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Investigating the hydrodynamic performance of a gross pollutant trap

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Abstract

Field studies show that the internal screens in a gross pollutant trap (GPT) are often clogged with organic matter, due to infrequent cleaning. The hydrodynamic performance of a GPT with fully blocked screens was comprehensively investigated under a typical range of onsite operating conditions. Using an acoustic Doppler velocimeter (ADV), velocity profiles across three critical sections of the GPT were measured and integrated to examine the net fluid flow at each section. The data revealed that when the screens are fully blocked, the flow structure within the GPT radically changes. Consequently, the capture/retention performance of the device rapidly deteriorates. Good agreement was achieved between the experimental and the previous 2D computational fluid dynamics (CFD) velocity profiles for the lower GPT inlet flow conditions.

Introduction

Gross pollutants are visible street waste consisting of anthropogenic litter and organic matter [6]. During a rainfall event, gross pollutants are collected by stormwater from urban areas and discharged into receiving waterways. Gross pollutant traps (GPTs) protect the ecological health of receiving waterways by screening visible street waste from the incoming stormwater. A plan view of a recently developed linear screening GPT, the LitterBank, (C-M Concrete Pty Ltd.) is shown in figure 1. Currently, there are twenty LitterBanks operating at strategic locations throughout Queensland, Australia.

Field monitoring of LitterBank GPTs in Brisbane, Queensland, showed that during wet weather a wide range of inlet, outflow and other operating conditions occurred [8]. For example, the extent and duration of rainfall influences the flow rate entering the GPT. The outflow level in the GPT determines the tidal or flood levels of the receiving waterways downstream. Due to infrequent cleaning, the retaining screens are often blocked with organic matter which influences the hydrodynamic and in turn, the 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 experimental and computational fluid dynamic (CFD) studies aimed at understanding the flow and capture/retention characteristics of the GPT.

To overcome these modelling challenges and to facilitate the study of steady-state conditions, an experimental approach was developed [7]. This approach used a downstream weir arrangement to control the flow and variation in free surface height in the GPT apart from the elevated outflow levels. With this arrangement, an experimental rig of a scale model pipe inlet configured GPT with solid internal walls was previously used to study pollutant-free flow in a trap with fully blocked screens. However, inside the GPT, fluid point velocity data was only collected at a fixed depth and at a single inlet flow rate. Thus, depth profiles were not investigated which is important for analysing capture/retention characteristics of pollutants particularly those with different densities. Furthermore, the internal geometrical configuration of the GPT and the acoustic Doppler velocimeter (ADV) probe presented difficulties when taking measurements close to the vertical walls inside the trap. Without such data, large errors (~ 50%) occur when integrity checks are performed [6].

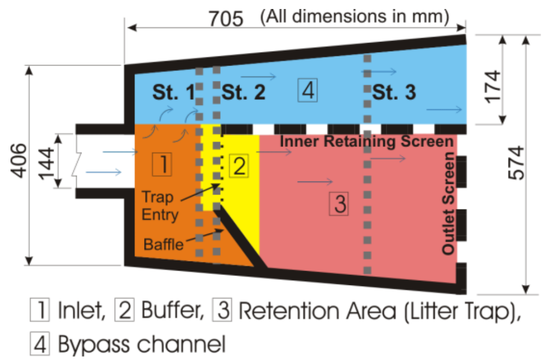


Figure 1. Plan view of the LitterBank with the measurement stations St.1 (x = 137.5), St. 2 (x =182.5) and St. 3 (x=450).

ADVs are widely used both in laboratory and field applications particularly as the instruments are robust. Scientific evidence shows that ADV signal outputs have had various issues with Doppler noise, signal aliasing and other disturbances [1]. ADV processing methods to minimise these effects have been developed and accepted within the scientific community. However, scientific investigations on the intrusive ADV probes and its performance in confined flow regions such as inside GPTs with complex internal geometrical wall configuration are not well established. Measurements with ADVs for evaluating the performance of larger stormwater treatment structures are considered essential tools [3]. For example, ADV studies have been used to understand the hydrodynamic behaviour of fluids in vortex separators, dissolved air floatation (DAF) tanks, sedimentation basins and aquaculture raceways [7].

