The development and calibration of a physical model to assist in optimising the hydraulic performance and design of maturation ponds

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Abstract A physical and a computational fluid dynamic (CFD) model (HYDRO-3D) were developed to simulate the effects of novel maturation pond configurations, and critical environmental factors (wind speed and direction) on the hydraulic efficiency (HE) of full-scale maturation ponds. The aims of the study were to assess the reliability of the physical model and convergence with HYDRO-3D, as tools for assessing and predicting best hydraulic performance of ponds. The physical model of the open ponds was scaled to provide a similar nominal retention time (NRT) of 52 hours. Under natural conditions, with a variable prevailing westerly wind opposite to the inlet, a rhodamine tracer study on the full-scale prototype pond produced a mean hydraulic retention time (MHRT) of 18.5 hours (HE = 35.5%). Simulations of these wind conditions, but with constant wind speed and direction in both the physical model and HYDRO-3D, produced a higher MHRT of 21 hours in both models and an HE of 40.4%. In the absence of wind tracer studies in the open pond physical model revealed incomplete mixing with peak concentrations leaving the model in several hours, but an increase in MHRT to 24.5–28 hours (HE = 50.2–57.1%). Although wind blowing opposite to the inlet flow increases dispersion (mixing), it reduced hydraulic performance by 18–25%. Much higher HE values were achieved by baffles (67–74%) and three channel configurations (69–92%), compared with the original open pond configuration. Good agreement was achieved between the two models where key environmental and flow parameters can be controlled and set, but it is difficult to accurately simulate full-scale works conditions due to the unpredictability of natural hourly and daily fluctuation in these parameters.

Keywords Computational model; dispersion number; hydraulic efficiency; hydraulic performance; hydraulic retention time; pond channels

Introduction

The evaluation of hydrodynamic behaviour in a full-scale waste stabilisation pond system (WSPS) is very complex and difficult to define precisely. It requires knowledge of a number of parameters internal and external to the lagoons. One methodology used to define hydraulic behaviour involves the addition of a dye tracer at the pond inlet and sampling the tracer at the outlet over a defined period. Different techniques are required to determine the pattern of flow in the field such as buoyant objects, whereas chemical salts and dyes have been used as tracers for many years.

The complex hydrodynamic behaviour of ponds has defied precise description using mathematical design formulae and models (Gloyna, 1971; Finney and Middlebrooks, 1980; Agunwamba, 1992). However, numerous authors have asserted that pond design, particularly for the most common facultative systems, is reliably performed using historical organic loading criteria on the basis of surface BOD loading (\(\lambda_s\), kg/ha/d), which is given by the design equation: \(\lambda_s = 10 \cdot \frac{L_i Q}{A_f}\) (Middlebrooks, 1987), where: \(L_i\) = influent BOD (mg/l); \(Q\) = flow (m³/d) and \(A_f\) = facultative pond area (m²). Furthermore, it is currently impossible to reliably predict how various modifications of pond
design, such as placement and number of inlets, use of baffles etc, might affect pond performance because these parameters are not included in the design equations.

Early design equations were based on the water volume, number of people contributing waste, flow per capita waste contribution and temperature reaction coefficient as in Gloyna’s equation (1971). In the 1970s, the retention time was used as a variable for the first time in an equation by Marais (1974). Marais’ equation was developed assuming complete mixing and rejecting plug flow conditions. At the end of the 1980s and in the beginning of the 1990s, a few researchers like Polprasert and Bhattarai (1985) and Agawamba (1992), put forward a dispersed design equation which resulted from a combination of plug and completely mixed flow. In those equations, the geometry of the lagoon was considered for the first time together with the retention time. The kinematic viscosity was also considered as a new variable influencing improvement in full-scale lagoon design, but the influence of the shape of WSPs and the wind effect (Wong and Lloyd, 2004) on them was not considered. The majority of these equations are based on false assumptions, such as nominal retention time and complete mixing which is not achieved. Tracer studies carried out in the field, show that the hydraulic retention time is often 50% less than the nominal one (Lloyd et al., 2002). Other calculations for retention time based on nominal capacity and flow (e.g. activated sludge, aerated lagoons), are based on complete mixing being achieved. In these calculations flow is controlled in channels with aeration and recycling (Camp, 1946).

