THE EFFECT OF INLET WIDTH ON THE PERFORMANCE OF SEDIMENT RETENTION PONDS IN THERMALLY INDUCED FLOWS

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ABSTRACT (500 WORDS MAXIMUM)

The effects of inlet and outlet configurations in sediment retention ponds (SRPs) have been widely investigated by a number of researchers; however, the challenges associated with the proper inlet and outlet design still exist when considering temperature differentials in the ponds. The buoyancy forces are arising from differences in temperature potentially changing the flow in the pond by forming density currents. Changing outlet configurations will not solve the issues associated with density stratified flows while the careful design of the inlet can predominantly control the density currents. This study evaluates the effects of different Inlet width ratios (IWRs) on the flow pattern and residence time in a sediment retention pond when inflow is colder or hotter than the water in the pond. In this research, an innovative experimental setup was used to create the temperature differentials. The physical model is a trapezoidal pond made from transparent acrylic sheets fitted on a steel frame with dimensions of 4.1 m × 1.6 m and is 0.3 m deep, and a bank slope of 2:1. The rig was designed so that the temperature differentials could be created using two separate systems in which each system consists of a heat exchanger unit to change the temperature of the water.

The results reveal that in cold influent test cases increasing the inlet width to 100% of the total width of the pond could effectively increase the performance of the pond while in hot influent cases decreasing the pond width to 30% the total width of the pond could successfully improve the performance of the pond.

KEYWORDS

Sediment retention ponds; Hydraulic performance; Temperature differential; Residence Time; Buoyancy driven flow; Inlet width ratio

PRESENTER PROFILE

Originally from Iran, I hold bachelor’s degree in Civil Engineering from Karaj Azad University, Iran. I did my masters in Hydraulic Structures at the Babol University of Technology in 2013. I’m currently in the last year of my PhD at the University of Auckland and working as a water resources engineer.

1 INTRODUCTION

Land disturbing activities and transported sediments to the receiving environment is of concern and finding the effective measures to control the adverse effects of them need special monitoring to quantify its sources (Hicks et al., 2008). Special strategies and technologies are needed to minimise the adverse effects of suspended sediments. One of the effective control devices is a sediment retention pond that can be effective in reducing loads of sediment discharged to receiving environments. Although the sediment retention ponds are effective in reducing sediment discharge to receiving environment their performance need to be carefully assessed to avoid low efficiency in the ponds.

Inflow residence time in the pond is one of the main parameters that can be effective to improve the hydraulic performance of the ponds. On the other hand, the insufficient residence time of suspended solids in the retention ponds will cause the fine particles of sediments to exit the pond without proper treating. Therefore, the treatment efficiency of a pond is directly related to the hydraulic residence time which is the spent time of each inflow particle within the pond prior exiting the pond via the outlet. To quantify the hydraulic residence time, the tracer study needs to be conducted.

The hydrodynamics of the ponds can be influenced by the physical parameters such as pond layout (Persson, 2000), length-to-width ratios (Persson et al., 2003), different inlet and outlet configurations (Adamsson, 2004; Holland et al., 2004; Shilton, 2005), deflector islands and floating treatment wetlands (Khan et al., 2013; Khan et al., 2011; Persson et al., 2003), configuration of baffles (Farjood et al., 2015; Khan, 2012; Persson et al., 2003), effect of Island topographies (Guzman et al., 2018).

Khan (2012) studied the hydrodynamics of the retention ponds by conducting a laboratory investigation on residence time and short-circuiting in sediment retention ponds using a 1:10 scale physical model of an operational sediment retention pond located at the ALPURT B2 motorway construction site, north of Auckland. In this study, the effects of different baffles configurations, deflector island and floating treatment wetland on the performance of a modelled retention pond were examined. (Farjood et al., 2015) also investigated several tracer studies on the similarly modelled pond to increase the hydraulic efficiency of the pond. This study proposed a new index to measure the hydraulic performance of the pond. Moreover, the effects of forebay spread inlet and decant outlet were also experimentally investigated in this research.

Apart from the physical parameters, there are many parameters such as temperature and wind that affect the stormwater pond performance. Three-dimensional numerical modelling has been used by Adamsson et al. (2006) to investigate the temperature difference of inflow and the ambient water in a detention tank. Temperature has also been investigated in waste stabilization ponds by using a physical laboratory model of the existing ponds in the Logan Pond System in USA (Watters, 1972). Watters (1972) used salt water to create the required density difference and simulate stratified flow situations. The results of this study showed that the densimetric Froude number was important in modelling the density stratified flows. However, using salt water to give necessary density difference was found to be ineffective as it couldn't preserve the densimetric Froude number between model and prototype.

The difficulties associated with providing good similarities between model and prototype is evident from the literature as there is very limited research that investigates the effect of temperature and the buoyancy-driven flows experimentally using temperature difference instead of creating density difference using fluids with different densities. Hendi et al. (2018) investigated the effect of temperature on the performance of the retention ponds using a state-of-the-art system to change the temperature of water for creating density difference instead of using two solutions with different densities.

