OPTIMISATION OF BAFFLES FOR SEDIMENT RETENTION PONDS

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ABSTRACT

Effective treatment of the polluted stormwater runoff from earthworks sites is a major concern for water authorities. Sediment retention ponds provide a quiescent place for settling the suspended particles in runoff. However, improper design of ponds can lead to significantly low treatment efficiency. As a retrofit practice, baffles have been utilised to improve the rate of settling of the suspended particles. Yet there is limited information in the design guides about the optimum configuration and type of baffles. This study investigates the effect of porous and submerged solid baffles on the hydraulic performance and trap efficiency of a model sediment retention pond. Several configurations were tested using four different metal meshes (with different aperture size and open area) as porous baffles, and acrylic sheets as solid baffles. The porous baffles were more effective in improving the overall hydraulic performance than the solid baffles. For 4 and 5 baffles, the medium-fine mesh with 1 mm aperture size and 42% open area was the best. The two porous baffles with same aperture sizes but different open areas had different hydraulic performance which highlights the importance of aperture size in addition to the total open area. The trap efficiency for the tested configurations was consistent with the result of hydraulic performance analysis. The present paper is continuation of the work presented at the Water New Zealand's 2014 Stormwater Conference.

KEYWORDS

Sediment retention ponds, Baffle, Hydraulic performance, Trap efficiency, Residence time

PRESENTER PROFILE

Originally from Iran, I hold bachelor's degree in Irrigation and Drainage Engineering from Shiraz University, Iran. I did my masters in Urban Water Engineering and Management at the University of Sheffield in the UK, in 2010. I'm currently at the last year of my PhD at the University of Auckland.

1 INTRODUCTION

Land development and earthwork significantly contribute to soil erosion and accelerated transport of sediment into water ways and reservoirs. In the Auckland region in New Zealand, it is estimated that unprotected earthworks sites could produce up to 66 tonnes of sediment/hectare/year (ARC 1999), which is hundreds of times the yield from a vegetated land. The major concern associated with soil erosion is movement of the soil off site during rainfall events and its subsequent severe (and sometimes irreversible) impact on the sediment budget and aquatic ecosystem of the receiving waters. Therefore, incorporation of effective practices for controlling the suspended sediments in the runoff from disturbed lands is vital for protecting receiving environments.

Among practices for treatment of sediment laden runoff, sediment retention ponds (also known as sediment basins or settling ponds) are one of the most important ones. Sediment retention ponds are built (usually temporarily) near construction sites and receive runoff from the nearby field. An effective pond provides a quiescent zone for the maximum removal of the suspended particles.

The treatment efficiency of ponds basically depends on hydraulic residence time, which defines the amount of time that each water particle remains in the pond (Thackston et al. 1987). The variations in residence time are explained by the residence time distribution (RTD). Interpretation of the RTD is a widely accepted method for analysis of hydraulic performance of ponds and basins. The plug flow condition provides the ideal condition for high treatment efficiencies in ponds, and hydraulic performance of the system can be attributed to the degree of departure of the flow from plug flow condition. However, this condition is practically impossible to achieve due to existence of physical phenomena such as short circuiting and mixing (Kadlec 1994). Short circuiting occurs when portions of the inflow travel at high velocity towards the outlet, and have limited mixing with the stored fluid (Stovin et al. 2008). This leads to reduced treatment for the particles trapped in short circuits. The other hydraulic phenomenon that significantly affects the performance of ponds is mixing, which is caused by molecular diffusion and turbulent diffusion (Levenspiel and Bischoff 1964).

2 BAFFLES

Several investigators have attempted to increase the performance of ponds by modifying the pond layout, design of inlet and outlet, deflector islands, floating treatment wetlands, and baffles (De Oliveira et al. 2011; Nighman and Harbor 1997; Sah et al. 2011). Baffles are solid or porous barriers which are installed in any orientation in ponds, to improve the rate of treatment. They may be constructed from various solid or porous materials such as plywood or a silt fence for solid baffles, and jute mesh or braced geotextile curtains for porous baffles (Thaxton and McLaughlin 2005). Baffles are used primarily to increase the residence time of the incoming water particles, which consequently improves the pond's hydraulic performance.

