Efficiency testing of a hydrodynamic vortex separator

D.A. Phipps[1]*, R.M.Alkhaddar[1], E. Loffill[1], R.Y.G Andoh[2] and M.G. Faram[3]

[1] The Liverpool Centre for Environmental Technology, Liverpool John Moores University, The Peter Jost Centre, Byrom Street, Liverpool L3 3AF, UK
[2] Hydro International, 94 Hutchins Drive, Portland, ME 04102, USA
[3] Hydro International, Shearwater House, Clevedon Hall Estate, Victoria Road, Clevedon BS21 7RD, UK

**Corresponding author, e-mail d.a.phipps@ljmu.ac.uk*

ABSTRACT

The factors affecting the overall efficiency for the removal of a solid from an influent stream of water by an HDVS (Hydrodynamic Vortex Separator) have been examined using a combination of solids capture/washout experiments and dye tracer studies. The overall solids removal efficiency of the device is a function of loading rate (overall flow). The efficiency can be considered in terms of the balance between initial capture of the sediment and any subsequent re-entrainment. Tracer studies have shown that a well-designed device offers almost complete separation into a mobile and quiescent zone, with slow exchange between the two. This enhances both sediment capture and its subsequent retention.

KEYWORDS

Hydrodynamic vortex separator (HDVS); stormwater treatment; sediment; solids removal; capture re-entrainment; efficiency.

INTRODUCTION

Stormwater, either urban run-off from impermeable surfaces or combined sewer overflows, is associated not only with flooding but also with pollution. Increasingly, proprietary ‘flow-through’ treatment devices, utilising hydrodynamic principles in their operation, have been adopted with the intention of removing both settleable and floatable pollutants from stormwater (US EPA, 1999). These have been categorised as follows:

- **Gravity Sedimentation Devices (GSD)** - Rely on simple gravitational settlement to perform their function.
- **Simple Vortex Separators (SVS)** - 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 (AVS) -** These operate in a similar manner to Simple Vortex Separators, but utilise specially designed internal components to control and enhance performance and provide isolated storage zones for captured pollutants. They are often referred to as Hydrodynamic Vortex Separators.

Hydrodynamic Vortex Separators (HDVS) remove solids from water by a combination of the gravity and other inertial forces. Generally, simple hydrodynamics would predict that their overall efficiency should depend approximately on both particle size and density, (summarised as settling velocity) and on the upflow rate of the water (summarised as the surface loading rate) i.e. capture occurs if settling velocity > surface loading rate. In practice, different designs offer widely different performance characteristics. Two key elements which need to be considered in resolving this are the residence time distribution and flow segregation (Alkhaddar *et al.*, 1998; 2001).

The HDVS is designed to give the influent stream a much longer flow path from inlet to outlet than occurs with a conventional settling tank. The rotary flow in the HDVS thus has the effect of increasing the residence time available for settling. In addition, the HDVS has internal components which segregate the flow so that captured solids are placed in an isolated region. These storage regions should offer minimal upflow velocities which are much lower than the nominal surface loading rates, hence reducing the probability of re-entrainment. Careful design, leading to optimisation of these effects, allows for much improved solids capture and retention.

MATERIALS AND METHODS

Experiments were conducted on a transparent small-scale HDVS (overall diameter 375mm, operating volume approximately 60 litres excluding any connecting pipe work) constructed of Perspex, as shown schematically in Figure 1. The device reproduced the features of a "Downstream Defender®", a commercially available HDVS, (manufactured and distributed by Hydro International) illustrated in Figure 2. Flow rates were measured by an in-line flowmeter in the inlet, set approximately 100 pipe diameters upstream. The flow meter was calibrated via volume/time measurements. Tracer experiments were carried out using fluorescent dye (Rhodamine WT). In each case dye was detected using a fluorimeter (SCUFA®, RS Aqua) with continuous data collection. Residence time experiments were conducted in the normal way by rapidly injecting a small volume of dye, at a point approximately 20 pipe diameters upstream of the inlet. For measurements on the upper chamber, the exit stream was continuously sampled at the overflow. The internal contents of the hopper were monitored continuously, sampling via a low-rate, peristaltic pump. A series of 8 sampling points were used, set on the central vertical axis as shown in Figure 1.

Results were obtained as fluorescence-time curves. As fluorescence is linearly related to concentration over the range used, fluorescence measurements were used directly. For subsequent comparison and analysis data was normalised, where $E(t)$ is:

$$E(t) = \frac{F(t)}{\int_0^\infty F(t)dt}$$

and F(t) is the fluorescence (in arbitrary units) at time t.

