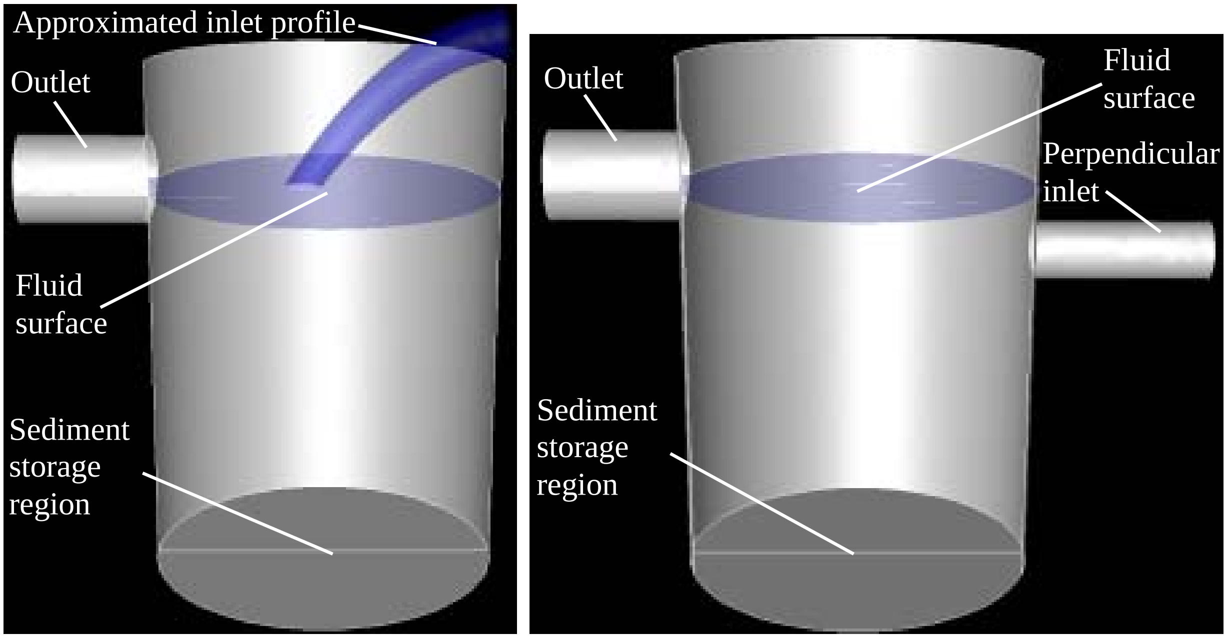
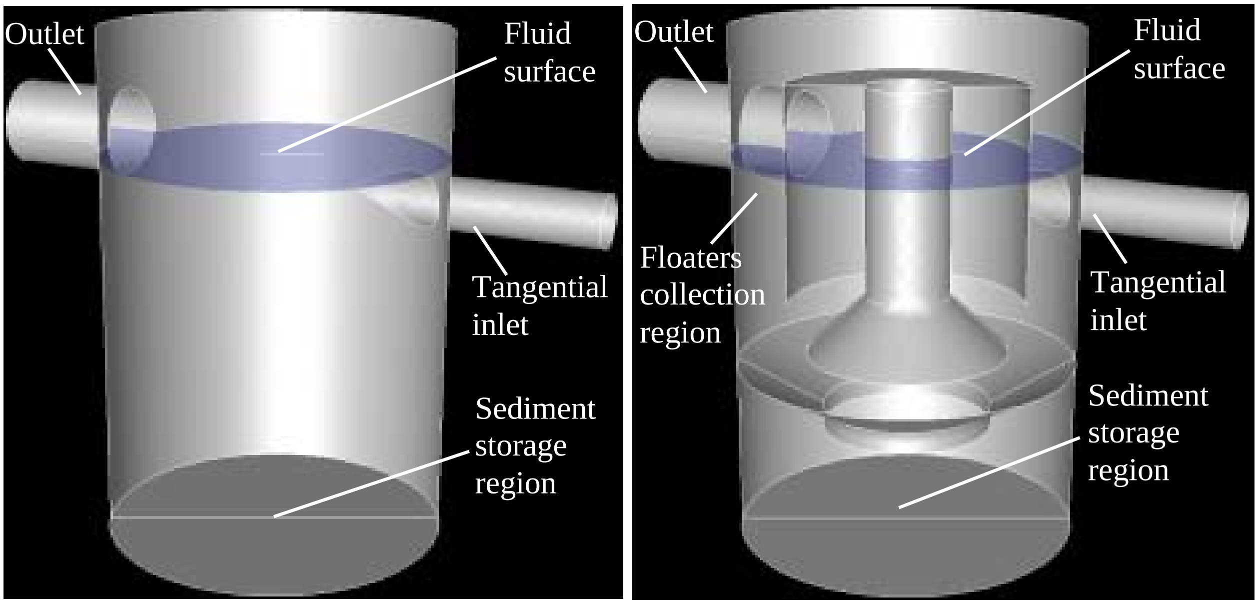