In this current research, the flow field characteristics of a channel-inlet-configured GPT with fully blocked screens were comprehensively investigated using ADV measurements to measure flow across the depth, multi-depth and near-wall measurements under a wider range of typical GPT inlet flow conditions. This was achieved by using a combination of the originally designed ADV probes to overcome measurement limitations from earlier hydrodynamic investigations [7].

A technique was developed to perform these measurements in confined flow spaces using a combination of ADV probes. The velocity data was checked using principle mass conservation and independent checks were made with the measured flow rate at the flume outlet. Furthermore, favourable comparisons were also achieved with previous CFD simulation [7].

Experimental method

The experimental rig (50% scale model) was placed in a square section (19 m long, 0.6 m wide and, 0.6 m deep) tilting flume at the QUT hydraulic laboratory. Inside the flume, flow into the GPT was through an upstream channel-inlet-configuration with its height extended to the full depth of the experimental model and its width 144 mm (See plan view in figure 1). At the flume outlet, a previously developed experimental methodology used a downstream weir arrangement to control the flow and variation in free surface height [7, 8]. A constant flow rate (table 1) was established through the GPT via controller settings on the centrifugal pumps which circulated the water from underground storage tanks into the flume. At lower flow rates, 1.3 L/s and 3.9 L/s (See Runs 1 and 2, table 1), the corresponding weir heights of 0.1 m and 0.3 m, respectively, were set above the floor level at the end of the flume terminus raceway. The establishment of these flows during the experiments was based on promoting smooth flow conditions free of any obvious wave-like disturbances [7]. Screens were also placed at the entrance of the raceway to prevent large-scale flow disturbances. Alternatively, at the higher flows regimes, the weir height was set at the floor level of the raceway (zero). Deviations in these flow conditions (± 10%) during the experiments were unavoidable since the constant head tank was not fitted to the flume. However, at the flume outlet, the flow rate was periodically measured in the collection tank with a known height and a stopwatch. The water temperature was also measured at intervals and corrections were made to the ADV software (HorizonADV version 1.04, SonTek^{TM}/YSI, San Diego, USA) when necessary. For further details on the experimental setup for velocity measurements in the GPT see Madhani et al. [7, 8] which also describe the physical modelling of blocked screens.

Run	Flow regime	Weir height (m)	Inlet velocity (m/s)	Flow rate (L/s)	Water depth (m)
1	Low	0.108	0.09	1.3	0.1
2	↑	0.286	0.09	3.9	0.3
3	↓	0	0.39	6.1	0.1
4	High	0	2.14	35.4	0.3

Table 1. A matrix of flow regimes used in the experimental setup for litter capture.

Velocity measurements were conducted with three ADVs: (1) Sontek^{TM} MicroField-ADV (16 MHz, 3D down-looking probe serial number A813F), (2) Sontek^{TM} MicroField-ADV (16 MHz, 3D side looking probe serial number A843F) and (3) Sontek^{TM} Micro-ADV (16 MHz, 3D down-looking probe serial number A919F). The approximate minimum submerged distances for proper operation of the 3D down and side-looking probes are 75 mm and 25 mm, respectively [11]. The ADV probes (figure 2) use an acoustic remote sampling volume (using a transmitter and three receivers with 120º separation) based on the Doppler shift to measure the flow component velocities of the seeding particles in the water [4, 5, 9, 12]. The centre of the sampling volume (See A, in figure 2) is typically located 5 cm from the transmitter, but some studies have shown that the distance might change slightly [1]. The current side-looking probe was found to be 5.1 cm. The size of the measuring volume was determined by sampling conditions and consists of a cylinder of water with a diameter of 6 mm and a height of 9 mm.