The mean residence time (t_m) was then calculated as:

$$t_m = \int_0^\infty tE(t)dt$$

Capture experiments were carried out by injecting a known amount of the solid, granulated active carbon, (GAC) into the inlet stream, via the same injection point used for dye injection, and capturing any material leaving via the overflow using a fine mesh filter-bag situated 1m downstream of the outlet pipe. GAC was chosen due to it having a density slightly higher than that of water and hence analogous with expected solids in a stormwater overflow.

Re-entrainment measurements were carried out by pre-loading the hopper, then initiating the flow and capturing solids transported to the outlet as before. Particle settling velocity was determined in still water by measuring the transit time between two points.

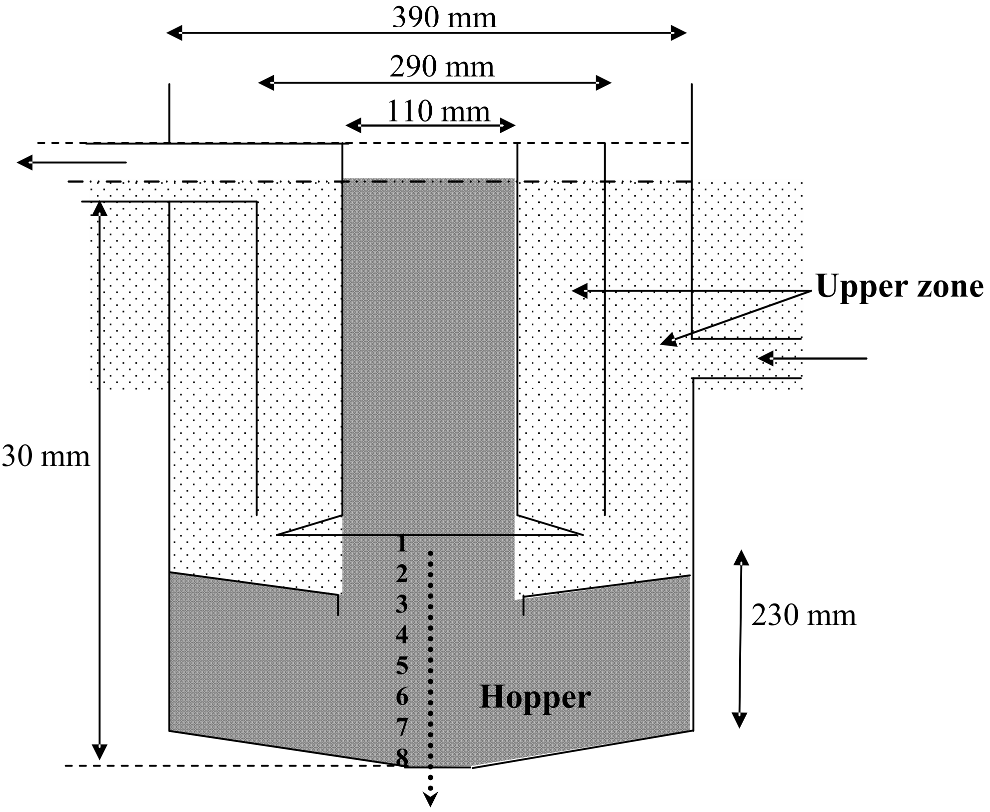


Figure 1. Schematic of the experimental HDVS (not to scale). Sampling points for internal sampling are shown as 1…..8. Dotted area = flow zone; grey area = hopper and central shaft. The mesh screen was situated 1m downstream of the outlet pipe. Total volume ~ 60 l, hopper ~ 30 l, main flow zone ~ 25 l

