OPEN SOURCE COMPUTATIONAL FLUID DYNAMICS MODELLING IMPROVES WASTEWATER POND DESIGN

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ABSTRACT

This paper describes how open source modeling software can be used to optimize pond design without having to rely on expensive off-the shelf software.

It explains the basic elements of the modeling toolbox and takes the Ohope Waste water pond improvement project as a real world example, where pond performance was improved with regards to E.coli reduction from 1.17 (winter operation) and 1.53 (summer operation) log units to 1.89 and 2.86 respectively. This is an increase in efficiency of 61 % (winter operation) and 87 % (summer operation). The reduction rates of E.coli counts were calculated using a segregated flow model and the RTD curve provided by the simulation.

KEYWORDS

Wastewater treatment pond performance, hydraulic modeling, open source, pond design, pathogen reduction, segregated flow model

PRESENTER PROFILE

Franz Resl is ERPRO's principal design engineer. His knowledge and skills stem from more than 30 years' experience in the water and wastewater industry, which he gained internationally (Europe and SE Asia) and for the last 12 years here in New Zealand.

1 INTRODUCTION

Many New Zealand councils operate wastewater treatment ponds. The majority of those are designed as facultative ponds. Facultative ponds are highly complex systems, comprising of aerobic, anoxic and anaerobic areas. They cater for bacteriological treatment capacity based on biofilms, they provide biological aeration using oxygen produced by algae in an efficient and sustainable manner and they deliver first class disinfection at rates that can compete with high tech UV disinfection equipment.

The chemical and biochemical reactions driving the processes in a chemical reactor are governed by the reaction rate which is expressed as "the change in concentration of a constituent with time"(Crittenden et al., 2005). The time available for chemical reactions is described by the time an element of flow spends in the system which depends on hydraulics.

This paper explains how the world of computational fluid dynamics (CFD), freely available on the World Wide Web, can be used as a valuable tool to optimize pond hydraulics to achieve optimal performance of these individual sub processes. The software is readily accessible and can enhance traditional design. We take a fresh look at the pond as a whole and showcase how quality flow modeling can improve the way we design ponds.

This is not a scientific paper on pond modeling, nor does it offer an exact solution using calibrated and validated simulations. It rather demonstrates the capacity of the modeling toolbox to be used for multiple scenarios with various input parameters and mesh densities. We want to demonstrate that open source modeling opens up new ways of understanding a pond's hydraulic behavior and how to achieve real life improvements based on free software.

2 THE TASK: OHOPE WASTEWATER TREATMENT PLANT HYDRAULIC STUDY

The objective of this investigation was to achieve operational improvements in the pond area that would benefit pathogen reduction. This requires good pond health as algae are a key contributor to disinfection due to their ability to increase DO and pH levels.

For pathogen reduction traditional pond design would recommend a transformation of the pond area to a high length to width ratio by introducing several baffles channeling the flow from inlet to outlet. We put this conventional design to the test.

We based our approach on the following facts:

- Baffles need to be carefully designed to avoid organic overload close to the pond inlet (Sperling (2007).
- Serpentine shaped baffles can cause flow channeling resulting in low disinfection rates (Pedahzur et al., 1993).
- Biofilm activity, contributing to about 50% of organic matter reduction in waste water stabilization ponds (Polprasert and Agarwalla 1995) and nitrification in situ at the bottom and banks (Munoz Sierra et al., 2014), requires continuous gentle mixing.

With these basic facts in mind we use the open source CFD toolbox to model optimal pond health conditions. The components that represent the CFD toolbox are described in the following chapter.

3 THE OPEN SOURCE CFD TOOLBOX

The first step before setting up CFD model simulations is to decide which software to use. There is a huge variety available just waiting for download. The key criteria that guided our decision were: open source, demonstrated long term development, robust performance, good and usable documentation and tutorials, successful use in academic and scientific projects, ability to run sophisticated compressible and incompressible scenarios even under multi-phase conditions, free parameterization.

Model development is a multi-step process. For the engineer the focus is without doubt on solving the hydraulic challenges. From a practical point of view, this is the easiest part. Algorithms are developed by experts, the user should strictly follow their rules. The biggest challenge for the software user is defining the exact 3D model and mesh it properly so that the CFD software can use it at the most efficient level.

Our work is based on three open source software packages which we briefly introduce in the following chapters.