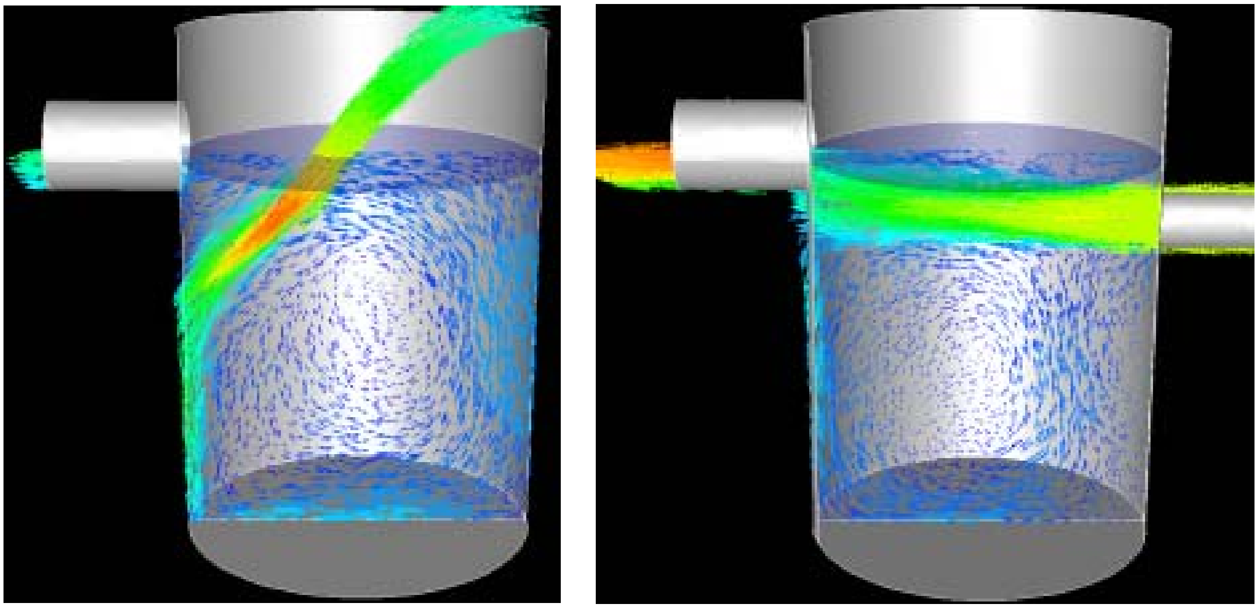