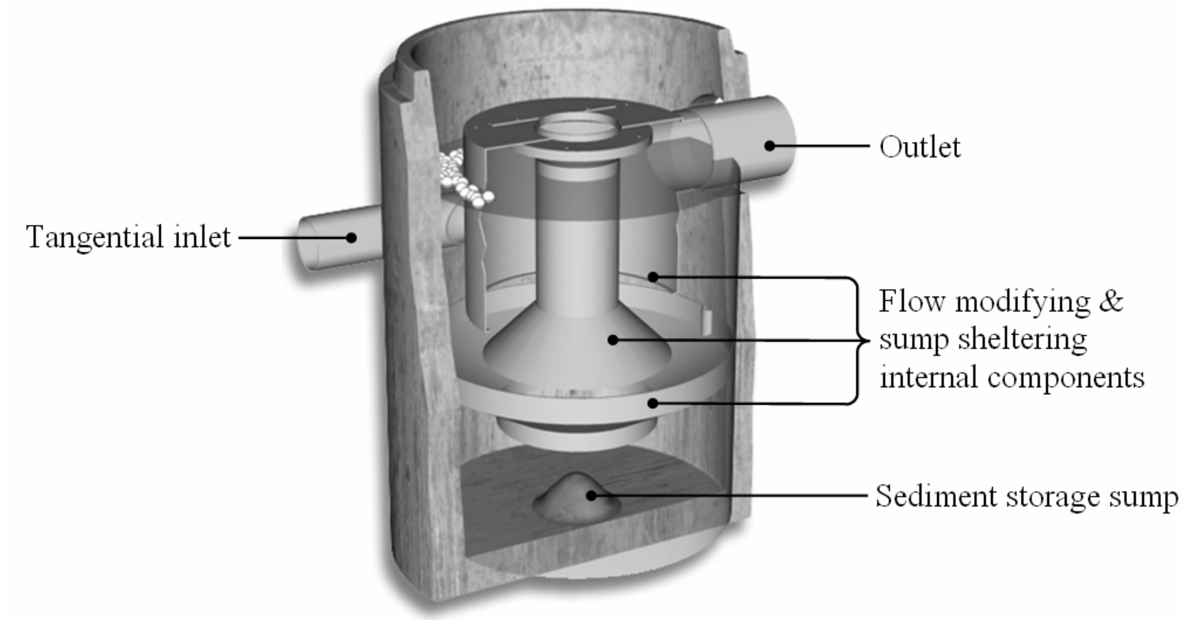


Figure 2. Cutaway diagram of the Downstream Defender®.

RESULTS

The results of typical dye tracer experiments are shown in Figure 3 below. These illustrate quite clearly the difference in the dye tracer response of the two flow zones.

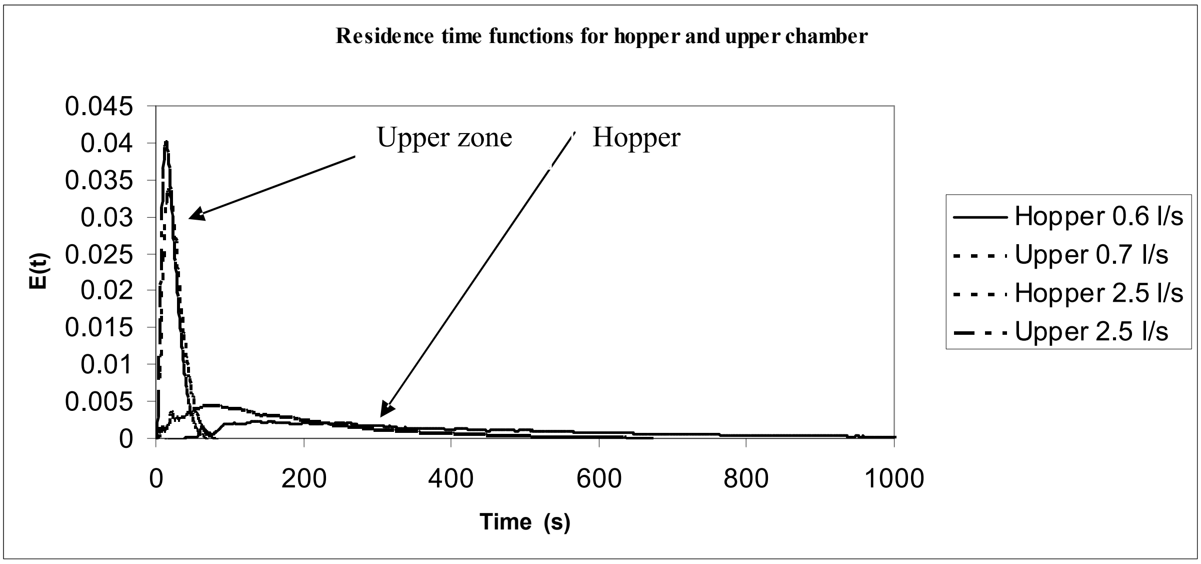
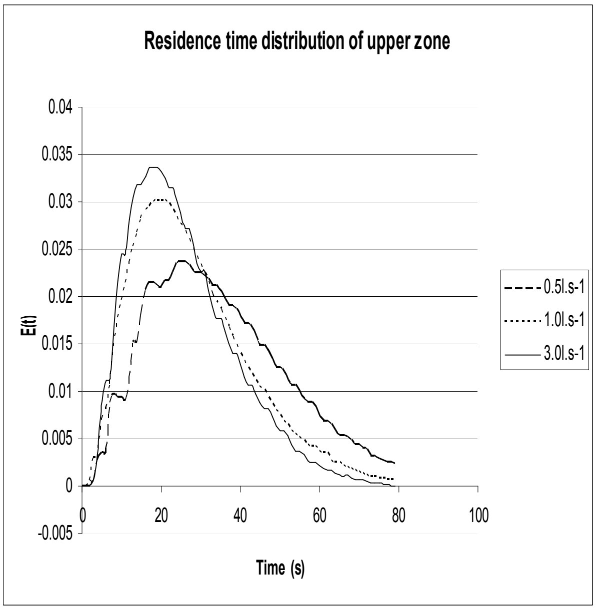