As previously discussed Inlet design has been widely investigated in a number of studies to identify the best configuration of the inlet in terms of the shape, location, and elevation. A well-designed inlet can reduce short-circuiting and improve the hydraulic efficiency of the pond (Agunwamba, 2006; Shih et al., 2017; Ta et al., 1998). The challenges associated with the proper inlet and outlet design still exist when considering temperature differentials in the ponds. However, changing outlet configurations will not solve the issues associated with density stratified flows while the careful design of the inlet can predominantly control the density currents (Crittenden et al., 2012).

This study examines the effect of various inlet width ratios on the performance of the pond when temperature differentials exist. The experiments is carried out using tracer studies for different temperature scenarios. Moreover, the potential changes in velocity vectors were also investigated using velocity measurements of the middle longitudinal section of the pond.

2 MATERIALS AND METHODS

2.1 TRACER STUDIES

Inflow residence time in the pond is one of the main parameters that can be effective to improve the hydraulic performance of the ponds. To quantify the hydraulic residence time, a tracer study needs to be conducted. After injecting tracer to the pond system, the concentration of the tracer is measured at the outlet to produce the Hydraulic Residence Time (HRT) that a parcel of water spends within a system(Nix, 1985; Thackston et al., 1987). Since each particle of water pursues a particular path, there is a specific HRT for each of the water parcels. These variations in HRT can be explained by generating the residence time distribution (RTD) curves which represent the temporal probability distribution of non-reacting tracer particles within the pond system (Thackston et al., 1987; Van de Vusse, 1959). Theoretically, in RTD curves, nominal residence time (t_n = pond volume/flow rate) is used to normalise the time ($t' = \frac{t}{t_n}$) that influent water remains in the system and C_0 (C_0 = total recovered mass of tracer divided by the pond volume) is used to normalise the measured concentration at outlet ($c'(t') = \frac{c(t)}{C_0}$, where $c'(t')$ is the normalised concentration at the normalised time, $c(t)$ is the measured concentration at the measured time and C_0 is the). Several parameters can be extracted from the RTD curves to evaluate the performance of the pond.

There are several possible indices to evaluate the short-circuiting phenomenon in the pond. The first one is the t'_i indicating the normalised initial detection time of tracer (Khan et al., 2013; Stamou et al., 1994; Stamou, 2008; Thackston et al., 1987). The second group is θ_n indicating the normalised time for n% of the added tracer to exit the pond such as t'_5, t'_{10}, t'_{16}, t'_{25}, t'_{50} (Farjood et al., 2015; Khan, 2012; Stamou et al., 1994; Stamou, 2008; Thackston et al., 1987).

The amount of mixing is also quantified by several indices such as dispersion index ($\sigma^2 = \frac{\sigma_{t'}^2}{t'^2_{mean}}$, where $\sigma_{t'}^2$ is temporal variance of the RTD and t'_{mean} is normalised mean residence time) (Kilani et al., 1984; Stamou, 2008; Thackston et al., 1987), Morril index ($Mo = \frac{t'_{90}}{t'_{10}}$) (Stamou et al., 1994; Stamou, 2008; Teixeira et al., 2008), time elapsed between t'_{10} and t'_{90} (t'_{90} - t'_{10}) and time elapsed between t'_{25} and t'_{75} (t'_{75} - t'_{25})(Stamou et al., 1994; Stamou, 2008; Teixeira et al., 2008).

Persson et al. (1999) provided a definition of a technique to measure the hydraulic efficiency of the ponds namely hydraulic efficiency ($\lambda = \frac{t_p}{t_n}$). This index represents the effective volume of the pond and the degree of mixing in the distribution of the hydraulic residence time. Higher λ value reflects a high hydraulic efficiency and more plug flow regime, and lower λ represents a high mixing flow regime. In this regards, Persson et al. (1999) proposed a range for A value of $\lambda > 0.75$ is considered good hydraulic efficiency, $0.5 < \lambda \leq 0.75$ is satisfactory, and $\lambda \leq 0.5$ is poor hydraulic efficiency.

Another useful index proposed by Wahl et al. (2010) is MI which is defined as follows:

$$MI = 1 - \int_0^1 (1 - t')C'(t')dt' \qquad (1)$$

MI for the hydraulic efficiency is bounded from zero to one, with MI = 1 described as maximum hydraulic efficiency and indicating plug-flow-like flow regime**.** MI consists of a first moment of the normalised RTD curve prior to the nominal residence time and therefore, not considered the long tail of the RTDs. The integration in MI indicates the mass of the tracer under the RTD while λ only picks the peak point of RTDs.

In this study the hydraulic performance of the pond was assessed using the hydraulic indices as recommended by Farjood et al. (2014) in which the short-circuiting (SC), the hydraulic efficiency and the mixing were measured using t_5, the moment index (MI), and the Morril index (Mo), respectively.

2.2 EXPERIMENTAL SETUP

The physical model used in this study is a trapezoidal pond made from transparent acrylic sheets fitted on a steel frame with dimensions of 4.1 m × 1.6 m and is 0.3 m deep, and bank slope of 2:1. A rectangular tank of dimensions 0.3 × 1.6 × 0.2 m was used to serve as the sediment forebay that ensures the uniform flow over a level spreader into the main pond. Perforated pipes that simulate the decant outlets was also used as the outlet.

