Modeling and validation of stratification and hydrodynamics in a wastewater stabilization pond using Delft3D

Ref # S2SMALL-99808

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Keywords: Wastewater Stabilization Ponds, Simulation, Wind-induced mixing, Baffles, CFD modelling, Delft3D

INTRODUCTION

Wastewater stabilization ponds (WSPs) use natural processes to both disinfect and stabilize wastewater, and are a frequently applied treatment method. Traditionally designed as perfectly mixed reactors of plug-flow, there is a need for an improved understanding of spatial variability in hydrodynamic processes. This would allow for applications coupled with biological and water quality models to investigate transport and fate of materials in these systems. The goal of this work is to setup and validate a 3-dimensional hydrodynamic model of a WSP using Delft3D--a commonly applied Reynolds-averaged Navier-Stokes model to simulate the water levels, temperature stratification and current velocities. A secondary facultative pond near Amherstview, Ontario was used as a field study location. Observed results in this site show significant thermal stratification during the summer season.

LITERATURE REVIEW

Wastewater stabilization ponds (WSP) have been studied significantly as a secondary or tertiary treatment option, focusing on disinfection, reducing turbidity, and nutrient load in an effluent stream (Gu & Stefan, 1995; Sah, Rousseau, & Hooijmans, 2012).

Although used in all regions, WSPs are particularly useful in rural and remote communities, owing to their lower maintenance, operation, and capital costs (Senzia, Mayo, Mbwette, Katima, & Jørgensen, 2002). When designed and operated correctly, WSPs are an effective tool for water treatment, reaching removal efficiencies for coliform of 99.99% and 100% removal of protozoan cysts and helminth eggs (MacDougall, 2017). WSPs can function as either aerobic, anaerobic, or facultative (combination) systems, employing several natural biologic processes found in bodies of water to self-purify. Notably, several species of bacteria, algae, and invertebrates act in tandem to fix nutrients such as phosphorus and nitrogen; as well as balance dissolved oxygen and pH (Spellman & Drinan, 2008). Specific to facultative WSPs, the interaction of photosynthetic algae/ cyanobacteria and heterotrophic bacteria acts as a critical pathway for the removal of BOD and nutrients, as well as some pathogens (Sah et al., 2012).

Early WSP design guidelines focused on water volume with adjustments due to temperature such as Gloyna's equation in 1971. Hydraulic retention time was introduced later as a design parameter, under the assumption of a completely mixed system. In the 1990s, models were introduced accounting for geometry and assuming a combination of plug and completely mixed flow. (Aldana, Lloyd, Guganesharajah, & Bracho, 2005). The most recent design manual incorporates loading rate, short circuiting prevention, number of cells, and bathymetry; but remains a fundamentally empirical process (Spellman & Drinan, 2008). These techniques have not adequately modeled real world systems. Traces studies have shown that hydraulic retention time can be 50% of nominally predicted values, due to short circuiting, unsteady flow rates, and sludge accumulation (Persson, 2000). Temperature differentials between the bottom and surface of WSPs of up to up to 8°C have also been observed (Gu & Stefan 1995).

Accurate hydrodynamics are critical for correct modeling of the biochemical processes responsible for treatment. The spatial variability of aerobic and anaerobic zones, temperature stratification, and flow speeds presents conditions that are not adequately captured through a plug flow reactor assumption. Moreover, variable inputs (such as environmental conditions and changing inflows) are not captured by empirical design formulas, but are included in hydrodynamic models (Sah et al., 2012).

Several hydrotechnical models have been proposed to describe WSPs; however, relatively few models have incorporated both biochemical processes and been accurately validated against real world performance (Sah et al., 2012). An early model (Gu & Stefan 1991) using the MINLAKE model adapted to account for WSPs specifically investigated the effect wind mixing had on stratification. After calibration, the model performed relatively well, but was only validated against temperature data. A later model using HYDRO-3D was completed in 2005 (Aldana et al. 2005). This study was unique in also validating against a physical model, as well as a full-scale pond.

A recent investigation simulated a complete WSP using Delft3D, a hydrodynamics and water quality modeling package (Sah et al. 2011). This model incorporated wind effects, and was three dimensional. Wind was used as a driver of the FLOW (hydrodynamics) module, and water quality was modeled. This model was not validated against observations, however, it showed considerable promise towards using Delft3D to model WSP systems.

METHODS

Delft3D is an open source, coupled, three-dimensional, finite difference numerical modeling package for coastal and estuary environments (Deltares 2014). Delft3D is commonly used in both industry and academic settings thanks to its flexibility and open source code. Specific to WSP applications, Delft3D is coupled to an included water quality model (WAQ).

A Delft3D model was created incorporating water levels, wind, influent water and air temperature fluctuations, solar radiation. The model was based on three coupled grids, allowing the moderately complex geometry of the site to be included. Delft3D grids are regular and orthogonal and implemented in this model at a resolution of 1 to 3 m^2. The model was run using a 1.2 second time step to preserve hydrodynamic continuity.

The Delft3D model was validated again st a secondary facultative WSP facility, receiving municipal wastewater after primary treatment was completed. During the summer, the WSP received approximately 30 L/s of inflow through an open discharge pipe at the north-west corner of the bed. A rubber baffle (visible in Figure 1 as a dashed line) separated the inflow and outflow sides of the site. Water flowed through 12 individual 1 m^2 holes in the west side of the grid, requiring the higher resolution grid in this area. Water flowed out on the south-west side via an open weir.