Figure 3. Typical residence time distributions for the upper zone and hopper

The mean residence time (t_m) for the upper zone was 20-35s, depending on flow (0.5–3.0 l/s), whilst for the hopper it was >150s under similar conditions. Despite the rather convoluted flow path, the upper zone behaves very much as a separate region with reasonably orderly flow characteristics.

Figure 4a shows data for the upper zone for three flow rates and Figures 4b-d show attempts to fit a Gaussian profile to each residence time distribution profile. In each case the residence time distribution is slightly positively skewed and the fit is not exact, but it is reasonable to conclude that the upper zone exhibits near plug flow behaviour with a certain degree of back-mixing.



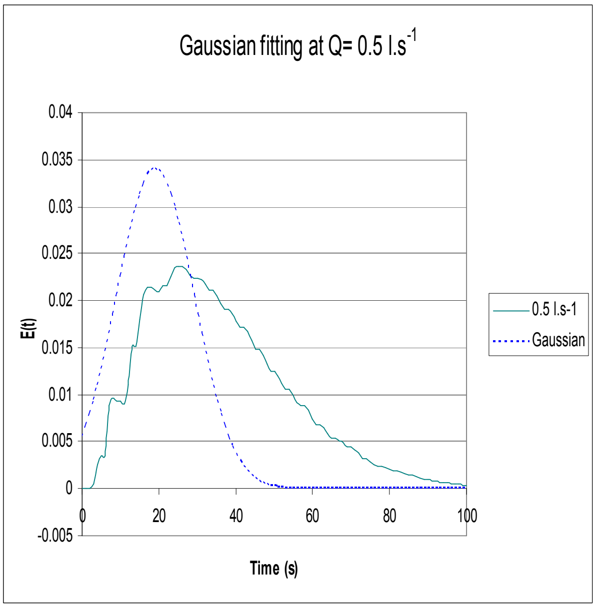
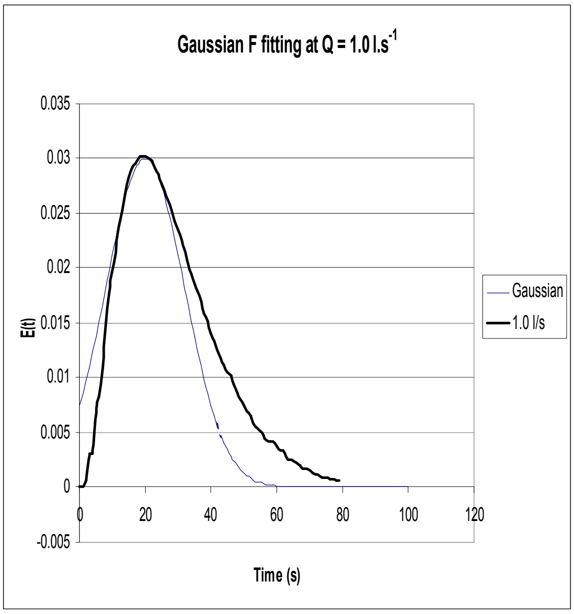


Figure 4a **Figure 4b**



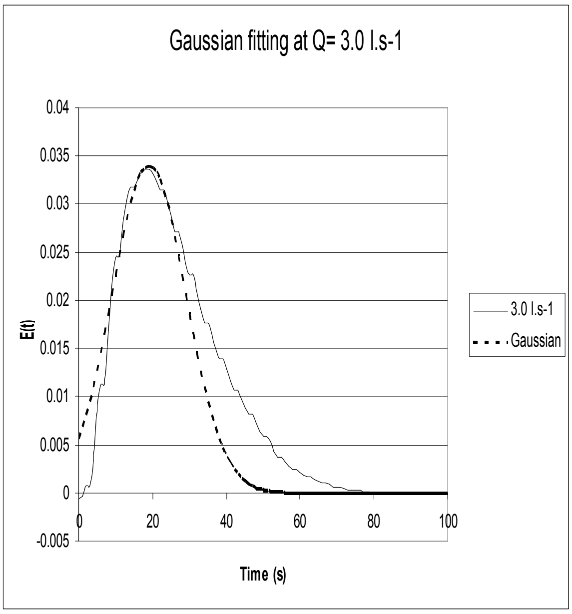


Figure 4c **Figure 4d**

Figure 4 (a-d). Examples of residence time distribution functions and comparison with a standard Gaussian curve set to peak at t = 25s.