(a) Simple Catchbasin (SCB) **(b) Gravity Sedimentation Device (GSD)**



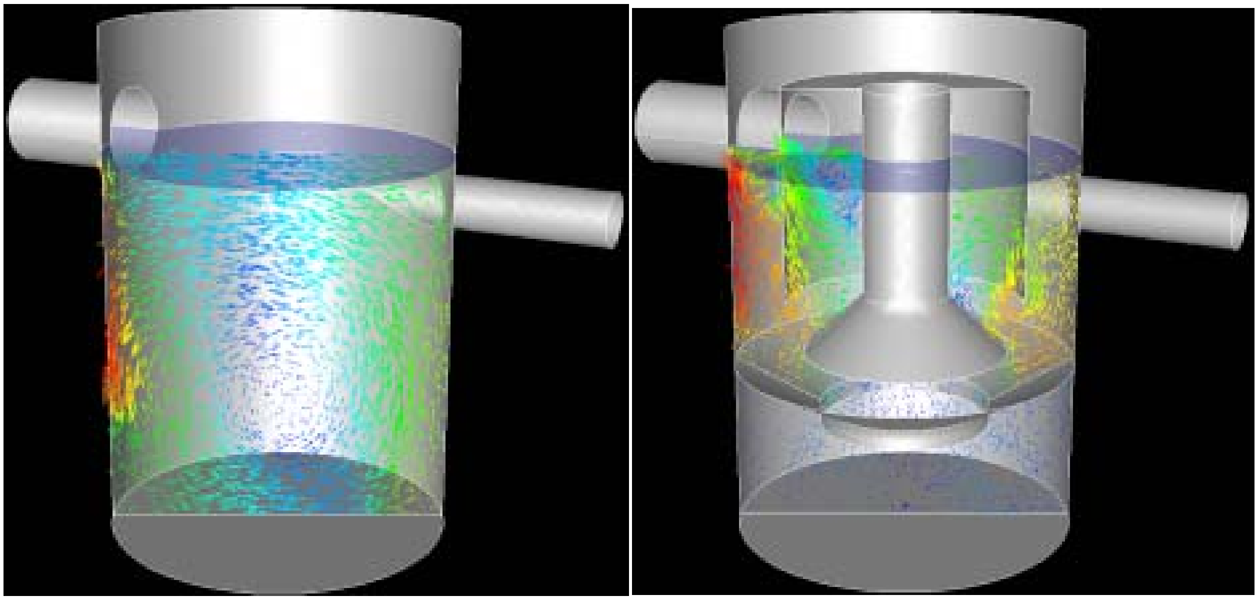
(c) Simple Vortex Separator (SVS) **(d) Advanced Vortex Separator (AVS) (cut-away)**

Figure 1 Stormwater Treatment Chamber Geometries



(a) Simple Catchbasin (SCB)
(peak vector 4.3 m/s)

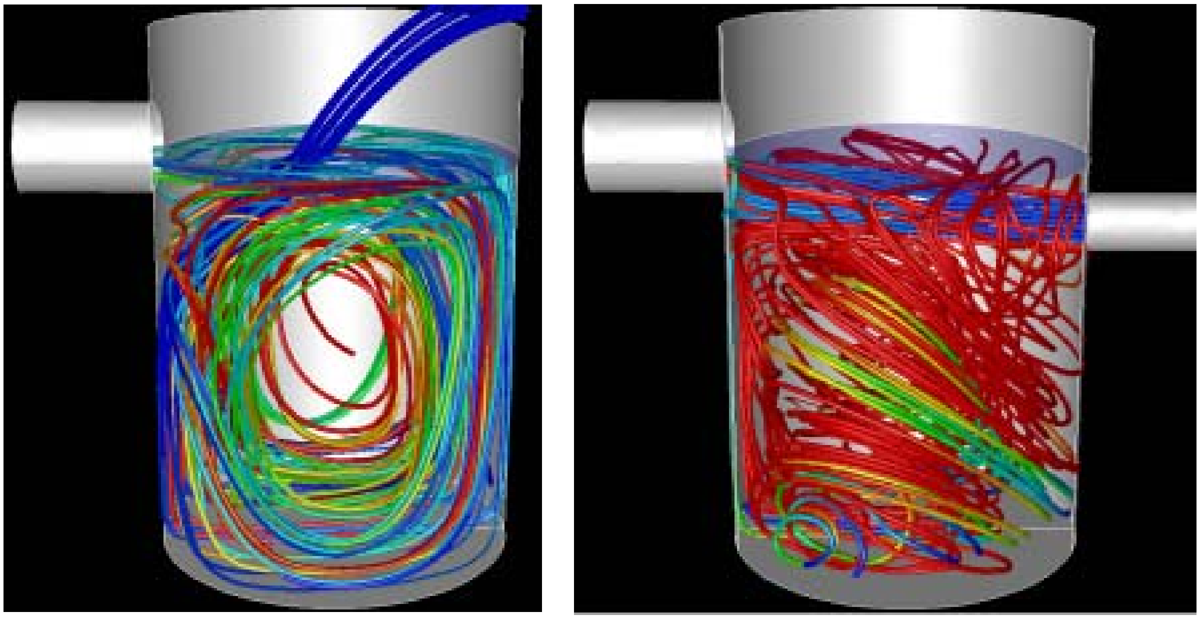
(b) Gravity Sedimentation Device (GSD)
(peak vector 2.0 m/s)



