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A Comprehensive Investigation into the Hydrodynamic and Capture/Retention Performance of a Gross Pollutant Trap

J.T. Madhani[1] and R.J. Brown[1]

[1]School of Engineering Systems
Queensland University of Technology
Brisbane QLD 4001
AUSTRALIA
E-mail: j.madhani@qut.edu.au

Abstract: *A novel and comprehensive testing approach to examine the performance of gross pollutant traps (GPTs) was developed. A proprietary GPT with internal screens for capturing gross pollutants—organic matter and anthropogenic litter—was used as a case study. This work is the first investigation of its kind and provides valuable practical information for the design, selection and operation of GPTs and also the management of street waste in an urban environment. It used a combination of physical and theoretical models to examine in detail the hydrodynamic and capture/retention characteristics of the GPT. The results showed that the GPT operated efficiently until at least 68% of the screens were blocked, particularly at high flow rates. At lower flow rates, the high capture/retention performance trend was reversed. It was also found that a raised inlet GPT offered a better capture/retention performance. This finding indicates that cleaning operations could be more effectively planned in conjunction with the deterioration in GPT's capture/retention performance.*

Keywords: *Gross pollutant trap (GPT), testing, hydrodynamic, capture, retention.*

1. INTRODUCTION

Gross pollutant traps (GPTs) play an important role in preventing visible street waste such as gross pollutants from contaminating the environment. The demand for these devices has led to the development of a range of proprietary GPTs.

Gross pollutant traps, including patented and registered designs developed by industry, have specific internal configurations and hydrodynamic separation characteristics which demand individual testing and performance assessments. Stormwater devices are usually evaluated by environmental protection agencies (EPAs), professional bodies and water research centres. In the USA, the American Society of Civil Engineers (ASCE) and the Environmental Water Resource Institute (EWRI) are examples of professional and research organisations actively involved in these evaluation/verification programs (Madhani, 2010). These programs largely rely on field evaluations alone which are limited in scope, mainly for cost and logistical reasons. In Australia, the evaluation and verification of new devices in the stormwater industry is not well established. An extensive literature review also revealed that, in general, scientific testing of GPTs is not well established [For a comprehensive list of authors, see Madhani (2010)].

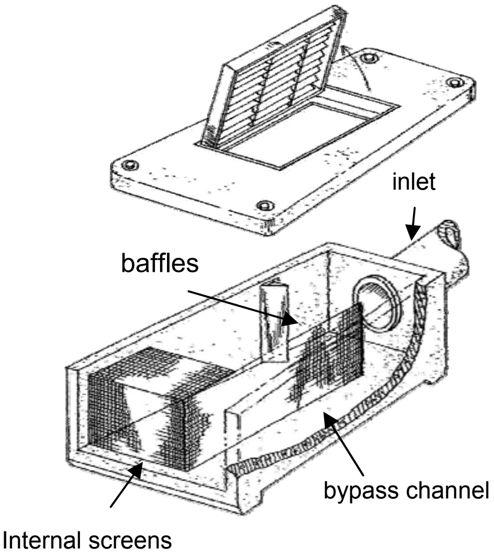


Figure 1 A view of the GPT LitterBank.

To this end, a novel and comprehensive testing approach was developed to overcome current limitations in the evaluation methodologies of GPTs. A proprietary GPT with internal screens to capture gross pollutants—organic matter and anthropogenic litter—was used as a case study.

This device, as shown in Figure 1, has not been previously investigated. The GPT device, the *LitterBank* was developed recently by C-M Concrete Products Pty Ltd. Unlike most such devices, the *LitterBank* GPT has a dry sump to avoid waste decomposition in water. The GPT design also has a separate bypass channel to minimise flooding due to blockages. The prefabricated device can be installed on ground level, thereby reducing installation costs. Currently, there are approximately, twenty *LitterBanks* operating at strategic stormwater locations throughout Queensland, Australia. However, despite the increasing use of this device, research on the *LitterBank*—or on a GPT of similar design—is also scant.

