

Impact of Control Structures on Hydraulic Retention Time in Wastewater Stabilization Ponds

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ABSTRACT

Wastewater stabilization ponds (WSP) use natural processes to improve water quality and are a commonly used treatment method for wastewater. WSP design guidelines rely on nominal hydraulic retention time (HRT), which assumes one-dimensional 'plug' flow. Accurate HRT measurements are vital for safe and effective treatment of wastewater while minimizing land usage. Previous studies have found the HRT of field systems to be significantly lower than plug flow values, and baffles are one method used to increase the HRT. In the present study, field monitoring and three-dimensional hydrodynamic modelling was conducted in a 5-hectare secondary facultative stabilization pond from March to November 2017. The WSP has several notable hydraulic control features including an inflow pipe, baffle, and outflow structure. During the study period, the inflows, water levels and meteorological data were measured. Simulations were conducted for three cases using a simulated tracer, including the base case with all features and two other cases with hydraulic structures altered for different pond operating conditions (constant water levels, and baffle removed). In all cases, the HRT was less than for one dimensional plug flow conditions. Constant water levels resulted in a similar mean HRT, with less variability compared to the base case. The baffle was found to inhibit mixing, and HRT increased without the baffle present. These results emphasize the hydraulic complexity of WSPs and the inaccuracy of plug flow assumptions suggesting that in some cases hydraulic structures may not improve hydraulic retention time.

Keywords: Wastewater Stabilization Ponds, Baffles, Hydrodynamic modelling

1 Background

Wastewater stabilization ponds (WSPs) have been studied extensively as wastewater treatment options to promote disinfection, reduce turbidity and decrease effluent nutrient loads [1]. WSPs are the most common wastewater treatment method in the world and are frequently used in small, rural or remote communities for secondary disinfection [2]. WSP systems benefit from their conceptual simplicity, and typically have lower maintenance, operation and capital requirements than a traditional wastewater treatment facility [3]. While WSPs are an effective wastewater treatment approach, they are critically dependent on flow through the pond in order to provide sufficient time for natural processes to occur. Notably the hydraulic retention time (HRT), defined as the mean number of days a parcel of water remains in the system, is frequently used to characterize the time water spends in a WSP. HRTs shorter than those estimated using the assumption of one-dimensional plug flow could result in lower treatment performance [4], [5].

Historically, WSP design guidelines have focused on a required WSP surface area and depth per capita, adjusted for operational temperatures. HRT was introduced as a design parameter, assuming a plug flow system. In the United States, treatment guidelines are set at the state level, and predominantly based on minimum HRTs and required depths [6].

Simple design guidelines do not effectively model real world WSP systems [7]. Hydraulic retention times have been shown to be as low as 50% of the values predicted from a plug flow assumption, which can be caused by short circuiting, where flow bypasses a section of the treatment train,

unsteady flow rates, wind driven flow, and sludge accumulation [7]. Moreover, in operational systems, thermal gradients of up to 8°C have been observed, leading to stratification and reduced mixing, suggesting that more comprehensive computational modelling is required to understand WSPs [1].

1.1 Hydrodynamic Modelling of WSPs

Hydrodynamic models can be used to simulate the hydraulics in a WSP. These models can be used to vary the environmental conditions such as the inflow and outflow rates, precipitation and wind over a model grid that resolves the pond geometry and bathymetry. Three dimensional models can include stratification and wind-driven circulation patterns. While numerical models have been proposed to study WSPs, few models have been able to incorporate biochemical processes and been accurately validated against real world performance [8]. In an early numerical study, [9] wind was added to the MINLAKE model to quantify stratification, but the results were only validated using temperature data. HYDRO-3D was also used to simulate a WSP [10] and was validated using data from both a physical model and a full-scale pond.

A WSP was simulated in 2011 using Delft3D, a hydrodynamics and water quality modeling package, with wind as the primary driver for the hydrodynamics [11]. This investigation showed considerable promise for the use of Delft3D in WSP modeling, but was not validated with field observations. A recent study [12], applied a detailed MIKE21 two-dimensional model to a WSP and simulated various baffle configurations. This model was validated against tracer measurements and showed generally good agreement.

1.2 Hydraulic Structures

To increase HRT in WSP, hydraulic reconfiguration of the inlet/outlet structures and flow baffles have been applied. Baffles aim to direct flow paths, prevent short-circuiting, and reduce wind driven currents. The design of baffles can vary significantly, but these structures are typically floating, impermeable, and anchored at the base. They typically allow for varying water levels and have low installation costs [13].