The US Water Pollution Control Federation (WPCF, 1990) described optimal flow as a discharge with a uniform velocity profile. That is, with the water plume moving parallel to the walls and no sideways water movement. Such plug flow conditions were argued to be able to prevent short-circuiting and dead zones, increase hydraulic efficiency, and thus come closer to the nominal (maximum theoretical) retention time. The Federation therefore recommended that ponds be designed to have plug flow. Such a flow is characterised by having a uniform velocity profile, but this does not exist even in ponds with a large length-to-width ratio. Generally the pond water does not move homogeneously, but rather in eddies, waves, with reverse flow and with re-circulation (Persson, 2000, Aldana, 2004). In practice, local velocity profiles are difficult to measure due to low velocity within the lagoon (< 1 mm/s). A field investigation using a flow meter resulted in limited information for the evaluation of the hydraulic performance as compared to velocity vectors from running calibrated CFD packages such as HYDRO-3D (Guganesarajah, 2001), and/or tracer experiments using chemical solutions such as dyes, or tritiated water [H\(^{1+}\)] (Aldana et al., 1999). These latter methods and techniques are more accurate and allow an understanding of the hydraulic behaviour of lagoons.

The following aspects of hydraulic deficiencies are of particular importance in the design of WSPs: 1) rapid surface flow; 2) arrangement of inlet and outlet (where outlet and inlet are opposite each other); 3) wind effect; and 4) differences between the nominal retention and the mean hydraulic time.

The aim of the present study is to use physical and computational modelling (HYDRO-3D), to analyse how hydraulic performance in full-scale maturation ponds is affected by design parameters, particularly inlet/outlet position, baffle configuration and wind. The overall objective is to identify interventions which will optimise performance by maximising hydraulic efficiency.

**Methods**

In this study three facilities were used to study the hydraulic performance of WSPs: full-scale maturation ponds, a physical model and a computational model, HYDRO-3D.
Full-scale ponds

The full-scale ponds under study were two of three equal sized, parallel, tertiary-stage maturation ponds at a small sewage treatment works serving the village of Lidsey in southern England. The ponds form the final, polishing stage of an otherwise conventional percolating filter treatment works. The central of the three ponds had the open pond configuration shown as number 1 in the physical model schematic Figure 1. Another prototype pond was converted into three channels with the layout shown as 9 in Figure 1. The material used to construct the prototype channel walls was a butyl geo-membrane supported by wood posts. The specifications and hydraulic characteristics from a tracer study of the central and three-channel prototypes are shown in Table 1. The ponds were constructed in the shape of channels to encourage plug flow, but with inlet at the top surface and outlet near the top. The central pond, with a L:w ratio of 8.4:1, had a dispersion number of 0.9, whereas the three-channel configuration (L:w ratio 78:1) had a very low dispersion number of 0.07, much closer to plug flow. However, the low hydraulic efficiency (35%) of both prototypes under natural wind conditions is noteworthy. The prevailing westerly wind conditions at the study site were recorded continuously at the ponds using a wind speed and direction logger throughout the year. The data recorded during field tracer studies were used for the model simulations.

Table 1 Dimensions and hydraulic characteristics of prototype full-scale tertiary ponds at Lidsey

<table>
<thead>
<tr>
<th>Description</th>
<th>L (m)</th>
<th>W (m)</th>
<th>D (m)</th>
<th>Q (l/s)</th>
<th>Re</th>
<th>d</th>
<th>NRT (d)</th>
<th>MHRT (d)</th>
<th>HE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central pond</td>
<td>122.4</td>
<td>14.5</td>
<td>1.0</td>
<td>9.0</td>
<td>512</td>
<td>0.9</td>
<td>2.17</td>
<td>0.77</td>
<td>35</td>
</tr>
<tr>
<td>Three-channel</td>
<td>122.4 × 3</td>
<td>4.65</td>
<td>1.1</td>
<td>4.5</td>
<td>557</td>
<td>0.07</td>
<td>4.76</td>
<td>1.66</td>
<td>35</td>
</tr>
</tbody>
</table>

Length (L), width (W), depth (D), flow rate (Q), Reynolds Number (Re), dispersion number (d), nominal retention time (NRT), mean hydraulic retention time (MHRT), hydraulic efficiency (HE)
liner material. The outlet discharged into the drain to the local sewerage system as shown in Figure 2.