Field studies conducted for the purpose of this research indicated that this type of GPT should be tested in laboratory conditions for abnormal or adverse conditions such as blockages caused by organic matter. Consequently, the focus of this investigation was on the operating efficiency of a GPT under screen blockage conditions using hydrodynamic studies, capture/retention experiments and computational fluid dynamics (CFD).

This investigation involved the use of equipment such as acoustic Doppler velocimeters (ADVs) and dye concentration (Komori) probes, which were deployed for the first time in a dry-sump GPT. The hydrodynamic studies led to the definition of global and local flow features important for describing the gross pollutant capture/retention performance. The gross pollutant capture/retention experiments included the use of anthropogenic litter components, tracer dye and custom modified artificial gross pollutants (spheres).

Overall, the results showed that when the internal retaining screens were fully blocked, the gross pollutant capture/retention performance of the GPT deteriorated rapidly. A design appraisal of a GPT with a raised inlet was also investigated and is reported in this paper.

2. METHODOLOGY AND GPT MODELLING CONSIDERATIONS

There are no established guidelines for testing GPTs. However, it is reported in literature that the design of GPTs should consider the following: site constraints; inlet flows; operation under adverse conditions; prevention of flooding when fully blocked by introducing a bypass system; the scouring of the captured/retained pollutants; high capture/retention efficiency; minimal adverse hydraulic properties such as low head losses; and inexpensive and infrequent maintenance (Field and Sullivan, 2003; Wong et al., 2000). These design considerations were incorporated into the testing methodology for examining in detail, the hydrodynamic and gross pollutant capture/retention characteristics of the *LitterBank* GPT. The new testing approach used a combination of physical and theoretical models (See Figure 2), which included review of gross pollutant data, field work, equipment calibration, hydrodynamic studies and gross pollutant capture/retention investigations. In this methodology, the experimental setup parameters in Figure 2 denoted, R1-R12, are described in Table 1, in terms of weir height, inlet velocity, flow rate, water depth and screen blockage.

The initial testing methodology in Figure 2, field studies, consisted of collecting and analysing gross pollutant—visible street waste—data. The data was used to identify public littering attitudes and typical street waste, which are important factors in the design and placement of GPTs. Gross pollutants were monitored and their movement in the stormwater gutters during wet weather was characterised (Madhani, 2010). Existing installations of GPTs were also monitored to collect field operating data necessary for performing theoretical studies and experiments in the laboratory.

Field monitoring of GPTs also showed that during wet weather a wide range of inlet, outflow and other operating conditions occurred (Madhani, 2010). The extent and duration of rainfall influences the flow rate entering the GPT. The outflow level in the GPT is determined by the tidal or flood levels downstream of the receiving waterways. Due to infrequent cleaning, the retaining screens were often found to be blocked with organic matter. Blocked screens can radically change the hydrodynamic and gross pollutant capture\retention characteristics of the GPT. Depending on these operating conditions, the possible flow regimes inside the GPT can range from turbulent time-dependent free surface flows to more steady-state conditions. This presents significant challenges for either experimental or CFD studies aimed at understanding the flow and capture/retention characteristics of GPTs.