Although installation of baffles facilitates settling of the suspended particles, improper utilisation of baffles can lead to undesirable performance. For example Nighman and Harbor (1997) investigated trap efficiency for a sediment pond with a solid baffle and observed that the trap efficiency significantly decreased when the incoming storm overtopped the baffle. A recent survey in the US revealed that only 16 agencies (48% of the surveyed agencies) use baffles for sediment basins (Zech et al. 2014). The main reasons for not using baffles, as listed by (Zech et al. 2014), are: the agency does not have standard drawings/specifications for inclusion of baffles; site-specific constraints; no regulatory guidance on use; found them unnecessary; and, it is optional and the contractor may elect to use if deemed necessary. This highlights the need for research into design and installation of baffles to improve the guidelines.

This paper reports on studies of different configurations of solid and porous baffles for a model sediment retention pond, with the objectives to investigate: 1- the effect of position and number of baffles, 2- the effect of mesh aperture and open area of baffles on the hydraulic performance, and 3- the relation between hydraulic performance and trap efficiency.

3 METHODOLOGY

Tracer studies were conducted to determine the hydraulic performance for different configurations of porous and solid baffles. The hydraulic performance indices were then extracted from the RTDs that were normalised to the nominal residence time (t_n). The nominal residence time is defined as the pond volume divided by inflow rate. The normalisation is executed using the following equations:

$$C' = \frac{C}{C_0} \quad (1)$$

$$\theta = \frac{t}{t_n} \quad (2)$$

where C' is the normalised tracer concentration, C is the measured concentration at each time step, C_0 is the mass of added tracer divided by the pond volume, θ is the normalised time and t is the time of measurement.

The hydraulic indices recommneded by Farjood et al. (2014) for sediment retention ponds are used in this study. The indices are θ_5 for short circuiting, the Morril Index (Mo) for mixing, and the Moment Index (MI) for hydraulic efficiency. θ_5 demonstrates the time for 5% of the added tracer to exit, and small values of θ_5 demonstrate existence of short circuiting. The Morril Index, Mo, is a mixing indicator and is defined as:

$$Mo = \frac{t_{90}}{t_{10}} \quad (3)$$

where t_{10} and t_{90} are the times for 10% and 90% of the added tracer to exit the system, respectively. Mo values close to 1 (i.e. $t_{10} = t_{90}$) indicate a flow condition close to the ideal plug flow. Mo increases with increase in the mixing level. In this paper inverse of the Mo (Mo^{-1}) is used for consistency in the trend of the hydraulic indices.

The Moment Index (MI) is used for evaluating the hydraulic efficiency and incorporates the effects of short circuiting and mixing. The advantage of MI to the other hydraulic efficiency indices such as λ (defined as the time to peak of the RTD divided by t_n) introduced by Persson et al. (1999), is that MI is not affected by the instantaneous changes in tracer concentration. MI is defined as:

$$MI = 1 - M_{pre} \quad (4)$$

where,

$$M_{pre} = \int_0^1 (1-\theta)\ C'(\theta)\ d(\theta) \quad (5)$$

where M_{pre} is the moment about the point of nominal divide (θ = 1). MI range is between 0 and 1. The higher the MI value, the more hydraulically efficient is the system. Full details of this index are given by Wahl et al. (2010).

In order to evaluate the degree of sediment removal, the trap efficiency index (TE) is used. The TE demonstrates the fraction of the inflow sediment that is trapped in the pond, and is defined as:

$$\text{Trap Efficiency}\left(TE\right) = \frac{S_T - S_o}{S_T} = \frac{S_s}{S_T} \quad (6)$$

where S_T is the total mass of sediment entering the pond, S_o is the mass of sediment that exits the pond, and S_s is the mass of settled sediment.