The behaviour of the upper chamber at first appears to be reasonably predictable over the range of flows used. As flow increases, t_m decreases as expected, see Table 1 below. However, on closer examination the change is less than might be expected. A ten-fold increase in flow rate only causes a decrease in t_m, the mean residence time, of about one third. The ratio τ/t_m (where τ = theoretical residence time = V/Q; V = volume and Q = flow rate) increases, suggesting some change in behaviour at higher flowrates.

If the measured mean residence time and flow are used to calculate an effective 'active' flow volume (V_{calc} = Q x t_m) then as can be seen the value increases from less than that of the flow zone (12 l rather than 24 l) to equivalent to the whole system volume, implying that at high flow rates some mixing of all sections occurs.

Table 1. Space-time, mean residence time and active volume calculated as a function of overall flow.

Q ($l.s^{-1}$)	**τ * (s)**	**t_m (s)**	**τ/t_m**	**V_{calc}** ** (l)**
0.35	57	35	1.63	12
0.40	50	35	1.43	14
0.50	40	36	1.12	18
0.67	30	29	1.03	19
0.70	29	26	1.10	18
1.00	20	28	0.71	28
1.40	14	25	0.57	35
2.50	8	21	0.39	52
3.00	7	20	0.33	60

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* τ is calculated assuming V = 20 l, the upper section volume
** $V_{calc} = Q \times t_m$

The behaviour of the hopper was quite different. The mean residence times were always substantially larger (> 10×) than those for the upper chamber, measured at the same flow rate. The data was rather more scattered as can be seen in Figure 5 below. This is not surprising, as at high concentrations, the tracer could be seen moving in plumes, showing very slow internal mixing within the hopper.

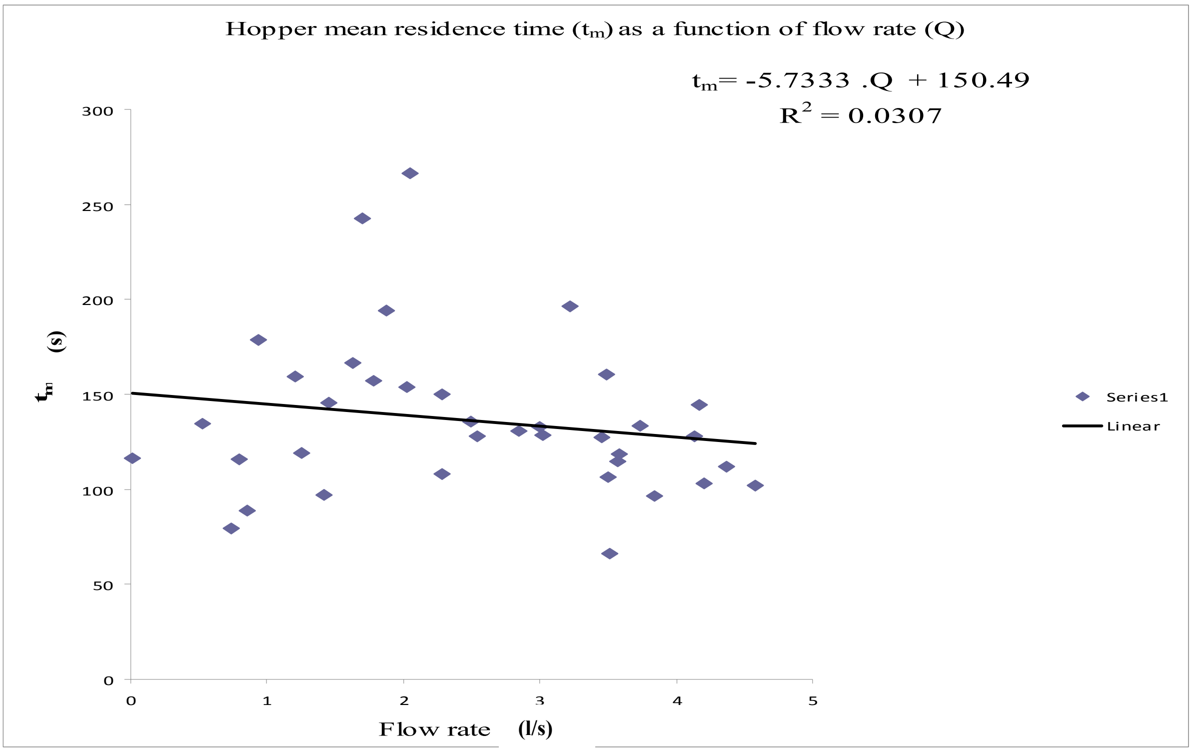

Figure 5. Mean residence time for the hopper as a function of flow.

