IMPROVING HYDRAULIC PERFORMANCE OF SEDIMENT RETENTION PONDS

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ABSTRACT

This study addresses the effect of different inlet and outlet configurations and the influence of baffles on the hydraulic performance of a model pond. The physical model is a trapezoidal pond with top dimensions of 4.1 × 1.6 m × 0.3 m deep and side and end slopes of 2:1.Three perforated T-bars were fixed to an outlet riser to simulate a floating decant dewatering system. Solid and partial-width baffles were also investigated for their influence on the hydraulic efficiency of the system. Compared with the conventional point inlet and outlet system, the results herein showed that distributing the inflow over the entire width of the pond could successfully improve the hydraulic efficiency, albeit with short circuiting along the sloping side walls. Monitoring the dye aided recognition of preferential flow paths which were subsequently removed by modifying the inlet. On the other hand, the outlet span was adjusted to boost the residence times. Hydraulic efficiencies of about 0.50 compared with 0.18 for the conventional system, illustrated the effectiveness of these configurations. Furthermore, both types of the tested baffles significantly lifted the hydraulic performance giving the highest hydraulic indices of all the tested cases.

KEYWORDS

Hydraulic efficiency, Tracer study, Sediment retention pond, Inlet and outlet, Baffles

PRESENTER PROFILE

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1 INTRODUCTION

Urban development activities such as construction of landfills and roads, significantly contribute to erosion and accelerated transport of sediment into natural water ways and reservoirs. The primary problem associated with erosion is the soil movement off site during rainfall events and its subsequent severe impact on the sediment budget and aquatic ecosystem of the receiving waters. Therefore, on-site management practices are inevitably required to reduce the sediment load. In this regard sediment retention ponds have proved to be efficacious for on-site treatment of the sediment laden runoff (Moglen and McCuen, 1988). Auckland Regional Council (ARC) recommended retention ponds as a low impact design for treatment of suspended sediments resulting from construction sites (ARC, 2000). In the sustainable urban drainage systems (SUDS), sediment retention ponds are the recommended source control practice for treatment of suspended sediment from a development site (National SUDS Working Group, 2004). However, recent studies in the Auckland region have evidenced the inefficiency of most of the constructed sediment ponds (ARC, 2008). In the U.S. regulations require that all the erosion prevention and sediment control measures must be designed for at least 80% removal efficiency for total suspended solids (SC-DHEC, 2005).

During the past decade several studies have focussed on improving the understanding of the hydraulic characteristics of such ponds by investigating different inlet and outlet positions (Khan *et al.*, 2009a; Persson *et al.*, 1999), pond layout (Khan *et al.*, 2009b; Persson *et al.*, 1999) , deflector islands (Khan *et al.*, 2011) and floating treatment wetlands (ARC, 2006; Khan, 2011). As yet, however, the design and arrangement of the inlet and outlet structures have not been well established.

This paper reports on exploration of the effect of alternative inlet and outlet designs on the hydraulic efficiency of sediment retention ponds. Experiments were carried out in a scaled rectangular model pond with sloping walls, incorporating a sediment forebay and a T-bar dewatering system. The results are compared with those from a conventional pond design. Employment of baffles for retrofitting existing ponds has also been investigated.

2 METHODOLOGY

2.1 TRACER STUDIES

The treatment efficiency of ponds and wetlands relies fundamentally on the hydraulic residence time (HRT) which delineates the time a parcel of water spends within a system, depending on the path taken as it flows across the system (Nix, 1985; Thackston *et al.*, 1987). As a result, there is a specific HRT for each of the water parcels, and a distribution of HRTs is indeed generated based on the hydraulic characteristics of the system (Nix, 1985; van de Vusse, 1959). The variations in HRT are explained by generating the residence time distribution (RTD) curves which represent the temporal probability distribution of non-reacting tracer particles within the system (van de Vusse, 1959).

Such an investigation is particularly of interest for an improved understanding of the RTD impact on the hydraulic performance of ponds and wetlands, which potentially influences sediment removal. RTD curves are commonly created by adding a conservative tracer such as the cation lithium (Kadlec, 1994), the anion bromide (Grismer *et al.*, 2001), or fluorescent dyes (Khan, 2011) at the system inlet as an impulse or step change (Werner and Kadlec, 1996). In this study Rhodamine WT (RWT) was selected as the tracer dye due to the numerous advantages over the other tracers such as being readily soluble in water, highly detectable by fluorometers, mostly unaffected by background fluorescence, minimally degradable in short times, harmless in low concentrations (Wilson et al., 1986) and cost effective.

