

Evaluation of hydraulic performance indices for retention ponds

Arash Farjood, Bruce W. Melville, Asaad Y. Shamseldin, Keith N. Adams and Sher Khan

ABSTRACT

Comprehensive hydraulic analysis of sediment retention ponds is commonly achieved through interpretation of residence time distribution and derivation of indices associated with short-circuiting and mixing. However, the availability of various indices indicates the need for careful selection of the most appropriate indices. This study compares some of the commonly used hydraulic performance indices, together with a new short-circuiting index, τ_5 , for five different flow regimes in a model sediment retention pond. The results show that τ_5 was the best measure for short-circuiting. Among the mixing indices, only the Morrill index correctly represented the physical behaviour of the experiments. In addition, two hydraulic efficiency indices, λ and a moment index (MI) were assessed and showed a good correlation with the short-circuiting and mixing indices, but MI was more reproducible than λ . Based on these results, this study recommends using τ_5 , Morrill index and MI for analysis of hydraulic performance in sediment retention ponds.

Key words | hydraulic performance, residence time distribution, sediment retention pond, short-circuiting

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INTRODUCTION

Sediment retention ponds have been used for decades as a sustainable *in-situ* treatment for sediment-laden runoff from construction sites (Moglen & McCuen 1988; Verstraten & Poesen 2000; Thaxton & McLaughlin 2005). It has been demonstrated that the sediment removal performance of ponds is determined by its hydraulic attributes (Verstraten & Poesen 2000; Koskiaho 2003; Persson & Wittgren 2003; Thaxton & McLaughlin 2005; McLaughlin *et al.* 2009). For example, Persson & Wittgren (2003) state that similar principles can be found in the models that are used for describing the removal of soluble pollutants, e.g., nitrogen and those used for removal of suspended solids. Thus, comprehensive understanding of the flow behaviour within the pond allows identification of the influential hydraulic aspects that affect the hydraulic performance, and ultimately the sediment removal performance of the ponds.

The treatment efficiency of ponds fundamentally relies on hydraulic residence time, which delineates the amount of time that each water particle spends within the pond (Kadlec 1994). Hydraulic residence time depends on the

path taken by the fluid particle as it flows through the system. As a result, there is a specific hydraulic residence time for each particle and a distribution of residence times is generated by the hydraulic characteristics of the pond (Headley & Kadlec 2007). These variations in hydraulic residence times are explained by the residence time distribution (RTD) which represents the temporal probability distribution of non-reacting tracer particles within the system (Kadlec 1994).

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 the plug flow condition. Plug flow concept assumes that fluid particles entering a system travel 'in single file', with no mixing with the adjacent fluid, and leave the system in the order in which they enter (Levenspiel & Bischoff 1964). Lightbody *et al.* (2009) state that the maximum degree of performance in treatment ponds is achieved with plug flow circulation, the condition which is created when the influent particles travel at the same velocity and exit the pond at exactly the nominal hydraulic residence

time, t_n (t_n is equal to the total volume of the system divided by the inflow flow rate). However, this condition is practically impossible to achieve due to physical phenomena such as short-circuiting (Kadlec 2000; Persson 2000; Lightbody *et al.* 2009) and mixing (Kadlec 1994; Headley & Kadlec 2007).

Short-circuiting occurs when the incoming flow parcels travel through preferential high-velocity pathways to the outlet with limited mixing with the stored fluid (Stovin *et al.* 2008). This leads to reduced treatment opportunities for the high-velocity parcels. The existence of short-circuiting is considered one of the greatest obstacles to successful pond design (Persson 2000). The degree of short-circuiting has been widely considered as a powerful indicator of a pond's hydraulic performance (Persson *et al.* 1999; Lightbody *et al.* 2009; Khan *et al.* 2013). The other phenomenon that significantly alters the hydraulic performance of ponds is mixing, which is a result of molecular diffusion and turbulent diffusion. Mixing affects ponds' performance by altering the velocity profile already existing in the pond (Kadlec 1994).

One of the most widely adopted methods for assessing the degree of short-circuiting and mixing, and consequently the hydraulic performance of the pond, is interpretation of the RTD (Kadlec 1994, 2000; Khan *et al.* 2011). In this method, an appropriate tracer is added at the inlet of the system and its concentration is measured as a function of time at the outlet. The effluent tracer concentration versus time gives an RTD, from which the required hydraulic indices can be derived. The existence of short circuits and mixing affects the RTD by altering the time that each water particle persists in the system (Badrot-Nico *et al.* 2009).

However, either of these two phenomena cannot be considered independent of the other one. Kadlec (1994) suggested that the variance of the RTD is influenced not only by mixing of water when travelling within the pond, but also by preferential flow paths (i.e., short-circuiting). Kilani & Ogunrombi (1984) investigated the effect of baffles on hydraulic characteristics of waste stabilisation ponds and observed lower residence times than t_n . They asserted that this could be a consequence of the mixing that is characterised by the combined effect of short-circuiting and dead zones inside the ponds. The studies cited above imply that the changes in one of the two phenomena affect the other one.