3.1 SALOME®

A great tool for designing and for pre as well as post processing of CFD simulations is Salome®. Salome® can be used for creating or manipulating geometries similar to CAD programs and provides a sophisticated environment for meshing the 3D designs offering a great variety of tools. Salome® is the key ingredient for transferring the geometrical model into OpenFOAM® for numerical simulation.

3.2 OPENFOAM®

OpenFOAM® was created in 1989 and has been under development for nearly 3 decades. OpenFOAM® is the leading open source CFD software providing solutions for complex fluid flows from chemical reactions, turbulence and heat transfer, to acoustics, solid mechanics and electromagnetics. The OpenFOAM® developer community is exclusively recruiting in academic environments to meet stringent quality assurance requirements. OpenFOAM® was repeatedly tested against commercial CFD packages and provided equal or superior solutions.

3.3 PARAVIEW®

Computational fluid dynamics modeling is directly coupled with visualization of results. Simulation models often exceed 1 million cells which make it impossible for a user to comprehend the data they produce. Our pond models usually range at about 2 to 4 million cells. Data analysis and data visualization are as important to CFD work as are a numerical solver or a mesh generator. Paraview® provides excellent filters for data analysis like simple and advanced statistics and plot functionalities as well as temporal filters like stream, streak and glyph visualization.

4 THE CFD PROCESS

The model created for the pond under investigation should represent reality as closely as possible. A simple way to obtain real world data is GoogleEarth®. Structures like inlet and outlet piping and slopes of banks need to be taken from as built drawings or measured on site.

4.1 THE MODEL SET UP

The actual set up of the model happens in Salome®. All details, like cuts between structures, positioning of mixers and baffles have to be designed in great detail and with meshing in mind.

4.1.1 THE ART OF MESHING

Creating the mesh for the model is a critical step and has to follow strict quality procedures. There are great tutorials available on the web demonstrating the skills required for different levels of simulation and sophistication.

4.2 SOLVERS, SCHEMES AND BOUNDARY CONDITIONS

OpenFOAM® offers a variety of applications. The applications fall into two categories: solvers, which are each designed to solve a specific problem in continuum mechanics; and utilities, which are designed to perform tasks that involve data manipulation (Greenshields, 2016). It is up to the user which library he wants to choose.

5 POST PROCESSING PROCEDURES AND SUB-MODELS FOR ADVANCED POND DESIGN

The data you get from the CFD model needs to be transformed into a format that can present the essential information needed for optimal pond design.

The following chapters describe methods of illustrating specific variables that describe pond performance.

5.1 VELOCITY DISTRIBUTION

The CFD model we develop shows velocity distributions (including 'active' and 'dead' zones, 'Shilton 2001). It enables us to perform finely graded analysis i.e. cumulative frequency analysis to study design variations.

5.2 CUMULATIVE FREQUENCY ANALYSIS

A cumulative frequency analysis chart shows the velocity percentage which is undercut by a certain rate of velocity.–Changes in velocity distribution from poor to good can be identified.

5.3 RESIDENCE TIME DISTRIBUTION

This methodology allows the description of flow conditions and subsequently the comparison of different flow scenarios and even different pond systems.

5.4 SEGREGATED FLOW MODEL

A segregated flow model allows us to describe reaction behavior of a non-ideal chemical reactor. The distribution curve is split into numerous individual reactors characterized by individual fractions of exit stream, detention time and reaction rate.

6 PRACTICAL APPLICATION OF THE CFD MODEL

6.1 MODEL 1: EXISTING POND LAYOUT

The wastewater treatment plant in Ohope consists of 7 ponds in series. 2 facultative ponds follow an aerated lagoon. We have chosen the first facultative pond 1 as example to demonstrate the CFD tools.

This pond covers an area of about 9,200 m^2 at a depth of 1.2 m (without sludge deposits), providing approximately 11,000 m^3 of volume. The pond is not mechanically mixed, inlet and outlet are located at opposite sides. Figure 1 shows an overview of the pond. Model 1 is a true representation of the pond geometry. Figure 2 shows the associated system schematic.