Layouts shown in Figure 1 as 4, 5 and 6 included baffle(s) constructed from a transparent plastic sheet 8 mm thick with eight circular holes of 5 mm diameter. The arrangement of holes drilled in the plastic sheet was designed to avoid the advection peaks short-circuiting in the top layer and to improve water distribution in the cross-section area, as this was the main problem identified in layouts 1 and 3. The holes were separated from each other by 5 cm and placed in three lines in the shape of a triangle (▲).

To convert the open pond model to the three-channel configuration (Figure 1, 7–9), the baffles were removed and corrugated plastic sheets were used to construct two longitudinal walls in the physical model. They were fixed to a metal frame which was reinforced and held in place with small pieces of the same metal and pieces of wood.

**Calibration.** A Watson Marlow peristaltic pump was calibrated in the selected flow range to determine linearity at various settings and flow reliability (Aldana, 2004). Flow into and out of the model was routinely checked at regular intervals throughout each experiment. Whenever flow deviated by > ± 5% from the set flow (12 ml/s), the pump was reset to the required flow to provide a NRT of 2 days. However, the time required for complete dye washout for each tracer experiment was about 6 days. The basic characteristics of the model are listed in Table 2 and variations in dimensions and flow for individual experiments shown below Figures 3 and 4.

Dye tracer experiments were run without either temperature control or wind effects during the period August 2001 to January 2003. Experiments with wind were carried out in July 2002. The wind was produced over the physical model surface by locating two, 60 W three-speed fans powered by 220 V, 50 Hz, either at the inlet or outlet, depending on whether a following (easterly) or opposite (westerly) wind was required. The wind speed over the surface of the model was calibrated as described by Wong and Lloyd (2004) to produce a velocity of 0.3 m/sec at the mid length of the pond or channels.

Rhodamine WT dye was used as the tracer, having a density of 1.019 kg/m³ and 20% active volume. All the readings in the experiments were taken on-line using a fluorimeter probe (Chelsea Instruments Ltd, UK) and were recorded every minute by a logger from Marine Instruments (Flexidata 1201). In all 44 tracer studies were conducted of which 10 were replicates. Replication of all tracer experiments could not be undertaken due to time constraints, each experiment taking almost a week. Only tracer experiments with good duplicate agreement were selected for presentation in this paper.

**Computational model**

A calibrated three dimensional model was required in order to produce simulations which accurately represent the hydraulic conditions of the full-scale and physical model.
Table 2 Basic characteristics of the CEHE physical model

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Length</td>
<td>6.60 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.86 m</td>
</tr>
<tr>
<td>Liquid depth</td>
<td>0.37 m</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0.012 l/s</td>
</tr>
<tr>
<td>Volume</td>
<td>2,100 l</td>
</tr>
<tr>
<td>Nominal retention time</td>
<td>2.19 d</td>
</tr>
<tr>
<td>Inlet/outlet</td>
<td>Top surface</td>
</tr>
</tbody>
</table>

Figure 3 Comparison of tracer age distribution in the physical model open and baffled pond layouts: 1) open centrally aligned in/out, 3) open diagonally opposite in/out, 4) baffle placed near inlet, and 6) baffle near outlet

<table>
<thead>
<tr>
<th>Expt No.</th>
<th>L (cm)</th>
<th>W (cm)</th>
<th>D (cm)</th>
<th>Q (l/s)</th>
<th>d (m/s)</th>
<th>NRT (d)</th>
<th>MHRT (d)</th>
<th>HE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>660</td>
<td>86</td>
<td>37.1</td>
<td>1.8</td>
<td>2.03</td>
<td>1.16</td>
<td>57.1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>660</td>
<td>86</td>
<td>36.8</td>
<td>1.8</td>
<td>2.03</td>
<td>1.02</td>
<td>50.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>746</td>
<td>86</td>
<td>37.0</td>
<td>0.48</td>
<td>2.04</td>
<td>1.40</td>
<td>68.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>746</td>
<td>86</td>
<td>38.3</td>
<td>0.36</td>
<td>2.09</td>
<td>1.56</td>
<td>74.6</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 Comparison of the age distribution in the physical model layouts: 5) double baffle, and three channels with 7) 50 cm, 8) 25 cm and 9) 5 cm gaps in the bends at the end of each channel