Investigation of the effects of temperature on the performance of sediment retention ponds is the core of this research. To do that, several temperature differentials needed to be created in the system in which the inlet water temperature was higher or lower than the temperature of the water in the pond. Therefore, it was not possible to use the laboratory tap water for each experiment as the temperature of the laboratory tap water was not controlled. Thus, a plastic water tank has been used with the volume of 10000 litres to provide the required inflow. Changing the temperature of this amount of water would be a daunting task as it is required 33520 kj energy to increase the temperature of 8000 litres of water by 1 °C. This challenging task has been resolved by designing a state-of-the-art system comprised of two separate recirculating systems. Each system composed of one heat pump in which the 11 kW was used to change the temperature of water in the pond and the 21 kW unit was used to change the temperature of water in the tank to be used as inflow. Before starting the experiments, the water in the tank is pumped to the forebay and over a level spreader into the retention pond. The effluent at this stage is carried by a 40 mm pipe to the waste. After ensuring steady flow conditions in the pond, the effluent in the pond and the water in the tank are recirculated in two different systems. After changing the temperature of the water, the direction of motorised valves was changed using a switch to pump the water in the tank to the pond. The motorised valves were used to prevent changing the velocity fields within the pond as all the valves were automatically rotated at the same time.

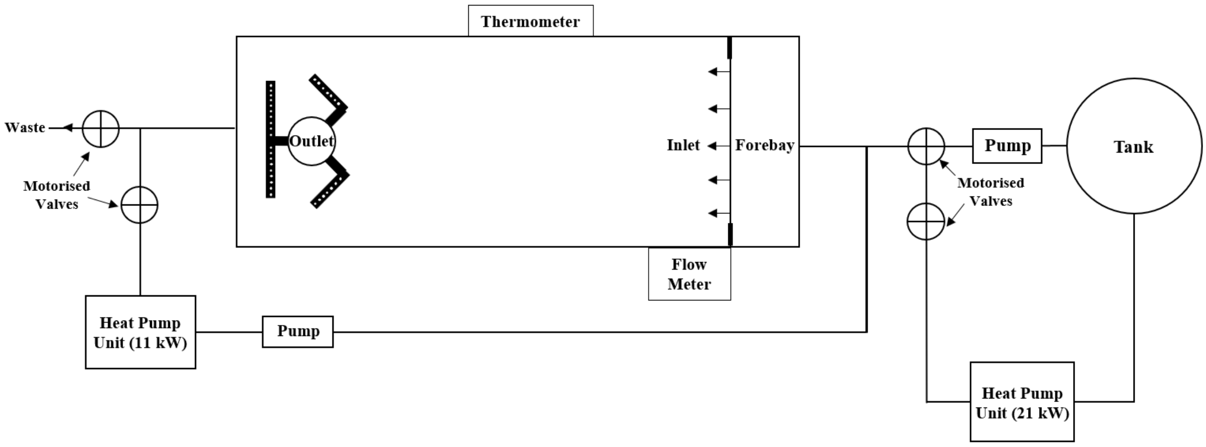
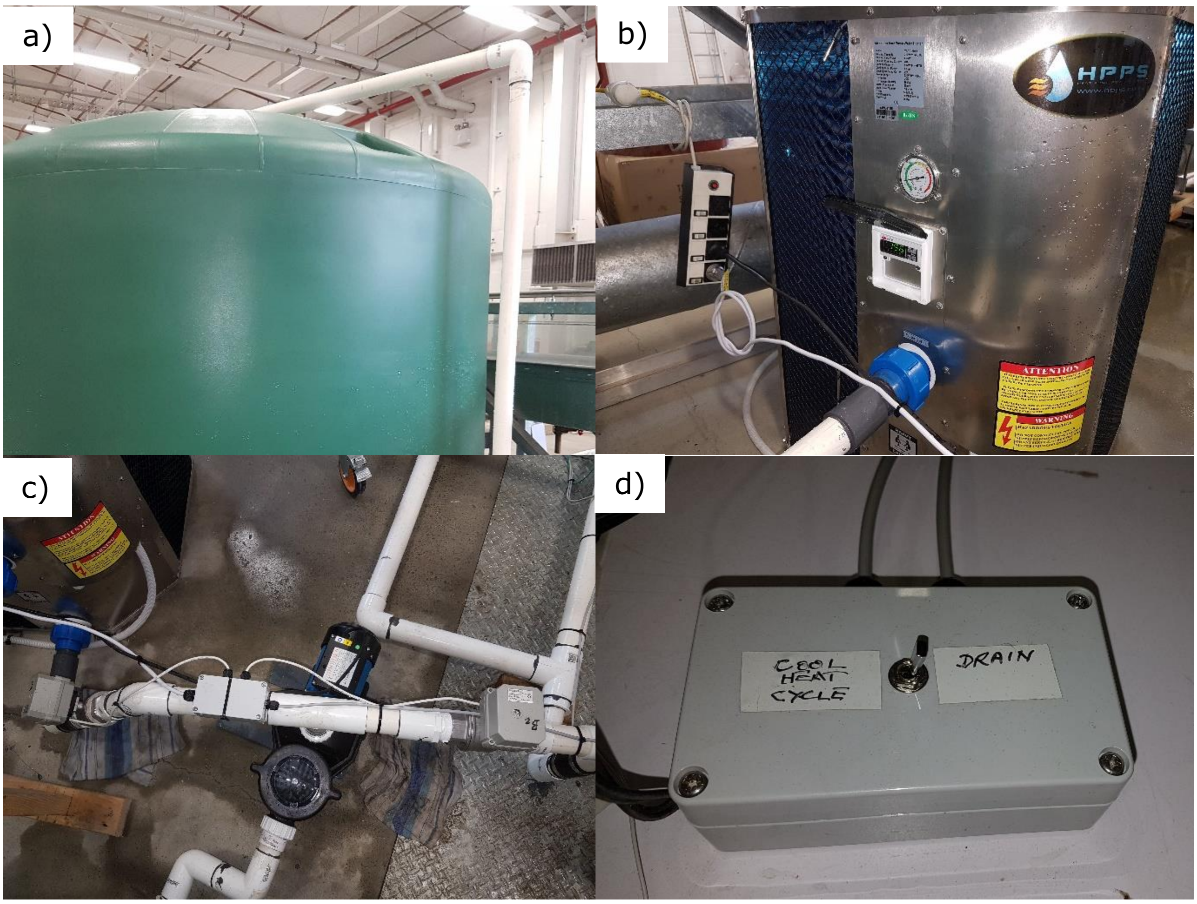