4 THE EXPERIMENTAL APPARATUS

The physical model is a rectangular pond with trapezoidal cross section (Fig. 1). The pond is constructed with acrylic sheets, with top dimensions of 4.1 m × 1.6 m, by 0.3 m depth, and bank slopes of 2:1 (horizontal:vertical). The experiments were conducted at a constant flow rate of 2 l/s which gives θ_n = 453 s. The pond is preceded by a rectangular tank of 0.3 × 1.6 × 0.2 m which simulates the sediment forebay. The tracer is added to the pond using a manual system which comprises 30 plastic caps fixed on a rotating bar. The desired amount of dye was added to each of the plastic caps, and by rotating the bar the dye was uniformly distributed along the width of the inlet.

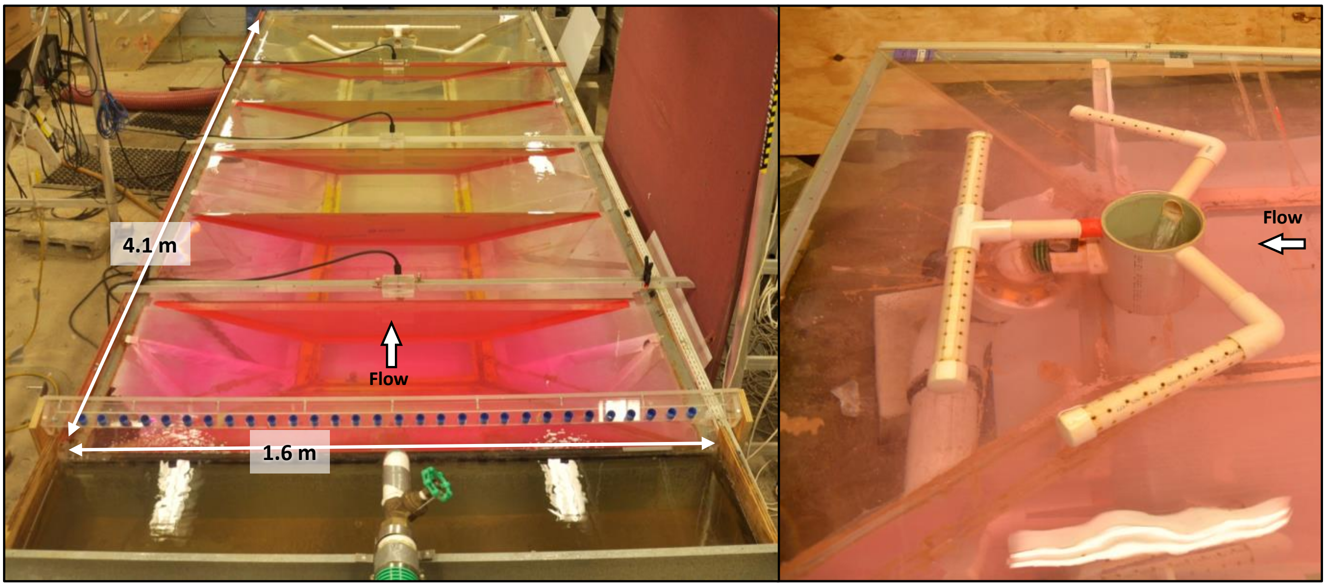

Fig. 1 – The experimental setup and the outlet structure: a trapezoidal model pond with top dimensions of 4.1 m × 1.6 m and 0.3 m depth, a rectangular tank precedes the pond serving as sediment forebay.

The tracer concentrations and amount of dye in each cap (varied between 2-6 ml) were selected according to the excitation limits of the fluorometer (0-5 Volts). The hydraulic analysis is performed on the RTDs that are normalised to C_0, and thus the differences in the tracer concentration do not affect results.

The outlet consists of three perforated pipes (diameter = 48 mm) were attached to an outlet riser pipe as the outlet. The pipes were perforated with five rows of 6 mm diameter holes. The outlet riser pipe which is placed vertically has 200 mm internal diameter and is 250 mm long. The perforated pipes were fixed to the outlet riser such that the centres of the pipes were 220 mm above the bottom of the pond. During the experiments water level was at 270 mm and the outlet pipes were completely submerged, flow exceeded the perforated pipes capacity and the excess exited the pond through the outlet riser. The tracer concentration was measured using a fluorometer (Cyclops-7™ Rhodamine), which was fixed inside the outlet riser.

