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Chemical Engineering Research and Design

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Predicting long-term solid accumulation in waste stabilisation lagoons through a combined CFD-process model approach

Mohammad Shakil Ahmed [a,*], *Alan Skerman* [b], *Damien J. Batstone* [a]

[a] *Australian Centre for Water and Environmental Biotechnology (formerly AWMC), The University of Queensland, Australia*

[b] *Department of Agriculture and Fisheries, Queensland, Australia*

ARTICLE INFO

Article history:
Received 18 December 2021
Received in revised form 24 May 2022
Accepted 7 June 2022
Available online 14 June 2022

Keywords:
Lagoons
Long-term sludge behaviour
Hydrodynamics
Biochemical process

ABSTRACT

Sludge accumulation in anaerobic lagoons is one of the major issues determining long-term operating costs. However, very little mechanistic analysis has been done on long-term sludge behaviour. A coupled hydrodynamic-biochemical model was developed using computational fluid dynamics (CFD), and results from this applied to a compartmental based model (CBM) for long-term simulation. The CFD model incorporates a mixture method for the spatial-and temporal evolution of fluid and solids with a non-Newtonian rheology. CFD was used to evaluate short term hydrodynamics, and a common CBM used to understand the fluid movement and sludge behaviour of full-scale anaerobic lagoons (with varying depths, sidewall slopes, and loading rates), operating in commercial piggeries located in Southern Queensland and Southern New South Wales, Australia. The results found that the lagoons had varying hydrodynamics, and sludge accumulates rapidly in sloped sidewall lagoons, forming a variable depth bed which occupied a substantial fraction of the lagoons. Shallow lagoons were dominated by significant surface recirculation dynamics, and were susceptible to solids accumulation, while deep lagoons allowed the formation of a well developed settled fraction. Predicted lagoon lifetimes varied substantially, but predicted long-term accumulation rates were approximately double that observed, due to long-term degradation of slowly degradable material.

1. Introduction

Waste stabilisation lagoons (WSL) are critical to intensive animal production across the world. They allow for effective treatment for water recycling, and when covered, capturing of methane emissions by covering the lagoon, with low-cost, minimal energy consumption and technical requirements (Shilton et al., 2008; Isosaari et al., 2010; Adhikari and Fedler, 2020). In WSL, the wastewater constituents are typically removed by sedimentation combining chemical and biological processes, resulting in a purified effluent and accumulation of sludge due to sedimentation and subsequent digestion (Nelson et al., 2004b; Coggins et al., 2018). The accumulated sludge has value as organic fertiliser and soil amendment (Adhikari and Fedler, 2020). However, long term accumulation of excess sludge is a major cost in operating lagoons. The accumulated sludge is difficult and expensive to extract, and accumulation rate can be difficult to monitor and predict. Lagoon lifetime can vary by orders of magnitude (e.g. about one year to twenty years). As the sludge progressively accumulates, the treatment capacity of a lagoon decreases. This potentially results in odour emission, ineffective treatment of the effluent, and carryover solids into the secondary effluent storage. Furthermore, the sludge's solid content and viscosity generally increase with storage time, and depth

* Corresponding author.
E-mail addresses: ahmmedshakil@gmail.com (M.S. Ahmed), skermos@bigpond.com (A. Skerman).

https://doi.org/10.1016/j.cherd.2022.06.012

Table 1 – Physical parameters of the lagoons used in simulations.

Lagoon	Depth, H (m)	Length, L (m)	Width, W (m)	Volume, V (m^3)	Inlet flow, Q (m^3/d)	Total solid, TS (kg/m^3)	Operating HRT (d)
A	8	70.55	29.64	7200	61.66	3	116.78
B	5.5	151	116	67600	276.78	3	244
C	4.2	120	115.95	43371	61.27	3	707.82
D	3	70.5	52.18	8500	1248	3	6.81

within the sludge profile, resulting in reducing hydraulic retention time (HRT) and affecting treatment efficiency of the lagoons (Nelson et al., 2004a).

A crucial aspect in lagoon management is predicting and minimising sludge accumulation. The sludge behaviour is intimately linked with lagoon hydrodynamics, including fluid movement, solid settling, and turbulent flow, and biochemical processes. There is very limited research into these fundamental processes in lagoons, governed by two-phase liquid-solid, non-Newtonian viscosity, variable density, and biological reactions. As a result, WSL systems are built and operated mainly based on empirical experience, without considering hydrodynamics from a mechanistic perspective. A mechanistic computational analysis of WSL would substantially assist in providing an optimised design of the lagoon for optimal accumulation, given varied lagoon designs and sizes.Experimental empirical optimisation is expensive and unwieldy to be used as an optimisation tool. Several experimental studies carried out to measure sludge accumulation rates in lagoons (Abis and Mara, 2005; Barth and Kroes, 1985; Barth, 1985; Chastain, 2006; Skerman et al., 2008; Birchall, 2013; Hamilton, 2010). The impact of design and management of anaerobic lagoons and sludge removal systems on the sludge distribution on lagoons' base and batters are also monitored for reducing dead zones (OKeefe et al., 2014; Papadopoulos et al., 2003; Picot et al., 2005; Gratziou and Chalatsi, 2015; Nelson et al., 2004a). While these studies suggested a clear interactions between sludge distribution and lagoon hydrodynamics, these processes are poorly understood and have not been well studied for anaerobic lagoons.

Computational modelling has evolved as a useful tool that can help understand sludge behaviour. The literature shows a considerable number of studies employed computational fluid dynamics (CFD) in evaluating hydraulic performance of the waste stabilisation lagoons using single phase model, without considering sludge accumulation, and rheology of the liquid as well (Ho and Goethals, 2020). Extensive work has been done in modelling facultative and open lagoons for the purposes of flow distribution modelling. This generally analyses steady state flow, with a single phase assumption to minimise short circuiting (Wood et al., 1995,1998; Shilton, 2000; Salter et al., 2000; Coggins et al., 2018). The impact of surface wind direction has also been assessed by varying top boundary condition (Sweeney et al., 2003; Aldana et al., 2005). The impact of sludge accumulation on shallow maturation Ponds in Brazil have been assessed (Passos et al., 2014,2019), but only as a static problem.Due to computational requirements, long-term simulation studies are very difficult, and most of the studies above have been with a steady state assumption or short term hydraulic flows with sludge being a static element. Alvarado et al. (2012) used a combined compartmental based model (CBM) and CFD approach for long-term simulations of a single waste stabilisation lagoon. The approach is based on developing an optimised, simplified compartmentalised model based on CFD. It focused on simplified representation of the waste stabilisation lagoons specific mixing behaviour and did not consider sludge accumulation. It is a single case, and general applicability of the CBM to lagoon systems has not been tested.