Figure 1: Ohope facultative pond 1 layout with inlet pipe, GoogleEarth®, 2017

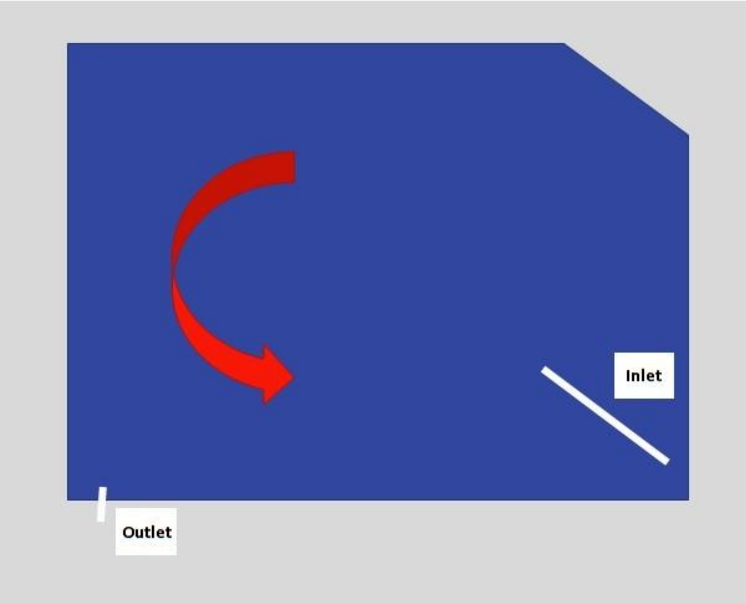

Figure 2: System schematic model 1

6.2 MODEL 2: SEPARATION OF FULLY MIXED AREAS USING DEFLECTORS

In order to activate the central dead zone cross baffles, which are not extended to the pond banks, were introduced into the model to divert parts of the flows into huge vortices and to fully mix the whole area. Mixing energy is provided by the inlet and an additional jet stream from an inline mixer delivering 30 l/s. The mixer was positioned so that it stimulates backflow at the opposite side of the inlet jet. The deflectors are shaped to influence area vortices. Figure 3 shows a schematic layout.

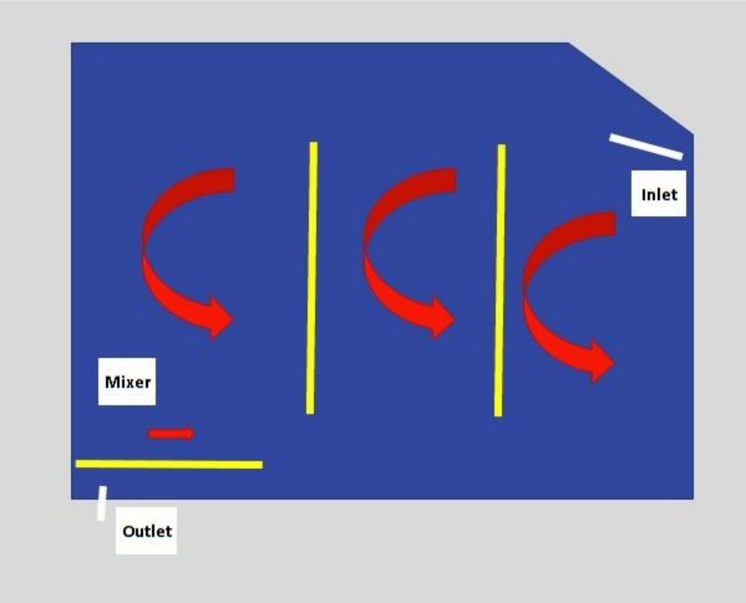

Figure 3: Schematic model 2, using 2 baffles to separate 3 zones

6.3 MODEL 3: SET OUT OF 2 DISITINCT ZONES FOR ADVANCED POND PERFORMANCE

Model 3 is an advanced design of model 2 which achieves two outcomes in one pond, namely pathogen reduction and improved velocity distribution. To accomplish this a stilling area with a meandering element was placed in front of the outlet. Back mixing from cell 3 into cell 2 is executed using an inline mixer with 20 l/s. The 2 targets, biological pond performance and pathogen reduction, require diagonally directed operational strategies: gentle but steady mixing for pond health and biological treatment (completely stirred reactor) and high retention time with delayed effluent for pathogen reduction (plug flow). Model 3 achieves this allowing development of both reactor types in one pond. Figure 4 shows the associated schematic.