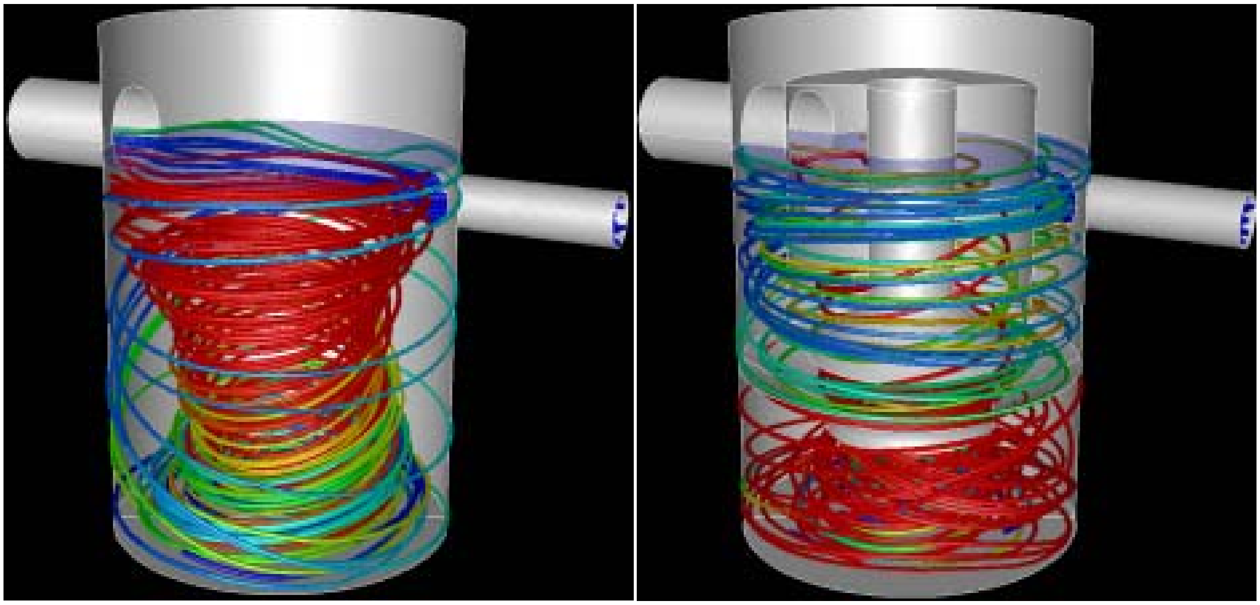
(c) Simple Vortex Separator (SVS)
(peak vector 0.9 m/s)

(d) Advanced Vortex Separator (AVS)
(peak vector 1.1 m/s)

Figure 2 Vertical Plane Velocity Vector Predictions at an Inlet Flowrate of 40 l/s