The porous baffles were made from stainless steel wire meshes (Table 1). The selected range of meshes facilitated investigating the effect of mesh aperture, independently of the open area. The baffles were installed perpendicular to the inflow path and covered the entire cross section of the pond.

Table 1 – Properties of the baffles

Mesh ID	Aperture (mm)	Wire diameter (mm)	Open area (%)
Coarse (C)	3.300	0.910	61
Medium-coarse (MC)	2.000	0.560	61
Medium-fine (MF)	1.000	0.560	42
Fine (F)	0.415	0.220	40

For solid baffles, transparent acrylic sheets with 10 mm thickness were used. They were approximately 240 mm in height, which blocked about 90% of the flow depth. Fig. 2 shows the tested configurations with positions of the baffles.

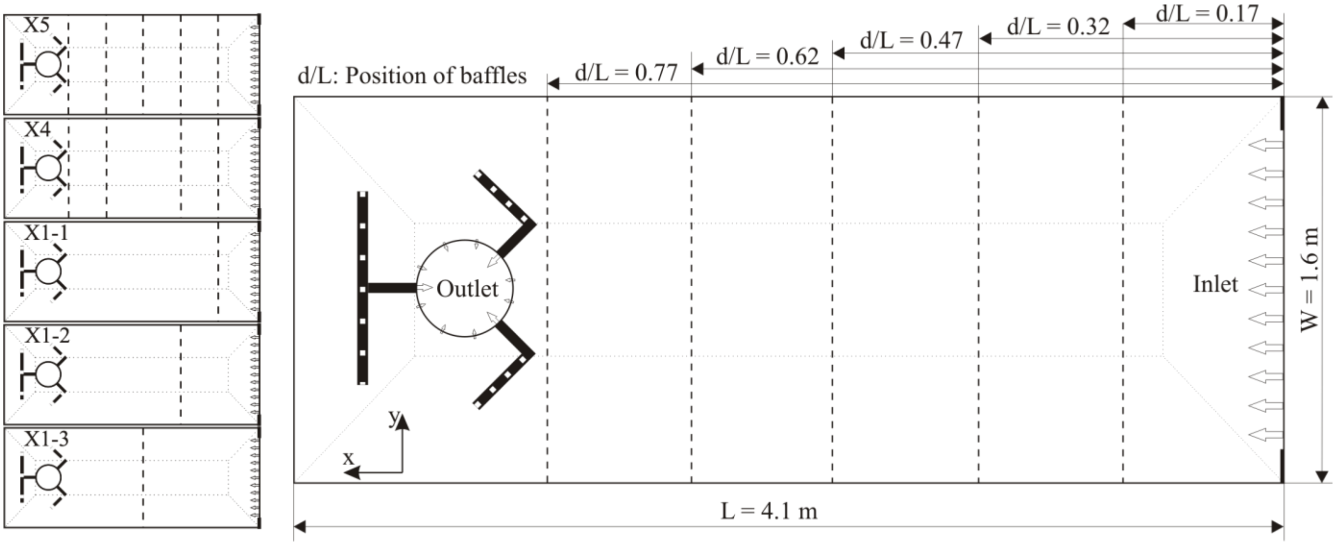

Fig. 2 – The tested baffle configurations, d/L shows the distance of the baffle from the inlet, normalised to the length of the pond (L), X is a general term for the mesh types (coarse, medium-coarse, medium-fine, or fine).

For trap efficiency experiments, dry sediment was mixed with water and then added into a tank with conical-shaped bottom (Fig. 3). The tank was equipped with an automatic stirrer which ran continuously to limit sediment settlement in the tank before addition to the pond. To direct the mixture to the pond, thirty plastic tubes with 6 mm internal diameter were connected to the throat of the container. A valve at the throat of the container controlled the flow. The other ends of the tubes were aligned above the pond inlet such that the sediment mixture flows into the pond with a similar angle to that of the inflow.