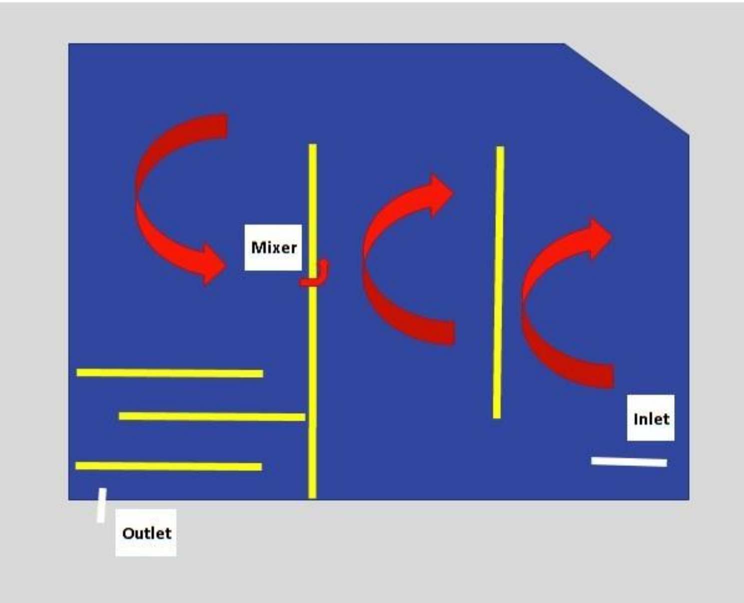

Figure 4: Schematic model 3, pond area split into 2 zones (mixing and retention)

6.4 MODEL PRE-REQUISITES

Pond 1 was modeled in an "as is" condition to show case the current hydraulic characteristics. Model data was retrieved via GoogleEarth® and also on site.

6.5 RESULTS

The following 4 chapters present the results according to the sub procedures describing pond performance.

6.5.1 VELOCITY DISTRIBUTION

The velocity distributions at the pond bottom are shown in Figures 5 to 7 for model 1 to 3 respectively. Velocities are scaled equally from 0 to 48 mm/s to allow visual comparison. The coloring is a 6 color blot scheme which ranks the velocity plots in 6 equally ranged bins (0 – 8 mm/s, 8 – 16 mm/s, 16 – 24 mm/s, 24 – 32 mm/s, 32 – 40 mms and 40 – 48 mm/s).

Model 1 clearly shows the effect of dead zones in the middle of the pond area. The jet produced by the inflow pipe is pointing towards the opposite bank and the outlet area, the backstream is pointing towards the inlet. A large dead zone covers the inner part of the pond area. This pattern is characteristic for this type of pond; hydraulics are influenced mainly by the energy produced by the incoming jet (Figure 5).

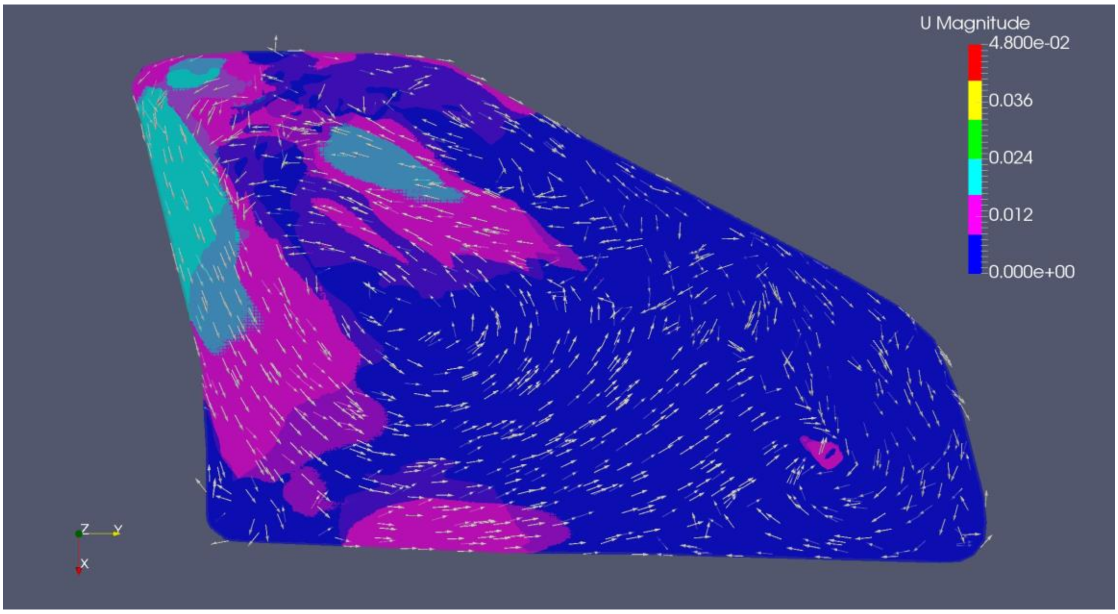

Figure 5: Bottom velocity distribution model 1

Model 2 shows a very advanced version of flow guidance, with an almost uniform flow coverage in the bottom area. The 3 compartments develop excellent vortices. The flow pattern is depicted in Figure 6.