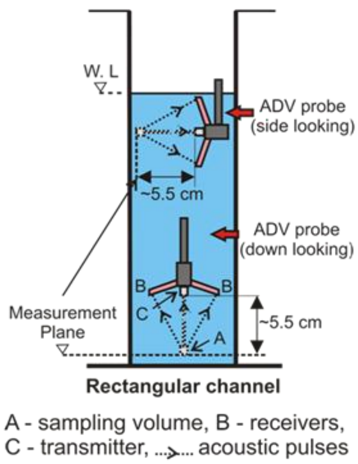


Figure 2. Front view of upstream inlet structure showing the measured planes.

The quality of data collected relies on the signal to noise ratios (SNRs) of the measured particles detected in the measuring volume. Diluted French chalk is used as seeding particles to improve this ratio. Apart from velocities, the ADV system also records the SNRs and the correlations (CORs) to filter signals that do not meet certain threshold values. The SNR and COR values indicate the quality of the data sampled for laboratory conditions, Sontek recommends 70% as the acceptable minimum COR and an SNR above 15 dB to reduce measurement uncertainties [11]. All measurements were sampled at 50 Hz for 120 s (time series length of 6000 samples). WinADV version 2.024 was used for batch post processing of ADV generated output data files [13].

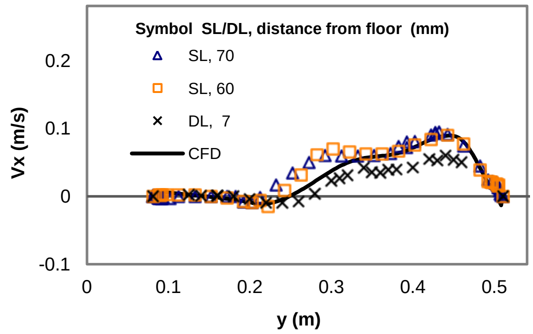
The ADV measurement technique

Due to the internal geometrical configuration of the GPT and confined spaces, a combination of different geometrical configured 3D ADV probes was used for three-dimensional velocity measurements. The down-looking probe in figure 2 is capable of taking measurements in the bulk flow and near the GPT bed. The orientation of the coordinates system for this probe was consistent throughout the measurement. The second ADV probe offered the additional capability of measuring next to the vertical GPT walls (See figure 2). However, the orientation of the local coordinate system, with respect to the mainstream flow, depended on which vertical wall this probe was facing. For measurements with this probe facing the inner wall, the local y_s coordinate was aligned with the flow. However, in the opposite wall face, the local y-axis became negative. To measure the distribution of flow across the width and water depth inside the GPT, the ADV probes were mounted on an instrument carriage mounted on the top of the flume rails. The carriage was fitted with fine adjustments on the vertical and transverse positions with 0.1 mm increments. In the horizontal direction, the accuracy of the ADV probe positions was less than 1 mm. The positions of the probes were referenced from the GPT's (x, y and z) global coordinate system. The stems of the probes were used as a reference for alignment and positioning in the GPT. The probe sampling volume distances to the solid boundary were reported by the ADV data acquisition software. However, at less than 20 mm, the reported distances become unreliable [11]. Thus, the probe distances outside this limit were initially recorded and moved at controlled distances towards the boundary. The Sontek^{TM} Beam-Check diagnostics module was also used [11] to check the position of the sampling volume with respect to the boundary walls. For a large number of data points, this procedure became time consuming and peak signal interferences obscured clarity in accurately interpreting boundary distances. Thus, visual checks were also carried out and other ADV parameters such as SNRs were monitored.

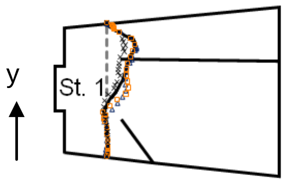
Scientific studies regarding the level of SNRs during ADV measurements as the probe sampling volume enters the proximity of the solid boundary, show lack of agreement. A loss of SNRs has been reported while other studies have indicated a rapid rise that reaches a peak value when this volume hits the target [1, 2, 10]. In the current research, both a loss and a rise in SNRs were experienced depending on the shear velocity gradients and the particle seeding. However, as the measuring volume changed within 10 mm proximity of the solid boundary, the SNRs generally rose sharply. This technique was used as a guideline to detect the position of the walls prior to taking measurements.