2.2 HYDRAULIC PERFORMANCE

The hydraulic efficiency of retention basins is often attributed to two basic characteristics of the hydrodynamic performance of the system. The first is the ability to uniformly spread the inflow over the basin and the second is the degree of mixing or re-circulation, which represents a departure of the flow in the basin from ideal flow (Persson *et al.*, 1999; Thackston *et al.*, 1987).

Persson (1999) examined the hydraulic efficiency of ponds with different configurations and developed a quantitative measure of flow hydrodynamics in ponds to enable easy comparison of systems with different shapes and inlet/outlet positions. This hydraulic efficiency measure (λ), is designed to reflect the effective volume of the pond and the distribution of the hydraulic residence time, and has the following equation:

$$\lambda = e\left(1 - \frac{1}{N}\right) = \frac{t_p}{t_n} \tag{1}$$

where t_p is the peak time, t_n is nominal residence time (pond volume / volumetric flow rate), *e* is the effective volume ratio and N represents the number of cells in the tank-in-series model.

The short circuiting index is calculated by:

$$S = \frac{t_{16}}{t_n} \tag{2}$$

where t_{16} is the time at which 16 percent of the added tracer has left the system

Wahl *et al,* (2010) presented the moment index (M_I) as a useful measure for quantifying hydraulic efficiency. The hydraulic efficiency defined by this method is mainly dependent on the proportion of tracer leaving the domain earlier than the nominal residence time. The higher the tracer concentration exiting earlier than the t_n, the lower the M_I. The equation used for M_I is calculated by taking the first moment about the nominal divide of the normalised RTD curve:

$$Moment..Index = 1 - M_{pre} \tag{3}$$

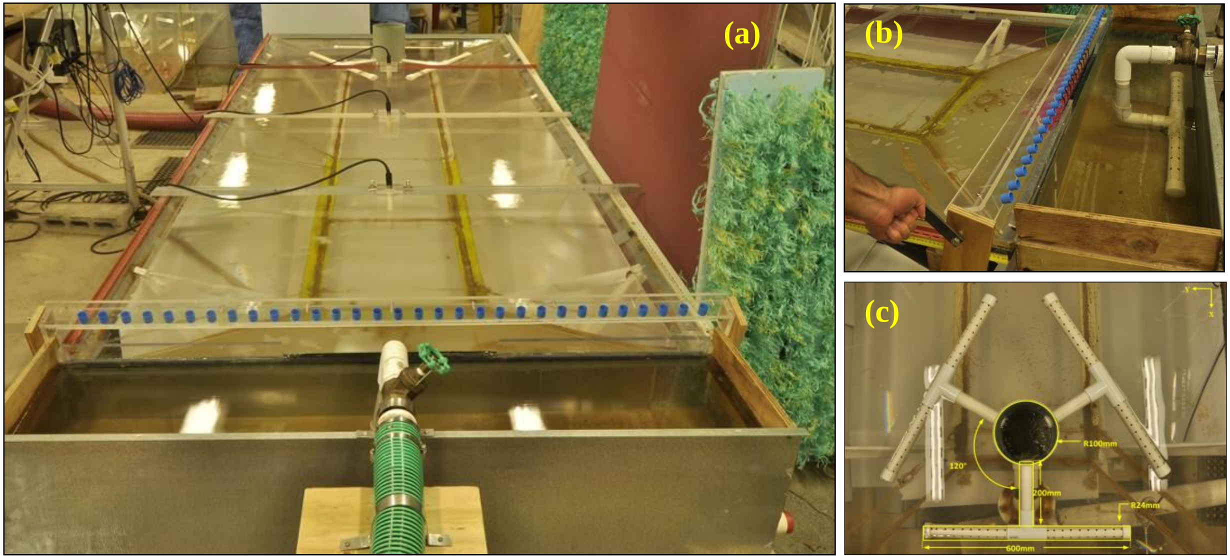
$$M_{pre} = \int_0^1 (1-\phi).C'(\phi)d(\phi) \tag{4}$$

where M_{pre} is the moment about the nominal divide for the normalised RTD bounded from zero to one, ϕ is the flow weighted time and C' is the normalised concentration. Full details of this method can be found in Wahl *et al.* (2010).