We extend the CBM approach applied by Alvarado et al. (2012) to four very different WSLs with variable geometry, loading, and feed concentration, by (a) characterising hydrodynamics and sedimentation behaviour in the short term using CFD (two-phase non-Newtonian rheology), (b) using the same generally applicable CBM on all four lagoons using results from CFD, and simulating these over the lifetime of the lagoon, and (c) comparing to long term field data. This allows assessment of long-term sludge accumulation rates, mean flow characteristics, and biochemical processes to identify the impact on achieving optimal performance on the wastewater treatment.

2. CFD-process modelling approach

2.1. Overview of the physical problem

The systems assessed are four primary anaerobic effluent lagoons operating in Southern Queensland and Southern New South Wales, Australia. The lagoons are namely: Lagoon-A (depth of 8 m), Lagoon-B (depth of 5.5 m), Lagoon-C (depth of 4.2 m), and Lagoon-D (depth of 3 m). Lagoons A, B, and C are operated in Southern Queensland, and Lagoon-D is in Southern New South Wales. Submerged pipes, with a diameter of 0.3 m, are used as inlet and outlet for the lagoons. A summary of the lagoons' physical parameters and operating conditions are given in Table 1. A schematic of the physical problem and positions of the inlet and outlet is shown in Fig. 1. Maps and diagrams of the lagoons are provided in Skerman et al. (2019), with lagoons A, B, C, D being systems 2, 5, 7, and 16 respectively.

2.2. CFD model for hydrodynamics and solid settling

The flow fields along with solid settling may be evaluated resolving mixture continuity and momentum equations as follows (Brennan, 2001),

$$\frac{\partial \alpha}{\partial t} + \nabla.\ (\alpha U) + \nabla.\ (\alpha V_s) - \nabla.\ (\Gamma \nabla \alpha) = 0, \tag{1}$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla.\ (\rho U U) = -\nabla P + \nabla.\ [(\tau + \tau^t)] + \rho g - \nabla.\ \left(\frac{\alpha}{1-\alpha}\frac{\rho_s \rho_l}{\rho} V_s V_s\right), \tag{2}$$

where, α is the sludge volume fraction; U, P, ρ, and Γ are the velocity, pressure, density, and diffusivity; ρ_l and ρ_s are the density of liquid and sludge, respectively; τ and τ^t are the stress tensors due to shear and turbulence, respectively; and V_s is the sludge settling velocity. The shear stress tensor

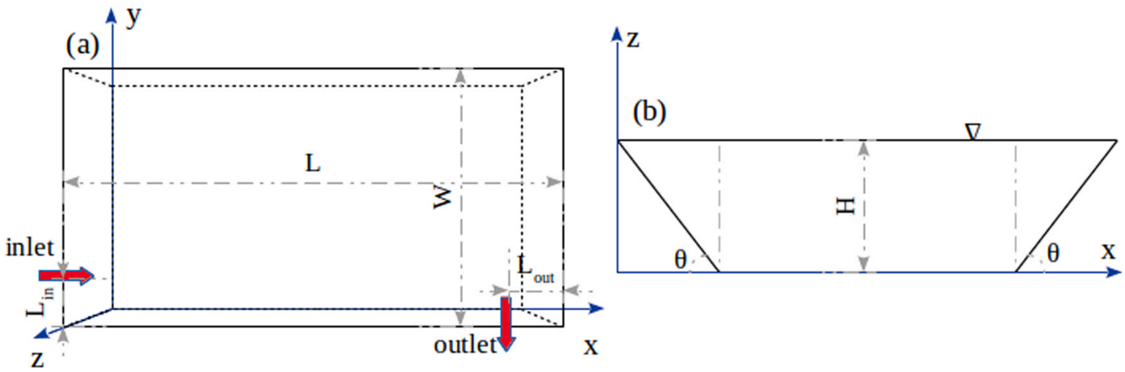

Fig. 1 – Schematic of the anaerobic effluent lagoons, (a) top-view, and (b) longitudinal-view. Here, L, W, H, L_{in}, L_{out}, θ, and ∇ represent the length, width, height, positions of the inlet and outlet, inclined angle, and free-surface, respectively. The schematic is presented for demonstration purpose only and not drawn in scale.

depends on the liquid viscosity, μ, whereas the turbulent stress tensor is influenced by the eddy viscosity, μ_t. The liquid is considered as shear-thinning and its viscosity μ follows the Bingham-plastic model as (Liu and Garcia, 2011),

$$\mu(\alpha, \dot{\gamma}) = \frac{\tau(\alpha)}{\dot{\gamma}} + \mu_p(\alpha), \tag{3}$$

where, $\dot{\gamma}$ is the shear strain-rate, τ is the yield stress, and μ_p is the plastic viscosity. The eddy viscosity μ_t is calculated resolving buoyancy-modified $k-\epsilon$ turbulence models (Brennan, 2001, 2005), where k and ϵ represent the turbulent kinetic energy and the rate of energy dissipation, respectively.The settling velocity may be calculated using the double-exponential settling velocity equation as (Takacs et al., 1991),

$$V_s = V_0 e^{-r_h (X - X_{min})} - V_0 e^{-r_p (X - X_{min})}, \tag{4}$$

where, V_0 is the maximum settling velocity; X and X_{min} are the actual and minimum sludge concentrations, respectively; and r_h and r_p are the coefficients of hindered settling and low-concentrations zone, respectively. The values of r_h and r_p are taken as 201.4 and 742 (non-dimensional), respectively, whereas the maximum settling velocity V_0 is considered as 0.0013 m/s (Gernaey et al., 2001). The temporal and spatial evaluations of the tracer particles are calculated resolving a convection-diffusion equation as,

$$\frac{\partial C}{\partial t} + \nabla.(UC) - \nabla.(\Gamma \nabla C) = 0, \tag{5}$$

where, C represents the tracer concentration.

2.3. Compartmental based model (CBM)

The CBM consists of two main and bypass compartments in series, a recycle and a outlet compartment, as demonstrated in Fig. 2. The geometry is based on general characteristic response of the lagoons as found during CFD. The recycle enables oscillatory behaviour, while the bypass allows for a high initial peak. A variable inactive zone is also added. Volumes of individual compartments, and internal bypass and recycle flows were fitted by parameter estimation. Furthermore, a delay is included, mainly simulating inlet retention.