Installation of baffles has been a common practice for reducing the short-circuiting and consequently improving the performance of ponds (Nighman & Harbor 1997;

Koskiaho 2003; Thaxton & McLaughlin 2005). Baffles are solid or porous impediments that are made from various materials such as plywood, or a silt fence for solid baffles (Nighman & Harbor 1997), and jute mesh or braced geotextile curtains for porous baffles (Thaxton *et al.* 2004). Implementation of porous baffles in ponds increases the rate of treatment by dissipating the inflow momentum and reducing short-circuiting, hence increasing the residence time of the incoming water particles. Previous studies have demonstrated the effectiveness of baffles for increasing the hydraulic performance and sediment removal performance of ponds (Nighman & Harbor 1997; Koskiaho 2003; Thaxton *et al.* 2004).

HYDRAULIC PERFORMANCE INDICES

The RTDs can be directly used for comparison between performances of different systems. However, a thorough analysis and comparison of RTDs is not always a simple task (Teixeira & do Nascimento Siqueira 2008). Therefore, hydraulic performance indices derived from an RTD are commonly used for this purpose. To enable comparison between different systems (i.e., with different physical properties or different flow rates), the RTDs are normalised. The normalisation method that is adapted in the present study is achieved by:

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

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

where C' is the normalised concentration, C is measured concentration at each time step, C_0 is the mass of added tracer divided by the pond volume, t is measurement time and τ is normalised time. The hydraulic performance indices are derived from normalised RTDs, hence are dimensionless.

There are various hydraulic performance indices available in literature. They can be categorised as short-circuiting, mixing and hydraulic efficiency indices. A comprehensive list of the indices is given by Teixeira & do Nascimento Siqueira (2008) who assessed a number of short-circuiting and mixing indices for five different flow regimes. The indices were assessed upon three criteria: (1) the correlation of the index to the physical phenomenon, (2) the capability of the index for detection of changes in

the physical phenomenon, and (3) the statistical variability of the index. They concluded that τ_{10} (that is the normalised time for 10% of the added tracer to exit the system) was the only short-circuiting index that fulfilled all three criteria. For mixing indices, although none of them met all three criteria, they recommended the dimensionless dispersion index, σ^2 , which is defined as

$$\sigma^2 = \frac{\sigma_\tau^2}{\tau_{\text{mean}}^2} \quad (3)$$

where σ_τ^2 is temporal variance of the RTD and τ_{mean} is mean residence time, which is the time to centroid of the RTD. For an ideal plug flow system, σ^2 is zero, and for a completely mixed system, it is unity. The dispersion index, σ^2 , shows the spread of residence times about the centroid of the RTD and, therefore, can be significantly affected by the long tail of the curve, which is mainly a consequence of dead zones and recirculation within the system (Thackston *et al.* 1987; Persson *et al.* 1999).

The Morrill index, Mo, is another commonly used mixing indicator (Thackston *et al.* 1987; Stamou 2008; Teixeira & do Nascimento Siqueira 2008) and is defined as

$$\text{Mo} = \frac{\tau_{90}}{\tau_{10}} \quad (4)$$

where τ_{90} is the normalised time for 90% of the added tracer to exit the system. Mo values close to 1 (i.e., $\tau_{10} = \tau_{90}$) show a more plug-flow-like regime, and it increases with an increase in the degree of mixing.

For short-circuiting, theoretically, the initial tracer detection time, τ_i , most closely describes the phenomenon (i.e., arrival of the tracer front). However, τ_i not only does not give any information about the amount of tracer leaving the pond, but is also reported to be difficult to reproduce (Teixeira & do Nascimento Siqueira 2008). Also, the derivation of τ_i from RTD requires either relatively complicated computational algorithms or manual inspection of the RTD. This can be a demanding task when a large number of experiments are to be analysed. This highlights the need for an alternative index to τ_i that can accurately identify short-circuiting and overcome the shortcomings associated with τ_i .

Persson *et al.* (1999) examined the hydraulic performance of ponds with different configurations and developed a quantitative measure of flow hydrodynamics in ponds, namely the hydraulic efficiency λ . It reflects the effective volume of the pond and the distribution of the hydraulic

residence time, and has the following equation:

$$\lambda = \frac{t_p}{t_n} \quad (5)$$

where t_p is time to peak of the RTD, and t_n is nominal residence time (i.e., corresponding to plug flow conditions). Values of λ are theoretically between 0 and 1 with higher values representing a more plug-flow-like flow regime.

Another useful measure for hydraulic performance is the moment index (MI), introduced by Wahl *et al.* (2010). MI incorporates both short-circuiting and mixing effects, while being independent of measures of both. The effect of the long tail of the RTDs affecting other indices (e.g., σ^2) is not an issue with MI, because it is related to the section of the RTD prior to the nominal residence time. Also, unlike λ , MI is not susceptible to instantaneous variations of tracer concentration, because MI intrinsically includes the mass of tracer under the RTD, whereas for λ , a single point of the RTD (i.e., t_p) is used. MI is defined as follows:

$$\text{MI} = 1 - M_{\text{pre}} \quad (6)$$

where

$$M_{\text{pre}} = \int_0^1 (1 - \tau) C'(\tau) d\tau \quad (7)$$

where M_{pre} is the moment about the nominal divide ($\tau = 1$) for the normalised RTD bounded from zero to one. MI values vary between 0 and 1, with higher values showing a more hydraulically efficient system. Full details of this method are given in Wahl *et al.* (2010).