Figure 1. Schematic diagram of the experimental setup



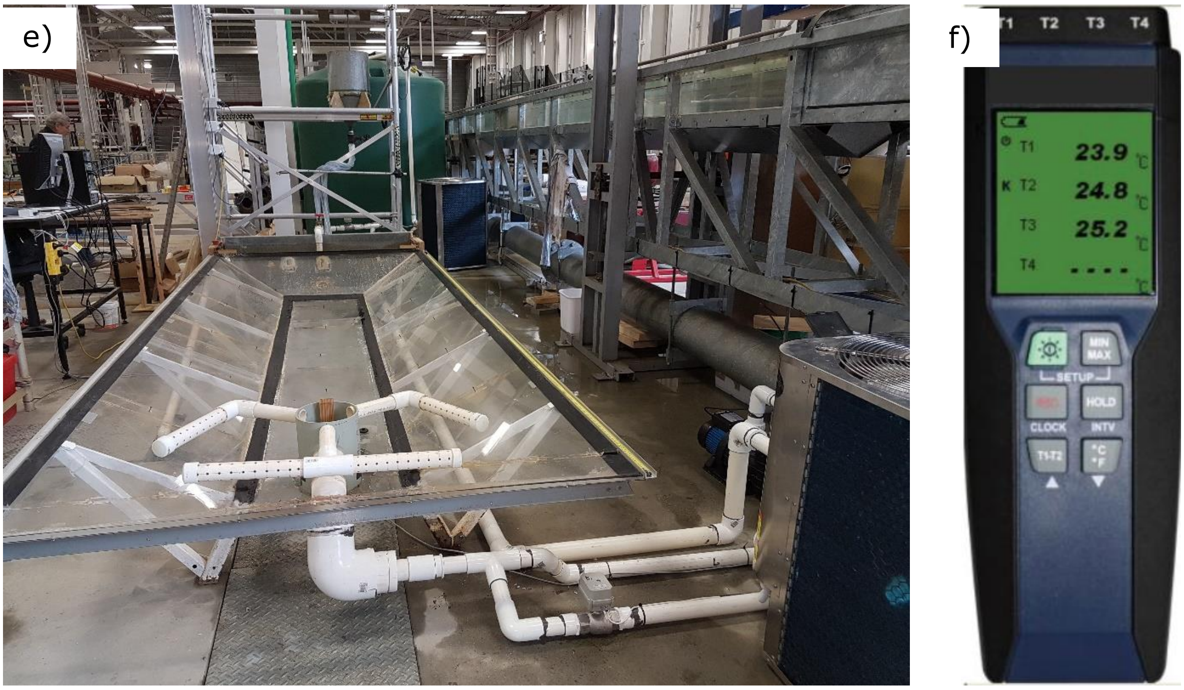


Figure 2. a) Tank, b) Heat pump, c) Pump and motorized valves, d) Switch, e) The physical model viewed from the outlet, f) Thermometer

2.3 THE TEST CASES

Several inlet width ratios were examined to find the best configuration in two different temperature configurations, colder influent and hotter influent (Figures 2). The Inlet Width Ratio (IWR) is the ratio of opening width to the pond width. To test the effect of temperature variations on the performance of the pond in the selected IWRs, two conditions were selected. In the first condition, the temperature of water in the pond was hotter than the influent, and in the second condition, the temperature of water in the pond was colder than the influent. In all experiments, the temperature of the pond water was the same, and the inflow water temperature was hotter or colder than the water in the pond depending on the adjusted temperature of the water tank. The flow rate used in this set of experiments was 1 l/s.