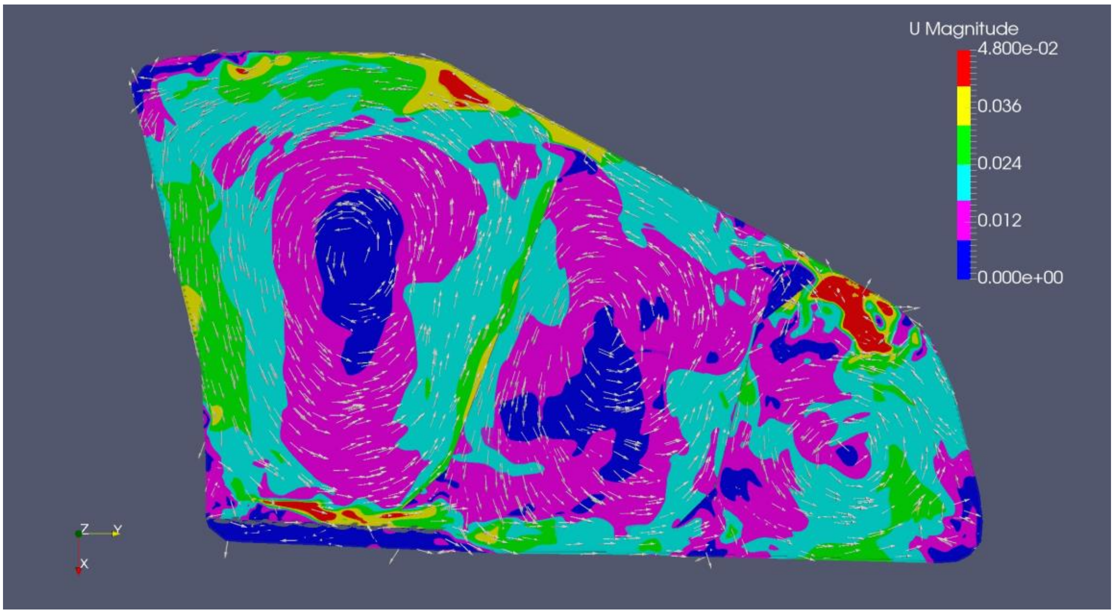

Figure 6: Bottom velocity distribution model 2

Model 3 represents the final stage of refining the improvements to achieve pathogen reduction. The first 2 cells are fully mixed with excellent velocity distribution. Cell 3 is still mixed in with circular shape but less intensively. The baffled area next to the outlet provides good flow retention. The pattern can be seen in Figure 7.