Because of the availability of various hydraulic performance indices, developing a comprehensive understanding of the indices behaviour in different flow regimes is vital for choosing the appropriate index. In this study, the commonly used hydraulic performance indices, as well as a new short-circuiting index τ_5 (that is the normalised time for 5% of the added tracer to exit), shown in Table 1, were evaluated for different configurations of a model sediment retention pond, using a series of tracer experiments. The aim is to assess whether the investigated indices indicate the changes in the associated hydraulic phenomena. It is worth noting that comparison between hydraulic performances of different pond configurations was beyond the scope of this research. That is, the trend of changes in the indices is analysed rather than their values for different cases.

Table 1 | The hydraulic performance indices evaluated in this study

Short-circuiting indices		References
τ_1	Initial detection time (normalised time)	Thackston <i>et al.</i> (1987), Stamou & Noutsopoulos (1994), Stamou (2008) and Khan <i>et al.</i> (2013)
τ_5	Normalised time for 5% of the added tracer to exit	
τ_{10}	Normalised time for 10% of the added tracer to exit	Thackston <i>et al.</i> (1987), Stamou & Noutsopoulos (1994), Stamou (2008) and Khan (2012)
τ_{16}	Normalised time for 16% of the added tracer to exit	Stovin <i>et al.</i> (2008), Ta & Brignal (1998) and Khan (2012)
τ_{25}	Normalised time for 25% of the added tracer to exit	
τ_{50}	Normalised time for 50% of the added tracer to exit	Thackston <i>et al.</i> (1987), Ta & Brignal (1998), Stovin <i>et al.</i> (2008) and Khan (2012)
τ_{mean}	Normalised time to centroid of the RTD, $\frac{\int_0^{\infty} \tau c'(\tau) d\tau}{\int_0^{\infty} c'(\tau) d\tau}$	Thackston <i>et al.</i> (1987) and Khan (2012)
Mixing indices		
σ^2	Dispersion index: temporal variance of RTD/ τ_{mean}^2	Kilani & Ogunrombi (1984), Thackston <i>et al.</i> (1987) and Stamou (2008)
Mo	Morril index: τ_{90}/τ_{10}	Thackston <i>et al.</i> (1987), Stamou (2008) and Teixeira & do Nascimento Siqueira (2008)
$\tau_{90}-\tau_{10}$	Time elapsed between τ_{10} and τ_{90}	Stamou & Noutsopoulos (1994), Stamou (2008) and Teixeira & do Nascimento Siqueira (2008)
$\tau_{75}-\tau_{25}$	Time elapsed between τ_{25} and τ_{75}	Stamou & Noutsopoulos (1994), Stamou (2008) and Teixeira & do Nascimento Siqueira (2008)
Hydraulic efficiency indices		
λ	Hydraulic efficiency: time to peak of RTD (t_p)/ nominal residence time (t_n)	Persson <i>et al.</i> (1999), Lightbody <i>et al.</i> (2009), Wahl <i>et al.</i> (2010) and (Khan 2012)
MI	Moment index	Wahl <i>et al.</i> (2010) and Khan (2012)

METHODOLOGY

Five distinct flow regimes were created in a model sediment retention pond. Each case had a different short-circuiting and mixing level. Tracer experiments were conducted with Rhodamine WT tracer dye to obtain RTDs and the performance indices.

The experimental set-up

The physical model is a trapezoidal pond made from acrylic sheets with top dimensions of $4.1 \times 1.6 \times 0.3$ m depth, bank slopes of 2:1 (horizontal:vertical) and $t_n = 453$ s at 2 l/s flow rate (Figure 1). The pond is preceded by a rectangular tank of $0.3 \times 1.6 \times 0.2$ m depth serving as the sediment forebay. As the tank is filled, water flows over a level spreader into the pond. For addition of tracer to the pond, 30 plastic caps were glued onto a rotating bar placed immediately upstream of the level spreader. The caps were filled with the desired amount of dye and then uniform dye distribution was achieved by rotating the bar. The caps were aligned

such that the dye was added just below the level spreader and introduced to the system with the same flow pattern as that of the inflow.

Each cap was filled with 4–5 ml of Rhodamine WT with a concentration of 5–10 ppm, depending on the configurations. The tracer concentrations were selected based on the excitation limits of the fluorometer (0–5 volts). The differences in the tracer concentration did not affect the analysis because the indices were derived from the RTDs normalised to C_0 .

For the outlet, three perforated T-bars with an internal diameter of 48 mm were fixed to an outlet riser. Five rows of 6 mm diameter holes on each of the T-bars allowed water to exit. The outlet riser is a 250 mm long, vertically placed, PVC pipe with a 200 mm internal diameter. During the experiments, the T-bars were fully submerged, the water depth was 270 mm, and water surpassed the capacity of the T-bars and flowed over the top of the outlet riser. A Cyclops-7™ fluorometer manufactured by Turner Designs (Sunnyvale, CA, USA) was fixed inside the drain pipe connected to the outlet riser, to continuously measure the tracer concentration during the experiments.