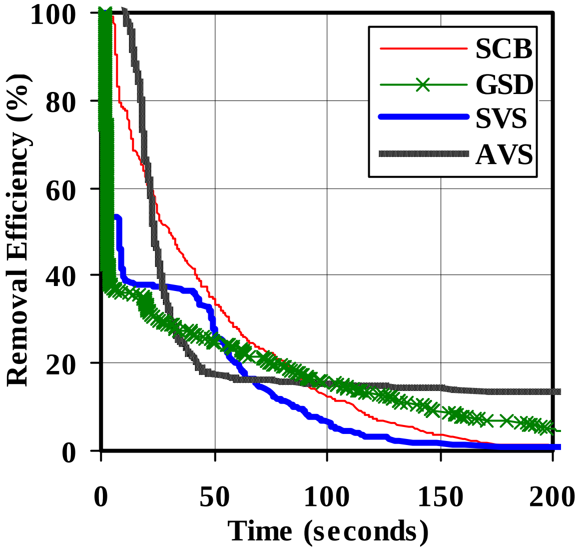


(a) Simple Catchbasin (SCB) **(b) Gravity Sedimentation Device (GSD)**

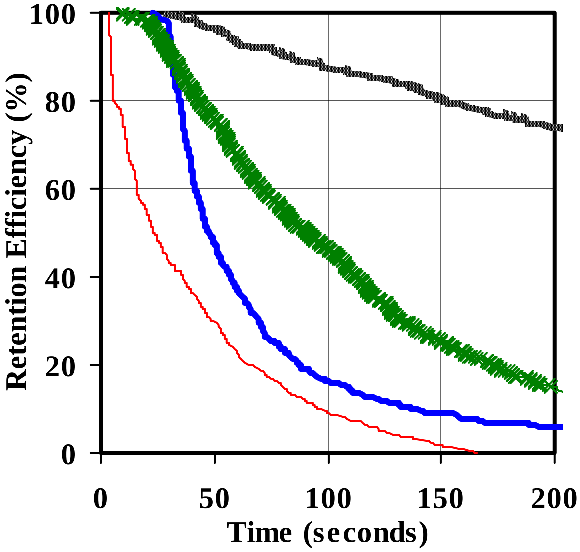


(c) Simple Vortex Separator (SVS) **(d) Advanced Vortex Separator (AVS)**

Figure 3 Fluid Pathline Predictions at an Inlet Flowrate of 40 l/s (Tracking Time of 20 Seconds)