The sediment used for the experiments was silica flour with mean particle size of 30 µm. For measurement of sediment concentration in the effluent, a turbidity sensor (Cyclops-7™ Turbidity) was used. The sensor was installed in the outlet riser and continuously recorded the concentration at a sampling rate of 10 Hz. Prior to the experiments, the sensor was calibrated for the silica flour and the linear calibration equation was applied to convert the raw data to the mass of sediment.

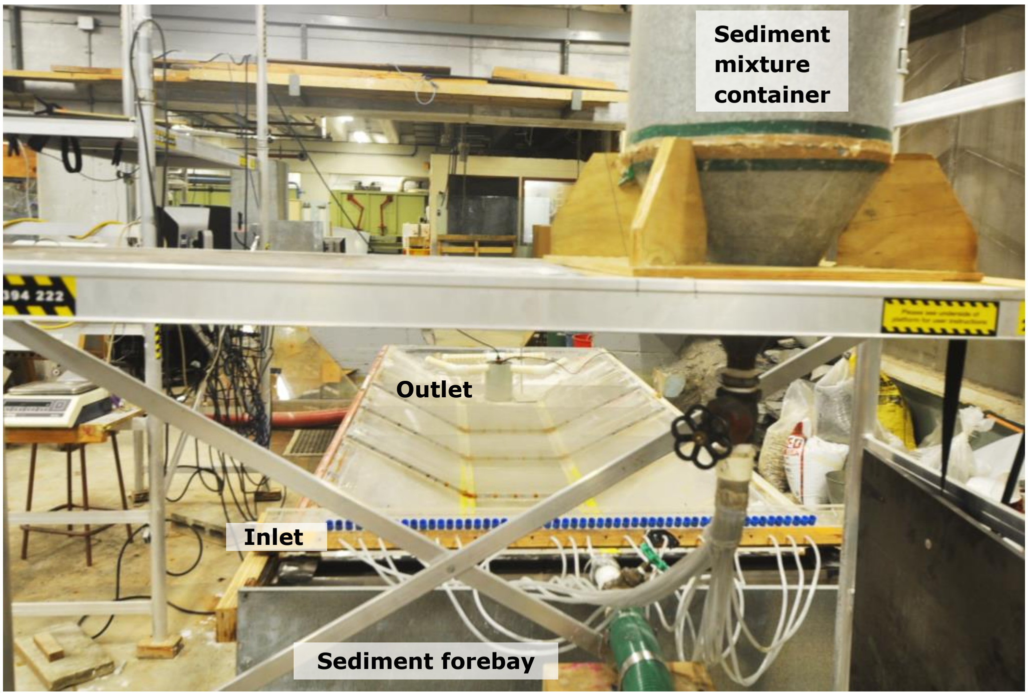

Fig. 3 – The experimental setup for trap efficiency experiments

5 RESULTS AND DISCUSSION

5.1 HYDRAULIC PERFROMANCE

The hydraulic indices for the studied baffle configurations are shown in Table 2.

Table 2 – Hydraulic performance indices for cases with porous baffles

Coarse baffle (3.3 mm aperture, 61% OA)					Med-coarse baffle (2 mm aperture, 61% OA)				
Case ID	**# baffles**	θ_5	MI	Mo^{-1}	**Case ID**	**# baffles**	θ_5	MI	Mo^{-1}
C5	5	0.60	0.87	0.35	MC5	5	0.66	0.91	0.35
C4	4	0.57	0.87	0.33	MC4	4	0.61	0.90	0.37
C1-3	1	0.38	0.80	0.23	MC1-3	1	0.42	0.83	0.28
C1-2	1	0.43	0.84	0.24	MC1-2	1	0.47	0.83	0.25
C1-1	1	0.33	0.79	0.20	MC1-1	1	0.40	0.82	0.28
Med-fine baffle (1 mm aperture, 42% OA)					Fine baffle (0.415 mm aperture, 40% OA)				
Case ID	**# baffles**	θ_5	MI	Mo^{-1}	**Case ID**	**# baffles**	θ_5	MI	Mo^{-1}
MF5	5	0.78	0.95	0.49	F5	5	0.70	0.92	0.45
MF4	4	0.74	0.93	0.48	F4	4	0.72	0.93	0.45
MF1-3	1	0.45	0.81	0.26	F1-3	1	0.48	0.84	0.26
MF1-2	1	0.48	0.85	0.28	F1-2	1	0.52	0.87	0.33
MF1-1	1	0.50	0.85	0.29	F1-1	1	0.56	0.88	0.35