In some cases, baffles have not been found to increase HRT in WSPs. Model studies have shown that with certain flow conditions and baffle arrangements, they can inhibit mixing and reduce HRTs. In particular, for very low flow velocities, baffles perpendicular to the flow direction and ponds with a very high length to width ratio, WSPs can have shorter HRTs resulting from the addition of hydraulic structures [12], [14].

1.3 Objective

The objective of this paper is to quantify the impact of selected hydraulic structures and conditions on HRT using a fully validated three-dimensional hydrodynamic model. This will improve the understanding of the effect of hydraulic structures in these systems and inform future designs and operational procedures for WSPs.

2 Methods

The site of the present study is one of the two operational facultative WSPs at the Amherstview Water Pollution Control Plant in eastern Ontario. This facility comprises conventional primary and secondary treatment before water is pumped to a 2-cell WSP system for effluent polishing and disinfection. The site is rated to handle an average daily flow of 6,400 m³/ day, with average daily flows during the study period of 3,696 m³/day. The pond geometry and water depth in the WSP is shown in Figure 1. The pond has an approximate surface area 52,000 m² and an operational depth of 1.61 m [2]. Water enters the facility through an inlet pipe at the bed (denoted by “A” in Figure 1) and slowly moves along the indicated flow path, restricted by a floating, rubber baffle. Twelve 1 m² holes in the baffle at the south-west end of the pond allow flow through to the other side of the

pond, where it ultimately discharges over an open weir (denoted by “B” in Figure 1). Meteorological data was collected from the Environment and Climate Change Canada Kingston Airport station. These data were used for model calibration and validation.

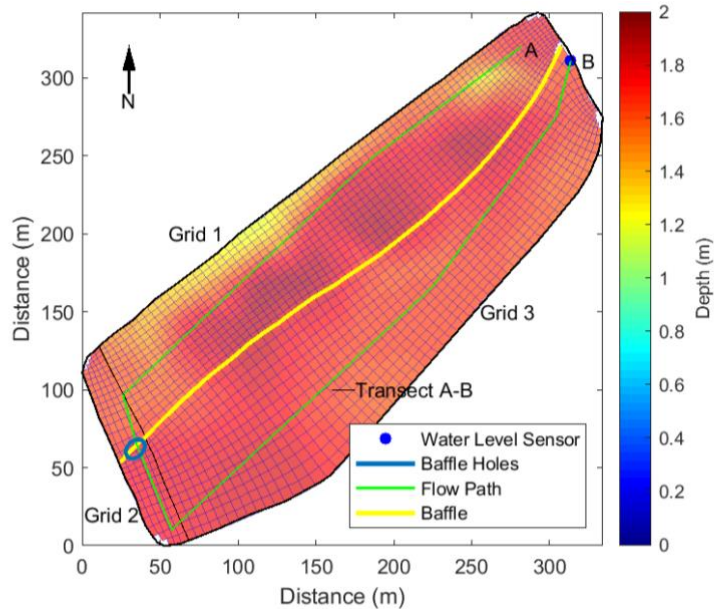


Figure 1. Site map indicating the computational grids, flow path, baffle, and water depth. The inflow pipe is located at “A” and the outflow weir is located at “B”.

2.1 WSP Observations

Water levels were recorded using an RBR DR-1050 sensor at the outflow weir, sampling every 50 seconds and accurate to approximately 1 mm. Inflows were recorded using the Loyalist Township data acquisition system and outflows calculated to match the measured water level (Figure 2).