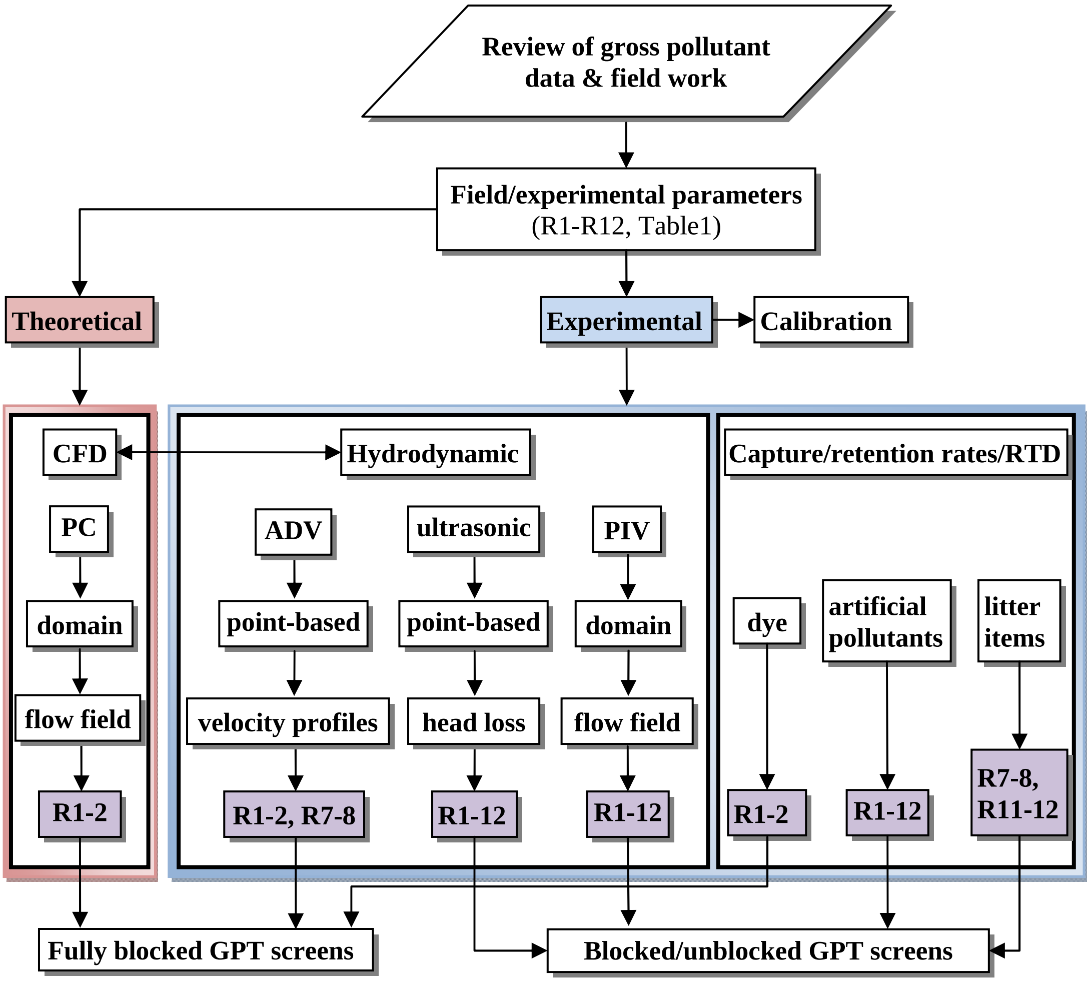


Figure 2 An overview of the testing approach (See Table 1 for experimental setup parameters, R1-R12).

Table 1 Experimental setup parameters for the GPT rig (See Figure 2).

Screen blockages %			Flow regime	Weir height (m)	Inlet velocity (m/s)	Flow rate (L/s)	Water depth (m)
100	68	33					
Experimental run							
R1	R3	R5	Low	0.108	0.09	1.3	0.1
R2	R4	R6	↕	0.286	0.09	3.9	0.3
R7	R9	R11		0.000	0.39	6.1	0.1
R8	R10	R12	High	0.000	2.14	35.0	0.3