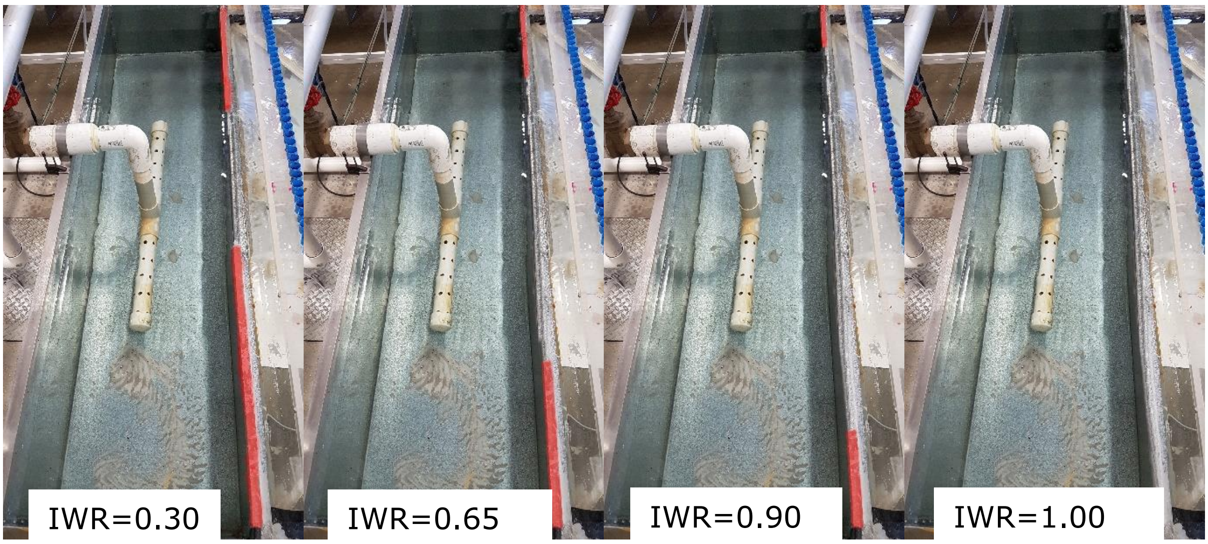


Figure 3. The physical model with different IWRs.

3 RESULTS AND DISCUSSION

3.1 EFFECT OF IWR VARIATIONS ON RTD CURVES

Since the cold influent tends to sink to the bottom and the hot influent tends to flow on the top of the pond, inlet width plays a critical role in changing the flow pattern as it changes the initial velocity of the inflow particles. Table 1 lists the hydraulic indices associated with different IWRs test cases. As can be seen from table 1 the index values increased with increase in IWR for cold influent test cases, while, the reverse was true for hot influent test cases. The results demonstrated that in cold influent cases, the widest inlet width decreased the short-circuiting issues in the pond and increased the hydraulic efficiency and promoted mixing, while in hot influent cases the shortest inlet width improved the performance of the pond in terms of lower short-circuiting, higher hydraulic efficiency and higher mixing. On the other hand, the wider the inlet width is the better the performance of the pond will be for the inflow colder than the water in the pond and the shorter the inflow width is the better the performance of the pond will be for the inflow hotter than the water in the pond.

Table-1 Hydraulic index values

IWR	Influent relative to that of pond temperature	SC (%)	MI (%)	Mo^{-1} (%)
0.30	Cold Influent	25.9	63.1	11.6
0.65		26.7	67.3	13.8
0.90		29.2	72.4	16.8
1.00		34.7	74.2	19.2
0.30	Hot Influent	29.1	73.6	16.7
0.65		26.4	72.5	15.4
0.90		23.3	63.5	13.6
1.00		19.1	61.9	12.1

The relationship between the IWRs and the hydraulic performance indices is graphically shown in Figure 4. As can be seen in this figure, in cold influent test cases, all of the hydraulic indices were reduced when IWR was reduced while the reverse is true for hot influent test cases. In IWRs of lower than 0.65, the MI index was slightly increased by about 1% in hot influent test cases. The significant increase in MI was observed in the transition from the inlet width ratio of 0.65 to 0.9 in hot influent test cases. In cold influent test cases, the trends were more uniform indicating a gradual increase of MI with increasing IWR from 0.3 to 1.0. Overall, MI index increased by about 11% with IWR increased from 0.3 to 1.0 for cold influent test cases, and it increased by about 12% with IWR decreased from 1.0 to 0.3 for hot influent test cases.

Similar trends were also observed in short-circuiting index trendlines except for cold influent test cases that SC slightly increased for about 1% with increasing the IWR from 0.3 to 0.65. The SC index was increased by about 9% in cold influent test cases with IWR increased from 0.3 to 1.0. In hot influent test cases, SC increased by about 10%. Therefore, the inlet width can be changed to reduce the short-circuiting issues in the pond when dealing with temperature differentials.

Mo^{-1} was also observed to follow the similar trends of MI and SC index emphasizing the fact that mixing was also improved when changing the inlet width in different configurations. However, the improvements made by changing IWR was not as significant as the improvements in MI and SC index. This implies that changing the inlet width cannot be considered as the main option to improve mixing in the ponds and other options such as baffles need to be included to be more effective.