The performance of the case with no baffles (NB) was used as the basis for comparison. The hydraulic indices for this case are as follows: $\theta_5 = 0.28$, MI = 0.75, $Mo^{-1} = 0.15$. For each of the four meshes the index values increased with increase in number of baffles, in most of the cases. The minimum improvement was associated with the case C1-1 for which a single coarse mesh was installed at d/L = 0.17. This configuration slightly improved the hydraulic indices (20% for θ_5, 6% for MI and 29% for Mo^{-1}), compared with the case NB. The maximum improvement in the hydraulic performance is associated with the case with 5 medium-fine baffles (MF5) (63% for θ_5, 20% for MI and 70% for Mo^{-1}).

This demonstrates that installation of porous baffles effectively improves the performance of ponds, regardless of number, mesh size and position of the baffle.

5.1.1 NUMBER OF BAFFLES

For coarse (C), medium-coarse (MF) and medium-fine (MF) meshes, the cases with 5 baffles had the highest hydraulic indices (except Mo^{-1} for MC mesh). This was as expected, because a large number of baffles encourages more uniform flow, and consequently longer residence times.

For the finest mesh (F), however a different pattern was observed. The case with 4 fine baffles had higher θ_5 and MI values than the case with 5 fine baffles. Also, the cases with 4 and 5 fine baffles had smaller hydraulic indices than cases with 4 and 5 medium-fine baffles. The higher number of meshes per unit area for the fine baffle together with its smaller aperture resulted in higher longitudinal velocities than the medium-fine baffle, when 4 and 5 baffles were installed. Also the smaller values of θ_5 for cases F5 and F4 than for cases MF5 and MF4 indicate higher short circuiting and shorter residence times.

This finding indicates that there is an optimal mesh aperture that is dependent on the number of the installed baffles. For less than 4 baffles, the mesh with 0.415 mm aperture had the highest performance. But for 4 and 5 baffles, the mesh with 1 mm aperture was the best of the four examined meshes.

5.1.2 THE EFFECT OF APERTURE AND OPEN AREA

The configurations with coarse (C) and medium-coarse (MC) baffles (which have similar open area of 61% but different aperture), have different performances. The medium-coarse baffle (with smaller aperture) resulted in higher hydraulic performance for most of the configurations. For fine (F) and medium-fine (MF) baffles the same trend was also observed. On this basis, it can be concluded that the mesh aperture affects the hydraulic performance of ponds, independent of the percentage of open area.

5.1.3 THE EFFECT OF THE FIRST BAFFLE

For fine and medium-fine baffles, the cases in which one of the baffles was installed at d/L = 0.17, had higher hydraulic performance than the other cases with the same number of baffles. One possible reason is that installation of the first baffle near the inlet, contributed to the early dispersion of the inflow energy, as soon as water flowed to the pond. However, when the first baffle was placed at a farther position (d/L = 0.32 and 0.47), the incoming water travelled a longer distance with the initial velocity, which resulted in reduced residence times.

5.1.4 SOLID BAFFLES

The RTDs for the configurations with solid baffles are demonstrated in Fig. 4. The peak of the curves shows the maximum instantaneous concentration. Qualitative analysis of the RTDs shows case S5 (5 submerged solid baffles) to be the most favourable because: 1- the peak occurs at a longer residence time and close to t_n, 2- the shape of the curve suggests that a large proportion of the tracer exits the pond at about t_n. Also, case S1-3 is considered to have the poorest hydraulic performance because the peak occurs at a time much earlier than t_n, which indicates higher short circuiting than the other cases.