To overcome these modelling challenges, an experimental approach was developed to initially study the steady-state conditions. This approach used a downstream weir arrangement to control the nature and variation of flow (Table 1) in the GPT apart from elevated outflow levels (Madhani, 2010). In this arrangement, the physical model consisted of a 50% scale model GPT rig with screen blockages 33%, 68% and 100%. To model fully blocked screens, normal GPT screens were replaced with Perspex solid walls. Perforations 3 mm and 5 mm in diameter were used to represent screen blockages of 68% and 33% screen blockages respectively. These percentages were based on the amount of material obstructing the flow path; no screens in the GPT represented a 0% blockage. The GPT rig was placed in a 19 m flume and various inlet and outflow operating conditions were modelled based on field observations (Table 1). Inside the flume, flow into the GPT was through an upstream inlet configuration with its height extended to the full depth of the experimental rig with a width of 144 mm (See plan view in Figure 3). For the gross capture/retention and head loss experiments, a second upstream inlet consisting of a pipe, 100 mm in diameter, which terminated with a small invert level at the GPT entrance, was also deployed.

Hydrodynamic and gross pollutant capture/retention investigations were conducted using experiments and CFD simulations (See Figure 2). The collection of experimental hydrodynamic data involved: measuring velocity profiles using the ADV across the cross sectional width (See St. 1-3, Figure 3); capturing the flow field using the PIV technique; and taking head loss measurements using the ultrasonic probes.

Velocity measurements were conducted with three ADVs: (1) SontekTM MicroField-ADV (16 MHz, 3D down-looking probe serial number A813F), (2) SontekTM MicroField-ADV (16 MHz, 3D side looking probe serial number A843F) and (3) SontekTM Micro-ADV (16 MHz, 3D down-looking probe serial number A919F). The use of ADVs and the issues relating to data processing have been discussed elsewhere (Madhani, 2010). All measurements were sampled at 50 Hz for 120 s (time series length of 6000 samples). WinADV version 2.024 was used for the batch post-processing of ADV generated output data files (Wahl, 2006).

Apart from ADV measurements, flow structures within the GPT were captured by tracking fluid particle motion with a PIV system supplied by Integrated Design Tools Inc. (IDT) via SciTech Pty Ltd., Melbourne, Australia. This system comprises a high-speed camera (X-StreamTM XS-4), image acquisition (X-StreamTM Vision version 1.13.05,) and PIV software (proVision-XSTM version 3.08.30). The recorded fluid motion was visualized through an image-based, line integral convolution (LIC) algorithm. For a detailed discussion of the PIV and LIC image techniques to capture data flow within a GPT for a range of blocked screens conditions, see Madhani (2010).

Supplementary to the collection of ADV and PIV data, the head loss of blocked screens was also recorded using four ultrasonic displacement sensing probes with an accuracy of 0.18 mm: (1) MicrosonicTM +25/IU/TC/E with a response time of 50 ms and (2) MicrosonicTM +35/IU/TC/E with a response time of 70 ms. These probes were also used to monitor the flow conditions in the flume during the collection of ADV, PIV and gross pollutant capture/retention data.

Gross pollutant capture/retention experiments were conducted with anthropogenic litter, generic, tracer dye measurements and custom modified large (≈ 40 mm) celluloid spherical particles (table tennis balls). Anthropogenic litter was limited to tin cans, bottle caps and plastic bags, while the artificial pollutants had a range of four buoyancies: floatable, partially buoyant, neutrally buoyant and sinkable. Tracer measurements were performed by injecting dye into the incoming fluid to continuously—as a function of time—monitor its concentration and the residence time distribution (RTD) at the GPT outlet.

The dye measuring system comprised: a voltage supply with zero adjustment, Komori probes, an injection unit and a data acquisition system (Data Translation DT9802). The injection unit consisted of a volumetric infusion pump (Alaris Medical Systems—formerly IVAC Corporation Model 597), a dye outlet probe/ injector tube and an intravenous (IV) /infusion bag filled with blue dye. For further details on the application of the Komori probes, see Madhani (2010).

In addition to the experimental investigations, complementary CFD modelling (using Fluent 6.3) was performed using a two-dimensional k-ε turbulence model along with either standard wall law boundary conditions or enhanced near-wall modelling approaches—for further details see Madhani (2010).