Further examination of the hopper, with sampling at point 1 (as shown in Figure 1) reveals that the whole of this zone is quiescent, with mean residence times of about 150 s, even at flow rates of up to 4.5 $l.s^{-1}$, more than the typical design loading for this type of system. In addition, as shown in Figure 6 the residence time distribution is much more positively skewed than for that of the upper section. It was not possible to fit a Gaussian profile to this with any reasonable success. This emphasises the slow exchange within this section and between sections.

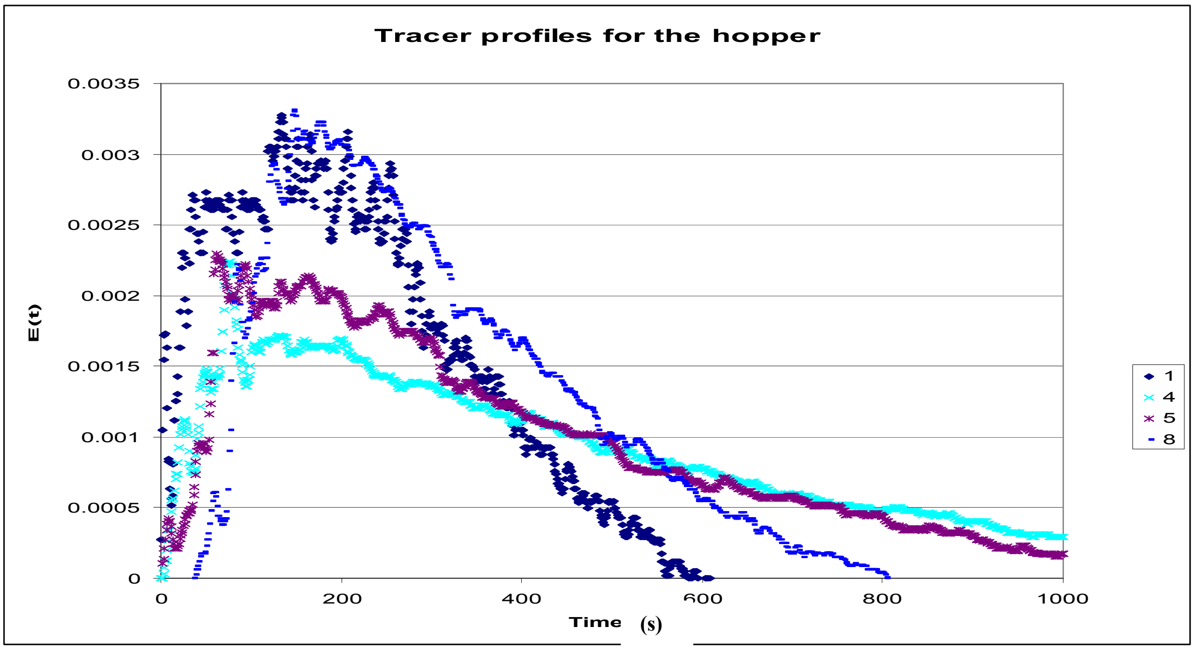

Figure 6. Dye tracer profiles taken within the hopper (positions as shown in Figure 1).

Taking an average over all the positions sampled gives the curve shown in Figure 7, with a mean residence time of 230 s. This seems a reasonable representation and confirms that most of the region behaves in a uniform manner.