3 THE PHYSICAL MODEL

The physical model (Fig. 1a) is a trapezoidal pond made from transparent acrylic sheets fitted on a steel frame with top dimensions of 4.1 × 1.6 m × 0.3 m deep and side and end slope of 2:1 (Khan 2011). The pond is preceded by a rectangular tank of 0.3 × 1.6 × 0.2 m serving as the sediment forebay. As the tank is filled, water flows over a level spreader into the retention pond. For the outlet, three perforated T-bars were fixed to an outlet riser to model the floating decant dewatering system. The perforated T-bars are constructed from PVC pipe with diameter of 48 mm. Five rows of 6 mm diameter holes on each of the T-bars allow the water to leave the pond. The T-bars are fixed to a 550 mm long PVC pipe with 200 mm diameter placed vertically, which serves as the outlet riser (Fig. 1b). This configuration contributes to dissipating the influent kinetic energy and reducing short circuiting, while the dewatering system removes the relatively clean surface water.

Figure 1: a) The physical model viewed from the inlet, b) dye adding system, c) The decant dewatering system.



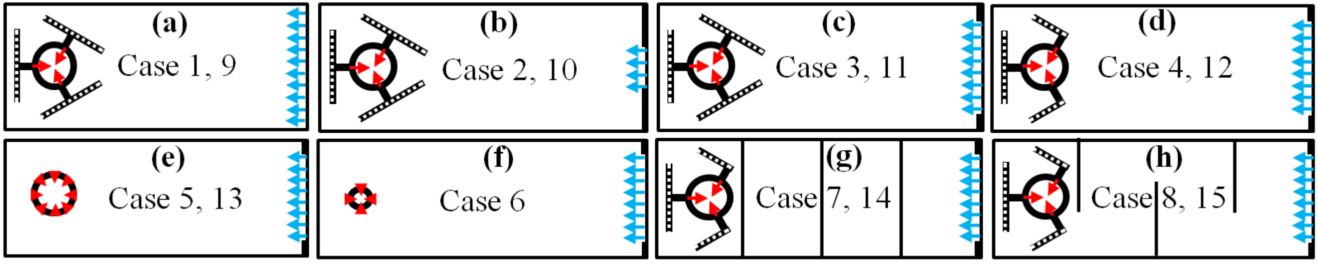
As well as tracer selection, it is important to carefully consider the method and location of tracer addition to the system so that it follows the behaviour of the inflow water. Figure 1c shows the system made for uniformly adding RWT across the spread inlet width: 30 plastic caps glued on a rotating bar placed immediately upstream of the level spreader are filled with the desired amount of dye and then uniform distribution of the dye is achieved by rotating the bar. Because the inflow water flows over the level spreader on the sloping wall of the pond, the caps are aligned such that the dye is added just below the level spreader and introduced to the system with same flow pattern as that of the inflow. To detect concentration of RWT four fluorometers (Cyclops-7 Submersible Sensor by Turner Designs), of which three were placed within the pond along the longitudinal centre line at equal spacing and 20 mm below the water surface, for studying short circuiting (not reported here) and one was placed in the outlet pipe to obtain the RTD curve, were simultaneously operating during the experiments.

With regards to mitigation of the performance of existing systems, baffles have been widely adopted as an established retrofitting practice. Baffles are solid or porous impediments used to improve the rate of treatment in ponds and wetlands. Inclusion of baffles in sediment retention ponds boosts the system's performance by means of promoting the settlement of suspended sediments by distributing the inflowing sediment laden water over the width of the pond and consequently providing longer retention times (Thaxton et al., 2004). Few studies on the details of baffles have been reported, signifying the need for further exploration of their effects on the hydraulic performance of sediment retention ponds. In this study effectiveness of full width and partial-width baffles was explored. Three 240 mm high baffles were made of the same material as that of the pond and were placed at 1.2 m, 2.2 m and 3.2 m downstream the inlet. The partial-width baffles were blocking roughly one third of the cross sectional area of the pond, allowing water to pass through a section of the pond with cross sectional shape of an inverted right-angled triangle with 500 mm long top edge and 245 mm height. Edges of the baffles were carefully sealed with waterproof rubber to ensure no water penetrated beneath the baffles and water only passed over the sheets. The number and locations of baffles were selected based on the previous works by Khan (2011) and Smolen (2006).

