water

MDPI

Article

Impact of Hydrodynamic Reconfiguration with Baffles on Treatment Performance in Waste Stabilisation Ponds: A Full-Scale Experiment

Liah X. Coggins [1], Jesse Sounness [1], Lianpeng Zheng [1], Marco Ghisalberti [1,2] and Anas Ghadouani [1,*]

1 Department of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Highway, M051, Crawley, WA 6009, Australia; liah.coggins@uwa.edu.au (L.X.C.); jesse.sounness@graduate.uwa.edu.au (J.S.); lianpeng.zheng@graduate.uwa.edu.au (L.Z.); marco.ghisalberti@unimelb.edu.au (M.G.)

2 Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC 3010, Australia

* Correspondence: anas.ghadouani@uwa.edu.au; Tel.: +61-8-6488-2687

Received: 5 January 2018; Accepted: 23 January 2018; Published: 27 January 2018

Abstract: Wastewater infrastructure is expensive to build and maintain, and there is a need to focus on improving and modernising existing infrastructure before large capital investments are made to service future population needs. Waste stabilisation ponds (WSPs) are used worldwide for the treatment of wastewater, but their performance is significantly affected by poor hydraulic control. Hydraulic reconfiguration of ponds is a possible solution to this problem, whereby the flow is controlled and short-circuiting is reduced. There is evidence to suggest that this approach has the potential to increase treatment performance, however in the absence of full-scale validation it is difficult to generalise this to a wide range of sites. For example, there is no consensus on the best baffle configuration to optimise hydraulic performance. The main objective of this study was to conduct a full-scale experiment of baffles in a WSP, and to investigate their impact on hydraulic performance. To achieve this objective, the approach combined high-resolution pond bathymetry and 2D hydrodynamic modelling, assessed with hydraulic indices, to determine the optimal baffle configuration for the site; it was shown that three baffles perpendicular to the inflow provided the greatest increase (up to 24%) in mean residence time. This configuration was then implemented in a working WSP. The effects of the baffles on the pond were then assessed using a combination of field tracer testing, revealing an increase in mean residence time of at least 20%, and further hydrodynamic modelling. Through the addition of wind data into the hydrodynamic model, it is shown that baffles not only improve the flow, but also attenuate the effect of wind on pond hydraulics. While the conclusions of this study are site-specific, the implementation of site-specific solutions is important for progress towards optimal pond design. The approach developed here is easily transferrable for use on other sites, and will enhance our ability to plan, design and operate WSP systems in the future.

Keywords: pond hydraulics; baffles; waste stabilization ponds; sludge; modelling; treatment performance

1. Introduction

As the world's population increases, water resources are being placed under ever increasing stress [1,2]. It is anticipated that by 2025, up to two-thirds of the world population could be living under water-stressed conditions as demand for safe water will exceed availability in many regions [3,4]. In addition to supply, the biggest challenges in water resource management are the lack of adequate infrastructure in some parts of the world, and the aging of existing networks [5]. While water services are essential for socioeconomic development and increased societal productivity, they remain severely underfunded on a global scale, with a large portion of the gap in the investment attributed to delays in infrastructure and inadequate maintenance [5]. In Australia, water assets in metropolitan areas are well maintained, however in regional areas there has been a large underspend on asset maintenance [6], and in the future this regional underspend will cost water utilities. In addition, it has been predicted that future liability in the water sector in Australia will occur due to population growth, urban sprawl, aging infrastructure, and climate change and variability [6,7].

More than 50% of the investment in the urban water industry in Australia is dedicated to wastewater services [8], and as stress on our freshwater resources increases, so will the stress on our existing wastewater infrastructure, not only in terms of volume of treatment, but also in terms of providing a higher level of treatment to increase re-use opportunities. The short-term challenge is to meet these higher expectations for wastewater treatment with infrastructure that has been designed, built and used in the past century, while the long-term challenge is to provide wastewater treatment across the world by engineering or re-engineering sustainable, appropriate and affordable infrastructure [2,7,9]. By 2025 it is anticipated that close to a trillion dollars will be spent on water in OECD countries, Russia, China, India and Brazil; more than triple of the amounts required for investment in the key sectors of electricity and transport [5,10]. Considering the significant investment required to make water infrastructure meet future demand worldwide, there will be increased focus on improving and/or modernising existing infrastructure and operations before any new major capital investments are made.

Waste stabilisation ponds (WSPs), the biggest wastewater treatment asset globally, are low-cost, robust systems widely used for decentralised wastewater treatment [11–14]. Waste removal efficiencies in these systems are highly dependent on hydraulic performance [15], and unsatisfactory hydraulic control is one of the main factors contributing to poor pond performance, especially after years of operation [16]. WSPs are notoriously hydraulically inefficient, and pond hydraulics are further compromised by sludge accumulation and distribution over time [17].

One of the possible solutions proposed is the hydraulic reconfiguration of these systems, through the installation of structures such as baffles: solid partitions installed in the pond to confine or direct flow. There are numerous studies that have investigated the link between baffled ponds and treatment efficiency, mainly through the use of hydrodynamic and/or laboratory physical models e.g., [18–21]. In general, previous hydrodynamic modelling has suggested that baffles will significantly improve pond hydraulics, and some of these models have been validated with lab-scale models or prototypes [22–28]. However, despite the value provided through model validation using small-scale controlled environments, there has been a lack of studies that demonstrate and validate the effectiveness of baffles at the operational pond-scale.

Furthermore, while modelling has shown that baffles improve pond hydraulics, there is a lack of consensus in recommending the best configuration for flow improvement e.g., [18,22,24,25]. Here we define flow optimisation as maximising pond residence time through a decrease in short-circuiting. For example, two baffles perpendicular to the inflow gave the optimum treatment performance (e.g., residence time, coliform removal, biological oxygen demand (BOD) removal) in some cases [24,25], while another suggested two or four baffles perpendicular to the inlet [18]. Another study found a single subsurface baffle or island baffle placed in front of the inlet was the best design option [22]. The lack of consensus on the assessment method of designs for the most effective performance/hydraulic control makes it difficult to generalise the results of these studies, and make consistent recommendations for optimal site-specific solutions.

Our ability to assess and determine the most optimal baffle configurations for WSPs will not only provide invaluable information for cost-effective hydraulic reconfiguration, but also allow for design to site-specific performance goals; these could vary between sites, regions, and climates, as well as due to operational considerations. Using this information in an integrated way will help to delay expensive upgrades, and could result in significant savings in capital investment, while improving overall treatment goals.

The overall objective of this study is to develop a framework for the assessment, planning and design of hydraulic reconfiguration in WSPs. Detailed hydrodynamic modelling, combined with tracer studies and a full-scale validation trial, will be used to demonstrate this framework; it is expected that the installation of baffles will improve pond hydraulics by significantly increasing mean residence time and decreasing flow velocity, which will, in turn, influence pond treatment efficiency. Specifically, the aims of this study are to: (1) determine the optimal baffle configuration for a particular WSP using a 2D hydrodynamic model that incorporates detailed bathymetry, (2) install baffles (in the optimal configuration) in that pond as part of a long-term full-scale trial, and (3) through a tracer study, determine the change in hydraulic efficiency generated by the baffles.

2. Materials and Methods

2.1. Study Site

The study site is located in a town 86 km south of Perth, Western Australia, and experiences a Mediterranean climate with yearly average temperatures ranging between 10–30 °C, and an average rainfall of 690 mm [29]. The site was selected specifically to have two parallel primary facultative ponds, referred to as Pond 1 (used as the reference system; Figure 1A) and Pond 2 (the trial system; Figure 1C). These ponds evenly share a total inflow of up to 770 kL·day^{-1}. Each pond has dimensions 120 m × 60 m × 1.3 m, with two inlets, and one outlet (Figure 1). The total treatment capacity/volume of each pond without any sludge accumulation is 9360 m^3, and under average flow conditions the nominal residence time (t_n) in each pond is 28 days.