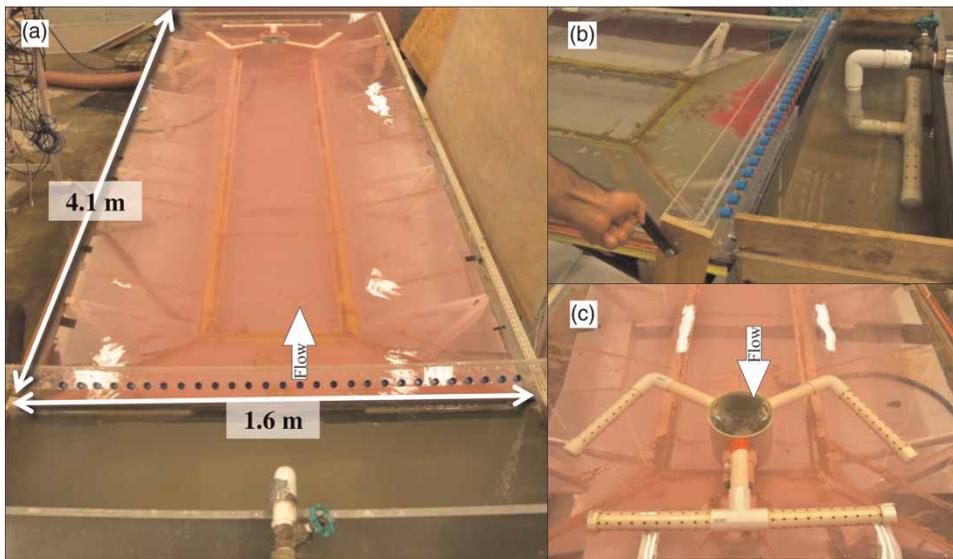


Figure 1 | The experimental set-up. (a) The trapezoidal model pond with top dimensions of 4.1×1.6 m and 0.3 m depth. A rectangular tank of $0.3 \times 1.6 \times 0.2$ m depth serving as a sediment forebay precedes the main pond. (b) The manual dye addition system: 30 plastic caps glued onto a rotating bar. (c) The outlet structure.

The five experimental cases, together with their associated RTDs, are depicted in Table 2. For case BP (base pond), the observed accelerated flow paths along the side walls, together with a long tail of RTDs indicated high levels of short-circuiting and mixing and thus low hydraulic performance. Case MNB (modified, no baffle) was then created by modifying the outlet span and shortening the inlet width by blocking 0.1 m of the inlet at each side. Visual inspection of tracer path, RTDs and cumulative concentration curves confirmed a reduction in short-circuiting and an improvement in the overall flow regime. The other three cases were created: case M2SB (modified, two solid baffles) with two partially blocking solid baffles, case M2PB (modified, two porous baffles), and case M5PB (modified, five porous baffles). The solid and porous baffles were made from acrylic sheets and metal mesh with 1 mm apertures and 42% open area, respectively. It should be noted that these five cases were purposefully selected such that they give a continuum of higher hydraulic performances from case BP to case M5PB to allow comparison between trends of the indices.

Tracer experiments were repeated 20 times for each case to generate sufficient data for statistical analysis. For the comparison between trends of the indices, average values of the 20 tests for each case are used. The criteria used to assess the indices in this study are as explained by Teixeira & do Nascimento Siqueira (2008): (1) ability to identify the physical phenomenon, (2) sensitivity to changes in the phenomenon, and (3) statistical variability.

RESULTS AND ANALYSIS

Short-circuiting indices

As shown in Figure 2(a) τ_1 clearly indicates the changes in short-circuiting levels. Besides, comparing the trend of τ_1 to that of the other indices shows that the longer the time element in an index, the less parallel the trend of that index is with τ_1 . Measurement times were the longest for τ_{50} and τ_{mean} , which resulted in their trend being significantly different than that of τ_1 . This behaviour was also observed by Teixeira & do Nascimento Siqueira (2008), who stated that it is due to the increased influence of other hydraulic phenomena, such as recirculation and dead zones, with time. This implies that short-circuiting indices that require much longer measurement times than t_1 , e.g., t_{16}/t_{50} (Ta & Brignal 1998) and t_{50}/t_n (Stovin *et al.* 2008), should be avoided. Therefore, τ_{50} and τ_{mean} are not further analysed in this study. Accordingly, an alternative index, τ_5 , for which the occurrence time is closer to τ_1 than the other indices, was included in the analysis. For the tested cases in this study, τ_5 had the most parallel trend to τ_1 than the other indices, because of proximity of measurement times for these two indices (Figure 2(a)).

To analyse the statistical variability of the experiments, the coefficient of variation (CV) of short-circuiting indices was computed for each of the five cases (Figure 2(b)). CV is defined as the ratio of the standard deviation to the mean and shows the precision of the experiments. The low

Table 2 | RTD curves from tracer experiments and description of the five tested cases

Case ID	RTD curve	Case description
BP		<p>Base pond</p>
MNB		<p>Modified: shortened inlet and modified outlet, no baffles</p>
M2SB		<p>2 solid partial baffles</p>
M2PB		<p>2 porous baffles</p>
M5PB		<p>5 porous baffles</p>

For each case, 20 experimental runs were conducted. BP: base pond, M: modified, NB: no baffles, PB: porous baffles, SB: solid baffles.