2.4. Biochemical model

The biochemical model is implemented using the optimal hydraulic configuration identified from CBM. To simplify the model and allowing long-term simulations over the course of years, the influent fraction is taken as the mineral solids (X_{MSS}), degradable organics (X_d), and non-degradable organics (X_i). The degradable organics are assumed to degrade according to a first-order hydrolysis as,

$$r_{x,hyd} = -k_{hyd} X_d, \tag{6}$$

where, k_{hyd} is the hydrolysis coefficient. Solids washout is modelled individually by determining solids accumulation rate in each compartment from CFD.

2.5. Numerical settings

2.5.1. Settings for CFD

The governing equations of the CFD are discretised using the using finite volume method (FVM) in OpenFOAM. In resolving the coupled velocity-pressure equations, the hybrid PISO [1] and SIMPLE [2] pressure-velocity based algorithm is used, whereas the phase fraction equation has been resolved using the MULES [3] method. A time-marching solution is conducted using a Euler scheme, which is a first-order temporal discretisation scheme. In setting-up the boundary conditions, inlet is a constant velocity boundary, whereas the pressure boundary is employed at the outlet. The walls are taken as no-slip, and the free-surface is modelled as slip boundary. A virtual tracer test is conducted to determine residence time distributions (RTD) for the each of the lagoons. The feed is simulated as a pulse injection at 1 mg/L for 1000 s (0.01 days).

2.5.2. Process model implementation

The CBM model was utilised for the process model, based on optimised volumes and flows from the RTD. For biochemical modelling, a methane potential of 340 mL $CH_{4/gVS}$ was applied based on measurements in these systems (Skerman et al., 2017). This equates to an approximate degradability of 60% based on the COD, VS, and BMP data of Gopalan et al. (2013). A hydrolysis coefficient of 0.1 1/d was used based on the range 0.06–0.3 1/d (Gopalan et al., 2013). A value in the lower range was applied based on ambient temperature operation, as well as lack of mixing in the lagoon. Within the compartments of main-1, main-2 and recycle, a fraction of the

[1] Pressure-Implicit with Splitting of Operators
[2] Semi-Implicit Method for Pressure Linked Equations
[3] Multidimensional Universal Limiter with Explicit Solution

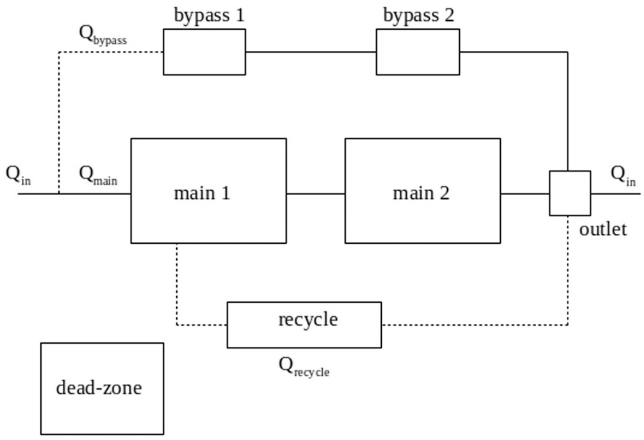

Fig. 2 – Compartmental based model (CBM) configuration. Here, Q_{in}, Q_{bypass}, $Q_{recycle}$, and Q_{main} represent the flow input, bypassed, recycled, and main, respectively.

solids (f_{sn}) is assumed to pass through to the effluent (does not sediment) in each pass through each reactor. This is estimated based on the observed effluent solids from the measured data (600 mg/L) and the results from CFD analysis, to be 10%. While the feed solids concentrations varied substantially, a common feed solids of 4% TS (40 g/L) was used to compare sludge accumulation on a common basis.The hydraulic volume occupied by the solids is calculated based on the observed concentration from the sampling campaign (15%), and this is represented as a separate, mixed compartment. No loss in degradation activity is applied to settled solids. The delay is excluded from the biochemical model, given it is likely mainly due to the inlet effects.

2.6. *Field Determination of the sludge accumulation rate*

Full details of field measurement are provided in Skerman et al. (2019). The first three lagoons were relatively old when sampled at 15 y (Lagoon-A), 13.5 y (Lagoon-B), 10 y (Lagoon-C) and unknown (Lagoon-D). Detailed data was not available for Lagoon D but it was added to the analysis to compare a high loaded, short HRT lagoon. Briefly, total solids and volatile solids (TS/VS) were measured by standard methods in the effluent, and the lagoon profiles were measured by surveying the lagoons via GPS in an aluminium punt and utilising a Lowrance HDS 5 echo sounder to survey the sludge depth. The sludge layer was also sampled, with an average sludge concentration across the four lagoons, and multiple locations of 15% (Lagoon D was lower at 10%). Geometric information was used to determine the volume occupied by sludge and was 95% of volume (Lagoon-A), 48% of volume (Lagoon-B), 84% of volume (Lagoon-C), and 59% of volume (Lagoon-D). Effluent TS was 640 mg/L (Lagoon-A), 900 mg/L (Lagoon-B), 420 (Lagoon-C), and unmeasured (Lagoon-D). The PigBal-4 model (Skerman et al., 2015) was used to estimate the total solids (TS) loading rates which had contributed to the sludge volumes measured in each of the lagoons. This modelling used historical pig herd, feed consumption and lagoon management data provided by the piggery operators. The resulting TS loading rates, estimated by the PigBal modelling, were used in conjunction with the sludge volumes determined by the sludge profiling survey, and the available lagoon desludging history, to estimate sludge accumulation rates ($m^3/kgTS_{fed}$) for each of the surveyed lagoons.