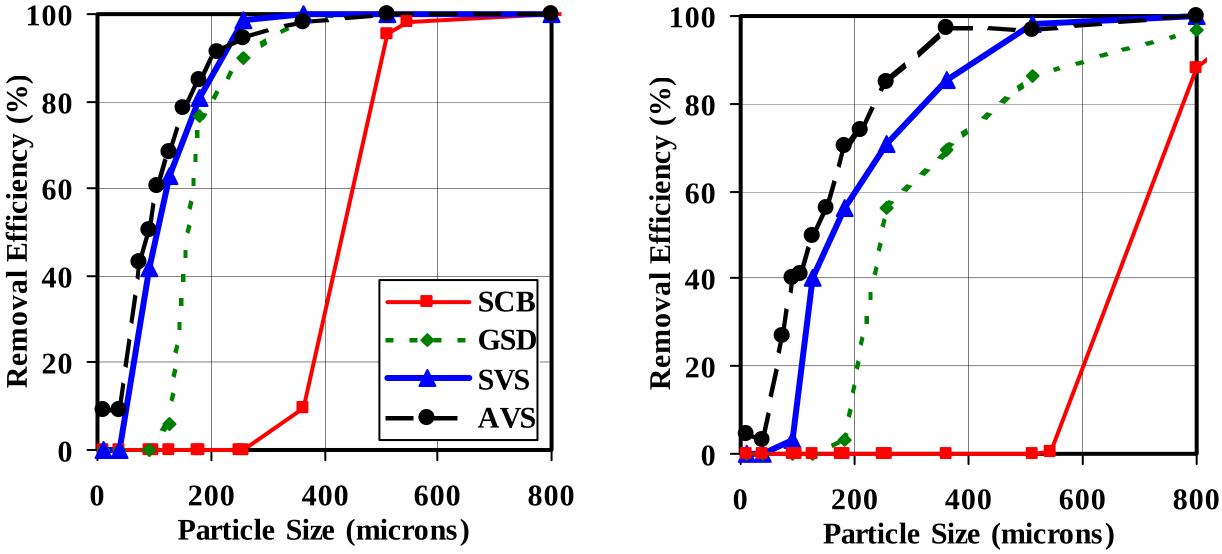


(a) Removal Efficiency Predictions



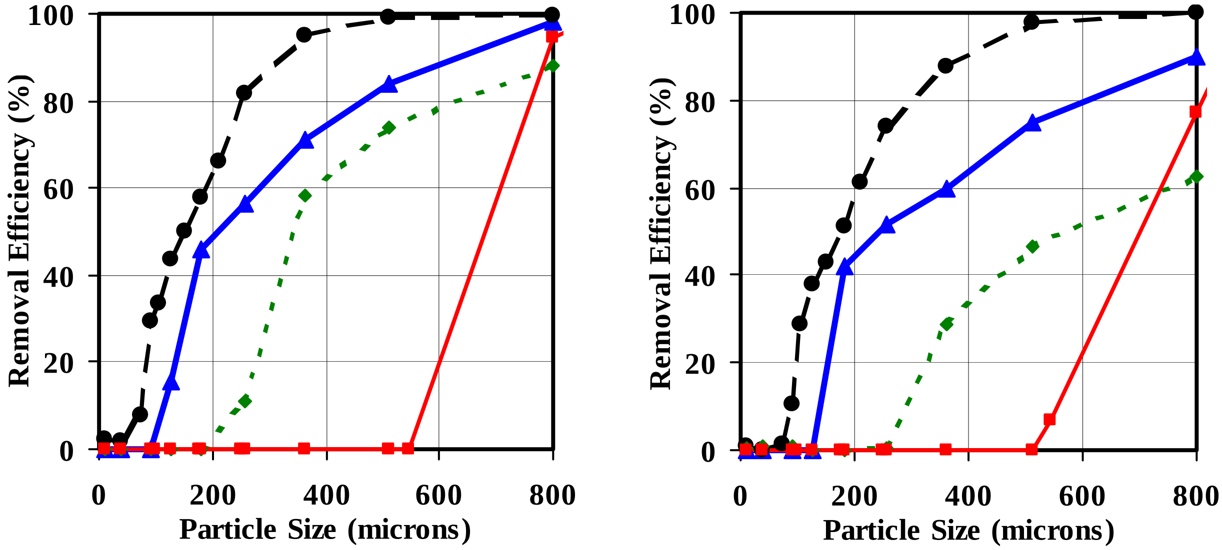
(b) Retention Efficiency Predictions

Figure 4 Time Dependent Efficiency Predictions for 10 micron Sediment Particles at an Inlet Flowrate of 40 l/s