3. RESULTS AND DISCUSSION

The outcome of the GPT case study investigation using the new testing approach (Figure 2) is discussed below. The discussion commences with a review of stormwater gross pollutant data and field work.

An extended literature review of gross pollutant data and field work showed that there is a need to address the long-term management of street waste, and that GPTs have a vital role to play in the future management of gross pollutants. The high amount of waste found on streets and in stormwater systems generally consists of anthropogenic litter and organic matter. Floating masses accumulating in our oceans due to non-biodegradable street litter entering stormwater systems have caused recent scientific and public concern. Organic matter causes blockages in stormwater systems such as roadside drains and GPTs, resulting in upstream flooding.

For example, it was noted that the internal retaining screens of GPTs are often clogged with grass clippings due to infrequent cleaning. Organic matter such as grass clippings may also constitute a fire hazard. With the advent of new urban design and planning concepts such as green roofs and walls it is envisaged that the increase in organic waste will cause further problems in the management of stormwater pollution (Madhani, 2010).

Following the literature review, preparatory work for the hydrodynamic and gross pollutant capture/retention experiments included, where necessary, the calibration and performance assessments of equipment. Experimental methodologies and data processing techniques were developed and refined to address the measurement issues associated with the Komori dye concentration probes. These issues involved noise levels, electrical drift, spiking and fluid turbulence. For measuring velocities, the effective use of ADV semi-intrusive probes in awkward and tight spaces, in addition to flow disturbance due to their geometrical configuration, were also considered.

Initial hydrodynamic studies focused on analysing flow regimes within the *LitterBank* GPT with fully blocked retaining screens using ADV measurements and CFD simulation (Figure 4). Figure 4 shows typically the ADV measured velocity profiles for St. 3 in the retention area of the GPT, for the lower flow rate GPT inlet conditions (See experimental run R1, Table 1). The two-dimensional CFD simulation for this assumed steady-state flow (R1, Table 1) was found to be in good agreement with the measured profiles, as shown in Figure 4. Some variations in the multi-depth velocity profiles near the inlet and neighbouring regions (St. 1 and St. 2) were observed (Not shown). At higher flows (R3 and R4, Table 1), the variations in the measured profiles were more noticeable at these stations due to high shear regions associated with flow separation.

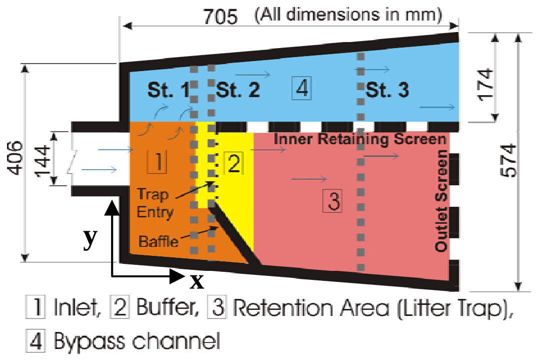


Figure 3. Plan view of the LitterBank with the measurement stations St.1 (x = 137.5), St. 2 (x =182.5) and St. 3 (x=450).

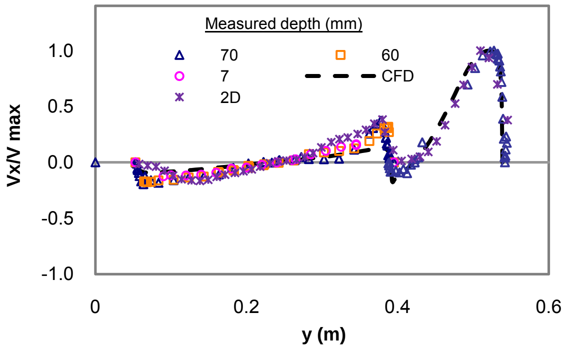


Figure 4. Typical velocity profiles from ADV measurements and CFD simulation in the retention area of the GPT (St. 3).