The experiments were carried out for two scenarios: (a) 1 l/s flow rate (representing treatable field flows) for which the T-bars were 80% submerged with the water level at 480-500 mm from the pond bottom (Cases 1 to 8); and (b) 2 l/s flow rate (representing a large rainfall event) for which the T-bars were fully submerged and water depth was

550-580 mm (Cases 9-15). For the latter scenario (b) water surpassed the capacity of the perforated T-bars and flowed over the outlet riser while for scenario (a) T-bars were the only means of outlet.

Figure 2: The tested cases: a) full width inlet and T-bars, b) central shortened inlet and T-bars, c) adjusted inlet and T-bars, d) adjusted inlet and modified outlet, e) adjusted inlet and 200 mm diameter outlet riser, f) adjusted inlet and 100 mm diameter outlet riser, g) three submerged solid baffles, h) three partial-width baffles.



4 RESULTS AND DISCUSSION

4.1 COMPARISON WITH CONVENTIONAL POINT INLET AND OUTLET POND

In Table 1 and Figure 3 test results are compared with those from the work by Khan (2011) who investigated a point inlet and outlet system. The full width inlet and the dewatering system in Case 1 resulted in an increase in λ of about 40% from 0.18 to 0.25 while M_I decreased slightly. This improvement in λ is chiefly attributed to the simulated flow from the sediment forebay which enhanced a distributed flow across the pond and thus promoted longer residence times. Despite the improvement in λ, short circuiting along the side walls was observed.

In Case 2 the inlet width was shortened to a 500 mm width at the centre. For this configuration, the pond performance decreased and the λ and M_I reduced to 0.19 and 0.59, respectively. In spite of this decline in performance relative to Case 1, λ was slightly higher than that of the point inlet and outlet system, but a slightly lower M_I indicated a reduced hydraulic performance.

Table 1: Hydraulic properties for the tested cases

Case No.	*Q (l/s)*	t_{mean} *(min)*	t_{50} *(min)*	t_{16} *(min)*	t_{peak} *(min)*	t_n *(min)*	S_c	λ	M_I
1	1	12.5	9.0	3.8	3.5	13.9	0.27	0.25	0.68
2	1	10.1	7.5	3.1	2.7	13.9	0.22	0.19	0.59
3	1	14.4	11.6	4.9	4.4	14.1	0.35	0.31	0.73
4	1	16.8	13.8	6.5	7.2	14.1	0.46	0.52	0.78
5	1	15.6	12.4	5.3	4.9	14.5	0.36	0.34	0.73
6	1	9.6	8.6	4.4	4.1	14.7	0.30	0.28	0.54
7	1	17.4	15.4	8.5	11.6	14.5	0.58	0.80	0.85
8	1	14.9	12.9	6.4	7.4	14.1	0.45	0.52	0.79
9	2	7.0	4.5	1.7	1.4	7.2	0.23	0.19	0.63
10	2	5.2	4.4	2.0	1.5	7.2	0.28	0.20	0.53
11	2	7.0	5.7	2.4	2.2	7.2	0.34	0.30	0.71
12	2	7.8	6.4	2.6	2.4	7.2	0.36	0.34	0.71
13	2	9.3	7.7	3.4	3.4	7.4	0.46	0.46	0.80
14	2	8.5	7.7	3.9	6.3	7.2	0.54	0.87	0.85
15	2	8.5	7.6	4.3	5.0	7.2	0.59	0.69	0.85

*Cases 1 to 8 were at 1 l/s flow rate and T-bars as outlet and Cases 9 to 15 at 2 l/s flow rate with submerged T-bars and riser as the combined outlet.

Figure 3: Hydraulic efficiency (λ) and Moment index (M_I) for the tested cases compared with results of Khan (2011)