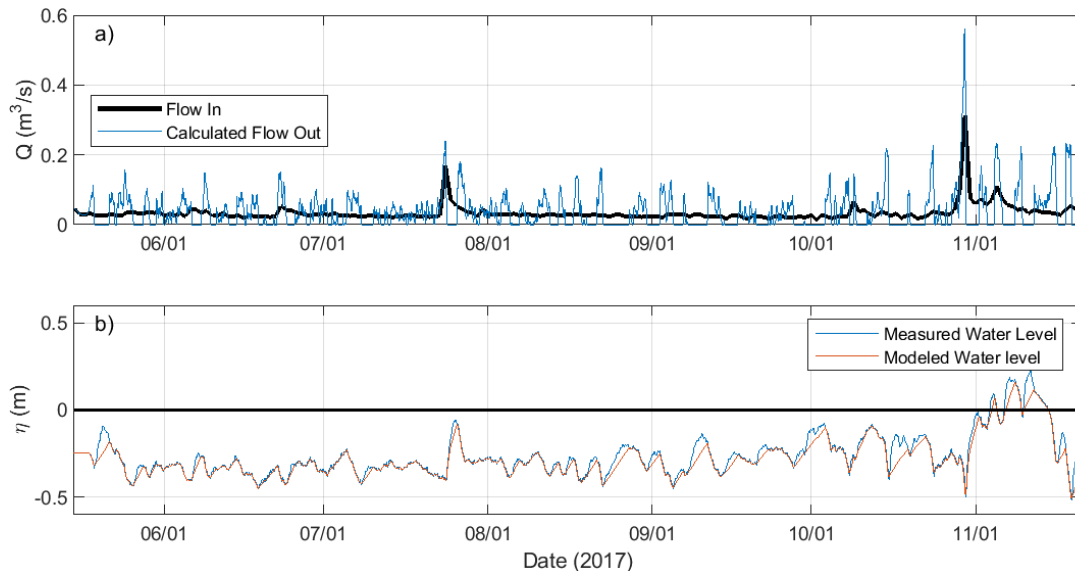


Figure 2. WSP hydraulic conditions: a) inflows and outflows; b) measured and modelled water levels.

Modelled water level results closely matched measured values, with an r^2 value of 0.91 and a root mean square error (RMSE) of 0.036 m. The considerable changes in water level (a range of up to 0.5 m over 36 hours) were driven by operational decisions related to the inflow rate and water added via major rainfall events.

2.2 Modelling Configuration

Hydrodynamic modelling was performed using Delft3D, an open source, three-dimensional, finite difference numerical modelling system for coastal and estuarine environments. The Delft3D ‘FLOW’ module was used to model the WSP hydraulics and the water quality module (WAQ) was used to simulate tracer transport and the HRTs. The model was run from May 11 to November 21, 2017 with a time step of 3 s.

The Delft3D FLOW model incorporated water level fluctuations, winds, and influent flow rates. A three-grid domain was constructed using “domain decomposition”, allowing the curving geometry of the baffle to be resolved in 3 orthogonal grids with 1 to 3 m resolution. The modelling was performed using the cluster of 12 high performance cores at the Center for Advanced Computing.

Hydraulic control structures were implemented in the model. Using separate grids on each side of the baffle, the baffle was modelled as a totally impermeable and perfectly smooth. Transfer between the two sides of the pond was accomplished by a third and higher resolution grid with 1 m “holes” in the baffle, allowing flow through an equivalent area to the operational system. Inflow was modelled through an open pipe discharge at the bed, and outflow as a discharge immediately below the water surface.

The WAQ module is integrated with Delft3D FLOW. WAQ utilizes hydrodynamic data from the FLOW module at 5-minute intervals and was used to track the injection of conservative tracers evenly spaced in time throughout the simulation period. Two commonly used factors were used to assess the overall efficiency of the pond and describe the hydrodynamic performance [12]. The simulated HRT was calculated as the average time a tracer spent in the system (t_{mean}) [15] given by:

$$t_{mean} = \frac{\sum_{0\%}^{95\%} m'_{tracer} * (t - t_{injection})}{m_{tracer}}$$

where m'_{tracer} is the mass of tracer exiting the system in each 5-minute time step, t is the simulation time, $t_{injection}$ is the initial time of injection, and m_{tracer} is the total mass of tracer injected.

The short circuit index (S) was also calculated to measure the skewness of the residence time distribution, and is defined as:

$$S = \frac{t_{16}}{t_n} \quad t_n = \frac{Q_{avg}}{V_{wsp}}$$

where t_{16} is the time required for 16% of the tracer mass to exit the system, t_n is the nominal residence time using the plug flow assumption defined by Q_{avg} the average flow rate and V_{wsp} is the total volume in the WSP. Perfect plug flow is represented by $S = 1$, and numerical models of operational systems typically find that S ranges from 0.25 to 0.5 [12].

2.3 Modelled Scenarios

Three different simulations were completed as summarized in Table 1. These scenarios were selected in order to assess the effect of baffle layout on HRT, as well as to inform potential future operational decisions and WSP design.