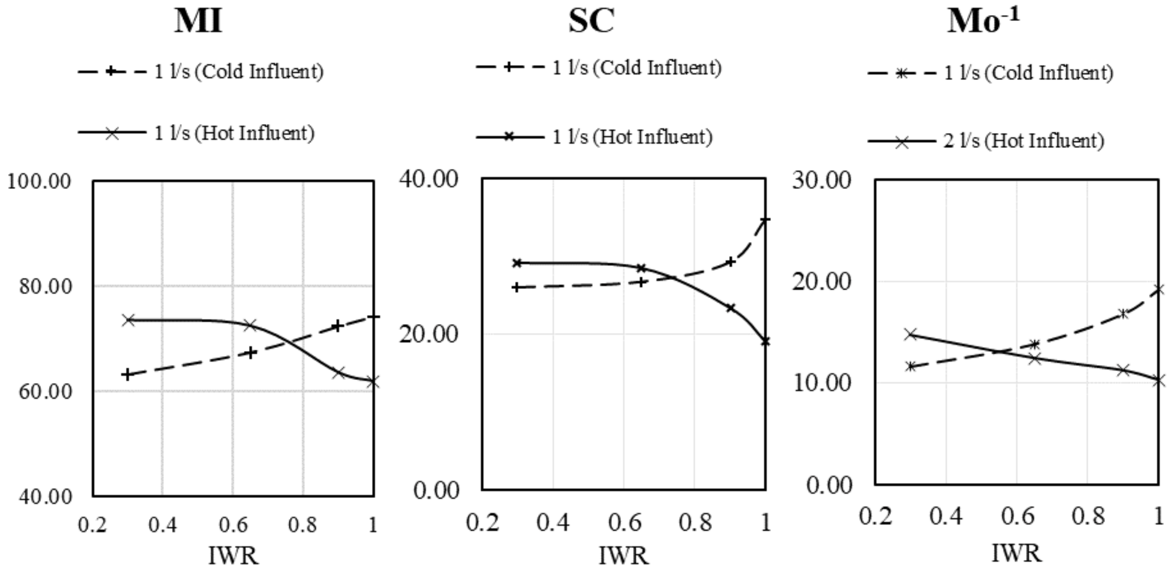


Figure 4. Relationships between the hydraulic index values and IWRs for flow rates of

3.2 EFFECT OF TEMPERATURE ON FLOW PATTERNS WITH VARIOUS IWRS

To shed light on the dissimilarities of hydraulic indices the velocity vectors have been measured in the middle longitudinal section of the pond from the inlet to the outlet riser. Three hundred equally spaced measurement points have been used to investigate the governing flow pattern in the pond. The longitudinal flow pattern was investigated using the velocity vectors to identify the circulation and stagnation zones.

The results presented here concern the two temperature configurations (hot influent and cold influent) in which four different IWRs were tested in each temperature configuration as shown in Figures 5 and 6. In cold influent test cases with the increasing IWR, the inflow particles generally need to follow longer flow paths. This is mainly due to the circulation zones created by buoyancy forces. As can be seen from Figure 5 the cold inflow of IWR=0.3 have to follow a straighter flow path to the outlet which is mainly due to the inflow momentum that pushed the streamlines to the bottom of the pond. In 0.65 ≤ IWR ≤ 1.0, the circulation zones have been created that increase the flow path length that inflow particles needed to follow to exit the pond. The circulation zones occurred due to the inadequate initial velocity that eventually forces the inflow to flow back to the inlet as the kinetic energy was insufficient to homogenize the flow. The Richardson number which is the ratio of buoyancy to the flow shear is a useful way to illustrate the differences between the selected IWRs. The Richardson number can be expressed as follows:

$$Ri = \frac{g}{\rho} \frac{\partial \rho / \partial z}{(\partial u / \partial z)^2} \qquad (1)$$

where g is the gravitational acceleration, ρ is density, and u is the characteristic velocity. When the IWR was increased the initial velocity decreased; therefore, the Richardson number increased indicating the importance of buoyancy on higher IWRs. At t_n = 0.125 the flow pattern was changed due to the progressive isothermalisation that occurred in the pond. As the time elapsed increased, when IWR was 0.3, the flow pattern became askew, so, the effect of inlet velocity was not significant anymore. When IWR was 0.65 and 0.9 the isothermalisation led to a similar flow path without visible circulation zones while in IWR=1.0 the circulation zones still exist in the pond and lengthen the flow path requires for inflow particles to exit the pond. Overall, the widest inlet increased the hydraulic residence time of the tracer as the influent need to travel a longer distance to reach to the pond outlet for cold influent test cases. The widest inlet also promoted the mixing in the pond due to the circulation zones.