3. Results

3.1. *CFD simulations*

Fig. 3 shows the velocity contours and glyphs at top surfaces (at x-y plane) of the Lagoon-A (Fig. 3(a)), Lagoon-B (Fig. 3(b)), Lagoon-C (Fig. 3(c)), and Lagoon-D (Fig. 3(d)). Fig. 4 shows the velocity glyphs along with accumulated sludge layer (black colour) in these Lagoons at the longitudinal section (at x-z plane). The hydrodynamics and accumulated sludge are shown at 70 days for Lagoons A, B and C, and about 16 days for Lagoon-D; where the velocity approaches to steady-state and gives an indication for long-term behaviours of the fluid movement. Lagoon-D approached steady state far more quickly due to the high loading (and was far more computationally intensive). Lagoon-A exhibits mostly chaotic, high-velocity flow without ordered patterns throughout the Lagoon. The high degree of turbulence due to this chaotic flow indicates a larger mixing capacity and effective treatment throughout the lagoon volume. For Lagoons B, C and D, the velocity shows a recirculating behaviour constituting a large fraction of the lagoons, with the inlet flow entering into the recirculation. The recirculation dominates at inlet and outlet regions of the lagoons, whereas the rest of the volumes mostly remain inactive, as identified in Figs. 4. These differences in flow pattern are mainly attributed to the lagoon depth. Lagoon-A possesses higher depth over Lagoons B, C and D, which allows more potential solids settling and greater prevalence of settling forces, as observed at the bottom in Fig. 4(a). The settling forces subsequently increase bulk liquid momentum and overall velocity in the deepest region of the lagoon. Conversely, Lagoons B, C and D (having shallow depth and less steep than Lagoon-A) exhibit a lower dependency on the behaviour of the solid and are mostly impacted by liquid superficial velocity, resulting in marginal solid-liquid momentum exchange and uniform velocity over depth.

Fig. 4 shows the sludge distribution of these lagoons-sludge accumulated and consequently formed sludge bed at the bottom of the lagoon. Most deposits in the sludge bed, but also along the embankment, which is most relevant for Lagoons A and D relative to Lagoons B and C. Fig. 5 shows a quantitative comparison of the accumulated sludge over depth of these lagoons. The sludge concentrations are significantly higher in Lagoons A and D compared to those of

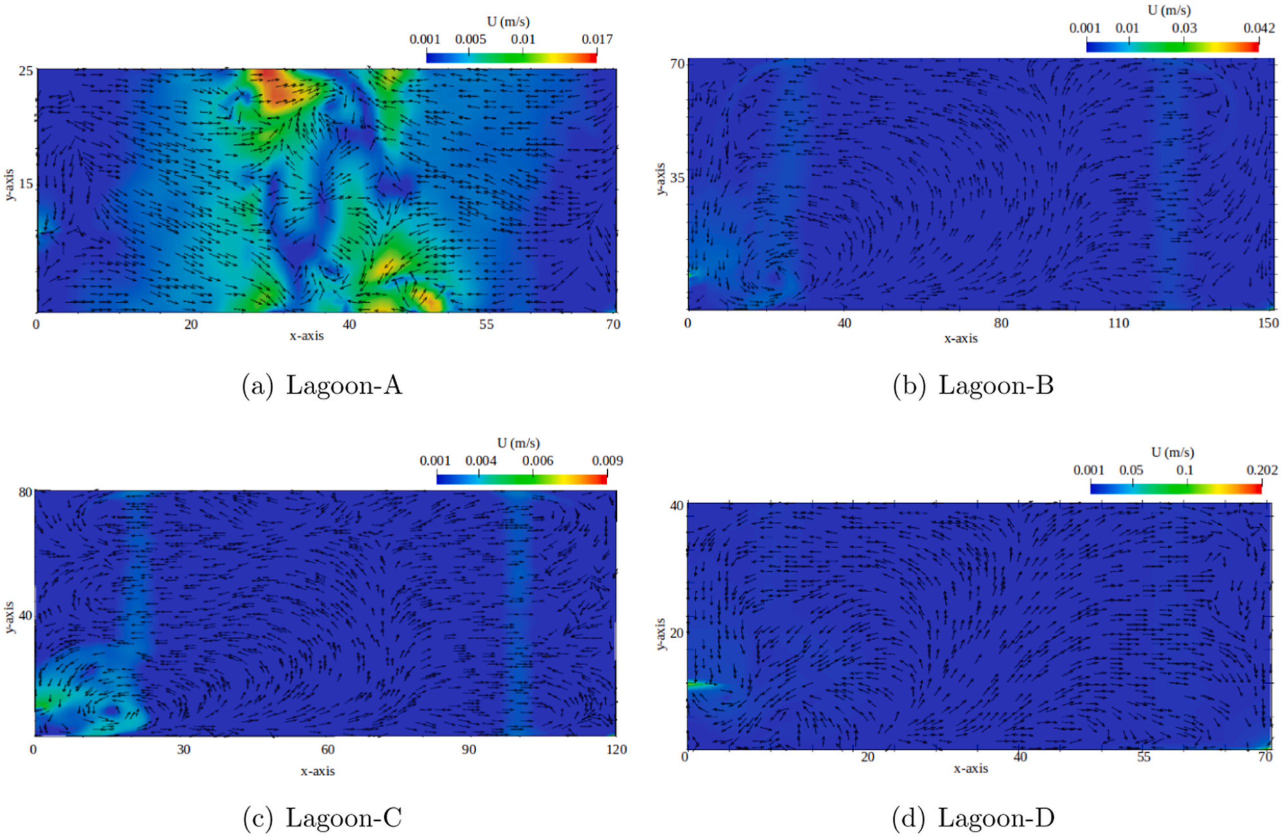

Fig. 3 – The velocity contours and glyph at the top (x-y plane) of the (a) Lagoon-A at Q = 61.66 m³/d, (b) Lagoon-B at Q = 276.78 m³/d, (c) Lagoon-C at Q = 61.27 m³/d, and (d) Lagoon-D at Q = 1248 m³/d. Here, Q represents the mass flow-rate, and units of the x-and y-axes are in m/s.

Lagoons B and C, which is mainly attributed to the geometry in Lagoon A, and loading rate in Lagoon D. Lagoon A possesses higher HRT over Lagoons B, C and D. In comparison between Lagoons A and D, the geometry of Lagoon A likely affects the sludge bed concentration- the higher depth, steeper embankment inclines and smaller basin surface area for higher volumes of sludge to form concentrated beds within a small area.The sludge deposition rates of these lagoons are found as 0.13 m^3/d for Lagoon-A, 0.72 m^3/d for Lagoon-B, 0.10 m^3/d for Lagoon-C, and 2.92 m^3/d for Lagoon-D. The substantially higher deposition rate of Lagoon-D compared to the others is mainly attributed to its higher flow-rate (1248 m^3/d for Lagoon-D, whereas 61.66 m^3/d, 276.78 m^3/d, and 61.27 m^3/d for Lagoon A, B, and C, respectively).