Table 1. Overview of simulation conditions

Scenario	Baffle Layout	Water Levels	Description	Rationale
1	Full baffle	Variable	Realistic simulation, used for model validation against field measurements. Includes inflows, winds, precipitation, and thermal stratification	Control scenario using realistic conditions present in an operational WSP
2	Full baffle	Constant	Outflows were matched to maintain constant water levels	Completed to investigate the impact rapid variations in water levels on HRT
3	No baffle	Variable	All hydraulic control structures removed	Completed to investigate the role of the baffle in the flow path and HRT

3 Results and Discussion

3.1 Comparison of Hydraulic Retention Time

To calculate the HRT, tracers were instantaneously injected in the model to track water mass movement at 4 evenly spaced times, and the averaged results are presented in Table 2. For flows that occurred during this simulation period and the design assumptions of one dimensional plug flow, the theoretical HRT was 32 days.

Table 2. Comparison of hydraulic retention time and short circuiting index

Scenario	t_{mean} (days)	S (short circuiting index)
1: Variable water levels and baffle	22.0	0.20
2: Constant water level and baffle	21.3	0.21
3: Variable water level, no baffle	26.0	0.17

In all scenarios, the HRT was below the 32-day plug flow time. Removing the baffle from the simulation increased the theoretical HRT noticeably, indicating that the water resided in the WSP for a longer period of time. The t_{mean} was similar for both the full model and the constant water level simulation, which suggests that the varying water levels did not have a significant effect on the overall HRT.

In all scenarios, the short circuiting index was well below $S = 1$ for ideal plug flow, and was in agreement with values obtained in previous studies [12]. This is consistent with the shorter HRTs

compared to the theoretical. The lower *S* in case 3, combined with the longer average HRT suggests that this case presents a rapid initial drop in tracer concentration, but a longer time for the residual tracer to flow through the WSP.

3.2 Tracer Mass

Figure 3 illustrates the total mass of tracer in the WSP after injection, averaged across the four instantaneous injections. Scenarios 1 and 2 have a similar trend for tracer mass with the tracer gradually exiting the WSP. In scenario 3, without the presence of a baffle, the tracer concentration decreased immediately because of short-circuiting. However, the enhanced mixing from the larger recirculation area resulted in a longer mean retention time as noted in Table 2.

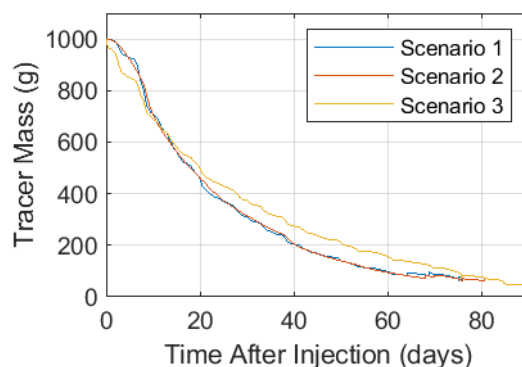


Figure 3. Total tracer mass in WSP for each model scenario

3.3 Depth Averaged Flow

Depth averaged currents 36 hours after the simulated tracers were injected are shown in Figure 4. Depth averaged water velocities were very low in all cases, averaging 1 mm/s. However, much higher velocities occurred in the near-surface layers due to wind.

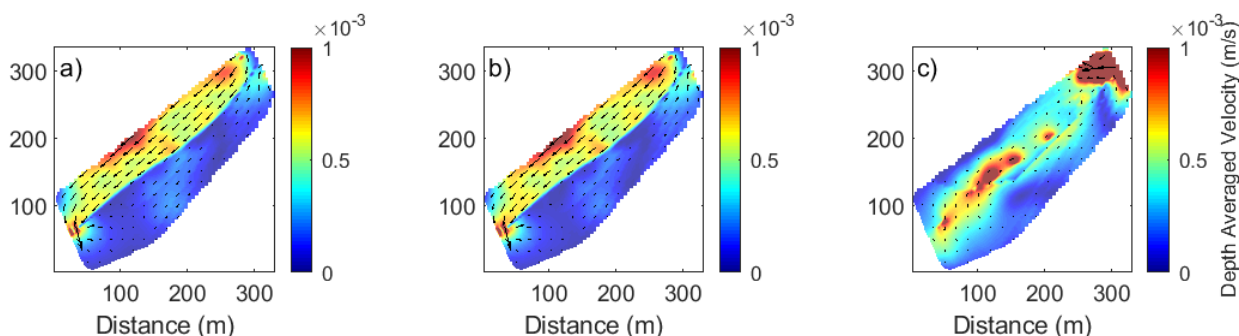


Figure 4. Depth averaged flow velocity for the three model scenarios 36 hours after tracer injection: a) scenario 1; b) scenario 2; c) scenario 3.