<table>
<thead>
<tr>
<th>Expt No.</th>
<th>L (cm)</th>
<th>W (cm)</th>
<th>D (cm)</th>
<th>Q (l/s)</th>
<th>d (m/s)</th>
<th>NRT (d)</th>
<th>MHRT (d)</th>
<th>HE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>832</td>
<td>86</td>
<td>37.2</td>
<td>1.84</td>
<td>3.4</td>
<td>1.34</td>
<td>67.4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1880</td>
<td>30</td>
<td>34.1</td>
<td>0.78</td>
<td>1.96</td>
<td>1.36</td>
<td>69.4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1930</td>
<td>30</td>
<td>34.0</td>
<td>0.21</td>
<td>1.83</td>
<td>1.64</td>
<td>89.6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1970</td>
<td>30</td>
<td>32.3</td>
<td>0.18</td>
<td>1.93</td>
<td>1.78</td>
<td>92.2</td>
<td></td>
</tr>
</tbody>
</table>
An application of HYDRO-3D was developed jointly by CEHE (University of Surrey) in collaboration with Mott MacDonald specifically for WSPs (Guganesharajah, 2001). HYDRO-3D is a CFD model, which has been successfully applied to water bodies including WSPs. The model can simulate impacts of wind on hydraulic conditions, and temperature on water quality parameters. HYDRO-3D was used to simulate the physical model shown in Figure 1 as a baseline for comparison with various subsequent interventions. Simulations included the production of hydrodynamic vector maps at 4 depths and the curves of tracer concentration against time. However, due to space limitations, only the simulation of layout 8 in Figure 1 (three channel lagoon with 25 cm gaps) with opposing wind, is presented in Figure 6.

Results

Physical model without wind

**Baffled model pond.** The impact of one baffle placed 1 m from the inlet-edge is shown in trace 4 (Figure 3) and, compared with the open pond (traces 1 and 3), is characterised by a substantial increased delay (414 minutes) before any dye leaves the model reactor. The MHRT is increased to 1.4 days and hence the HE is also increased, to 68.6%. However, the first dye fraction leaves the model in less than one third of NRT indicating that there is still major short-circuiting. Trace 5 (Figure 4) shows the effect of the second baffle in the physical model reactor, placed 1 m from the outlet. Surprisingly the double baffle reduced the dye exit delay time to about 85 minutes, and there was no increase in hydraulic efficiency; in fact it was marginally reduced to 67.4%, probably due to higher flow (13.23 ml/s). Trace 6 (Figure 3) shows the effect of the baffle placed 1 m from the outlet. This produced a MHRT of 1.56 days, and hence an HE of 74.6%, the best of the three, although all three baffle configurations are superior to the open pond model.

**Three-channel model pond.** The traces (7–9) shown in Figure 4 for the three channels constructed in the physical model, showed progressive and significant improvement for the two end of channel gap sizes, 50 cm, 25 cm and 5 cm. The hydraulic efficiencies were respectively, 69.4%, 89.6% and 92.2%; this reflects increasing MHRTs of 1.36 d, 1.64 d and 1.78 d, and also corresponded to progressive reductions in dispersion numbers, from 0.78, to 0.21, to 0.18, reflecting a trend towards plug flow. For trace 7 the first dye peak exited the pond after 4.30 h (258 min), and as expected this delay was much greater than in layout 1. Trace 8 shows an even greater time delay of almost 9 hours, demonstrating that the reduced channel gaps (25 cm) significantly reduce short-circuiting. The age-distribution showed in trace 9 is very similar to that of trace 8. However, in trace 9, a further large increase was noticed in the delay, and the dye first exited at 12.25 hours. Overall the curve is less skewed than in layout 8 and closer to plug flow. The last 2 channel configurations (8 and 9) are clearly significantly superior to all three baffle configurations, demonstrating the importance of the combination of narrow channels and the gap size at the end of each channel.