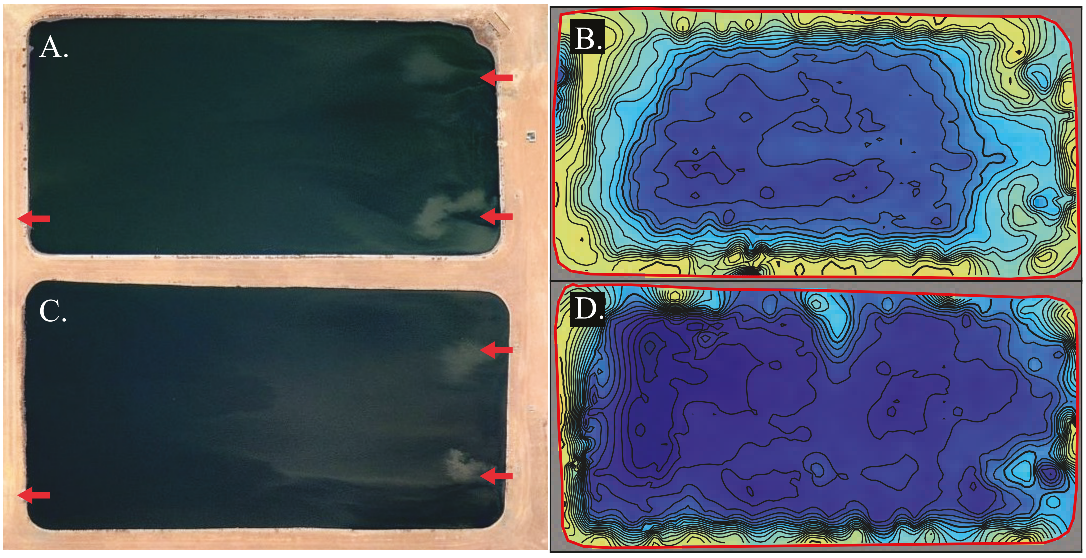

Figure 1. Aerial view of the study site, and the sludge profiles in each pond in 2015. (**A**) Pond 1 and (**B**) its sludge profile (45% infill), and (**C**) Pond 2 with (**D**) its sludge profile (29% infill). Sludge accumulation in these ponds is mostly around the edges, along with a bench in front of the inlets; the inlets and outlets indicated by red arrows (**A**, **C**). For tracer testing, the dye was added at into the northern inlet only.

2.2. Bathymetry Mapping

Coggins et al. [17] developed a system dedicated to the acquisition of high-resolution bathymetric data in ponds with a remotely operated vehicle (ROV); this high-resolution data is critical for the accurate modelling of the hydrodynamics of these pond systems.

Bathymetric data was collected using a remote-control boat fitted with sonar. The sonar unit has in-built GPS, and logs water depth information and GPS location simultaneously onto a memory card.

While collecting data, the ROV is maintained at a constant 2–4 km·h^{-1}, allowing for the collection of thousands of data points per transect. The data collected using the ROV has significantly higher spatial resolution than that collected with traditional pond profiling techniques; for more detail about ROV sludge profiling refer to Coggins et al. [17]. Collected data was processed by removing outliers, converting from water depth to sludge height, and gridded; this processing was completed though a software package, SludgePro©, developed by Coggins et al. [17]. The high-resolution data (1 m resolution) collected using the ROV is suitable for input into hydrodynamic models, and is vital for model accuracy and reliability. The bathymetry of these ponds was first measured in July 2013, and profiling of the study site ponds was carried out regularly throughout the study period 2013–2015. The sludge profiles for Ponds 1 and 2 in 2015 are shown in Figures 1B and 1D, respectively.

2.3. Hydrodynamic Modelling

Two-dimensional (2D) modelling of ponds was the preferred option over 3D, for its simplicity, computational economy, and accessibility. 2D modelling was conducted with MIKE21 (Release 2012, DHI, Hørsholm, Denmark), using the hydrodynamics (HD) and advection-dispersion (AD) modules of the software. The model used in this study was set-up, calibrated, and validated for our previous investigation on sludge accumulation and distribution in WSPs [17]; the following briefly describes the process of model set-up, calibration and validation.

The post processed data water depth data set from SludgePro© (V1, The University of Western Australia, Perth, WA, Australia) was used to create the bathymetry files for the WSPs; bathymetry files were created using bilinear interpolation, resulting in a rectangular grid area with 1 m × 1 m cells. The water depth/sludge height in each cell is constant, and pond walls were defined as having no perpendicular flux. Inlets and outlet were defined as sources and sink (Figure 1), respectively, with constant inflow/outflow rates. The model was calibrated using values for Manning's roughness and dispersion, and then validated by comparing the calibrated model results to the results of two field tracer tests. A Manning's roughness value of 0.01 s·m$^{-1/3}$ was determined to be the best fit for WSPs, and is a reasonable assumption for a consolidated sludge layer. Dispersion coefficients were defined according to the following:

$$D = K \times \Delta x \times u \quad (1)$$

where D is the dispersion coefficient, K is a constant value, Δx is the constant grid spacing (1 m), and u is the local current velocity component [30,31]. The value of K is not prescribed directly, rather it is part of the MIKE21 model algorithm, and is defined by setting upper and lower boundaries for dispersion; values in the range 3.5×10^{-5} and 1.0×10^{-4} m^2·s^{-1} achieved the best results. Finally, the Courant number was everywhere << 1, as required in hydrodynamic models.

The agreement between signals of concentration at the pond outlet from the calibrated model and field tracer testing is strong across two sites (Figure 2). All models were set-up to run for 91.5 days with a 1 s time step, including a 5 days warm-up period to reach steady state and 86.5 days of tracer simulation.

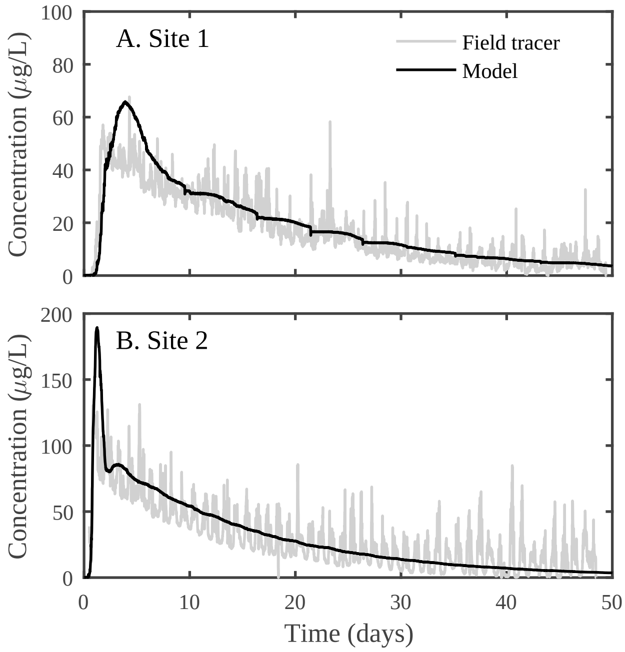

Figure 2. Validation of the model through the agreement of the calibrated model output (black) and field tracer data (grey) for two sites. Tracer data and bathymetries for (**A**) Site 1 and (**B**) Site 2, both in Western Australia, were collected in 2013.

2.4. Tracer Testing

Tracer testing was carried out at the study site on two occasions: Pond 2 only in June–July 2013 and both ponds in July–August 2015. Testing was conducted with Rhodamine WT (Product code: 703-010-27, Keystone Aniline Corporation, Chicago, IL, USA) containing 20% true dye, and the fluorescence signal was monitored at the outlet at 15-min intervals over a period of 6 weeks. This period is equivalent to 1.5–2 nominal residence times in these ponds at the average flow rate. For all testing, the dye was only released into the northern inlet of each pond (see Figure 1); in 2013, 370 g true dye was released into Pond 2, while 360 g true dye was released into each pond in 2015.