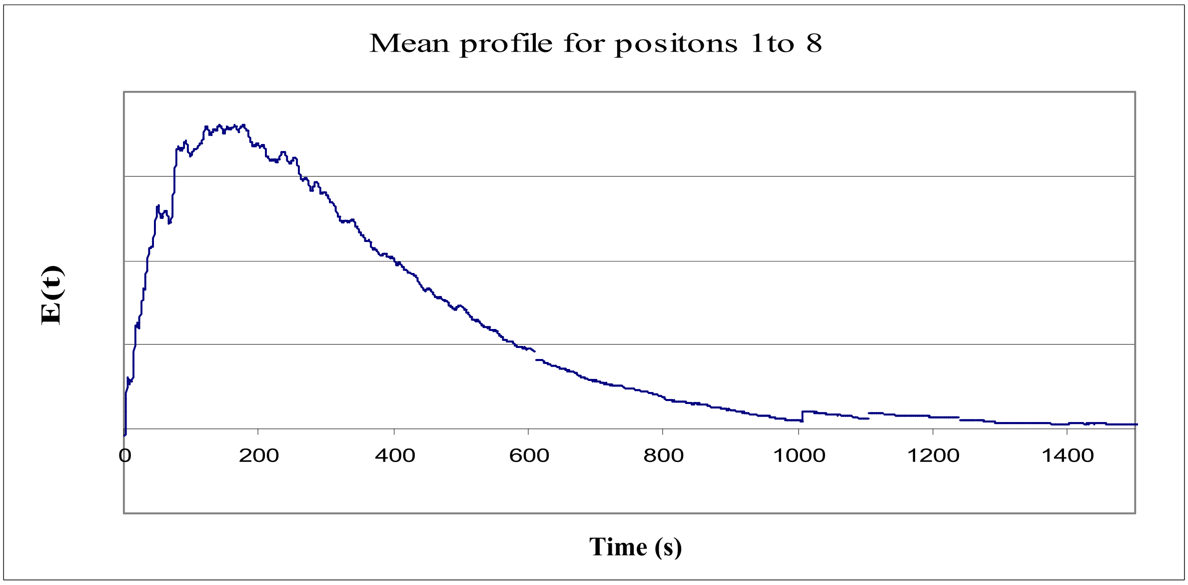

Figure 7. Average of eight positions, showing positive skewing leading to extended mean residence times.

The capture and re-entrainment of GAC (settling velocity in still water = 0.054 $m.s^{-1}$) was then examined. As shown in Figure 8 capture was entirely effective up to a flow of 2.0 $l.s^{-1}$, corresponding to a typical design loading rate for this type of system. Notably, re-entrainment up this point was negligible, with retention of over 90% of material even at twice typical design loadings.

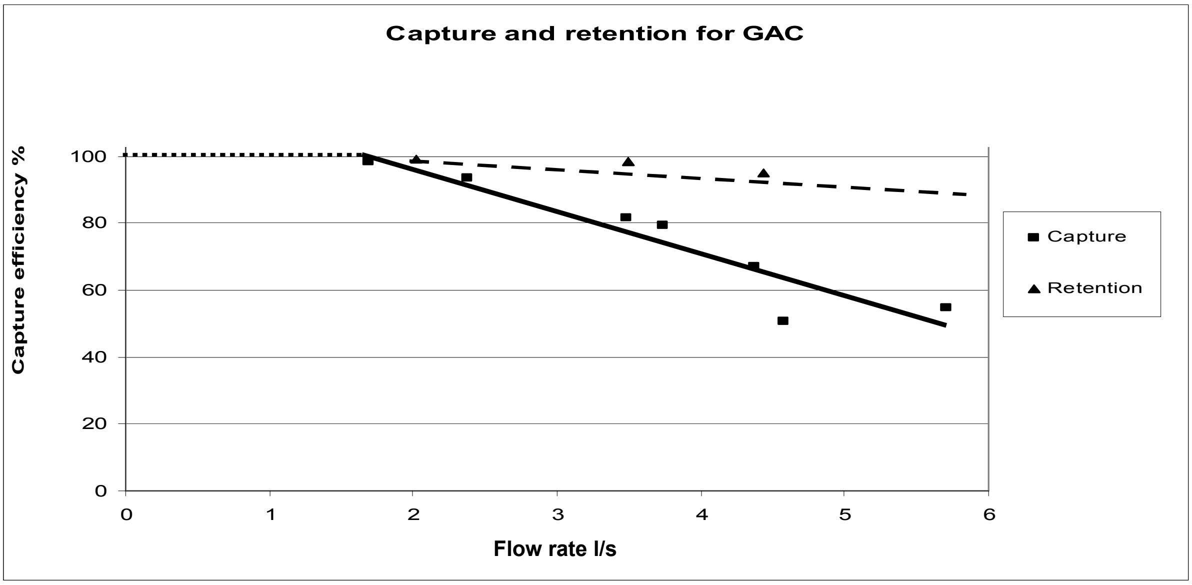

Figure 8. The capture and retention of GAC at different flow rates.

It is difficult to assess the actual rise velocity from the hopper, but assuming that the full volume (approximately 25 l) exchanges in mean residence time (say 150 s) through the aperture (cross section ~ 700 cm^2) the rise velocity can be estimated as $0.0023 m.s^{-1}$, which is considerably less than the sedimentation velocity of the GAC ($0.054 m.s^{-1}$), clearly accounting for the high retention efficiency of the system.