**Effects of wind action on models and full-scale ponds**

**Wind effects on open pond configuration.** It is noteworthy that the HE of all configurations of the physical model (in the absence of wind) were much higher than those of the prototype full-scale open pond and three-channel Lidsey ponds under natural conditions. However, all the physical model tests discussed thus far were conducted in still air, it is therefore essential to assess the impact of a similar, opposing wind condition as indicated in layout 2. The results from the full scale open pond and layout 2 (both with wind opposite to the inlet) are presented in Figure 5. They demonstrate similar
curves and similar MHRTs of 18.4 h (full scale) and 21 h (physical model), and similarly low HEs of 35% (at full scale) and 40% (physical model), reflecting high short-circuiting with the peak tracer concentrations leaving the ponds in <1.5 h (<90 min). Similar reductions in hydraulic efficiency were demonstrated using HYDRO-3D simulations.

**Wind effects on three-channel configuration.** In Figure 6 the tracer curves from 1) the Lidsey full-scale south three-channel configuration, 2) the physical model (layout 8), and 3) a HYDRO-3D simulation are compared. All three traces present a similar type of skew distribution and overall curve shape, however the similarity between 2) the physical model (layout 8) and 3) the HYDRO-3D simulation is the most impressive. The main
reason for the close similarity between 2) and 3) is because the flow rate (9 l/s) is constant, and the wind condition is constant in direction, speed and duration. By contrast, the flow in the full-scale pond, could not be controlled precisely and the flow rate varied between 4.5 and 9 l/s, so taking a reasonable mean flow for the experimental period as 8 l/s, this gave a NRT of 2.36 days. The fact that there is a much greater delay time at full scale is primarily attributable to this lower flow rate, but also to periods of lower or no wind, or changing direction of wind. It is important to note that the MHRTs were 33 h (physical model), 34 h (HYDRO-3D) and 39.35 h (full scale). Their respective hydraulic efficiencies were 83%, 68% and 70%, which are all significantly higher than open pond configuration. This emphasises the value of channels with (or without) wind conditions in raising hydraulic performance efficiency.

Discussion and conclusions
In still air, under similar hydraulic loading, the comparison of physical model open pond, with baffled and three-channel pond configurations clearly demonstrated that the open pond configuration produced the lowest hydraulic efficiency (HE 50–57%), baffles produced a significant increase to 67–74.6%, whilst the narrow three-channel configuration produced the highest efficiency (69–92.2%). The best configuration (HE 92.2%) was with the smallest (5 cm) gaps between each of the three channels. Delay times, for the first detectable dye to leave the three-channel model, ranged from a minimum of 4.3 hours to a maximum of 12.25 hours, which represented a large improvement in hydraulic efficiency within the physical model. It is fair to recommend channels for use in WSPs in order to increase hydraulic performance.

There are, however, a number of factors, in addition to pond configuration, which influence hydraulic performance and can influence advective (short-circuiting plume) flow paths in full-scale ponds under natural conditions: these include wind stress, temperature, viscous effects, boundary shear, inlet discharge, and during this study it was observed that wind aggravates short-circuiting and reduces HE. In numerical terms it was demonstrated that wind could reduce MHRT by more than 25%. This adds significantly to the growing body of evidence that wind is damaging rather than enhancing pond performance (Wong and Lloyd, 2004, Lloyd et al., 2002). However, it was also demonstrated that, even under conditions of natural or generated wind, the channel configuration substantially outperforms the open pond. Whereas, with opposing wind, the HE of the open configuration physical model was only 40%, and the open full-scale pond was 35%, the corresponding winds on the three-channel configuration still produced much higher efficiencies. Thus the three channel physical model HE was 83%, the HYDRO-3D was 68% and the full-scale prototype was 70%. Although further increases in the precision and convergence of model simulations are desirable, in practical terms it is already clear that channel designs, derived from model simulations, are likely to replace open ponds in the future where space is at a premium and performance must be maximised to meet more demanding effluent standards.

References