The measured and CFD data revealed several unique flow features important in understanding gross pollutant capture/retention characteristics of the GPT (See Figure 5). At this stage, 3D CFD modelling could be considered for further studies, although further measurements revealed similar trends for all inlet flow rates.

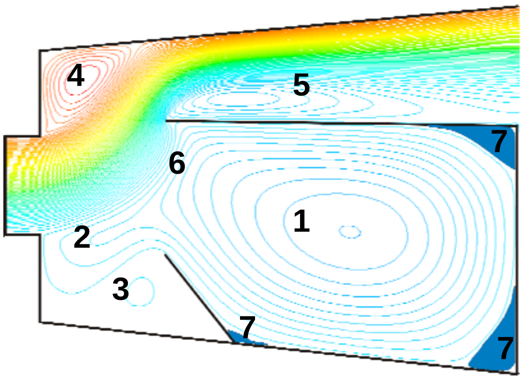
The velocity data were integrated to examine the net fluid flow at each section using principle mass conservation and independent checks were made with measurements at the flume outlet. The results indicated that under fully blocked conditions, approximately 80% of the fluid bypassed the retention area of the GPT. This suggests that the majority of the gross pollutants entering the GPT would eventually escape through the bypass channel. This assumption would hold true provided the fluid does not recirculate at the entry to the retention region. Under the same GPT operating conditions with fully blocked screens, it was also noted that the capture/retention experiments for the partially submerged particles (RD = 0.9) resulted in a maximum of 75% of pollutants escaping the GPT. In both cases the ADV and gross pollutant capture/retention results were comparable.

The PIV images were useful for comparison of the set of flow features in the GPT under various operating conditions that was not possible with the ADV data. For example, a greater fluid coverage was facilitated with the PIV technique. The PIV flow dataset collected was uniquely visualised using image-based LIC algorithms, as is typically shown in Figure 5 (Madhani, 2010).

The results for the GPT with fully blocked screens compared favourably with the ADV velocity profiles (Figure 4) and the CFD flow structures (Figure 6). The PIV images showed that beyond at least 68% screen blockage, the streamlines in the retention area of the GPT were weaker than the flow entering the bypass. This suggests that the capture/retention performance would rapidly deteriorate, as confirmed by the capture/retention experiments (Madhani, 2010).

Similarly, the irregularity in the rotational flow pattern of the deeper water flow regimes also suggests a poorer capture/retention performance. This behaviour was also observed in the capture/retention experiments, with the exception of the sinkable pollutants (RD=1.1). The sinkable pollutants were influenced by high negative shear velocity gradients—obtained with ADV measurements—in the lower vicinity of the inner wall. Consequently, the GPT capture/retention results for these pollutants tended to differ, for a more in-depth discussion see Madhani (2010).

The final hydrodynamic investigation, the head loss experiments, included the investigation of the GPT with different inlet configurations (circular pipe and open rectangular channel) and no internal screens. A clear difference in the hydraulic head loss performance between the GPT with fully and partially blocked screens was observed. This distinction was also noted in the gross pollutant capture/retention experiments for the same configurations and operating conditions. Lastly, it was found that when the blockage of the internal screens approached 100%, the head loss of the GPT increased and the gross pollutant capture/retention performance decreased rapidly.



Feature zones

1, inner recirculation; 2, diverticulum; 3, 4, dead zone (secondary recirculation); 5, flow separation; 6, mixing; 7, low velocity corner eddies.

Figure 5. Streamlines illustrating global flow structure for EWT (enhanced wall treatment).

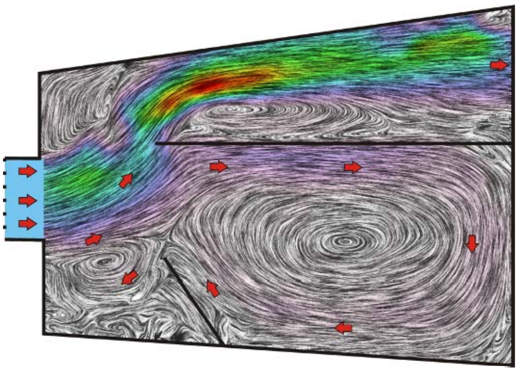


Figure 6. Images processed from PIV technique using LIC algorithms.