Scenarios 1 and 2 had a very similar flow pattern, with water entering the pond through the inflow pipe and following the flow path created by the baffle, with some local variability. The holes in the baffle create a localized region of higher speed as the flows travelled to the other side of the WSP.

A short-circuiting flow pattern was visible in scenario 3, where flows traced directly to the outflow. However, wind-driven flows were present in the rest of the WSP and produced water movement throughout the system. The highest speeds of up to 1 mm/s were in the central areas of the WSP due to the slightly increased depth and distance from the shoreline.

3.4 Tracer Distribution

Figure 5 shows the distribution of the simulated tracer 36 hours after injection. Scenarios 1 and 2 indicated similar tracer distributions 36 hours after injection and different concentrations on each side of the baffle. Scenario 3, without any baffle had greater mixing with approximately equal concentrations throughout the entire WSP.

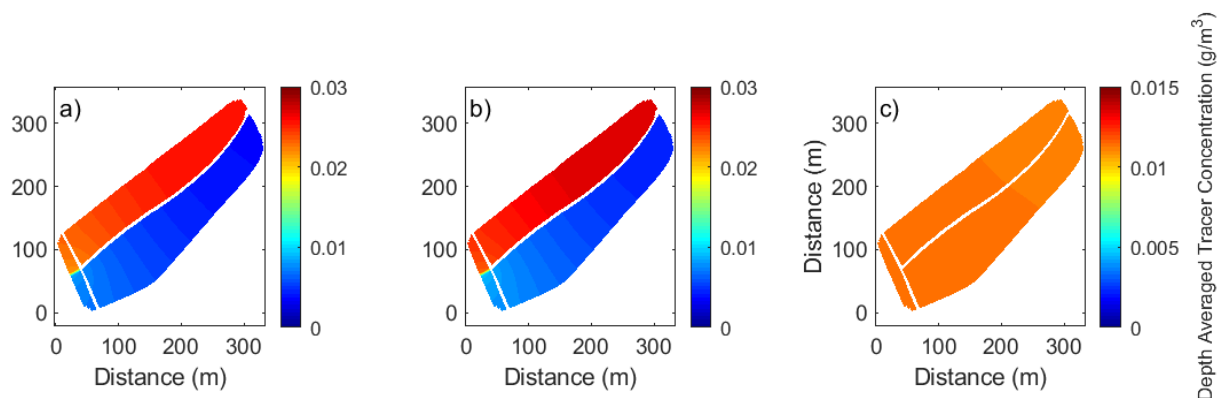


Figure 5. Depth averaged tracer concentration for the three model scenarios 36 hours after tracer injection: a) scenario 1; b) scenario 2; c) scenario 3.

4 Conclusions

The hydraulic complexity of WSPs is clearly demonstrated in this numerical model study. Using field observations to validate a three-dimensional hydrodynamic model, HRTs were calculated for a wastewater stabilization pond in Amherstview, Ontario. Additional scenarios, modelling the impact of changing water levels and a baffle were also simulated and compared to the real-world case.

The Delft3D model included inflows, outflows, and winds and the model accurately captured the water level variation with a root mean square error of 0.036 m. In all model scenarios, the HRT of the WSP was much shorter than for the case of an idealized, one-dimensional plug flow system, which is the current standard used in the design of WSPs. This suggests the potential for inaccurate design, especially in cases with complex geometries or hydraulic structures. Without a baffle, the simulated HRT was longer than cases with a baffle. Hydrodynamic results suggested that the baffle inhibits wind-driven mixing that would otherwise occur, shortening the HRT. Varying water levels had a limited effect on overall HRT but did introduce some variability depending on the timing of flow events and water level fluctuations.

These results suggest WSP design and operational guidelines may not fully account for the mixing processes that occur in these small ponds, and that the plug flow assumption is not valid in all cases. It also suggests that baffles may not always lengthen HRTs, which is consistent with previous studies. Water levels were found to have a relatively small role on the total HRT. Further study is required to more accurately understand the hydrodynamics and their effect on HRT and, hence, treatment performance.

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