Conversely, in the hot influent test cases, the shortest inlet width provided the best performance. As can be seen from Figure 6, the flow paths tend to remain on top of the pond. Initially, in IWR=0.3, the inflow velocity was high enough to push the streamlines to the bottom of the pond, and after that, since the density of hot influent was lower than the water in the pond, it returned to the surface and formed a circulation zone. This flow pattern was the same for other IWRs, however, in wider inlet widths, the inlet velocity was not high enough to enforce the inflow to reach to the bottom of the pond, and the circulation zones created closer to the inlet area. As the time elapsed increased, the circulation zones still existed in the pond for inlet width ratios of 0.3, 0.65, and 0.9 while in IWR=1.0 no circulation zone was observed, and the flow path followed a straight line to the outlet. Therefore, the shortest width encouraged a longer flow path in the pond followed by a circulation zone that became larger as the time elapsed increased. The mixing also increased in the pond for the shortest inlet width as it needed to follow the askew flow path to return to the surface of the pond.

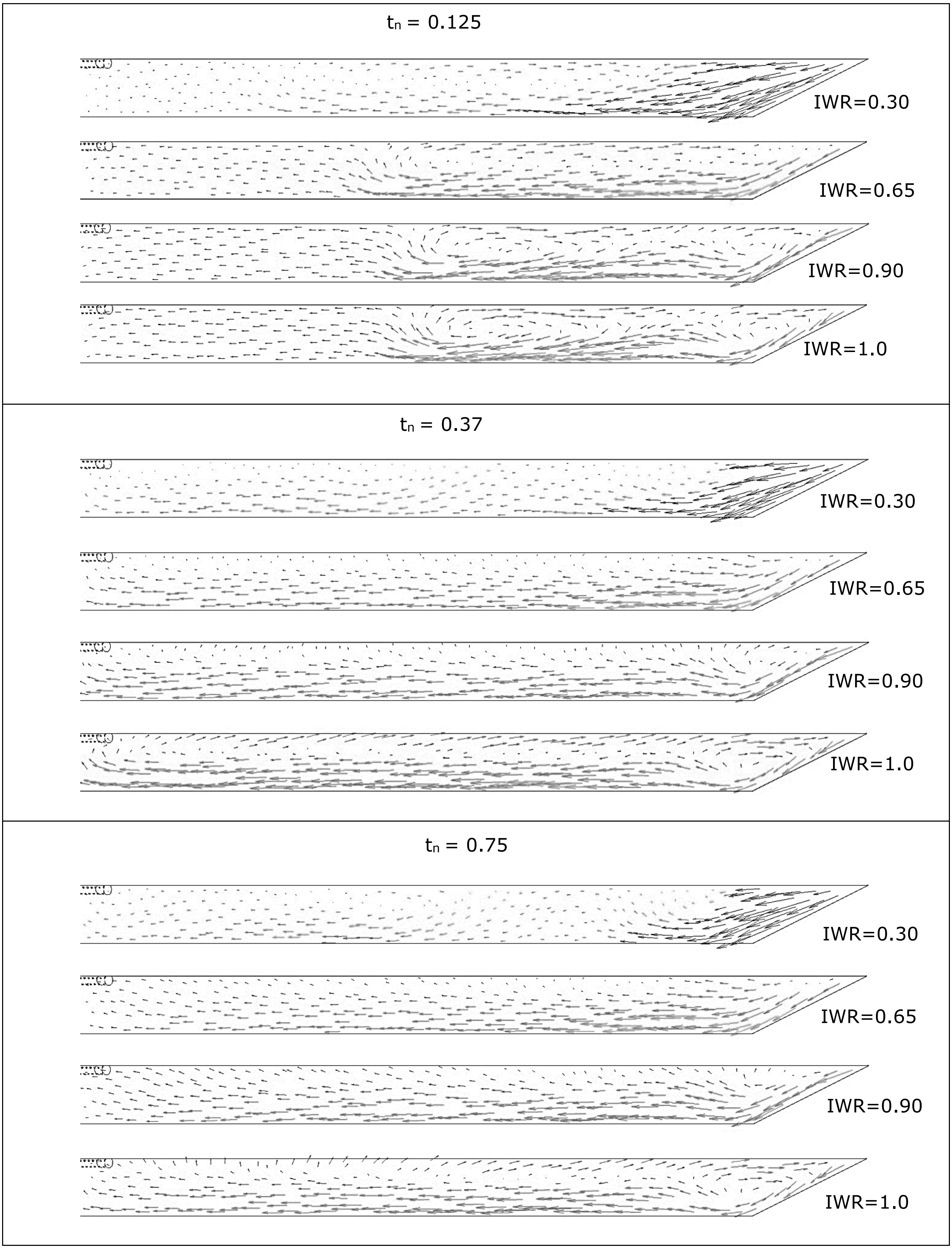


Figure 5. The velocity contours on the centreline longitudinal section of the pond, with inflow colder than the pond