2.5. Modelling Scenarios and Analysis

Three baffle configurations were modelled (Figure 3): parallel baffles (PA), perpendicular baffles (PE), and an island baffle configuration followed by perpendicular baffles (IPE). The modelled scenarios were chosen based upon previous studies showing the improvement in pond hydrodynamics provided by perpendicular e.g., [18,26] and island baffle [22] configurations, as well as a previous study which used parallel baffles to grow algal biofilm [32]. For each configuration, the number of baffles was adjusted, with a no baffle scenario run as a control. For PA scenarios, the baffle length was set at two-thirds of the length of the pond, while for PE it was two-thirds of the width of the pond. IPE configurations had an island baffle two-thirds the width of the pond, followed by two one-third pond width baffles, and then two two-third width perpendicular baffles. Three PA scenarios were run with 1–3 baffles (PA1, PA2, PA3), nine PE scenarios with 1–9 baffles (PE1, PE2, PE3, PE4, PE5, PE6, PE7, PE8, PE9), and three IPE scenarios with an island baffle configuration followed by 1, 3 or 5 perpendicular baffles (IPE1, IPE3, IPE5). The modelling of all scenarios was completed for three different flow rates experienced on-site: low (279 kL·day^{-1}), average (332 kL·day^{-1}) and high (385 kL·day^{-1}). The model tracer mass input was kept constant to allow direct comparison of the effect of baffle configuration on the residence time distribution. All modelling of baffle configurations were run under the scenario of 21.5% sludge infill in Pond 2, as measured in 2013. Subsequent modelling was carried out with the sludge profiling data collected in 2015.

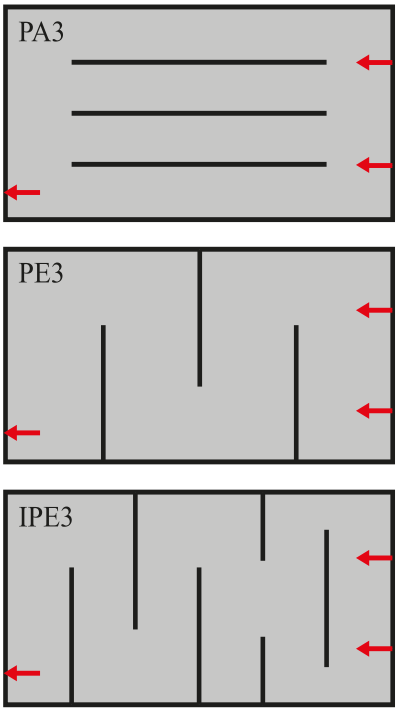

Figure 3. Selected examples for each baffle configuration from the 15 baffle scenarios modelled for the study site (Table 1). Note: PA = parallel, PE = perpendicular, and IPE = island perpendicular. PA3 shows three baffles parallel to the inlet flow, PE3 shows three baffles placed perpendicular to the flow, while IPE3 shows an island baffle configuration followed by three perpendicular baffles. The ponds at the study site both have twin inlets and one outlet, as shown by red arrows.

To compare the results of each modelling scenario, the mean residence time, moment index, and short-circuiting index were employed. The mean residence time (t_{mean}) for each scenario was calculated from the model output according to:

$$t_{mean} = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt} \tag{2}$$

where $C(t)$ is the tracer concentration at time t. The mean residence time is defined as the centroid of the residence time distribution (RTD), and is the average time a tracer particle spends in a system [22]. In reality, not all of the added tracer exits the pond during the duration of the experiment, such that calculated values of t_{mean} are likely to represent minimum estimates.

Hydraulic indices reliant on mean residence time or variance are heavily influenced by the long tails of measured RTDs, which can lead to the over prediction of residence time [33]. The moment index, developed by Wahl et al. [33], overcomes this problem as it is derived from the prenominal portion (i.e., data collected prior to t_n) of the RTD only. The moment index (*MI*) as defined by Wahl et al. [33] is as follows:

$$Moment\ index = 1 - \int_0^1 (1-\phi)C\prime(\phi)d\phi \tag{3}$$

where $C'(\phi)$ is a dimensionless function defined by the following:

$$C\prime(\phi) = \frac{C(\phi)V(\phi)}{M} \tag{4}$$

where $C(\phi)$ is the outflow concentration and $V(\phi)$ the volume, and M is the total mass, at a given flow-weighted time, and where the dimensionless flow-weighted variable (ϕ) is defined as:

$$\phi = \int_{t_0}^{t} \frac{Q(t\prime)}{V(t\prime)} dt\prime \tag{5}$$

where t' is a dummy variable of integration, $Q(t')$ the variable outflow rate, and $V(t')$ represents volume changes due to unsteady flow. This hydraulic index assumes that perfect pond efficiency (i.e., $MI = 1$) is indicated by the actual residence time (t_{mean}) being equal to the nominal residence time (t_n).

The short-circuiting index (S) is a measure of the skewness of the residence time distribution, and as defined by Persson [22] is:

$$S = \frac{t_{16}}{t_n} \tag{6}$$

where t_{16} is the time taken for 16% of the injected tracer to reach the outlet. The value of S is inversely proportional to the strength of short-circuiting, and a positive change indicates a decrease in the strength of short-circuiting and thus an increase in hydraulic performance, i.e., $S = 1$ represents no short-circuiting/ideal plug flow.

These three indices were chosen to assess hydraulic efficiency in ponds, as each describes different features of the hydraulics, and no one of these parameters alone can be used to fully describe the flow or treatment performance.

2.6. Baffle Design

Rather than traditional non-porous media, a geotextile material was selected for the baffles as it has the ability to act as a barrier to train flow, as well as promote the growth of biofilm or attached growth. Geotextile sample strips were tested in-pond for 2 months to determine the material that would result in the highest amount of growth. The chosen non-woven polypropylene geotextile (TerraTex D1 PP, Polyfabrics Australia, Kingsgrove, NSW, Australia) was then used to construct baffle curtains which could be deployed in the pond in the optimal configuration as determined by modelling.

2.7. Wind Measurement

Prior to the 2015 tracer experiments, a weather station was installed between Pond 1 and Pond 2 to collect wind data. Wind speed was collected using an Onset HOBO U30 unit with wind speed sensor (Onset Computer Corporation, Bourne, MA, USA). 3-hourly wind direction data for the testing period was sourced from the nearest Bureau of Meteorology (BOM) site. The collected wind speed data was combined with the direction data sourced from BOM, and used as a forcing for the model to determine the effect of wind on pond hydrodynamics.

3. Results

3.1. Baffle Configuration Modelling

A summary of the modelling results and analysis is provided in Table 1, and Figure 4 illustrates the net change in S for all 15 scenarios. Under all flow rates, the mean residence time calculated for all non-baffled scenarios is 5–10% lower than the nominal residence time (allowing for the volume occupied by the sludge). The values for MI and S for the non-baffled scenarios indicate superior hydraulic efficiency at the low flow rate. As the flow rate increases, MI and S both indicate decreasing hydraulic efficiency and more short-circuiting within the system.

Table 1. Values for mean residence time (t_{mean}, days), moment index (*MI*) and short-circuiting index (*S*) for all modelled baffle configurations under low (279 kL·day^{-1}), average (332 kL·day^{-1}), and high-flow conditions (385 kL·day^{-1}). The nominal residence time (t_n, days) was calculated for each flow condition with 21.5% sludge infill (as modelled), and these were then used to calculate *MI* and *S*. Note: PA = parallel, PE = perpendicular, and IPE = island perpendicular.

Configuration	Low; t_n = 26.3 Days			Average; t_n = 22.1 Days			High; t_n = 19.1 Days		
	t_{mean}	*MI*	*S*	t_{mean}	*MI*	*S*	t_{mean}	*MI*	*S*
No baffles	23.6	0.86	0.27	20.2	0.81	0.23	18.1	0.79	0.24
PA1	24.5	0.86	0.30	20.2	0.82	0.27	17.7	0.79	0.26
PA2	23.0	0.85	0.28	20.2	0.82	0.28	18.1	0.80	0.27
PA3	23.4	0.85	0.28	20.3	0.82	0.26	16.9	0.78	0.23
PE1	22.4	0.86	0.29	21.2	0.84	0.31	19.2	0.82	0.32
PE2	23.9	0.87	0.33	19.4	0.81	0.24	18.7	0.82	0.33
PE3	27.6	0.91	0.48	23.8	0.89	0.48	20.0	0.87	0.50
PE4	22.5	0.84	0.21	20.9	0.83	0.27	17.4	0.78	0.22
PE5	26.9	0.90	0.42	21.6	0.84	0.36	18.9	0.81	0.31
PE6	24.2	0.86	0.30	20.6	0.83	0.29	17.4	0.80	0.27
PE7	23.8	0.87	0.33	19.7	0.84	0.36	17.4	0.82	0.35
PE8	27.8	0.90	0.44	23.6	0.88	0.43	18.7	0.84	0.41
PE9	27.7	0.90	0.44	24.2	0.89	0.47	20.3	0.85	0.40
IPE1	23.2	0.88	0.41	21.0	0.86	0.39	18.5	0.84	0.41
IPE3	27.0	0.92	0.55	23.0	0.90	0.56	22.4	0.89	0.55
IPE5	26.3	0.88	0.38	22.6	0.86	0.38	20.3	0.86	0.45

Across all flow rates, parallel baffles (PA1, PA2, PA3) exert minimal influence on the flow, with very little change in t_{mean} and *MI* for all scenarios; *S* for each of these scenarios improved slightly, however the improvement was not consistent across all flow conditions (Figure 4).