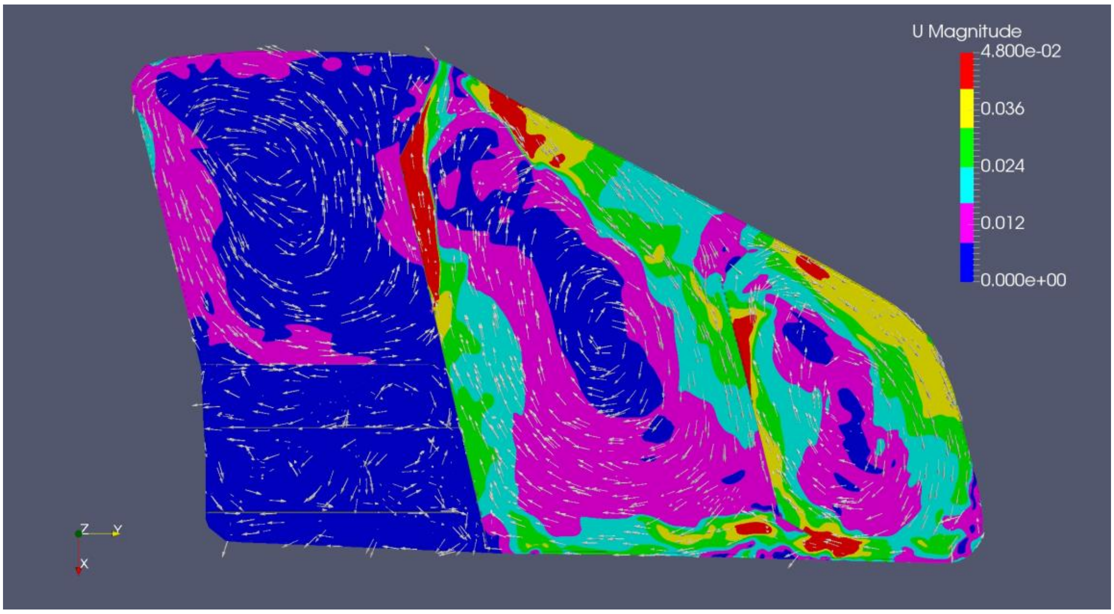

Figure 7: Bottom velocity distribution model 3

6.5.2 CUMULATIVE FREQUENCY ANALYSIS (CFA)

Figure 8 shows the CFA results in a comparative chart. The existing pond shows the lowest velocity with 80% of the bottom area moving at less than 5 mm/s. The "2 deflector" scenario provides the highest exchange rate with about 24 % of velocities below 5 mm/s, and the "2 zone" model sits in between, with 45%. The existing layout is characterized by a dominant stagnant area which is reflected in the CFA, the "2 Zone" model is designed for pathogen reduction and also shows large areas with low velocities. This demonstrates that biological performance and pathogen reduction require different hydraulic schemes.

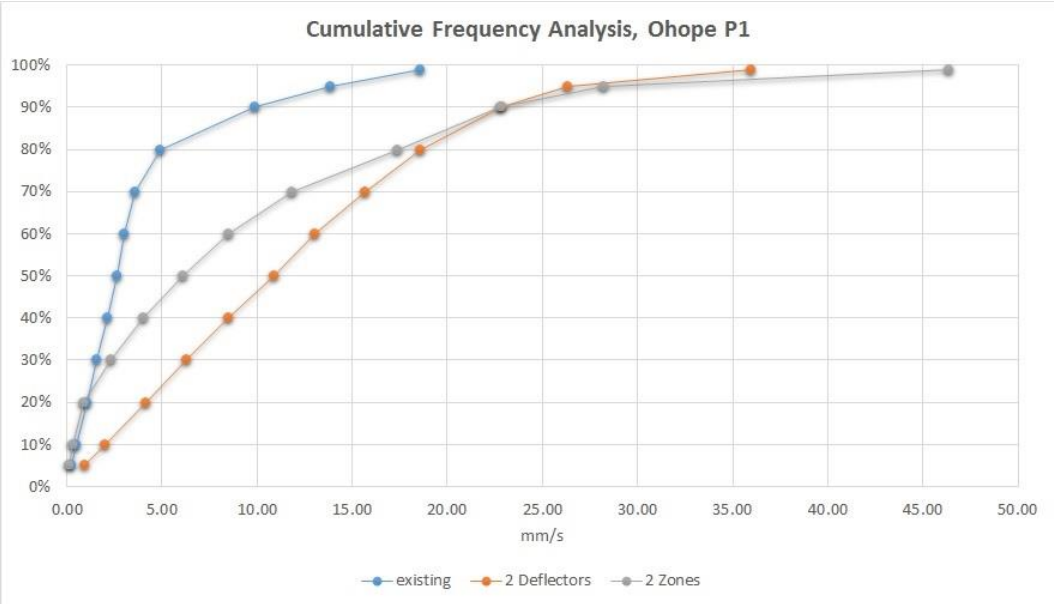

Figure 8: Cumulative frequency analysis Ohope facultative pond 1

6.5.3 FLOW CHARCTAERISTICS, RTD

The RTD curves for the existing pond lay out and the fully mixed 2 deflector scenario show a completely mixed tank behavior (1 cell only) – see Figure 9. The "2 zone" scenario is defined by a distinct shift of the E curve towards the right side (high Θ values), pushing the peak response (highest E(Θ)) towards the average retention time (Θ = 1). The shift to the right side helps to reduce pathogens. These characteristics represent a 3 to 4 cells in series scenario.