Results and discussion

We commence the discussion with the experimental axial velocity profiles across three cross sections of the channel-inlet-configured GPT for the inlet flow conditions in table 1 (figures 3-5). At the inlet region, the experimental data shows the asymmetrical distribution of flow velocities in both directions due to the sudden geometrical expansion of the GPT (St. 1, figure 3). At the trap entry, the flow entered a narrow opening where the velocities were redistributed to account for outgoing fluid (St. 2, figure 4). The fluid entering and leaving the retention area resulted in a near two-dimensional recirculation pattern (St. 3, figure 5).



(a) Velocity profiles at St. 1.

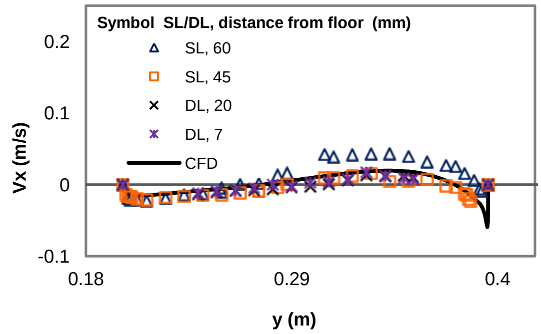


(b) Plan view of St. 1.

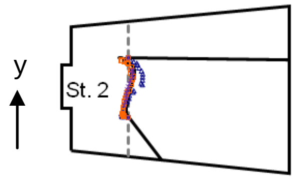
Figure 3. (a) Experimental and computed axial velocity profiles (Run 1, table 1, water depth = 100 mm) at St. 1 (b). Measurements taken with 3D side (SL) and down-looking (DL) ADV probes. Comparison made with previous 2D CFD simulation [7].

The approximately 2D flow in the experimental setup (Run 1 and 2, table 1) has been compared with computation which was previously obtained using the standard two-equation k-ε (denoted SKE) turbulence model [7]. Both the SKE with standard and near-wall (EWT) modelling approaches have been studied and described in depth, together with the computational grid, numerical method and the outcome of the grid sensitivity analysis [7]. In this paper, only EWT is considered. The CFD values from the EWT turbulence model are shown in figures 3-5 and in general show good comparison with the current comprehensive experimental dataset. The current dataset included near-wall measurements, previously this was not taken [7]. In the bulk flow, the computed values, which were not corrected for depth, show good correlations with the measured profiles. Differences were noted in the near-wall velocities, which appear to be higher in most cases for the CFD predictions (figures 3 and 4). However, the CFD model under predicted the experimental shear velocity gradients in the retention area and in the bypass (figure 5). A better comparison was achieved with the same inlet velocity but deeper flow conditions (Run 2, table 1).

In view of the measurement uncertainty, the ADV data were examined to investigate the net flow across each station by integrating the velocity profiles. Good correlations were achieved with the measured flow rate at the collection tank with 5% maximum error. In evaluating the percentage of the net flow rate, the average depth of flow was generally taken between each profile, with the flow at the inlet assumed to be 100%. Furthermore, in areas inaccessible to ADV probes such as between the walls and floor, a series of data fits—with a piecewise cubic interpolating polynomial—was used to estimate the end conditions for the bottom profiles The net percentage errors between the positive and negative integrals were obtained by integrating the velocity profiles at each station; an overall average error of 10% was achieved.



(a) Velocity profiles at St. 2



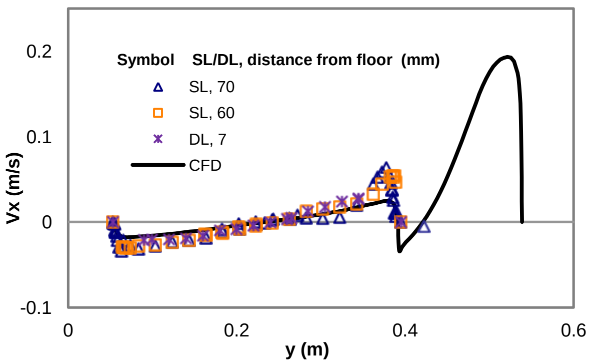
(b) Plan view of St. 2.