In general, the addition of odd numbers of perpendicular baffles (i.e., PE1, PE3, PE5, PE9) generate superior hydraulic efficiency, as the *MI* values for these scenarios are higher than those for even-numbered scenarios. Generally, odd-numbered scenarios (particularly PE3, under all flow conditions) also show increases in *S*, indicative of a decrease in short-circuiting intensity. The scenarios that showed the greatest improvement in *MI* also showed the greatest improvement in *S* (Figure 4). Compared to the parallel baffles, perpendicular baffle configurations more consistently improve the hydraulics under different flow conditions, and overall, the best improvement across all three flow scenarios was achieved with the PE3 configuration.

The island baffle configurations (IPE1, IPE3, IPE5) generally provided the best improvement in hydraulic efficiency, all having the highest net change in *MI* and *S* from the baseline no-baffle scenario. The IPE3 configuration provides the best overall improvement to flow efficiency, with the highest net change (relative to no baffles) in both *MI* and *S* across all 15 modelled scenarios (Figure 4). Here is it clear that perpendicular baffle configurations significantly improve pond hydraulic efficiency, while parallel baffles provide little to no improvement.

Overall, by comparing changes in *MI* and *S* for all flow and baffle scenarios, the best performing configurations for this pond are IPE3 and PE3. To illustrate the improvement to the flow provided by these configurations, the RTDs of no baffles, PA3, PE3 and IPE3 under average flow conditions are shown in Figure 5. This clearly demonstrates that parallel baffles exert little influence on the shape of the RTD (and thus flow), while perpendicular and island configurations move the time of peak outlet concentration closer to the nominal residence time (i.e., increasing the *MI* and *S* indices). While the values of *MI* for PE3 and IPE3 are not vastly different at 0.89 and 0.90, respectively, PE3 creates a greater reduction in peak concentration, while IPE3 is more effective at delaying the time of peak concentration. The delay of the IPE3 peak explains the greater change in *S* for this scenario (relative to PE3).

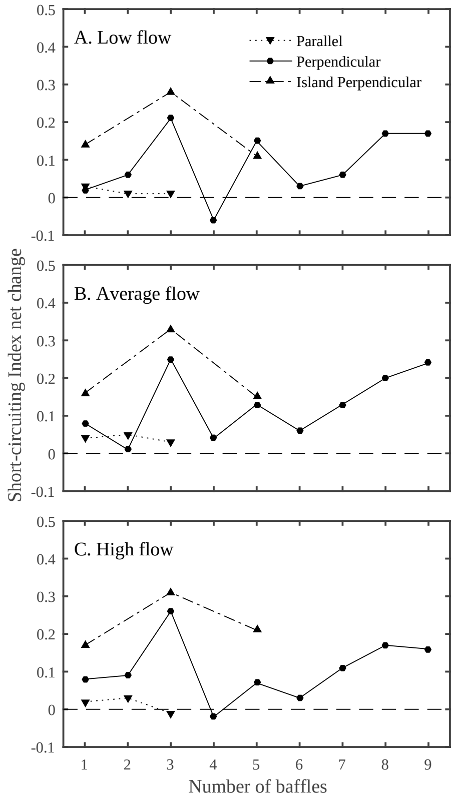

Figure 4. The net change in the short-circuiting index for each baffle configuration modelled under: (**A**) low, (**B**) average, and (**C**) high flow conditions. The dotted line (0) represents the baseline no-baffle scenario. For all flow scenarios, except PE4, the net change is positive, indicating that the addition of baffles decreases short-circuiting in this pond. IPE3 and PE3 configurations consistently provide the greatest improvement, while all parallel configurations provide little improvement.

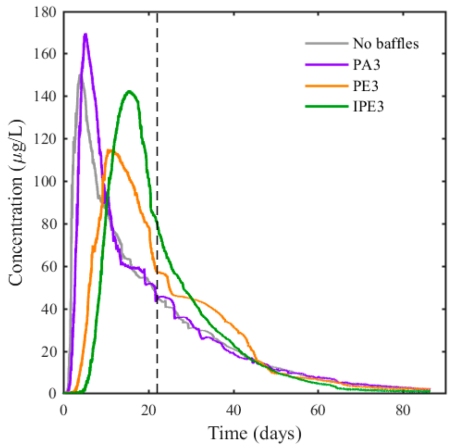

Figure 5. Modelled residence time distribution (RTD) of the non-baffled scenario compared to PA3, PE3, and IPE3 under average flow conditions, all with a sludge volume of 21.5%. The black dotted line represents t_n for this flow condition. The RTD with parallel baffles (PA3; purple) is not vastly different from the non-baffled scenario (grey), both with high concentration peaks early on. The addition of perpendicular baffles (PE3; orange) not only delays the initial peak but also reduces the peak concentration, while the island baffle configuration (IPE3; green) also delays the initial peak and moves the RTD closer to that expected in plug flow. The RTDs for the PE3 and IPE3 configurations both show that short-circuiting in the pond has been reduced.

3.2. Baffle Installation

The modelling determined that IPE3 and PE3 best optimised the flow in the pond, and both were considered for installation for the full-scale field trial. Due to the complexity of installing the IPE3 baffle configuration (see Figure 3), it was deemed inappropriate for this trial. Thus, PE3 was deemed the most appropriate choice for reasons of flow improvement, practicality of construction and cost effectiveness.

The baffles were installed in Pond 2, the same one used in the hydrodynamic model, in October 2014. An aerial photo of the baffles a few days after installation is shown in Figure 6A, and a view of the baffles in pond is shown in Figure 6B. Along with the baffles, a weather station for monitoring wind speed was also installed (Figure 6C).

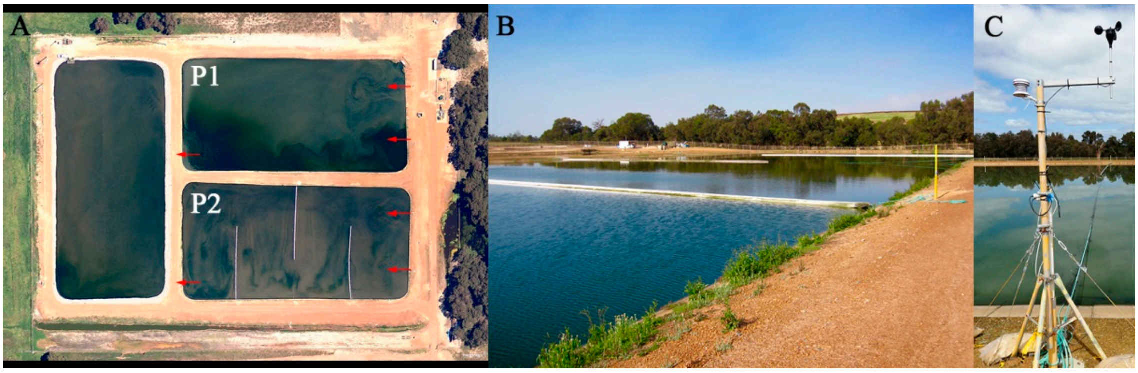

Figure 6. (**A**) Aerial view of the study site taken shortly after baffles were installed in Pond 2 (P2) (Image: NearMap). Inlets and outlets for Pond 1 (P1) and P2 are shown by red arrows. (**B**) A ground level view of the installed baffles, which had a flotation device at the top and were anchored at the bottom of the pond with heavy chain, and (**C**) the weather station used for on-site monitoring of local conditions.