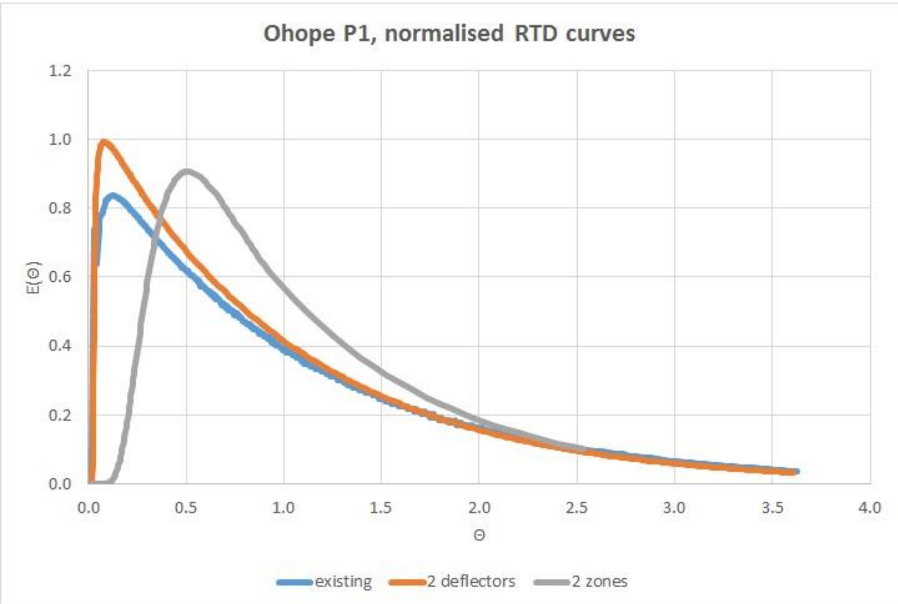

Figure 9: Comparison of RTD curves, 3 models

6.5.4 SEGRAGATED FLOW MODEL, PATHOGEN ELIMINATION

Pathogen elimination can be described as first order kinetic following the Chick's law equation (Crittenden et al., 2005)

$N_t = N_0 e^{-kt}$ (1)

N_t bacteria concentration at time t

N_0 bacteria concentration at time 0

k kinetic coefficient (h^{-1})

t time (hours)

Craggs et al (2004) conducted a very detailed study on die off rates for sunlight disinfection on high rate ponds and found the overall k rates with 0.99 d^{-1} for winter and 1.89 d^{-1} for summer conditions, which equals 0.041 h^{-1} and 0.079 h^{-1} respectively which we use in our assessment. The bacteria concentration at the beginning (N_0) is based on lab results with 5 x 10^6 cells / 100 ml. Table 1 shows a summary of the SFM results for the individual models.

Model #	Winter E.coli at the outlet	Winter Log-reduction	Summer E.coli at the outlet	Summer Log-reduction
1) Existing pond	$3.41 * 10^5$	1.17	$1.48 * 10^5$	1.53
2) 2 Deflector	$3.87 * 10^5$	1.11	$1.64 * 10^5$	1.48
3) 2 Zone	$6.44 * 10^4$	1.89	$6.93 * 10^3$	2.86

Table 1: Pathogen reduction for separate models

The application of a 2 zone concept positively shows advantages for pathogen reduction. E.coli reduction rates improved from 1.17 (winter operation) and 1.53 (summer operation) log units to 1.89 and 2.86 respectively. This is an increase in efficiency of 61 % (winter operation) and 87 % (summer operation).

7 CONCLUSIONS

CFD models are a flexible and variable tool for hydraulic evaluation of facultative ponds. Open source models like OpenFOAM® are freely available and can be used in an "out of the box" set up as a powerful technique for comparing pond design options. Background information like pond mixing and specification of retention time requirements will still guide the design engineer when he chooses between several options. In depth assessment of pond performance, like segregated flow model techniques, are easily applicable; Desktop scenarios representing the as built reality can be readily tested and compared.

ACKNOWLEDGEMENTS

Thanks to the Whakatane District Council and especially thanks to Gareth Philips, Manager Three Waters Operations for his on-going support. We would also want to emphasize the inspiring role that Prof. Andrew Shilton's work has had on the development of this paper. Dr. Shilton's research on new ways of understanding wastewater pond hydraulic performance is world leading. We would like to thank Dr. Shilton for peer reviewing this paper.

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