Preliminary gross pollutant capture/retention experiments using anthropogenic litter, such as various sized tin cans, plastic caps and bags, showed that the GPT captured the larger cans more efficiently at a lower inlet flow rate (10 L/s). The plastic bags were the worst performers and at higher flow rates (21-26 L/s), all anthropogenic litter was captured efficiently.

The capture/retention experiments also revealed that the release of custom-modified artificial spheres into the GPT inlet resulted in the rapid deterioration of the capture/retention efficiency when the internal screens were fully blocked (Figure 7). The plots in Figure 7 highlight the capture/retention trends of the variable density spheres (RD = 0.1, 0.9, 1.0 and 1.1); 1.0 on the vertical axis represents 100%. In these experiments, the total average capture/retention was 4%. Below this average, the sinkable and neutrally buoyant spheres (RD = 1.0 and 1.1) appeared to be the worst performers. Figure 8 shows the poor capture/retention performance of the GPT in a visual snapshot of the neutrally buoyant spheres escaping via the outflow path upon entry into the *LitterBank* GPT with a channel inlet. Here, a large number of spheres entered the GPT inlet within a very short time. This behaviour is described as the continuous or step input method of introducing the spheres into the inlet. The variable density spheres were also characterised by comparing the RTD from dye measurements at the GPT outlet using the step input method. The experimental dye data was found to be in close agreement with the CFD simulation and comparable to the behaviour of the partially buoyant pollutants (RD = 0.9). The neutrally buoyant spheres displayed the shortest occupation times when the screens were 100% blocked (Madhani, 2010). During higher inlet flow rates, it was found that at up to 68% screen blockage, the capture/retention performance of the GPT remained efficient.

Figure 9 shows an example of the deposition pattern in the retention area of the GPT with 68% blocked screens for the highest flow rate. The overall results for this blockage condition are graphically depicted in Figure 10.

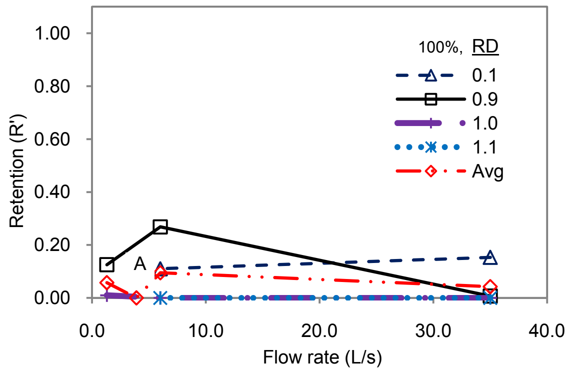


Figure 7. Normalised capture/retention profiles (R') for continuously fed variable density spheres (RD) = 0.1, 0.9, 1.0 and 1.1. The channel-inlet-configured GPT experiment was with fully blocked screens tested under varying flow rates (See Table 1). A (See left of figure) denotes poor capture/retention performance which may be attributed to large negative velocities denoted by B in Figure 8.

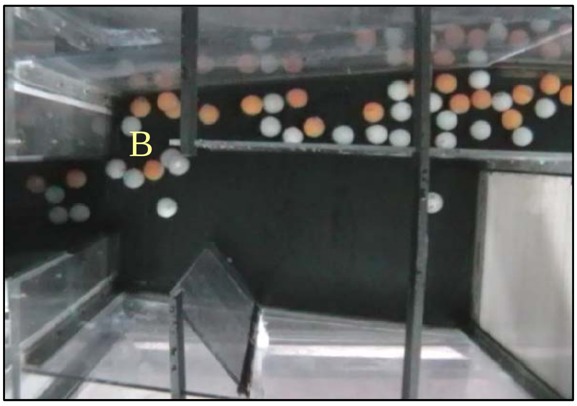


Figure 8. Experiments with fully blocked screen show the neutrally buoyant spheres (RD =1.0) escaping the GPT via the bypass (See data point A in Figure 7 at 1.3 L/s on the abscissa). B (See left of figure) denotes the existence of large negative horizontal velocities.