3.3. Effect of Baffles on Pond Hydrodynamics

In 2015, during the 42-day tracer testing period, Pond 1 had 45% sludge infill with a calculated t_n of 14.0 days, while Pond 2 had 29% sludge infill and a t_n of 18.1 days (Table 2). The average flow rate over the testing period was 372 kL·day^{-1}. The effects of the baffles on residence time distribution are presented in Figure 7. With Pond 1 acting as a control, we can see that the non-baffled pond experiences a much higher concentration peak than Pond 2 (Figure 7A), and that this peak also occurs earlier; this is evidence of a higher level of short-circuiting in this pond. In addition, the data shows that the fluctuations in concentration in Pond 1 are much more pronounced than in Pond 2. Overall, the presence of baffles in Pond 2 appears to attenuate the fluctuations in concentration, indicative of increased small-scale mixing and a more uniform concentration within this pond. Over the testing period, t_{mean} in Pond 1 was 11.9 days, while in Pond 2 it was 17.0 days, showing that the baffled pond had smaller discrepancies between t_{mean} and t_n (6% in Pond 2, 15% in Pond 1; Table 2). Overall, the residence time in Pond 2 is 43% higher than in Pond 1.

Table 2. Summary of results of field tracer testing in each pond. In general, the reduction in residence time is higher the non-baffled ponds, Pond 1 and Pond 2 (2013), while the baffled pond, Pond 2 (2015) shows a 20% increase in residence time despite increase sludge infill. The % change was calculated with respect to t_n for each scenario.

Site	Date	Sludge infill %	t_n (days)	t_{mean} (days)	% change	Mass recovery %
Pond 1	2015	45	14.0	11.9	−15	76
Pond 2	2013	21.5	19.1	14.0	−27	84
	2015	29	18.1	17.0	−6	94

The tracer mass recovery for each pond calculated using weekly-averaged flow rates over the monitoring period is shown in Figure 7B. Of the Rhodamine WT released into each pond, 76% and 94% was recovered from Ponds 1 and 2, respectively. In Pond 1, it is clear that more tracer exits the system over the first 26 days compared to Pond 2, a sign of short-circuiting within the system, but this tapers off as dye becomes trapped in dead zones or re-circulates waiting to be flushed out. In Pond 2, the recovery of tracer is steadily linear, indicative of a decrease in short-circuiting and fewer dead zones, i.e., the baffles have the desired effect of training the flow and optimising pond hydraulics.

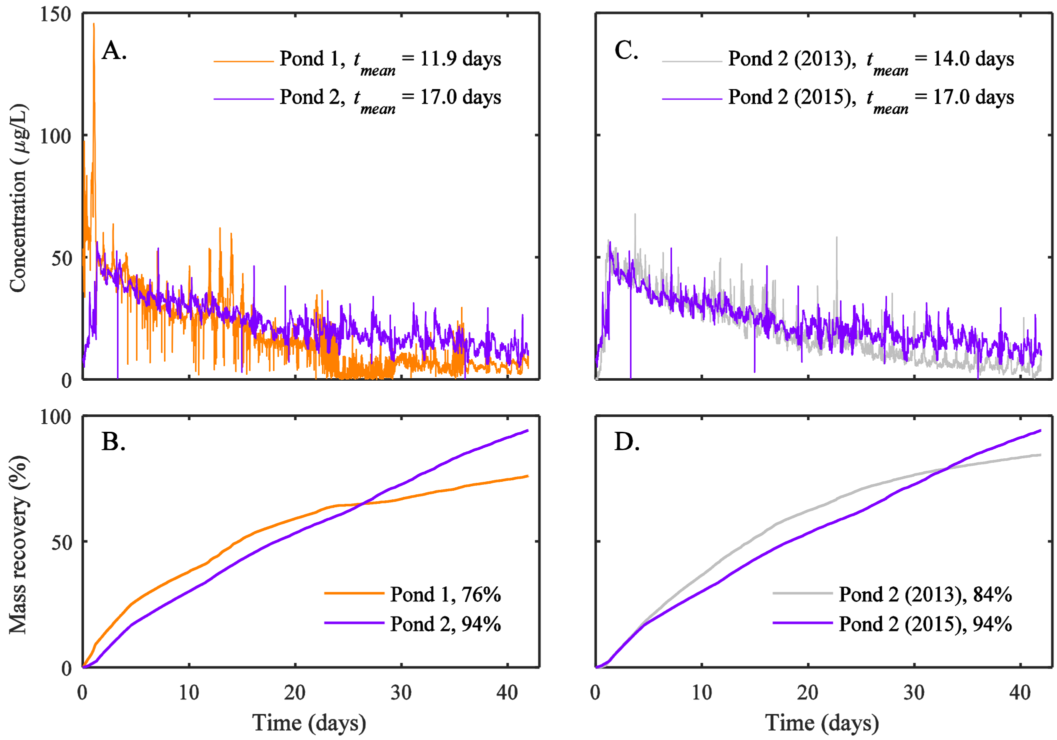

Figure 7. Residence time distributions (RTD) and mass recovery of the field tracer tests on Ponds 1 and 2 in 2013 and 2015, each over a 42-day period. (**A**) RTDs in 2015 tracer study. Pond 1 (no baffles; orange) experiences a much higher concentration peak earlier than in Pond 2 (purple), indicative of a higher level of short-circuiting. (**B**) Field tracer mass recoveries of Pond 1 (orange) and Pond 2 (purple) in 2015, where 76% and 94% of the mass released had been recovered at end of the monitoring period, respectively. (**C**) Tracer response in Pond 2, before (2013) and after (2015) baffle installation. Residence time has increased by at least 20% due to baffle installation. (**D**) Mass recovery from Pond 2, pre- and post- baffle installation, where recovery has increased by 10%. Overall, the baffles appear to attenuate concentration fluctuations, decrease short-circuiting and the presence of dead zones, and increase residence time.

In 2013, prior to baffle installation, Pond 2 had a sludge infill of 21.5% (as modelled) and, using the flow rate over the winter period (the "high" flow rate, 385 kL·day^{-1}) a nominal residence time (t_n) of 19.1 days (Table 2). Over the 42-day tracer testing period, t_{mean} was calculated to be 14.0 days, 27% lower than the nominal residence time. The mean residence time in Pond 2 increased by 20% with the addition of baffles (Figure 7C), despite sludge infill over this time increasing by 7.5%. This is a very clear indication that baffles have improved the pond hydraulics through decreasing short-circuiting. Furthermore, mass recovery of tracer increased by 10% (Figure 7D; Table 2), indicating that there are fewer dead zones in the presence of baffles, and thus more of the effective volume of the pond is being used for treatment.

To further illustrate the effect that baffles have on the flow in ponds, output of flow patterns from the hydrodynamic model using the actual bathymetry over the tracer testing period is shown in Figure 8. As the ponds both have the same inlet configuration, the effect that the baffles in Pond 2 (Figure 8B) have on the flow compared to the Pond 1 is clear (Figure 8A). With the addition of baffles in Pond 2, flow patterns show that the first baffle slows down incoming flow significantly, and that the flow is directed around baffles, as expected. Without the presence of baffles in Pond 1, the flow speeds across the pond are much higher, and more flow recirculation is apparent. Again, this demonstrates that baffles have the desired effect of training flow and improving pond hydraulics.