3.2. *CBM parameters estimation*

Fig. 6 shows the RTD profiles obtained from the CFD and CBM simulations for Lagoon-A (Fig. 6(a)), Lagoon-B (Fig. 6(b)), Lagoon-C (Fig. 6(c)), and Lagoon-D (Fig. 6(d)). Note that, the tracer concentration and time are normalised against the initial concentration and HRT, respectively. Lagoon A and B exhibit very narrow initial peaks with a sharp decline before steadying to a more gradual response, which is representative of a significant fraction of flow bypassing. While all lagoons have delays, Lagoon-D has a shorter delay. Furthermore, Lagoon-D exhibits heavy oscillations after the first peak before reaching a steady decline, attributing to tracer recirculating at the outlet. This could not be effectively represented by a high internal recycle (likely due to the lack of individual compartments in the recycle model), but a common model was retained.

Table 2 shows a summary of the predicted CBM results. The apparent active fraction varied substantially, with long HRT and shallow depth causing a lower active fraction. Lagoons A and B possess a comparable HRT, with Lagoon-A is deep and Lagoon-B is shallow. The deep Lagoon-A shows a very limited recycle. The shallow depth in Lagoon-B causes an increase in the apparent cycle, which also likely resulted in increased apparent bypass. This slightly decreases the overall effectiveness of the main volume, resulting in an increased fraction with limited retention time in the lagoon.Lagoon-C exhibits a substantial bypass and virtually eliminating recycle. This high bypass volume is mainly attributed to increasing dispersion of the bypass flow into the main hydraulic volume. It should be noticed that Lagoon-C has the lowest active fraction compared to those of others. In comparison with Lagoons A, B, and C, a different scenario is observed in Lagoon-D, where the system is dominated by the recycling, with a high bypass.

3.3. *Long term simulations and comparison with the experimental results*

Fig. 7 shows the occupied volume (i.e. volume not occupied by the sludge) long-term, which varies between 38 days (Lagoon-D), and 7.9 years (Lagoon-C). Table 3 demonstrates a summary of the predicted biochemical results along with measured sludge accumulation rates. Lagoon-D is the clear outlier, with a very short effective life, and otherwise lower performance, in terms of both solids destruction (high sludge

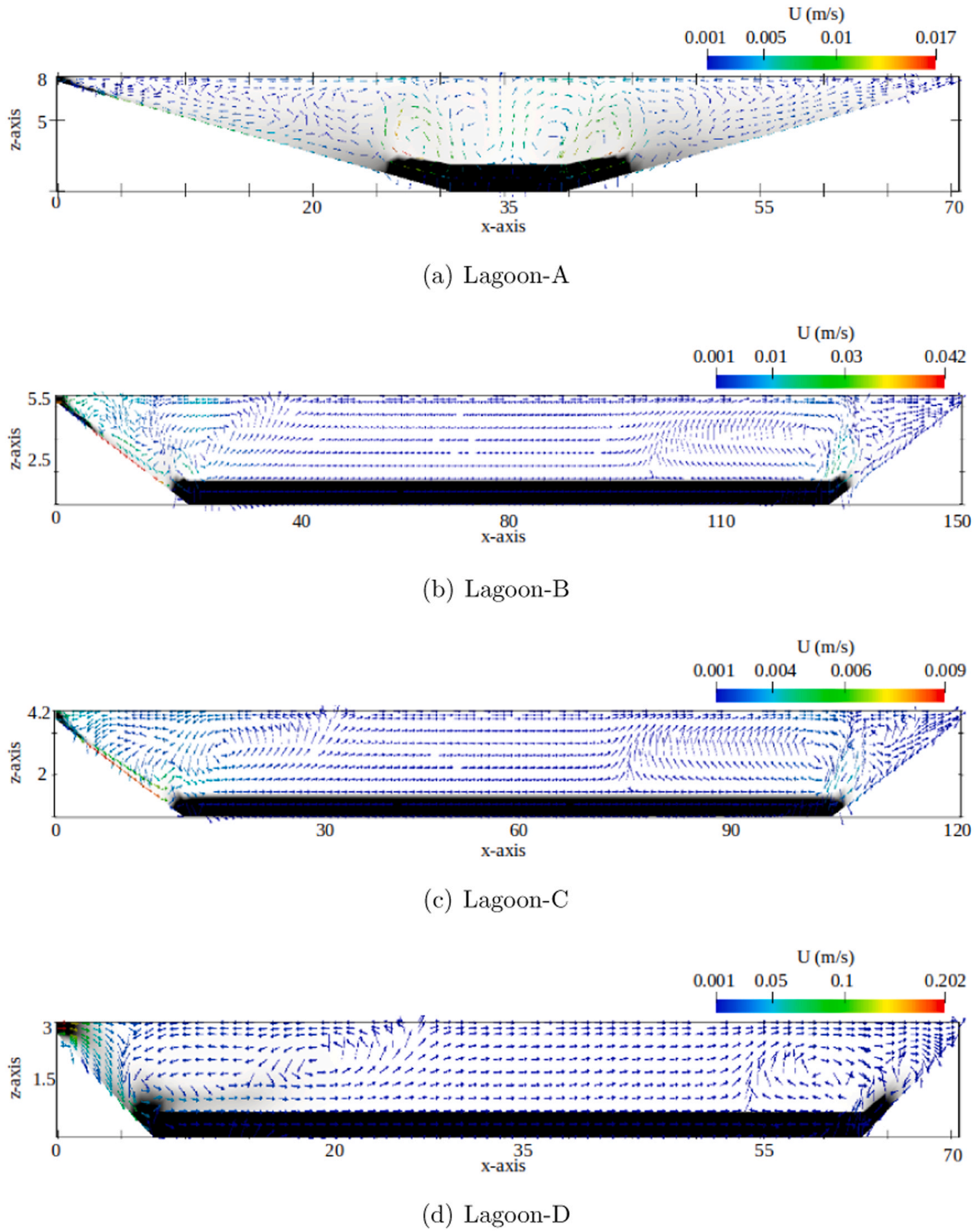

Fig. 4 – The velocity glyph and sludge layer (black colour) at the longitudinal (x-z plane) of the (a) Lagoon-A at Q = 61.66 m^3/d, (b) Lagoon-B at Q = 276.78 m^3/d, (c) Lagoon-C at Q = 61.27 m^3/d, and (d) Lagoon-D at Q = 1248 m^3/d. Here, Q represents the mass flow-rate, and units of the x-and y-axes are in m/s. For the sake of visualisation, scaling is used at z-axis for Lagoon-B, Lagoon-C, and Lagoon-D, and the units for x-and z-axes are in m/s.