(a) 20 l/s Inlet Flowrate

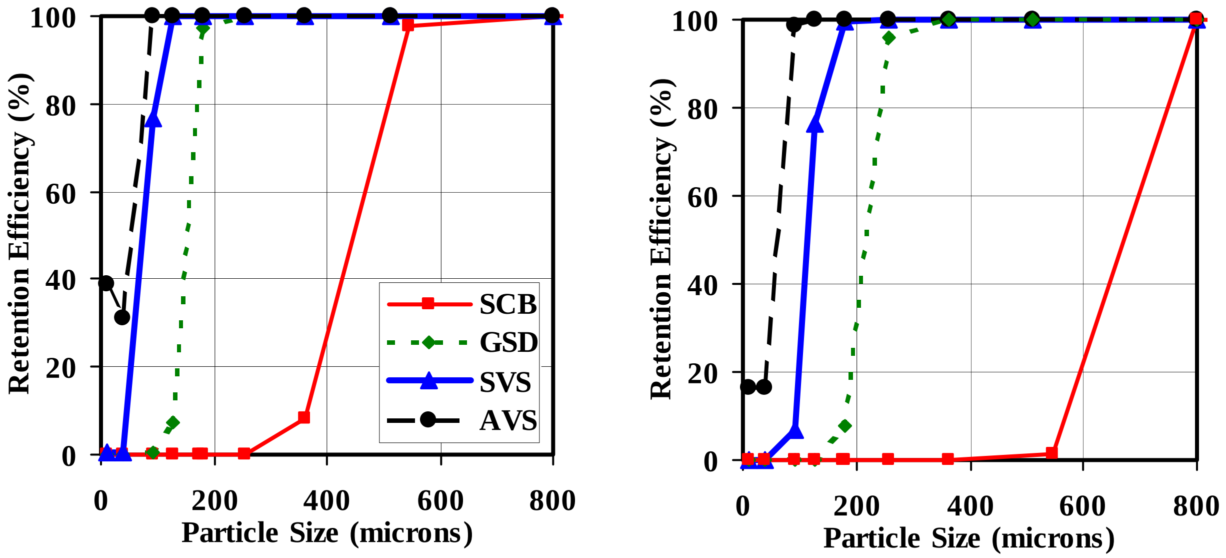
(b) 40 l/s Inlet Flowrate



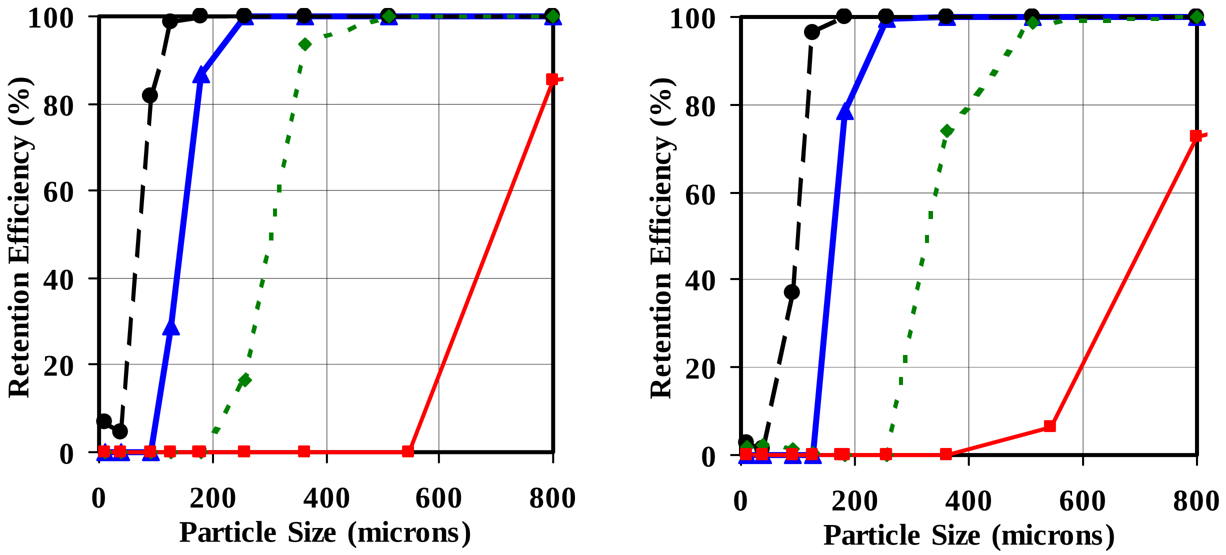
(c) 60 l/s Inlet Flowrate

(d) 80 l/s Inlet Flowrate

Figure 5 Particle Removal Efficiency Predictions after a 'Test Time' of 20 minutes



(a) 20 l/s Inlet Flowrate **(b) 40 l/s Inlet Flowrate**



(c) 60 l/s Inlet Flowrate **(d) 80 l/s Inlet Flowrate**

Figure 6 Particle Retention Efficiency Predictions after a 'Test Time' of 20 minutes