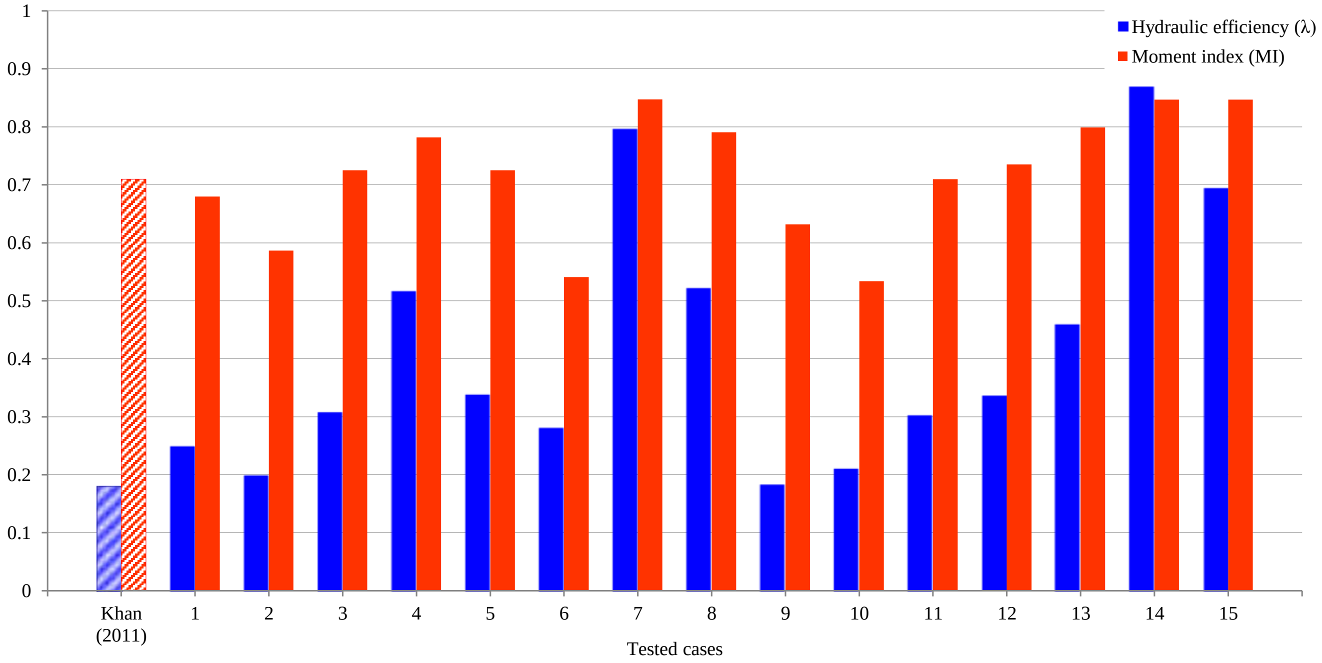


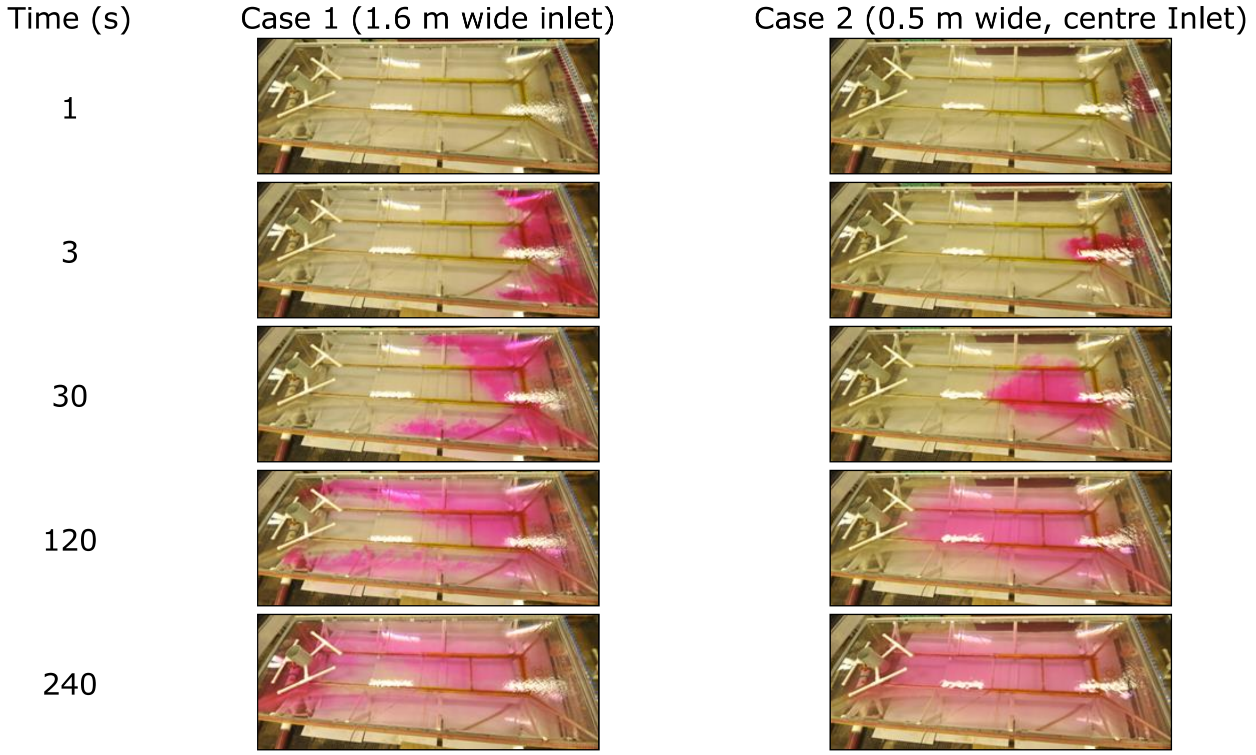
Figure 4 shows RWT spatially monitored for Cases 1 and 2. In Case 1, when the inflow was distributed over the entire inlet width, the sloping walls and the direction of the water entering the pond have caused strong short circuitings at both sides. Such a flow pattern was observed by Khan (2011) when the inflow from a point inlet was conveyed to the side walls by a floating island. This phenomenon is believed to be due to shallow water near the walls that causes the streams to travel at a higher speed and minimal mixing with the adjacent water. In Case 2 where the inlet width was shortened to avoid the sloping sides, higher inflow velocities induced the dye to accelerate towards the outlet, resulting in lower efficiencies.