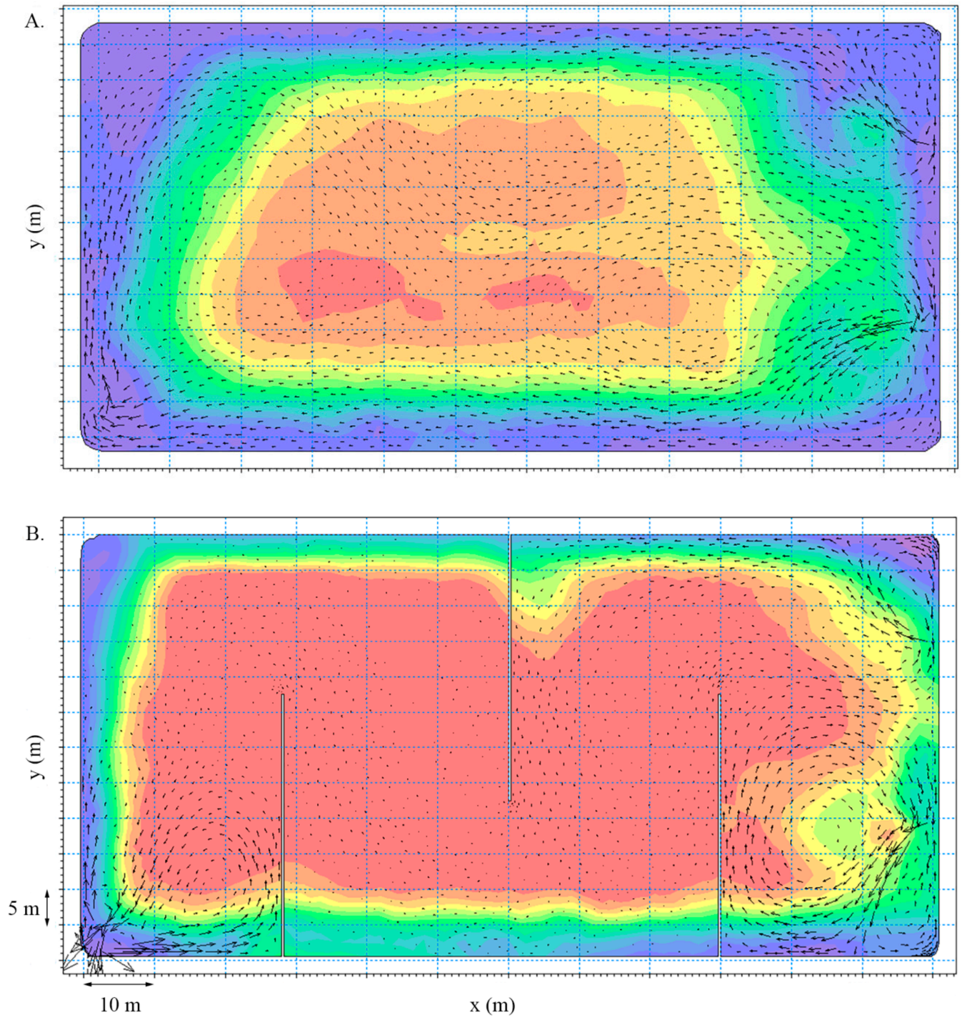

Figure 8. Hydrodynamic model flow output plots for (**A**) Pond 1 with 45 % sludge infill, and (**B**) Pond 2 with 29% sludge infill. Installing perpendicular baffles in Pond 2 changed the flow within the pond significantly, particularly near the inlets, and directed the flow through the entire pond volume. Grid spacing shown is 10 m in x and 5 m in y.

It is important to note that the concentration peak in Pond 2 before and after the installation of baffles is similar (Figure 7C), while Pond 1 clearly shows different behaviour (Figure 7A). The differing behaviour measured with the field tracer in non-baffled conditions may be attributed to unequal inflow splitting between not only the two ponds as a whole, but also between the twin inlets in each pond; for all analyses it is assumed that the inflow into each pond and through each inlet is equal. This indicates that Pond 1 cannot be considered a true control pond, and therefore it is only used a non-baffled reference.

3.4. Modelled Effect of Wind on Flow

Sludge bathymetry of both ponds from the tracer testing period was input into the model with and without wind forcing, and the results for the 42-day period were compared to the tracer results. The influence of wind in (non-baffled) Pond 1 is shown in Figure 9A. Without the influence of wind (Figure 9A; purple), the model captures the timing of the initial peak relatively well, however the length of this peak is over-predicted. After the initial peak, the trend of the model fits that of the field tracer data quite well. With the addition of wind (Figure 9A; orange), the initial peak occurs earlier than previously, with a peak concentration higher and earlier than seen in the field. After the peak, the rest of the RTD agrees well. The values of t_{mean} calculated for both model scenarios (11.2 days) are very similar to the field tracer, showing that the model is effective at capturing the hydrodynamics of this pond. These RTD results show that in Pond 1 the addition of wind into the model mostly affects the peak value and its timing, and less so the mean residence time.

Wind influence on the baffled Pond 2 is shown in Figure 9B. In the no wind scenario (Figure 9B; purple) the model predicts the peak value of the tracer output relatively well; however, it predicts a later peak. With the addition of wind into the Pond 2 model (Figure 9B; orange) there is very little change from the no wind scenario, with no change in the overall shape of the distribution, peak, nor the timing of the peak. The t_{mean} calculated for no wind and wind scenarios are 14.2 and 14.5 days respectively. For both scenarios, the model does not appear to capture the same gradual decrease in tracer concentration as shown in the field measurement. Overall, the results for Pond 2 show that baffles attenuate any major hydrodynamic influence of wind.

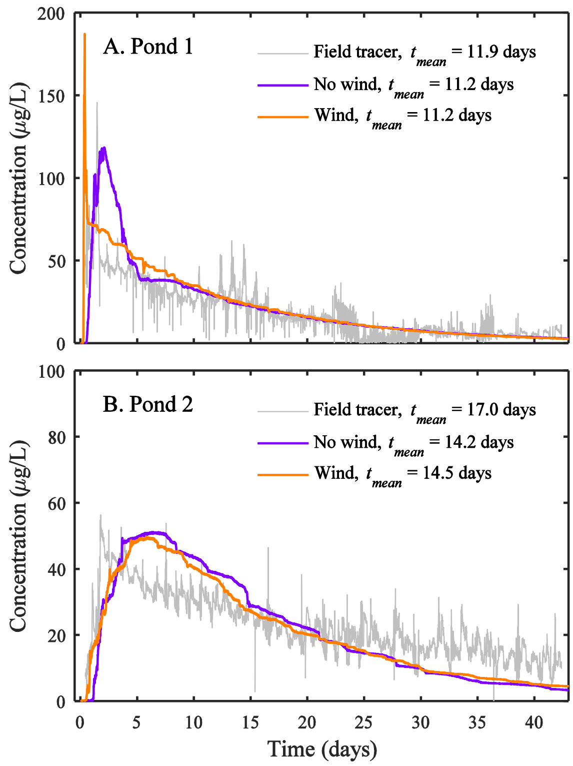

Figure 9. The modelling results for (**A**) non-baffled Pond 1 and (**B)** baffled Pond 2 with and without the influence of wind, compared to field tracer testing over a 42-day period. In Pond 1 (**A**) with the addition of wind to the model (orange), the initial peak is higher and occurs earlier, compared to both the no wind scenario (purple) and field tracer (grey). Overall, the Pond 1 model RTD with wind is in better agreement with that of the tracer study; however, this has no influence on the residence time. Modelling suggests that wind does not appear to greatly influence the flow in Pond 2 (**B**). Overall, baffling in Pond 2 appears to attenuate the influence of wind on the RTD, compared to Pond 1 (**A**).

4. Discussion

4.1. Determination of Optimal Baffle Configuration

Our ability to capture high-resolution data of pond bathymetry, coupled with a validated 2D hydrodynamics model of ponds, is very useful for pond managers to assess the performance of their assets. Furthermore, it can be used as a tool to determine the optimal design of flow control structures in ponds, such as baffles. In this study, by determining key hydraulic indices from model flows in ponds with different baffle configurations, the most effective configurations for this particular site could be readily determined. While the short-circuiting index has been used to assess different pond layouts previously e.g., [22], the use of the moment index is new in its application to WSPs [34,35], and provides an index that is not reliant on mixing or short-circuiting, or influenced by the long tails characteristic of most residence time distributions [33]. In this study, we for the first time used a suite of three hydraulic indices (t_{mean}, *MI* and *S*), all describing different but complementary aspects of hydraulic efficiency, to better assess the overall behaviour of ponds.

By modelling the pond under low, average and high flow conditions and assessment of the changes in *MI* and *S* (Table 1, Figure 5), it was determined that pond residence time could increase by up to 24% with the addition of baffles, and two possible configurations were identified as suitable to consistently improve the flow characteristics in this system. Through this modelling and analysis exercise, a well-informed decision could then be made about which configuration to adopt. This is pertinent here as while the IPE3 configuration showed the greatest overall improvement, it was only slightly better than PE3, and PE3 was significantly easier and cheaper to construct.