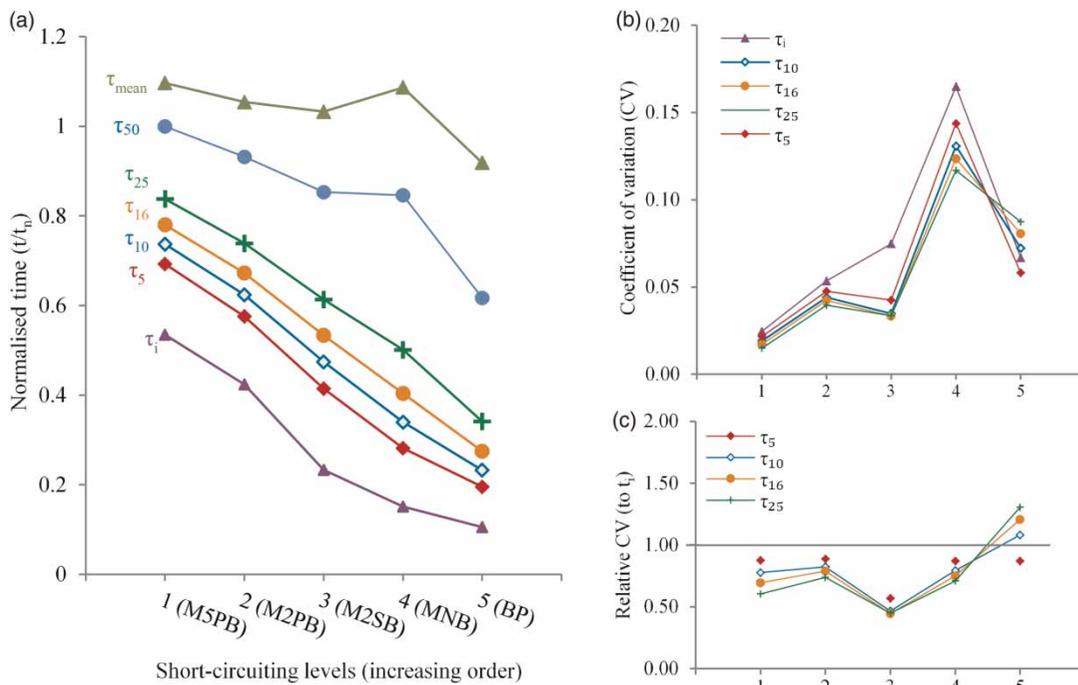


Figure 2 | Analysis of short-circuiting indices. (a) The trend of change in short-circuiting indices. Note that τ_{50} and τ_{mean} did not meet the first assessment criteria for all the cases (a decreasing trend for increasing short-circuiting) and thus were not included in the statistical analysis. (b) CV, showing accuracy of the experiments. (c) Relative CV to CV of τ_1 , showing reproducibility of the tested indices compared with that of τ_1 . Values below 1 show a more reproducible index than τ_1 . Only τ_5 was more reproducible than τ_1 for all the cases.

coefficients of variation for the indices indicate high precision for all the experiments. Teixeira & do Nascimento Siqueira (2008) reported a significant increase in CV with an increase in short-circuiting levels, and suggested that this increase was because of smaller mean values of indices for higher levels of short-circuiting. However, a different pattern was observed in the present study. Although all the indices indicated an overall increase in short-circuiting level from case M5PB to case BP, the maximum CV was for case MNB, with a subsequent decrease from case MNB to case BP, which had the highest short-circuiting level. The flow pattern differences between cases MNB and BP could be the reason for this behaviour. In case BP, persistent accelerated velocity pathways were visually observed along the side walls. However, in case MNB, these short circuits were reduced and it was observed that the tracer took random paths toward the outlet, resulting in variability in residence time. As a result, the values of indices for case MNB had higher variations than the values for case BP. This implies that variability of the measurements cannot always be associated with the degree of short-circuiting, which is contrary to the conclusions of Teixeira & do Nascimento Siqueira (2008).

Another noticeable pattern in Figure 2(b) is the drop in CV of τ_5 , τ_{10} , τ_{16} and τ_{25} in case M2SB while the increasing trend of τ_1 was maintained. In case M2SB, it was visually observed that the two partial baffles deflected the inflow to one side of the pond and created a well-defined flow path towards the outlet. This resulted in less variation in values of τ_5 , τ_{10} , τ_{16} and τ_{25} , all of which depend on the mass of tracer. However, despite this well-defined flow path, CV for τ_1 were higher for case M2SB than for cases with lower short-circuiting levels (cases M5PB and M2PB). This could be due to the combined effect of the size of the short circuit in case M2SB and the partially blocking baffles in front of the inlet. When the tracer was added along the inlet width, it was observed that a portion of it travelled through the open space between the first partial baffle and side wall, much faster than the main tracer plume. As these parcels of tracer passed the second baffle, they adopted locally random paths within the deflected flow. Because τ_1 is derived from a single point of the RTD, these small variabilities resulted in higher CV.

Reproducibility is another useful statistical measure for assessment of the experimental measurements. The reproducibility, in this context, defines whether the index being tested has less statistical variability than the reference

index and hence, is more reproducible. It is measured by calculating the relative coefficient of variation (RCV) (Teixeira & do Nascimento Siqueira 2008), which is defined as follows:

$$\text{RCV} = \frac{\text{CV}_x}{\text{CV}_r} \quad (8)$$

where CV_x is the coefficient of variation of the index being tested and CV_r is the reference coefficient of variation.