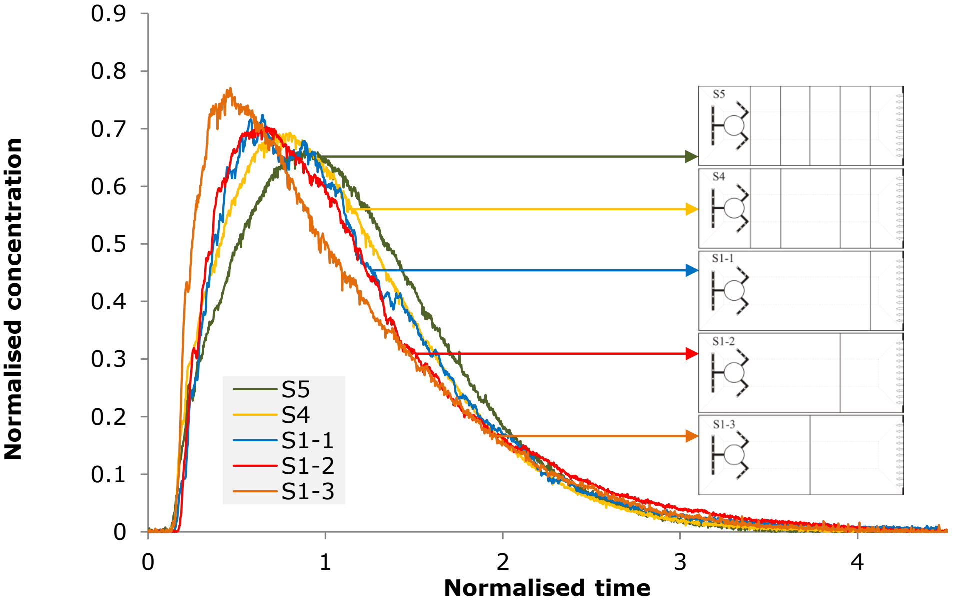

Fig. 4 – RTDs for the cases with solid baffles

The associated hydraulic indices are shown in Table 3. The maximum improvement in hydraulic performance was for the case with 5 solid baffles (S5).

Table 3 – Hydraulic performance indices for the cases with solid baffles

Case ID	**Number of baffles**	θ_5	MI	Mo^{-1}
S5	5	0.34	0.84	0.23
S4	4	0.32	0.82	0.22
S1-3	1	0.28	0.77	0.18
S1-2	1	0.34	0.81	0.20
S1-1	1	0.35	0.82	0.22

For the case with 1 baffle installed at d/L = 0.17 (S1-1), relatively higher index values were observed compared with the other configurations with one baffle. During the experiments, qualitative observations showed that due to the downward direction of the inflow, the submerged solid baffle at d/L = 0.17 created a recirculation zone for the added tracer (Fig. 5). Installation of a single baffle at farther positions from the inlet reduced water velocity near the baffle and created a bigger dead zone. Thus, more of the added tracer passed over the baffle due to higher upward velocities. The smaller value of θ_5 for cases S2 and S3 (0.34 and 0.28, respectively) than case S1 (0.35) indicates increased short circuiting when the baffle was installed at d/L = 0.32 and 0.47.

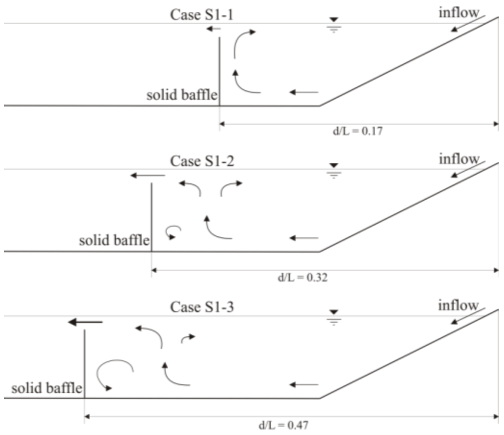

Fig. 5 – The effect of position of the first solid baffle on the flow pattern

5.2 TRAP EFFICIENCY

The trap efficiency experiments were conducted for fine, medium-fine and submerged solid baffles. The trap efficiency values together with the hydraulic performance indices are plotted in Fig. 6. Also shown in this figure are the performance indices for the pond with no baffles (case NB), for the purpose of comparison.