VS/TS), and poor outlet solids. This indicates that such a short HRT is not suitable for an anaerobic lagoon where solids accumulation is a significant mechanism. Lagoons A and B possess a similar behaviour- the same amount of effluent concentrations and sludge VS/TS. On the contrary, Lagoon-C experiences higher effluent concentration levels than those of the Lagoons A and B. This is mainly attributed to relatively high bypass, which was identified as being due to the very long retention-time, and relatively shallow depth of Lagoon-C. The results reinforce the conclusion that this combination is not an effective use of the lagoon volume.

The modelled accumulation rates are approximately double the observed accumulation rates for all of these lagoons. The observed accumulation rate for Lagoon-D was not available. For Lagoons A, B and C, the higher accumulation rates relative to the observed results may be attributed to either (a) additional solids degradation beyond the expected biochemical degradation (i.e. more than 60% is degrading) due to long retention times, or (b) differential separation of organic and mineral solids. The analysis of lagoon lifetime shown assume the lower degradation extent as found by biochemical modelling. If further degradation occurs (as field

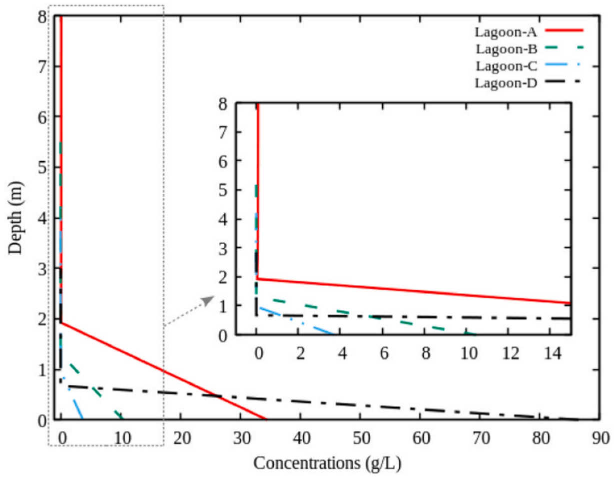

Fig. 5 – The profiles of sludge accumulation along depth of the (a) Lagoon-A, (b) Lagoon-B, (c) Lagoon-C, and (d) Lagoon-D, at the flow-rates of Q = 61.66 m^3/d, 276.78 m^3/d, 61.27 m^3/d, and 1248 m^3/d, respectively.

observations would indicate), lagoon lifetime would naturally further extend. In lagoons with longer retention times, the hydrolysis coefficient, and its decrease related to lower temperatures becomes less important than the inherent degradability of the material.

The observed sludge accumulation rates ranged from 0.00054 to 0.00324 $m^3/kgTS_{fed}$, with a mean value of 0.00228 ± 0.00053 $m^3/kgTS$ (95% confidence intervals). This mean value is approximately equal to the mean of the previous design standard 0.00303 $m^3/kgTS$ Barth (1985) and the current design standard 0.00137 $m^3/kgTS$ ASABE (2011). The variability in the sludge accumulation rate estimates probably reflects the uncertainty regarding lagoon desludging times and volumes of sludge removed, and lagoon design variations. Actual sludge measured concentrations across all lagoons were 55.5%, with similar values across all lagoons, with similar variability, but significantly lower than modelled results (Skerman et al., 2019). This aligns with the lower actual (compared with model) accumulation rates as shown in Table 2.

4. Discussion

4.1. Model performances

The fluid movement largely varies throughout the lagoons, resulting in a varying flow regime and distinct flow pattern. The solid settling forces and momentum become the primary drivers of the fluid movement, indicating 3-D flow and representation of solids is important to CFD prediction of hydraulics. The short-term CFD simulations are insufficient to find a realistic picture of the sludge accumulation. This is because there is an initial stabilisation, or warm-up period, immediately after commissioning the lagoon. The sludge bed must then develop to a height where it approaches an equilibrium between sludge depositing onto the bed and sludge exiting the lagoon. This can also be thought of as a critical bed depth. Until then, accumulation rates will likely be at levels not representative of long-term operation. The length of this theoretical period is unclear. It is not possible to conduct CFD simulations on this time scale, but different initial conditions may be used to simulate a system with a substantive existing inventory.

The CBM could reasonably represent tracer results from the CFD analysis and expand the simulation time-frame from months to years. Notably, the study identified that as lagoon HRT increased from smaller lagoons (days) to moderately sized lagoons (months), the hydraulics conformed more to ideal hydraulics, with decreased short-term dynamics due to internal recycles. As the system extended to very long HRTs (years), bypass emerged, probably due to insufficient turbulent dissipation. The effective volume variation with lagoon depth and HRT further confirmed the critical design HRT of ~ 150 d, and depth of > 6 m. CBM was relatively effective at representing simple hydraulics, but particularly oscillation caused by recycles are difficult to simulate in a common model.

The biochemical model allows translation of short-term sludge behaviour results by CFD (and CBM) into long-term behaviour and provides a more accurate prediction of sludge accumulation rates. The CFD model predicts almost complete sludge capture, but this is related to the short simulation periods (from an empty lagoon), and better accumulation rates may be represented where the initial condition is a lagoon with a high sludge inventory. The CBM more effectively predicts accumulation rate, but still substantially under-predicts this. This is not related to effluent solids loss (since in at least one case, the effluent solids was higher than predicted) (and the CBM model used increased effluent solids over time). It is far more likely that long-term degradability is higher than that predicted by the biochemical methane potential. This is further evidenced by the observed VS/TS fraction of 42% vs the simulation prediction of 62% (at long retention times). This highlights the issues in determining long-term parameters (including apparent degradability) from short term tests such as a methane potential test. The results here tend to indicate that short term tests are very conservative.

4.2. Design and operational factors

Depth appears as one of the primary design factors controlling fluid movement and solid settling and the lagoons' overall sludge behaviour. The back-mixing and short-circuiting behaviour found to reduce with increasing depth, while HRT was kept constant. Furthermore, the higher depth typically enables a higher inventory and clear water separation, which allows the water to either react in the active treatment volume or enter the exiting currents to the outlet before settling.