Figure 9. Deposition pattern for the GPT with 68% blocked screen shows total (100%) capture/retention of the lightest pollutants (RD = 0.1) at a high (35 L/s—Table 1) flow rate (See C, Figure 10).

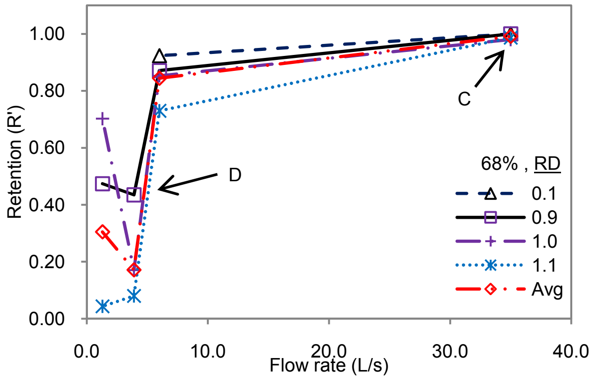


Figure 10. Normalised capture/retention profiles (R') for continuously fed variable density spheres (RD) = 0.1, 0.9, 1.0 and 1.1. The channel-inlet-configured GPT experiment was with 68% blocked screens tested under varying flow rates (Table 1). See snapshots of capture/retention performances in Figures 8 and 9 for C and D, respectively.

During lower flow rates, the performance of the GPT also deteriorated, regardless of the screen conditions. Furthermore, there was little difference in the poor performance between a fully blocked GPT and a partially or empty GPT with fully blocked screens.

The results from the head loss experiments were found to be similar with the gross pollutant capture/retention investigation indicating that maximum performance was reached when the screens were approximately 68% blocked. Beyond 68%, the head loss rapidly increased indicating that the performance of the GPT will suffer.
The practical significance of the above findings is that the GPT does not require cleaning until at least 68% of screens are blocked. This information is important for the management and maintenance of the GPT in the field, in that cleaning operations could be less frequent.

With regards to design improvements, the gross pollutant capture/retention experiments were partially repeated with a second inlet structure—a raised circular pipe—GPT. The results showed a marginal capture/retention improvement (16.5%).

4. CONCLUSION

This study used a novel and comprehensive testing approach to examine the performance of gross pollutant traps (GPTs). A proprietary GPT with internal screens for capturing gross pollutants—organic matter and anthropogenic litter—was used as a case study. The case study methodology included a review of gross pollutant data, field work; equipment calibration, hydrodynamic studies, and capture/retention experiments.

The overall results support the need to address the long term management of street waste, and the idea that GPTs have a vital role to play in the future management of gross pollutants.

The hydrodynamic data collected from the laboratory experiments was used to complement the capture/retention experimental results. These results showed that when the internal screens of the GPT were fully blocked, the capture/retention efficiency deteriorate rapidly. Up to at least 68% screen blockage, the capture/retention performance of the GPT remained efficient, particularly during higher flow rates. At lower flow rates, the performance of the GPT deteriorated, regardless of the screen condition.

The head loss and, by implication, the hydrodynamic flow field and capture/retention characteristics of the GPT for both inlet structures appeared not to be affected until at least 70% of its internal screens were blocked.

The practical significance of this finding is that the GPT can operate until the screens are approximately 68% blocked without prior maintenance. This is valuable information for the management of the maintenance schedules of one type of GPT, the *LitterBank*.

5. ACKNOWLEDGMENTS

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