Values of RCV smaller than 1 indicate a more reproducible index than the reference index, which is τ_1 herein. The RCV values shown in Figure 2(c) indicate that only τ_5 was more reproducible than τ_1 for all the cases, and therefore only τ_5 met the third criterion (i.e., being more reproducible than the reference index for all the cases). However, the lower values of other indices (τ_{10} , τ_{16} , τ_{25}) suggest they were more reproducible than τ_5 except for case BP. One explanation for this is that the calculation of these short-circuiting indices is based on the area under the RTD curve (i.e., mass of tracer) and as the area gets larger, the influence of the instantaneous concentration fluctuations gets smaller, hence lower RCV values. However, for case BP, because of less variability in the route taken by the early portion of the tracer that followed the strong short-circuiting (as was explained above), RCV values increased from τ_5 to τ_{25} .

Analysis of short-circuiting indices indicates that only τ_5 met the three assessment criteria and therefore is the appropriate short-circuiting index.

Mixing indices

Figure 3(a) shows the trends of the mixing indices (see Table 1 for definition of the indices) for the five levels of mixing. The values of M_o are normalised to their maximum so that the trend of all the indices can be compared conveniently in one figure. Although all the indices correctly identified the increase in mixing levels from case M5PB to case MNB, only M_o increased for case BP, while the other three indices had almost similar values for cases MNB and BP.

The proximity of values of dispersion index for cases MNB and BP ($\sigma^2 = 0.63$ and $\sigma^2 = 0.62$, respectively) indicate similarly extended RTDs despite their different overall shapes. However, despite similar values of σ^2 , cases MNB and BP have different hydraulic performances, which are illustrated by the cumulative concentration curves in Figure 3(b). As shown in this figure, about 90% of the added tracer for case BP exited the pond in shorter residence times than for case MNB. This implies longer residence times for the majority of the inflow fluid particles for case MNB, and hence more treatment and higher hydraulic performance.

The trend for $\tau_{75} - \tau_{25}$ (time elapsed between the normalised times for 25 and 75% of the added tracer to exit) and $\tau_{90} - \tau_{10}$ (time elapsed between τ_{10} and τ_{90}) was also very similar to that of σ^2 . This was as expected because they all (more or less) represent the spread of the RTD. Teixeira & do Nascimento Siqueira (2008) reported that $\tau_{75} - \tau_{25}$, $\tau_{90} - \tau_{10}$ and σ^2 performed well, but as discussed above, in this study none of them identified the changes between cases

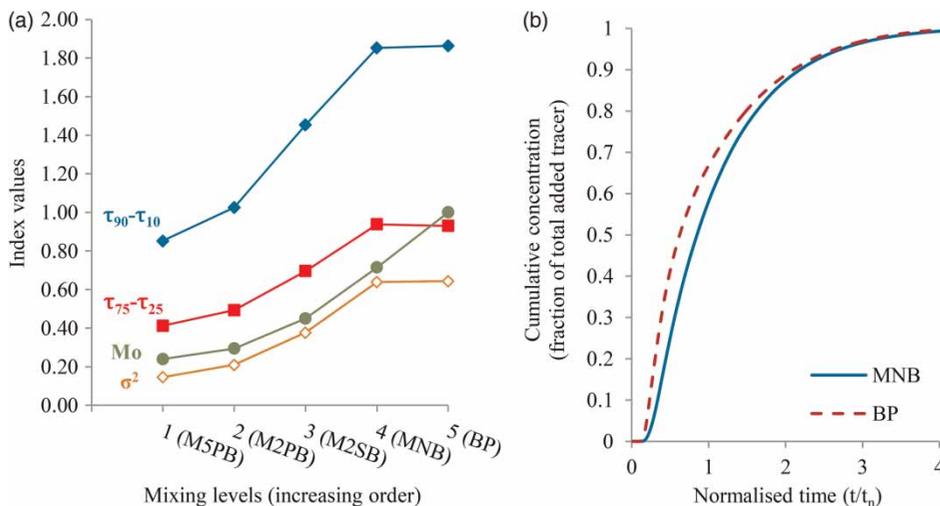


Figure 3 | Analysis of the mixing indices. (a) The trend of the indices for different levels of mixing. Only M_o (Morrill index) indicated the changes from case MNB to case BP. (b) Cumulative distribution of concentration curves for case MNB and case BP, showing higher hydraulic performance for MNB. Note that each curve is the average of 20 tracer tests.

MNB and BP. Thus, Mo is the only acceptable mixing index, and the statistical analysis between the indices is not performed.

Hydraulic efficiency indices

In addition to the short-circuiting and mixing indices, the hydraulic efficiency indices MI and λ were analysed (Figure 4). To enable comparison between the trends of these indices (MI and λ) and short-circuiting and mixing indices, τ_5 and Mo were also plotted on Figure 4(a). This figure shows that both of the hydraulic efficiency indices clearly demonstrated the changes in the hydraulic performance (i.e., both short-circuiting and mixing) for the different cases.

To identify the relation between λ and the other indices, correlation coefficients between them were computed. The index with the highest correlation with λ was τ_5 with $r=0.973$. Mo also had a high correlation with λ , with $r=0.964$. This indicates that, for the tested cases, λ was able to identify short-circuiting and mixing phenomena. MI also had a high correlation with λ , with $r=0.954$.

Statistical analysis of the variabilities of the indices shown in Figure 4(b) suggests that MI was significantly more reproducible than λ for all the tested cases. This is explained by the derivation method of these two indices: MI implicitly covers a large section of the RTD, while λ is based on a single point

(i.e., t_p). Therefore, because of higher reproducibility of MI and its good correlation with λ , MI was the hydraulic efficiency indicator that met all three testing criteria.