While inlet configuration can have a significant influence on flow [24], this study did not consider the possible improvement that could be provided by altering the inlet/outlet geometry in these ponds. In this case, the location of the inlets could explain the hydrodynamic model under predicting the influence of baffles on the flow (Figure 9B). For consistency, tracer was released into the northern inlet of each pond; doing so in Pond 2 with baffles (see Figure 3) reduced the distance between tracer release and pond outlet. Therefore, redesign of the inlet configuration with the addition of baffles could further improve the hydraulic efficiency of this pond.

The results of this modelling exercise are site-specific but, as demonstrated here, all that is required to apply this methodology is high-resolution bathymetry data for model input: information which can easily be obtained for other sites with the right tool, such as the ROV used here. Thus, modelling and the use of informative hydraulic indices can successfully be used to inform re-design and retrofitting of pond infrastructure, but in the future it could also be used to determine the design of new ponds.

4.2. Flow and Treatment Improvement Provided by Baffles

The results of the tracer testing show that baffles have a clear effect on the characteristics of the flow in the pond (Figure 7A,C), with daily fluctuations in tracer concentration decreasing in intensity compared to the non-baffled system. While Pond 1 was not a true control pond, as it had a higher sludge infill than Pond 2 (45% vs. 29%), the distributions of sludge in Ponds 1 and 2 are similar (Figure 1B,D), with accumulation mainly occurring around the edges of the pond and slight benches of sludge near the inlets. Indeed, the overall flow patterns in the ponds are comparable. The changes induced by the introduction of baffles is made clear in Figure 8B where the first baffle significantly slows down the incoming flow from the twin inlets. The presence of baffles in Pond 2 explains the attenuation of concentration fluctuations compared to Pond 1 (Figure 7A), where there is a significant amount of short-circuiting around the edges of the pond, particularly between the southern inlet and the outlet.

Overall, through the full-scale implementation of baffles, we show that the increase in residence time in Pond 2 is at least 20%. This result validates the outputs of our modelling, where results suggested that residence time could increase by up to 24%. While treatment efficiency is only assessed in terms of pond hydraulics in this study, the removal efficiencies of constituents of concern are strongly dependent on hydraulics [15]. Through increasing residence time in WSPs, it is believed that baffles can improve the removal of *E. coli* [26] and BOD [28]; the pollutant removal efficiencies in this system after the installation of the attached growth baffles will be reported in the future.

It is also important to note the effect of sludge accumulation and distribution over time on the hydraulic performance of ponds; a previous study by Coggins et al. [17] showed that mean residence time reduced almost directly proportionally to the amount of sludge infill. The previous study also showed that the distribution of sludge had an effect on hydrodynamics, with the formation of a bench of sludge and a preferential flow channel having positive and negative effects, respectively [17]. Considering the sludge infill in Pond 2 increased from 21.5% (2013; pre-baffle) to 29% (2015; post-baffle), we would have expected a decrease in mean residence time; however, as shown by field tracer results (Table 2), the mean residence of the baffled pond increased despite the accumulation of sludge. This improvement, despite an increase in sludge infill, can be attributed to the baffles significantly reducing short-circuiting within the system. Over time, we would still expect the mean residence time to decrease with increased sludge infill with the presence of baffles, however the effect will be less pronounced, and will allow pond managers to delay desludging. In addition, the presence of baffles create a preferential zone of deposition in front of the first baffle, which will simplify and reduce the cost of sludge removal.

In general, the assessment of baffles installed in a full-scale WSP has shown that they improve the flow as suggested by results of modelling with high-resolution bathymetry. The improvement provided by baffles in ponds is not only better hydraulic performance through reducing short-circuiting and increasing residence time, but also through the promotion of small-scale mixing and increasing the pond effective volume for treatment.

4.3. The Impact of Wind on Ponds

The inclusion of wind in hydrodynamics modelling of WSPs is not a recent development, with several previous studies incorporating wind into WSP models e.g., [36–39], however there is still a need to better understand the effect that environmental conditions have on the function of WSPs, including wind [40].

In this study, with the addition of wind data into the model, it is clear that wind has the most influence on the non-baffled Pond 1 (Figure 9A), with a much greater peak concentration. By comparison, wind has an insignificant influence on the hydraulics of Pond 2 (Figure 9B). Overall, the most significant insight provided by modelling the ponds with and without the influence of wind is that wind affects the overall shape of the RTD for Pond 1, but not the residence time (Figure 9A). In Pond 2 wind has a negligible effect on the hydraulic behaviour, with no change in the shape of the RTD, and only a slight change in t_{mean} (Figure 9B). This result suggests that, in addition to improving pond hydrodynamics, baffles also attenuate the effects of wind on the flow. The prevailing wind directions throughout the day at the study site are always 45° against the inflow, which could explain this slight difference, as the wind could be acting to slow the flow down in this pond. Our modelling confirms the earlier observation that the influence of wind on pond hydraulics may have been overestimated [24]. Overall, our results suggest that the influence of wind on the hydraulics in these ponds is not significant, and that a hydrodynamic model without the inclusion of wind is a sufficient approach to assess the hydrodynamic behaviour of ponds, as suggested in Shilton et al. [41]. Nonetheless, wind may still play a role in other systems under different climatic forcings.

5. Conclusions

From this study, we have demonstrated that 2D hydrodynamic modelling of WSPs combined with moment and short-circuiting indices can be used to determine the baffle configurations that optimise hydraulic efficiency. This approach determined two optimal configurations for the site, which were then assessed for practicality and cost-effectiveness to install. The most practical design for this site was three perpendicular baffles, which were then constructed to allow a full-scale investigation. After the installation, tracer testing on site confirmed that the chosen baffle configuration significantly improved the hydrodynamics. The baffles both decreased short-circuiting and increased mean residence time by at least 20%, thus improving the hydraulic performance of the pond. The addition of wind data into the hydrodynamic model did not have a major impact on calculated residence times, but showed that baffles can also attenuate the effect of wind on pond hydraulics. Overall, based on the results of the full-scale experiment, the approach developed here to assess optimal baffle configuration is appropriate to make site-specific recommendations. As demonstrated here, more than one baffle configuration could lead to significant improvement in hydraulic performance, however it is recommended that the best design should be decided based upon practicality, feasibility and cost-effectiveness, as well as site characteristics.

Acknowledgments: This project was funded by the Water Corporation of Western Australia R&D grants, and an Australian Research Council Linkage grant (LP130100856). We wish to thank Binod Agarwalla and Dean Italiano from the Water Corporation, Christopher Murphy and Cyprien Bosserelle for their help with modelling, Dipak Raghvani, Elke Reichwaldt, John Langan, James Hehre for their assistance in the field operations, and Sébastien Bourget for setting up the weather station. Liah X. Coggins was supported by a Prescott Postgraduate Scholarship from The University of Western Australia, and the TasWater Wastewater Engineering Scholarship.