Along with depths, the embankment is a crucial design parameter. In this study, the steeper embankments showed to induce turbulence in the lower layers of the lagoons. This is likely a result of counteractive force as two-phase liquid impacts onto the embankment. If the turbulence occurs low enough to contact the sludge beds, this will induce remixing of the sludge into the active treatment, effectively reducing sludge accumulation and increasing treated throughput. On the other hand, steep enough embankment inclines may cause funnelling of solids towards the basin, allowing for selective zoning of sludge settling (and easier desludging) but possibly higher accumulation rates. After a literature review, only one article appears to have studied sludge accumulation in wastewater stabilisation lagoons through computational hydrodynamic models Alvarado et al. (2012). A primary

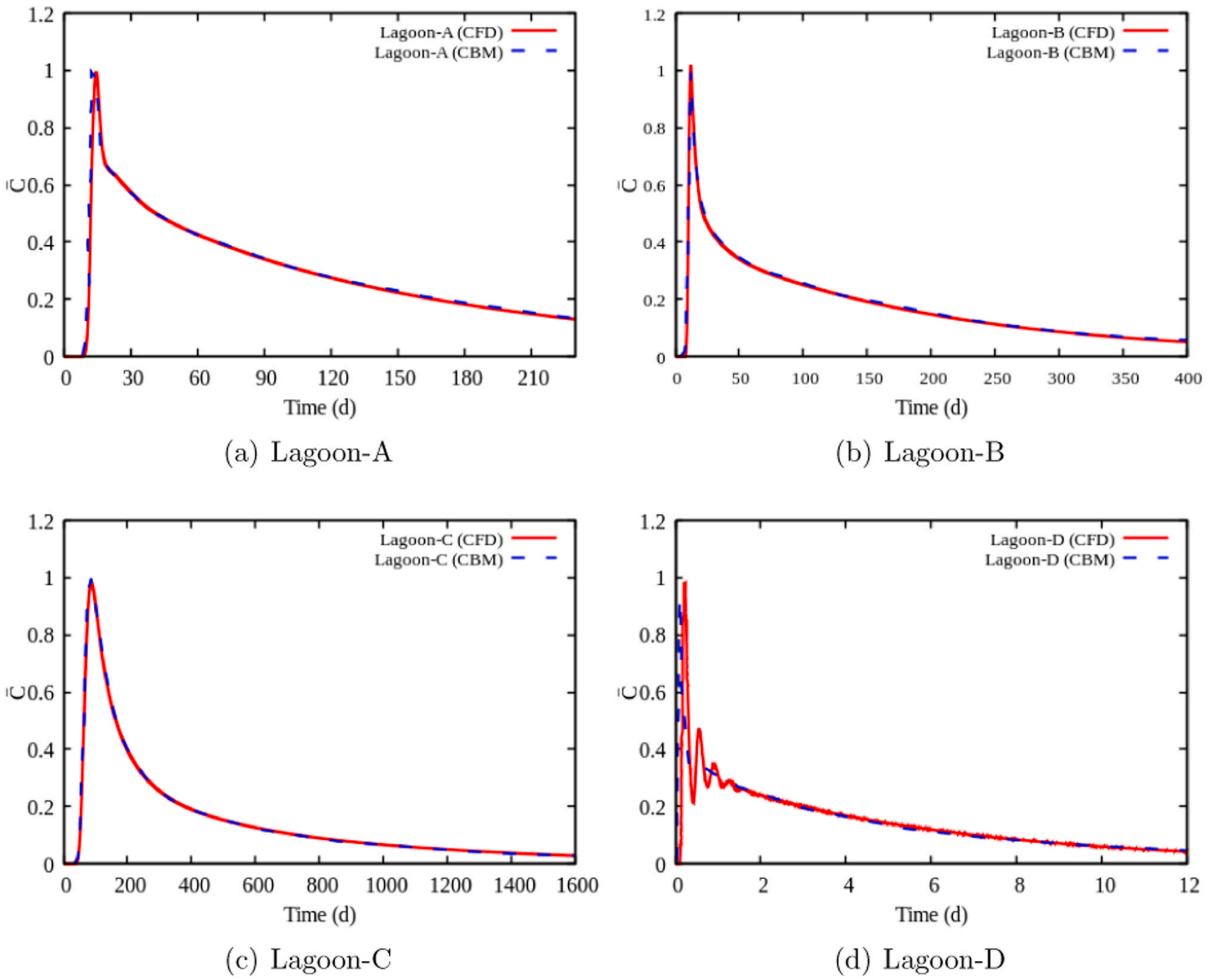

Fig. 6 – The residence time distribution (RTD) profiles of (a) Lagoon-A at Q = 61.66 m^3/d, (b) Lagoon-B at Q = 276.78 m^3/d, (c) Lagoon-C at Q = 61.27 m^3/d, and (d) Lagoon-D at Q = 1248 m^3/d, using CFD and CBM. Here, $\bar{C}$ represents the normalised tracer concentrations.

Table 2 – A summary of the compartmental based model (CBM) results. Here, V_{main}, $V_{recycle}$, and V_{bypass} represent the volume main, recycled, and bypassed, respectively; $Q_{recycle}$, and V_{bypass} represent the flow recycled, and bypassed, respectively.

	Lagoon-A	Lagoon-B	Lagoon-C	Lagoon-D
Theoretical V (m^3)	7200	67600	43371	8500
Modelled V (m^3)	8164	48744	24605	6963
Active fraction	113%	72%	57%	82%
Input flow (m^3/d)	61.77	276	61.27	1248
Theoretical HRT (d)	117	244	708	6.81
Actual HRT (d)	131	177	402	6
Delay (d)	11.2	10.2	54	0.11
V_{main} (m^3)	8341	25357	23867	4626
$V_{recycle}$ (m^3)	599	23364	0	2254
$Q_{recycle}$ (m^3/d)	20	1268	0	3238
V_{bypass} (m^3)	4	23	738	83
Q_{bypass} (m^3/d)	2	17	13	253
Fraction bypassed	3%	6%	6%	20%

finding among this study, as well as other studies using non-computational models of sludge accumulation (Nelson et al., 2004a; Abis and Mara, 2005; Picot et al., 2005), is that sludge deposits accumulate rapidly in tall mounds at a location relatively near the inlet as a result of high settling velocities and downward fluid velocities. In contrast, each lagoon of the current study has its inlet surrounded by embankments which, rather than allowing the build-up of sludge mounds, direct sludge towards the flat basin into graded beds. This is a substantial advantage of a graded lagoon and significant to lagoon longevity. A critical incline value at which embankments induce optimal turbulence would be valuable to lagoon designers. Such a value will likely vary according to the sizing dimensions and will need to be calculated for individual lagoons.