VALIDATION OF THE RESULTS

It is desirable that the hydraulic indices can be used for different flow conditions and for ponds with different configurations. Thus, validity of the presented indices (i.e., capability to indicate the changes in the hydraulic performance for different configurations) is determined for four cases selected from the work by Khan (2012). Using these cases, the hydraulic performance of the model sediment retention pond with and without an artificial floating wetland was investigated. The experiments were carried out using the same model pond presented in this paper, at 1 and 1.5 l/s flow rates. The inlet was a pipe with a 45 mm diameter that was fixed in the front wall of the pond, at 0.25 m offset from the longitudinal axis of the pond. For outlet, a pipe with 105 mm diameter, which was positioned on the opposite end wall of the pond, at its centre in the plan, was used. The four configurations of the experimental cases are as follows: (1) pond with a floating wetland at 1 l/s flow rate (case F1), (2) pond with a floating wetland at 1.5 l/s flow rate (case F1.5), (3) pond without a floating wetland at

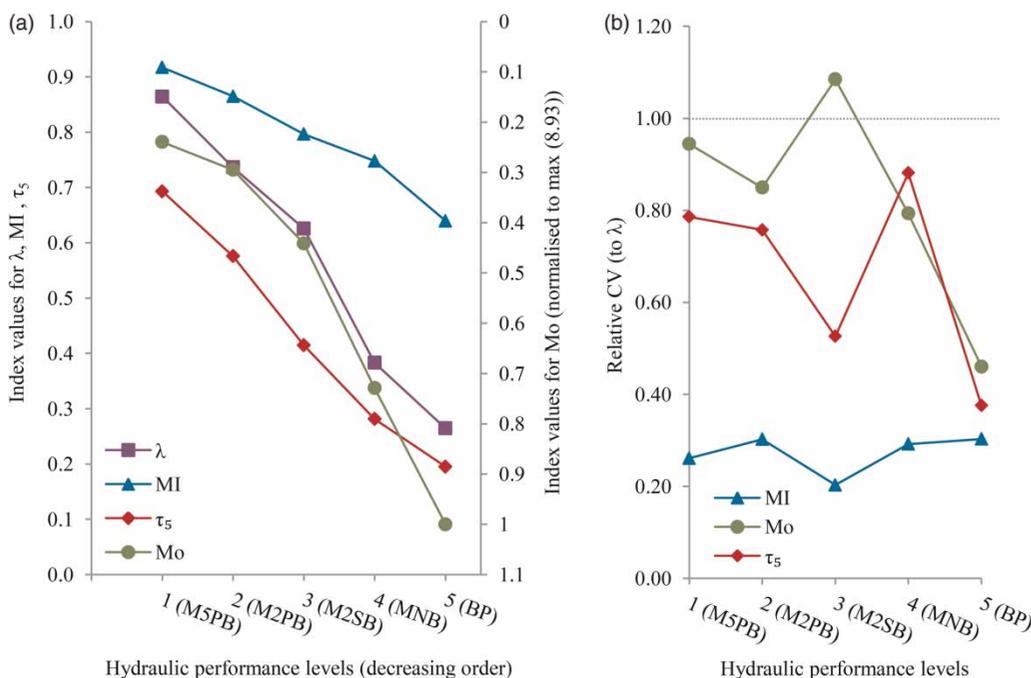


Figure 4 | Analysis of hydraulic efficiency indices. (a) Trend of the hydraulic efficiency indices compared with short-circuiting and mixing indices (Mo is normalised to its maximum value, 8.93). (b) RCV to λ showing reproducibility of the indices compared with λ . MI was more reproducible than λ with CV much lower than those of λ .

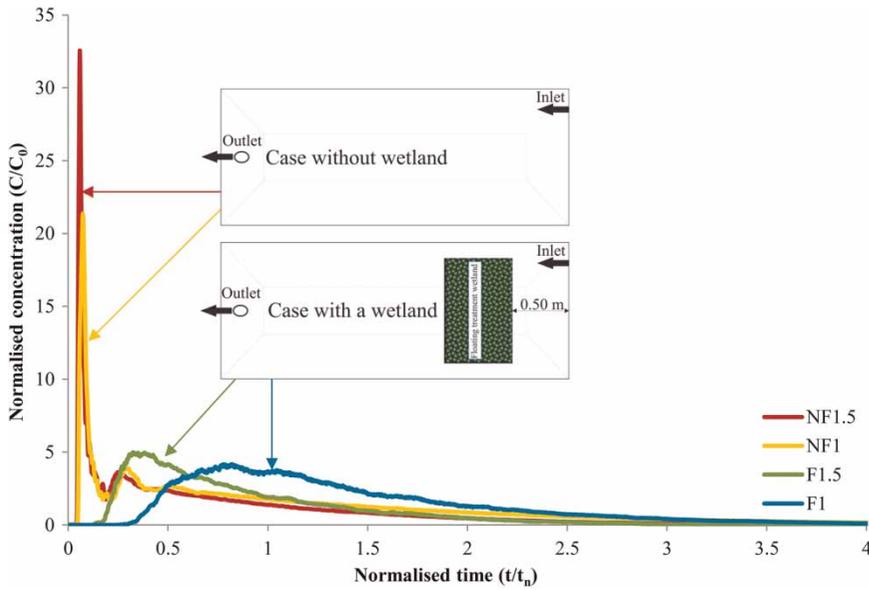


Figure 5 | RTDs and diagrams of the cases with and without floating wetland, reprinted from the study by Khan (2012). RTDs indicate severe short-circuiting and circulation for the cases without floating wetland at 1 and 1.5 l/s flow rates (NF1 and NF1.5).