Cases 9 and 10 have the same inlet and outlet configurations as Cases 1 and 2, respectively, but the flow rate was doubled. Doubling the flow rate resulted in an increase in water level and overflow from the outlet riser. Compared with Case 1 both of the hydraulic performance indices reduced for Case 9. While the change in flow pattern in Case 10 caused no change in λ, but a reduction in M_I. This deterioration in performance of Cases 9 and 10 is likely associated with the higher inflow velocities and momentum which caused a larger proportion of the added dye to travel rapidly along the sloping walls to the outlet.

In Cases 3 and 11, 80 mm at each side of the inlet width (accounting for 10% of inlet width) was blocked to reduce the preferential flows along the sides. This successfully lengthened the peak time and increased the λ and M_I for Cases 1 and 9.

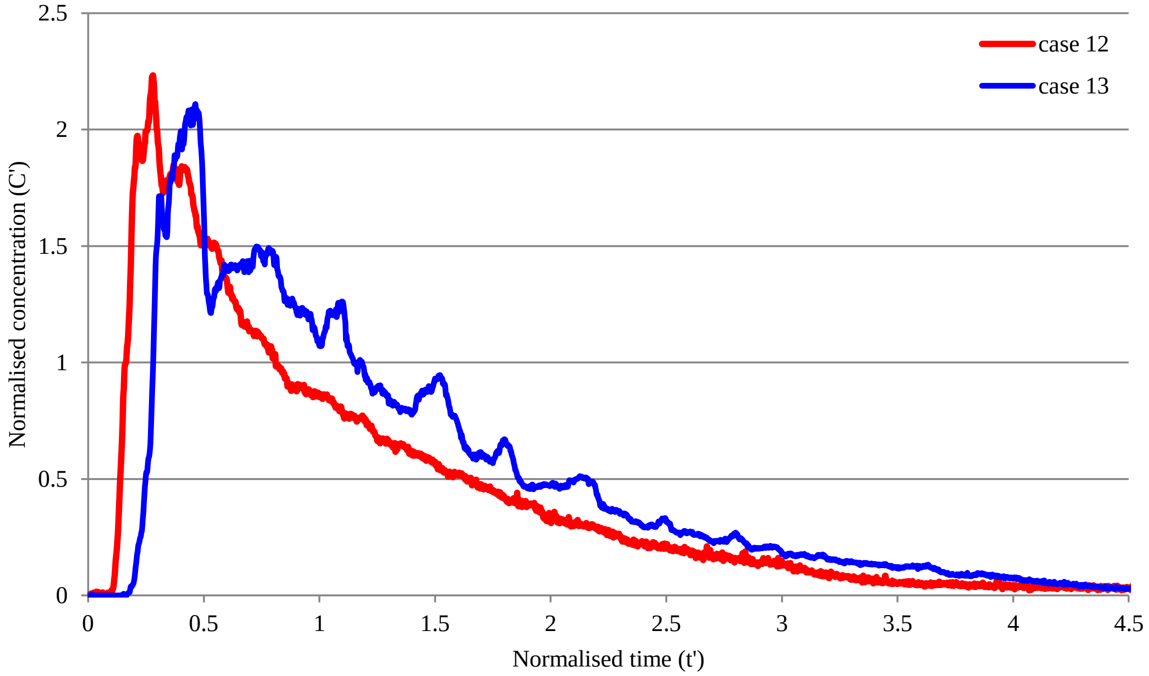
In Cases 4 and 12, the arms of the T-bars that extended back into the pond (Figs. 1 and 2) were trimmed, because it was envisaged that this could provide water parcels with longer residence times and thus increase the λ. The inlet had the same adjusted inlet width as in Cases 3 and 11. These modifications extended the peak time from 4.4 min (Case 3) to 7.2 min (Case 4) and significantly boosted the λ by more than 100% compared with Case 1. The M_I of 0.78 also shows the improvement towards the plug flow. Hence, it was decided that all further experiments using decant dewatering system would be carried out with the above described modifications to the inlet and outlet.