The optimal HRT for the mentioned lagoons was estimated at 150 days, which suggests the period to maximise the lagoon performance and lifetime considering the potential costs incurred by unpredictable flow dynamics. The CBM and CFD analysis showed that exceeding this HRT causes back-mixing, short-circuiting and/or increased presence of low velocity and inactive regions.Furthermore, the high VS/TS ratios and accumulation rates in Lagoon-D suggest that a low HRT lagoon is not suitable for the high solids concentration of piggery effluent. If sludge is actively recycled, it

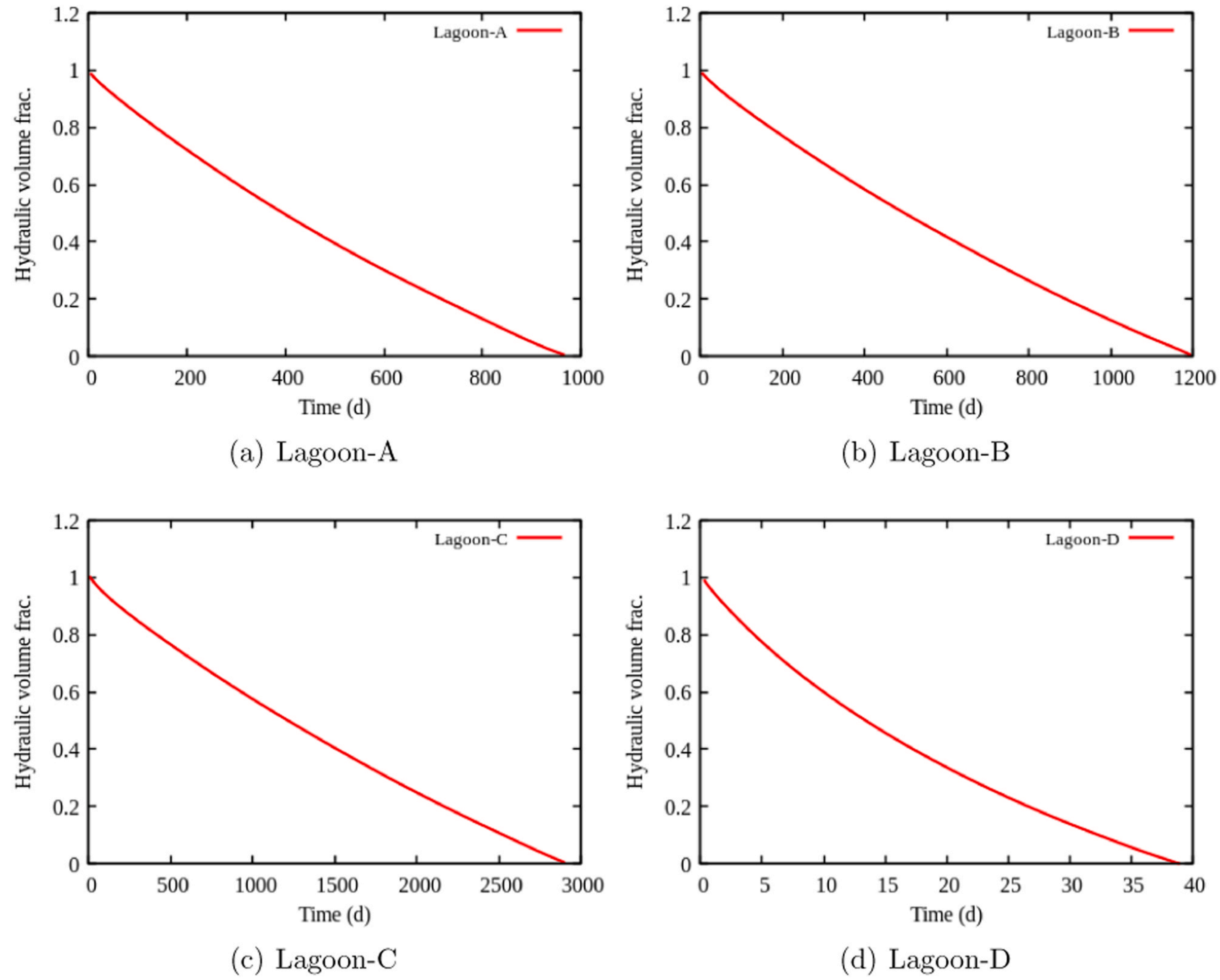

Fig. 7 – The biochemical model simulation results of occupied volume over Lagoon life for (a) Lagoon-A, (b) Lagoon-B, (c) Lagoon-C, and (d) Lagoon-D.

Table 3 – A summary of the simulation results and observed accumulation rates. Here, EOL represents the End-Of-Life; VS, and TS represent the volatile solid, and total solid, respectively.

Values	Lagoon-A	Lagoon-B	Lagoon-C	Lagoon-D
Lifetime	2.6 y	3.3 y	7.9 y	38.3 d
Model effluent TS conc. (EOL)	1.1%	1.1%	1.28%	1.40%
Model sludge VS/TS (EOL)	62%	62%	62%	68%
Modelled accumulation rate ($m^3/kgTS_{fed}$)	0.0050	0.0049	0.0042	0.0061
Observed accumulation rate ($m^3/kgTS_{fed}$)	0.0026	0.0028	0.0018	–

will effectively act as a solids digester and remove organic solids. Still, in this case, the design should incorporate this (as a high-rate solids lagoon) and include downstream treatment to achieve the same performance as long retention time lagoons.

5. Conclusions

The results showed that mixing and sludge behaviour is sensitive to the lagoons depth and side-wall angle. A deep lagoon results in a better mixing and active fractions, and, subsequently, improves the ability to manage and accumulate solids without affecting lagoon performance. For example, the study found that a deep lagoon (depth of 8 m) outperforms a shallow lagoon (depth of 3 m) with regards to (a) increasing sludge holding capacity, (b) decreasing the hydrodynamic impacts on the sludge accumulations, and (c) minimising internal recycles and bypass flows. Furthermore, it observed that the higher depth combining with sharply sloped side-walls of the lagoon could substantially minimise the dead zones, and eventually, allow sludge accumulation in the desludging zones. Finally, the results found, combining with these geometric parameters, HRTs should be maintained within a range of 100 days to 300 days to maintain active fraction, minimise short-circuiting, and maintain an effective lifetime. While a CBM allowed use of CFD results to predict long-term sludge accumulation rates, it over-predicted sludge accumulation rate compared with that observed, largely due to long-term degradation of material in excess with that identified by BMP testing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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