Field results were collected using a Hydrolab DataSonde in vertical profiles taken at 12 points, marked in Figure 1. Data was saved at 13 vertical depths for each location. Results were processed to interpolate temperatures along the flow path, as shown in Figure 1.

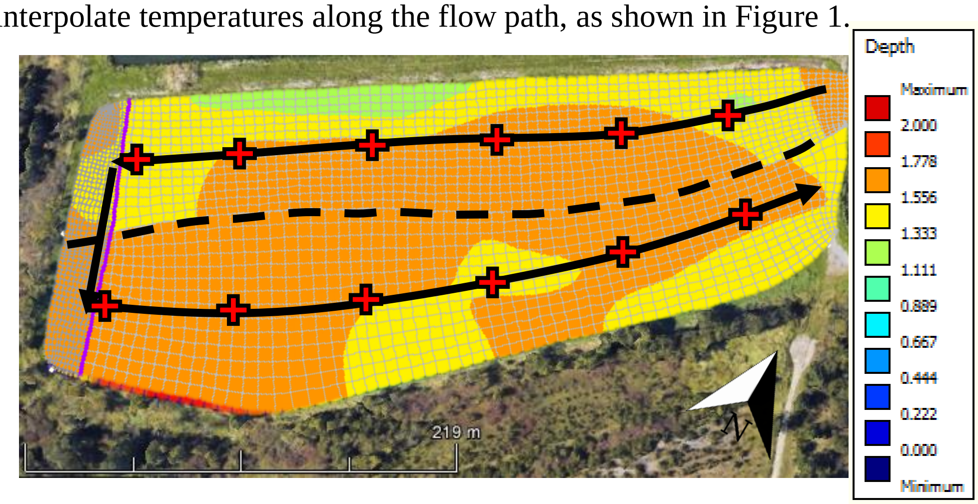

Figure 1. Site overview in Amherstview, Ontario, Canada with computational grid, flow path, sampling locations, and water depth

RESULTS AND DISCUSSION

Figure 2 displays selected temperature profiles along the flow path taken on July 6 and July 13. Flow entered the WSP on the lower corner of the plot, and exited on the top right. Flow through the holes in the baffle occurs at 375 m. Results show stratification throughout the length of flow through the system, with temperature differentials of up to 5 degrees being observed.

These results suggest that perfectly mixed or plug flow models may not accurately capture the flows at play in WSP systems, consistent with previous investigations. Both plug flow and completely mixed assumptions predict more consistent conditions throughout the treatment length.

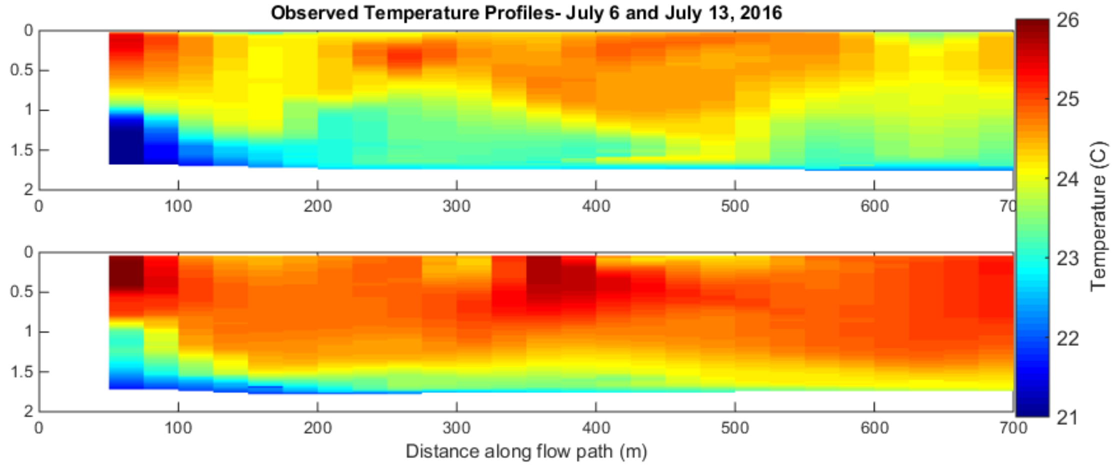

Figure 2. Observed temperature profiles

The results point towards the use of Delft3D to model these systems. As a full hydrodynamic model, Delft3D contains the required implementations to capture the complex processes at play in WSPs. Furthermore, the included water quality coupling module simplifies the process of including key environmental parameters in simulations, describing a complete hydrodynamic and biochemical picture.

CONCLUSIONS

Wastewater stabilization ponds (WSPs) are a well-established treatment technique. Particularly well suited for use in rural or remote communities, WSPs have the capacity to effectively treat wastewater using natural and biological processes. Existing design guidelines for WSPs rely on empirical equations and either completely mixed or plug flow assumptions. Data collected from a WSP using vertical temperature profiles showed significant thermal stratification varying throughout the treatment path. These results support the use Delft3D as a hydrodynamic model to analyze WSPs, to account for the observed thermal stratification and accurately model biochemical treatment processes.

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