Figure 4: Photo sequence of the tracer test for Cases 1 and 2



In Cases 5 and 13 the T-bars were completely removed, leaving only the 200 mm riser as the outlet. For Case 5, this change did not improve the hydraulic efficiencies compared with Case 4. However, the λ and M_I values for Case 13 were increased compared with those for Case 12. RTD curves for these two cases (Fig. 5) show that when the outlet riser was performing without the T-bars (Case 13) not only did the t_p increase from 122 s to 204 s, but also lower concentrations of dye exited the pond at t_p despite a t_f (first detection time) value close to that of Case 12 (43 s and 52 s for Cases 12 and 13, respectively). The 100 mm diameter riser in Case 6 was only tested at 1 l/s flow rate because of insufficient pond volume for 2 l/s flow rate. This smaller outlet riser decreased the hydraulic performance values because of the increased streamline velocities towards the outlet.

Figure 5: RTD curves for Cases 12 and 13

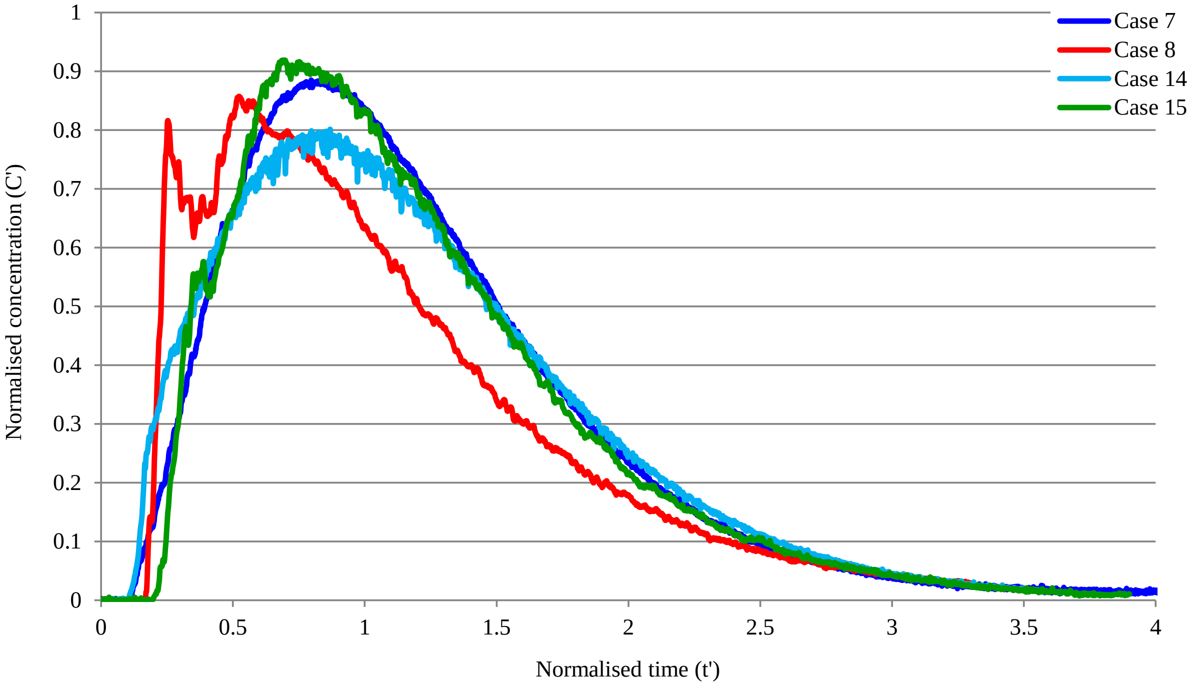


4.2 INCLUSION OF BAFFLES

The baffles significantly elevated the λ and M_I by lengthening the residence times and dispersing the momentum of the inflow over the entire domain. Three submerged solid baffles increased the λ to the highest values of all the tested cases with 0.80 and 0.87 for Cases 7 and 14, respectively. The M_I of 0.85 for both cases was also the maximum achieved value. This enhancement in hydraulic performance is credited to the closed chambers created by the baffles where water recirculation mixed the added dye with the stored water, although only a negligibly small portion of the dye passed over the submerged baffles to produce the first peak in the RTD curves shown in Figure 6. The partial-width baffles though were less effective than the submerged ones.

Although employing the partial-width baffles increased the t_f from 92 s (Case 7) to 140 s (Case 8) and 41 s (Case 14) to 83 s (Case 15), obvious dead zones were created in the corners. The dead zones decreased the effective pond volume and induced the movement towards the outlet of higher dye concentrations that were not being mixed with the stored water. This resulted in shorter peak times and thus reduction of the hydraulic efficiencies (Fig. 6).

Figure 6: RTD curves for cases with baffles



The first peaks of RTD curves in Figure 6 correspond to zones of short circuiting which are apparently higher for Case 8, while increasing the flow rate to 2 l/s in Case 15 mitigated these preferential flow paths. This could be attributed to firstly the combined effect of more turbulence along with higher inflow velocities that pushed the water to the corners and increased the effective volume; and secondly a change in flow pattern due to the more distributed outlet in Case 15 where the T-bars and outlet riser decanted the pond together. Consequently, λ and M_I values increased, indicating a higher hydraulic performance for Case 15 compared with Case 8.