Author Contributions: L.X.C., M.G. and A.G. conceived and designed the experiments; J.S., L.Z. and L.X.C. performed the modelling and collected field tracer measurements. L.X.C., J.S. and L.Z. analysed the data; L.X.C. wrote the paper, which A.G. and M.G. provided input on.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Daigger, G.T. Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, and Resource Recovery. *Water Environ. Res.* **2009**, *81*, 809–823. [CrossRef] [PubMed]
2. Shannon, M.A.; Bohn, P.W.; Elimelech, M.; Georgiadis, J.G.; Marinas, B.J.; Mayes, A.M. Science and technology for water purification in the coming decades. *Nature* **2008**, *452*, 301–310. [CrossRef] [PubMed]
3. United Nations Development Programme. *Human Development Report 2006 - Beyond Scarcity: Power, Poverty and the Global Water Crisis*; United Nations Development Programme (UNDP): NY, USA, 2006.
4. UN-Water, Food and Agriculture Organization of the United Nations (FAO). *Coping With Water Scarcity: Challenge of the Twenty-First Century*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2007.
5. Rodriguez, D.J.; van den Berg, C.; McMahon, A. *Investing in Water Infrastructure: Capital, Operations and Maintenance*; World Bank: Washington, DC, USA, 2012.
6. GHD. *Infrastructure Maintenance—A Report for Infrastructure Australia*; GHD: Sydney, Australia, 2015.
7. Hering, J.G.; Waite, T.D.; Luthy, R.G.; Drewes, J.E.; Sedlak, D.L. A Changing Framework for Urban Water Systems. *Environ. Sci. Technol.* **2013**, *47*, 10721–10726. [CrossRef] [PubMed]
8. Water Services Association of Australia (WSAA), Infrastructure Partnerships Australia (IPA). *Doing the Important as Well as the Urgent: Reforming the Urban Water Sector*; WSAA and IPA: Sydney, Australia, 2015.
9. Grant, S.B.; Saphores, J.-D.; Feldman, D.L.; Hamilton, A.J.; Fletcher, T.D.; Cook, P.L.M.; Stewardson, M.; Sanders, B.F.; Levin, L.A.; Ambrose, R.F.; et al. Taking the "Waste" Out of "Wastewater" for Human Water Security and Ecosystem Sustainability. *Science* **2012**, *337*, 681–686. [CrossRef] [PubMed]
10. Organisation for Economic Co-operation and Development (OECD). *Infrastructure to 2030: Telecom, Land Transport, Water and Electricity*; OECD Publishing: Paris, France, 2006.
11. Mara, D. *Domestic Wastewater Treatment in Developing Countries*; Earthscan: London, UK, 2004.
12. Nelson, K.L.; Cisneros, B.J.; Tchobanoglous, G.; Darby, J.L. Sludge accumulation, characteristics, and pathogen inactivation in four primary waste stabilization ponds in central Mexico. *Water Res.* **2004**, *38*, 111–127. [CrossRef] [PubMed]
13. Peña Varón, M.; Mara, D. *Waste Stabilisation Ponds*; IRC International Water and Sanitation Centre: Delft, The Netherlands, 2004.

14. Picot, B.; Sambuco, J.P.; Brouillet, J.L.; Riviere, Y. Wastewater stabilisation ponds: sludge accumulation, technical and financial study on desludging and sludge disposal case studies in France. *Water Sci. Technol.* **2005**, *51*, 227–234. [PubMed]
15. Laurent, J.; Bois, P.; Nuel, M.; Wanko, A. Systemic models of full-scale Surface Flow Treatment Wetlands: Determination by application of fluorescent tracers. *Chem. Eng. J.* **2015**, *264*, 389–398. [CrossRef]
16. Persson, J.; Wittgren, H.B. How hydrological and hydraulic conditions affect performance of ponds. *Ecol. Eng.* **2003**, *21*, 259–269. [CrossRef]
17. Coggins, L.X.; Ghisalberti, M.; Ghadouani, A. Sludge accumulation and distribution impact the hydraulic performance in waste stabilisation ponds. *Water Res.* **2017**, *110*, 354–365. [CrossRef] [PubMed]
18. Olukanni, D.O.; Ducoste, J.J. Optimization of waste stabilization pond design for developing nations using computational fluid dynamics. *Ecol. Eng.* **2011**, *37*, 1878–1888. [CrossRef]
19. Muttamara, S.; Puetpaiboon, U. Roles of baffles in waste stabilization ponds. *Water Sci. Technol.* **1997**, *35*, 275–284.
20. Muttamara, S.; Puetpaiboon, U. Nitrogen removal in baffled waste stabilization ponds. *Water Sci. Technol.* **1996**, *33*, 173–181.
21. Farjood, A.; Melville, B.W.; Shamseldin, A.Y. The effect of different baffles on hydraulic performance of a sediment retention pond. *Ecol. Eng.* **2015**, *81*, 228–232. [CrossRef]
22. Persson, J. The hydraulic performance of ponds of various layouts. *Urban Water* **2000**, *2*, 243–250. [CrossRef]
23. Salter, H.E.; Ta, C.T.; Williams, S.C. Three-dimensional computational fluid dynamic modelling of a facultative lagoon. *Water Sci. Technol.* **2000**, *42*, 335–342.
24. Shilton, A.; Harrison, J. Development of guidelines for improved hydraulic design of waste stabilisation ponds. *Water Sci. Technol.* **2003**, *48*, 173–180. [PubMed]
25. Vega, G.P.; Pena, M.R.; Ramirez, C.; Mara, D.D. Application of CFD modelling to study the hydrodynamics of various anaerobic pond configurations. *Water Sci. Technol.* **2003**, *48*, 163–171. [PubMed]
26. Shilton, A.; Mara, D.D. CFD (computational fluid dynamics) modelling of baffles for optimizing tropical waste stabilization pond systems. *Water Sci. Technol.* **2005**, *51*, 103–106. [PubMed]
27. Aldana, G.J.; Lloyd, B.J.; Guganesharajah, K.; Bracho, N. The development and calibration of a physical model to assist in optimising the hydraulic performance and design of maturation ponds. *Water Sci. Technol.* **2005**, *51*, 173–181. [PubMed]
28. Abbas, H.; Nasr, R.; Seif, H. Study of waste stabilization pond geometry for the wastewater treatment efficiency. *Ecol. Eng.* **2006**, *28*, 25–34. [CrossRef]
29. Bureau of Meteorology (BOM). Climate Data. Available online: http://www.bom.gov.au/climate/data/ (accessed on 19 July 2016).
30. DHI. *MIKE 21 Flow Model: Advection-Dispersion Module Scientific Documentation*; DHI: Hørsholm, Denmark, 2012.
31. DHI. *MIKE 21 Flow Model: Advection-Dispersion Module User Guide*; DHI: Hørsholm, Denmark, 2012.
32. Babu, M.A.; Hes, E.M.A.; van der Steen, N.P.; Hooijmans, C.M.; Gijzen, H.J. Nitrification rates of algal-bacterial biofilms in wastewater stabilization ponds under light and dark conditions. *Ecol. Eng.* **2010**, *36*, 1741–1746. [CrossRef]
33. Wahl, M.D.; Brown, L.C.; Soboyejo, A.O.; Martin, J.; Dong, B. Quantifying the hydraulic performance of treatment wetlands using the moment index. *Ecol. Eng.* **2010**, *36*, 1691–1699. [CrossRef]
34. Murphy, C. Quantifying the Impact of Sludge Accumulation on the Hydraulic Performance of Waste Stabilisation Ponds. Bachelor's Thesis, The University of Western Australia, Crawley, Australia, 5 November 2012.
35. Ouedraogo, F.R.; Zhang, J.; Cornejo, P.K.; Zhang, Q.; Mihelcic, J.R.; Tejada-Martinez, A.E. Impact of sludge layer geometry on the hydraulic performance of a waste stabilization pond. *Water Res.* **2016**, *99*, 253–262. [CrossRef] [PubMed]
36. Sweeney, D.G.; Cromar, N.J.; Nixon, J.B.; Ta, C.T.; Fallowfield, H.J. The spatial significance of water quality indicators in waste stabilization ponds - limitations of residence time distribution analysis in predicting treatment efficiency. *Water Sci. Technol.* **2003**, *48*, 211–218. [PubMed]
37. Banda, C.G.; Sleigh, P.A.; Mara, D.D. CFD-based design of waste stabilization ponds: Significance of wind velocity. In Proceedings of the 7th IWA Specialist Group Conference on Waste Stabilization Ponds, Bangkok, Thailand, 25–27 September 2006.
38. Badrot-Nico, F.; Guinot, V.; Brissaud, F. Taking wind into account in the design of waste stabilisation ponds. *Water Sci. Technol.* **2010**, *61*, 937–944. [CrossRef] [PubMed]

39. Sah, L.; Rousseau, D.P.L.; Hooijmans, C.M.; Lens, P.N.L. 3D model for a secondary facultative pond. *Ecol. Model.* **2011**, *222*, 1592–1603. [CrossRef]
40. Passos, R.G.; Dias, D.F.C.; von Sperling, M. Review of practical aspects for modelling of stabilization ponds using Computational Fluid Dynamics. *Environ. Technol. Rev.* **2016**, *5*, 78–102. [CrossRef]
41. Shilton, A.; Kreegher, S.; Grigg, N. Comparison of Computation Fluid Dynamics Simulation against Tracer Data from a Scale Model and Full-Sized Waste Stabilization Pond. *J. Environ. Eng.-ASCE* **2008**, *134*, 845–850. [CrossRef]