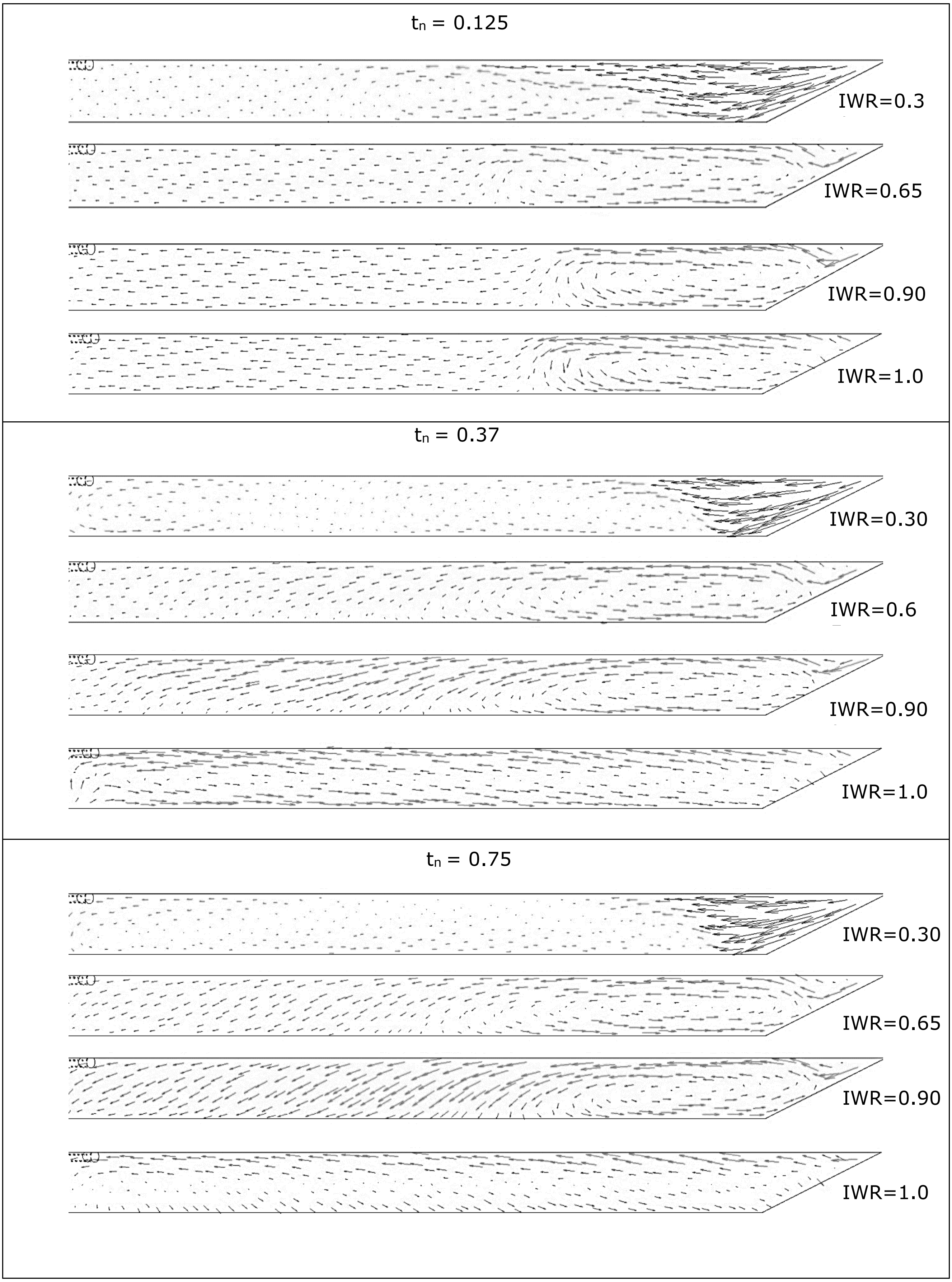


Figure 6. The velocity contours on the centreline longitudinal section of the pond, with inflow warmer than the pond

Figure 7.

4 CONCLUSIONS

The effect of inlet configurations has been widely investigated in many previous studies. However, temperature differences between the inflow and water in the pond can change the scenario to a more complicated topic. Therefore, two different temperature configurations (hot influent and cold influent) have been investigated in this study to determine the differences between various inlet width ratios when considering temperature differentials existed in the pond.

The inlet width ratio of 0.9 was previously recommended by Farjood (2016) to avoid short-circuiting along the pond sides and to reach the best performance in an isothermal condition. However, the results of this study showed that in cold influent test cases the wider inlet provided the best hydraulic efficiency and less short-circuiting issues with better mixing in the pond. Conversely, the results illustrated that in hot influent test cases the shortest inlet width produced the best performance in the pond.

The results of velocity measurements were also shed light on the dissimilarities by showing the dominant flow path in the pond for various IWRs. In cold influent test cases, the IWR=1.0 was found to achieve a better performance due to the longer flow path that inflow particles needed to follow to reach the outlet. This was also accompanied by circulation zones created at the beginning of the experiments due to the domination of the buoyancy forces resulted from lower inlet velocity. The circulation pattern gradually became weaker; however, it was not entirely vanished in IWR=1.0.

Interestingly, in hot influent test cases, the shortest inlet width provided the best performance as the flow path, in this case, need to remain on the surface of the pond, and the shortest inlet width enforced the streamlines to reach to the bottom of the pond due to the higher inlet velocity. Therefore, the inflow returned to the top of the pond and formed a circulation flow path. This pattern was also the same for the other IWRs test cases; however, in wider inlet width ratios, the circulation zones were closer to the inlet. The circulation zones gradually became weaker; however, it was entirely vanished in IWR=1.0 and made it susceptible to the short-circuiting issues.

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