DISCUSSION

Studies on any flow-through treatment device can be defined as those measuring practical performance (capture/retention), practical investigations on fluid flow, (usually via tracer studies), and theoretical or modelling studies (either analytical or using CFD). An analytical model, based on the Tanks in Series Model (TSM), clearly shows that in a well-designed vortex separator system, similar to that described here, the hopper, or storage region, was effectively decoupled from the main flow and could best be described as a "slow-exchange region" (Alkhaddar *et al.,* 2001). More recently, Faram and Harwood (2002) and Faram *et al.* (2003) have reinforced this using computational fluid dynamics (CFD). These findings were supported by a report of a photographic and video study of dye washout experiments which allowed the zones to be observed on a macroscopic level (Phipps *et al.*,2005).

The main findings here confirm the relevance of the hopper to retention efficiency as a performance parameter, highlighting the importance of sheltering the pollutants storage region in such systems. Although detailed profiles of capture and retention efficiency will vary from system to system, the principal is quite clear

PRE (Pollutants Removal Efficiency) for sedimentation devices is usually measured under conditions of constant flow, usually expressed as (HLR) hydraulic loading rate, (flow/free surface area), which allows comparison between devices of different sizes. Importantly however, overall PRE can be separated into terms of capture and retention efficiency, so that:

$$\frac{\sum_{t(0)}^{t(n)}\left\{(Capture efficiency)_{t(n)}\times(Pollutants influx)_{t(n)}\right\}+\left\{(Retention efficiency)_{t(n)}\times(Stored pollutants)_{t(n-1)}\right\}}{\sum_{t(0)}^{t(n)} Pollutants influx}$$

Where Capture and Retention efficiencies are taken to be instantaneous values applicable to flows at time $t_{(n)}$.

For simplicity and practical reasons, PRE measurements are normally made over a series of discrete, constant flow rates. This gives measures of the IPRE (Instantaneous Pollutants Removal Efficiency) which is a time independent measure of efficiency. The overall performance is then obtained by averaging performance over the measurement period to give the net removal.

$$PRE = \frac{\sum_{t(0)}^{t(n)} \left\{ \left(Instantaneous\ Pollutants\ Removal\ Efficiency \right)_{t(n)} \times \left(Pollutants\ influx \right)_{t(n)} \right\}}{\sum_{t(0)}^{t(n)} Pollutants\ influx}$$

However, it has been shown previously, and is confirmed here, that capture and retention efficiencies themselves are flow and hence time dependent functions (Faram *et al.*, 2003). Although the capture and retention efficiencies will change with flow in broadly the same fashion, i.e. they are inversely related to flow, they will affect the overall performance in substantially different ways. Therefore, as described previously, (Phipps *et al.*, 2005) if the storm hydrographs were known, it would be possible to estimate the time dependent overall performance under conditions of varying flow, though this is often implicitly ignored.

The design of an efficient HDVS should ideally take account of the storm hydrograph. Consideration needs to be given to both the condition of the plant at the start of the storm event and its performance as the storm flow increases. If the plant is already loaded, i.e previously captured material is in the hopper, and assuming that most of the polluting load in a storm occurs at the beginning when flow is still low (i.e. in the form of a ‘first flush’), it might be deduced that the performance during this period will be highly effective (high efficiency for both capture and retention) and so increase the load in the hopper substantially. Conversely, at a storm peak when flow rates are highest, capture efficiencies tend to be at their lowest thus reducing the IPRE at that point. However, importantly, an efficient plant will be able to retain the accumulated pollutants despite the increase in flow.

Previous studies, Faram and Harwood (2002) and Phipps *et al.* (2004) have also made a similar point but on this occasion tracer studies have shown the extent of the hopper quiescent zone and provided verification that in this design of plant the quiescent zone is maintained over the whole range of flows studied, so explaining why re-entrainment is low.

CONCLUSIONS

Both tracer and capture/retention studies have clearly shown that the HDVS investigated in this study is best considered as a two component system. The design of this particular configuration has very successfully created a hopper which, although physically connected, is hydraulically separate from the upper flow region. With mean residence times of > 100s, the hopper shows very low exchange flow, which accounts for the ability of the system to retain captured solids even at flow rates significantly exceeding typical design loading rates for this type of system.

Studies of proprietary treatment chambers have tended to focus on performance in terms of overall removal efficiency under conditions up to their ‘design’ flowrates. However, the question of performance outside design range has generally been neglected. In the current studies, the effect of chamber design on performance beyond the design range has been considered, and the ability of this particular configuration to efficiently 'retain' stored pollutants has been demonstrated.

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