Figure 4. (a) Experimental and computed axial velocity profiles (Run 1, table 1, water depth = 100 mm) at St. 2 (b). Measurement taken with 3D side (SL) and down-looking (DL) ADV probes. Comparisons are made with the 2D CFD simulation [7].

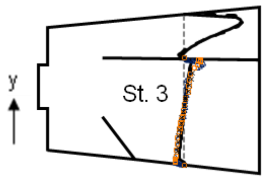
Figures 3-5 are also typical for the remaining inlet flow rates investigated. It was generally observed with these profiles that maximum velocity did not always occur at the free surface. However, near the inlet with maximum flow rate, profile variations across the depth of water were noted, particularly for the higher flow rate (not shown). These flow regions were further complicated by the high negative shear velocity gradients next to the inner wall, as shown on the right of figure 4 (See y >0.29<0.4 m on the abscissa). Such velocities were caused by the detachment of the flow due to the deflection of the entry jet into the bypass [7]. Consequently, the geometrical configuration of the ADV probe disturbed these velocities and shielded the nature of the flow in these regions. Some shielding was observed visually when measurements were compared between the side and down-looking probes. While in some flow regions the probes gave similar readings, dampening of the velocities has been clearly observed (not shown). The measurement uncertainties were also attenuated since the down-looking probe was incapable of measuring close to the walls and the minimum floor distance with the side-looking probe was 30–40 mm. In these regions, measurements were taken repeatedly to minimise uncertainty.

The proportion of fluid directly bypassing the retention area of the GPT was estimated by determining the net flow between the inlet and trap entry region (St. 1 and 2). This estimation assumed that there was no fluid recirculating at St. 2.

The percentage of fluid directly bypassing the retention area appeared to be consistent for all experimental runs with an average of ~ 80%. This trend indicated that the capture and retention characteristics of the GPT with fully blocked retaining screens would be poor. Such indications have since been confirmed by experiments in which an average of 4% capture/retention was achieved for this GPT configuration with fully blocked screens [6].



(a) Velocity profiles at St. 3.



(b) Plan view of St. 3.

Figure 5 (a) Experimental and computed axial velocity profiles (Run 1, table 1, water depth = 100 mm) at St. 3 (b). Measurement taken with 3D side (SL) and down-looking (DL) ADV probes. Comparisons are made with the with the previous 2D CFD simulation [7].

Conclusion

The potential capture/retention characteristic of a gross pollutant trap (GPT) with fully blocked screens was evaluated using a combination of experimental and data processing methodologies. The methodology developed for this research facilitated a rigorous hydrodynamic assessment of the GPT which can be applied to other treatment devices. This was achieved by conducting detailed velocity measurements at critical sections of the GPT. The collected data was integrated using a mathematical fit with a piecewise cubic interpolating polynomial to analyse the net internal flow. The quality of the data collected was also examined to assess the technique developed for measurements in confined spaces due to the internal configuration of the GPT and the acoustic Doppler velocimeter (ADV) probe.

The main findings reveal that the hydrodynamic performance rapidly deteriorated when the internal screens of the GPT were blocked. Approximately 80% of the fluid entering the GPT escaped via the bypass for all inlet flow conditions investigated. Subsequently, gross pollutants entering the trap will, in general, follow this flow with the same consequences. The computational fluid dynamics (CFD) velocity profiles were in good agreement with the experimental data for the same inlet flow conditions.

The methodology developed and tested here, demonstrates the usefulness and effectiveness of describing the hydrodynamic and in turn the capture/retention characteristics of a GPT under typical operating conditions. Similar GPTs have received little attention in scientific research since velocity measurement techniques are generally difficult to perform in these devices, as was demonstrated in this research. Further work is recommended to extend the measurements and the CFD technique in order to investigate a wider range of design configurations.

Acknowledgments

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