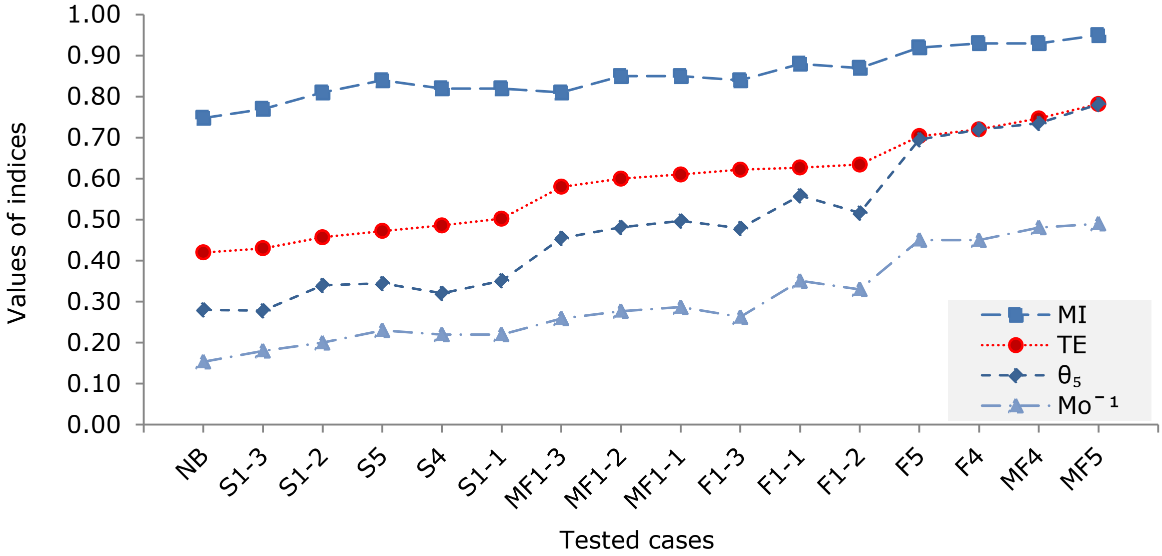

Fig. 6 – Trend of changes in hydraulic indices and TE values for the tested cases

The trends of changes for the hydraulic performance indices and trap efficiency values were similar for most of the cases. The cases with solid baffles have the lowest trap efficiency among the different baffle configurations and the case with 5 medium-fine baffles (MF5) has the highest hydraulic performance and trap efficiency. This figure suggests that trap efficiency of sediment ponds can be estimated using hydraulic performance indices obtained from a tracer study.

6 CONCLUSIONS

The objective of this study was to determine the optimum configuration of baffles for sediment retention ponds. Several configurations of solid and porous baffles were experimentally tested in a model sediment retention pond. The results indicated that porous baffles are superior to solid baffles for improving the pond performance. The optimum configuration of porous baffles was shown to be dependent on the mesh size. Among the tested configurations the case with 5 porous baffles with 1 mm aperture and 42% open area had the highest performance. Also, it was demonstrated that installation of the first porous baffle near the inlet structure is preferable, because the inflow momentum is dispersed as soon as it enters the pond and the hydraulic residence time is increased. With regards to sediment removal, there was a close correlation between the trends of trap efficiency and hydraulic performance indices. This can be helpful for estimation of trap efficiency of ponds using the hydraulic performance indices that are derived from a tracer experiment.

The results presented in this paper suggest that significantly higher sediment removal can be achieved by proper design and installation of baffles in the existing ponds. Consequently, the desired treatment can be achieved by fewer ponds that are highly effective, which ultimately reduces the treatment costs.

ACKNOWLEDGEMENTS

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