1 l/s flow rate (case NF1), and (4) pond without a floating wetland at 1.5 l/s flow rate (case NF1.5).

The RTDs were generated from the original tracer experiment data, which were made available by Khan (2012) (Figure 5). Severe short-circuiting can be observed for the cases without floating wetland. Installation of floating wetland not only reduced the peak concentrations, but also delayed its time of occurrence. Considering the RTDs, both of the cases without floating wetland, have very similar

and poor hydraulic performances. Also, case F1 outperformed the other arrangement of floating wetland (i.e., case F1.5), as well as the cases without floating wetland.

The hydraulic performance indices derived from the RTDs are shown in Figure 6. Note that values of M_o and σ^2 are shown in reverse order, on the right-hand side axis. Also, values of M_o are normalised to their maximum (33.14). The trend of changes in the indices (τ_5 , M_o and MI), is in agreement with the RTDs for these four cases

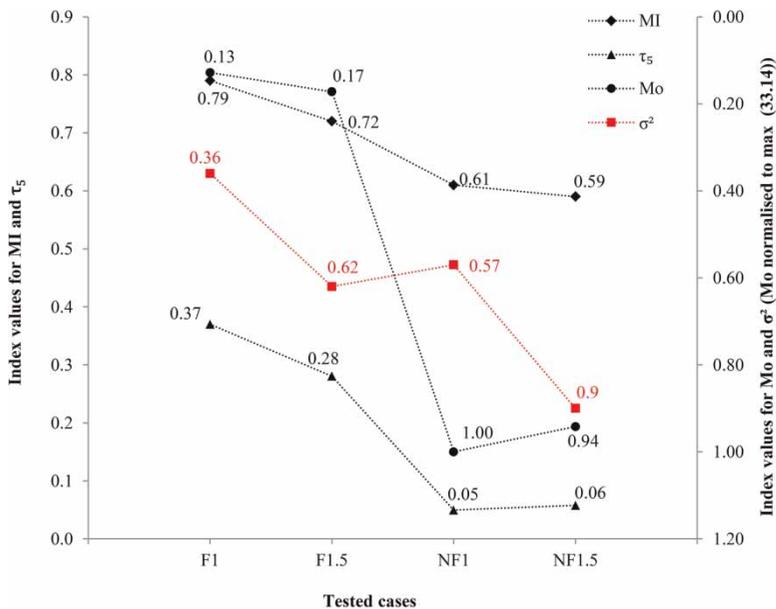


Figure 6 | Hydraulic performance indices for the four cases with and without floating treatment wetland. The value of M_o (normalised to its maximum value, 33.14) and σ^2 are shown in reverse order, on the right-hand side axis. MI , M_o and τ_5 , indicate the changes in the RTDs for the tested cases, while σ^2 shows a different trend to the other indices.

(Figure 6). Regarding short-circuiting, τ_5 is the highest for case F1 (0.37) and it decreased for case F1.5 (0.28). Cases NF1 and NF1.5 have similar τ_5 values of 0.05 and 0.06, respectively. The values of Mo and MI also demonstrate the same pattern of changes. However, the dispersion index, σ^2 , showed a different trend to the other indices. According to values of σ^2 , case NF1 has higher performance than case F1.5, while the RTDs revealed that there existed a significant short-circuiting for case NF1. This is in agreement with the experimental results of this study, that the Mo was superior to σ^2 for indicating the hydraulic performance.

CONCLUSION

The performances of a number of the most common hydraulic performance indices, together with an alternative short-circuiting index, τ_5 , were assessed in a model sediment retention pond. The trends of short-circuiting indices demonstrated that the indices calculated at times closer to τ_i more accurately identify the short-circuiting phenomenon. In addition, τ_5 not only followed the trend of τ_i more closely, but also was the only index to be more reproducible than τ_i for all the tested cases. It was also shown that statistical variability of short-circuiting indices is not always correlated with the degree of short-circuiting. Based on the presented results, the authors make the novel recommendation that τ_5 be used for assessment of short-circuiting phenomenon.

For the mixing indices, only Mo correctly distinguished between all the different cases. The dispersion index σ^2 , $\tau_{75}-\tau_{25}$ and $\tau_{90}-\tau_{10}$ remained almost unchanged for an increase in hydraulic performance from case MNB to case BP. Although the hydraulic efficiency indices, λ and MI, successfully identified the changes in the hydraulic performance for the five different cases, MI outperformed λ by being significantly more reproducible, and thus is the recommended index.

Validation of the presented indices (τ_5 , Mo and MI) with different configurations of the model pond at different flow conditions showed that the indices can be globally used for evaluation of performance of different works.

In this study, only the hydraulic performance was taken into account for evaluation of the indices. Further work to investigate the relation between the hydraulic indices and sediment settlement efficiency, the effect of different sediment particles, their size distribution, and deposition profiles in ponds would be valuable.

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