5 CONCLUSIONS

Efficient design and operation of sediment retention ponds requires careful consideration of the system components, specifically inlet and outlet structures. In this study a distributed inlet flow along with a three T-bar decanting system were tested for assessing hydraulic performance of the modelled sediment retention pond. Several combinations of variations of both the inlet and outlet were tested, all at two different flow rates. The hydraulic efficiency and moment index for each case were obtained from analyses of the RTD curves.

Despite the short circuiting along the sides which was associated with the shallow water on the sloping walls, distributing the inflow over the entire inlet and employing the T-bar dewatering system increased the λ compared with the conventional point inlet and outlet system. While the low M_I values revealed large departure from the ideal plug flow, restricting the distributed inflow to the centre was not successful for improving the hydraulic performance because not all the pond area was used.

The flow pattern acquired through dye monitoring for the first two cases revealed short circuiting flow paths. These were successfully mitigated by blocking short lengths at both ends of the inlet width. It was found that the long T-bars extending back up into the pond decreased the flow path lengths, resulting in lower retention times. Shortening the T-bars resulted in an increase in residence times and thus a more hydraulically efficient system. Complete removal of the T-bars and using two different sizes of outlet risers did not increase the hydraulic efficiency at 1 l/s, while at 2 l/s the 200 mm diameter outlet riser outperformed the combined outlet riser and T-bars (submerged at this flow rate) dewatering system.

The highest λ and M_I values were obtained when baffles were employed in the pond. In this study, although the full-width submerged baffles outperformed the partial-width baffles with higher λ values, high values of M_I were an indication of improvement in hydraulic performance for the both types.

The results presented show sensitivity of the hydraulic performance of ponds and wetlands to inlet and outlet configurations, and highlight the need for physical modelling and investigations. Furthermore, the results clearly demonstrate that baffles can be recommended for retrofitting existing systems.

ACKNOWLEDGEMENTS

The author would like to acknowledge helpful comments from Dr. Keith Adams. Financial support of this research by Auckland Council is also gratefully acknowledged.

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